Air temperature measurement uncertainty associated to a mounting configuration temperature sensor-radiation shield

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Abstract: In weather stations, the air temperature sensors are mounted inside different types of enclosures, designed to protect them from precipitations and direct solar radiation. As a consequence, the measured parameter is not open air true temperature. Existing studies on radiation shields influence on air temperature measurements, either experimental or numerical, focuses on differences between various shield designs and choice of the most appropriate configuration to minimize measurement errors. Our approach is to use numerical simulation of heat transfer between air temperature sensor and meteorological radiation shield to determine an uncertainty associated with the shield-sensor ensemble. In particular calculations were performed for a sensor mounted inside a Stevenson screen for the worst case of low wind speed and high solar irradiation with different values for 6 ambient parameters (sun position, ground absorptivity, air temperature, ground temperature, paint absorptivity, sensor material). The presented method may also be used for finding the optimal position of the temperature sensors inside the radiation shields, to achieve the lowest uncertainty of the measurements.

1. Introduction

In meteorology and climatology air temperature is always measured with a sensor protected from direct sun radiation, rain and wind by a screen. Air temperature is an important variable for monitoring climate change and the adoption of different screens by meteorological institutes constitutes a serious threat to comparability of measurements over the world. Therefore numerous field intercomparisons of different screens are performed since the XIX century. More recently, error estimations based on modelling the heat transfer around temperature sensor are proposed [1,2]. The present work follows this approach in order to first estimate differences in temperature inside the naturally ventilated wooden Stevenson screen and open field air temperature attributable to ambient conditions for a given screen and sensor and second to deduce uncertainty components.

The simulation model is shown in figure 1. The model consists of Stevenson screen, a temperature sensor mounted in the centre of the screen, the sun as an external radiation source, ground, and surrounding air. The screen is heated by direct sun radiation and radiation reflected from the ground. The surrounding air flows in parallel to the ground and reaches the shield from its front side. Besides the shortwave direct and reflected solar radiation, the model also includes longwave radiative heat exchange between the shield and the surrounding ground.

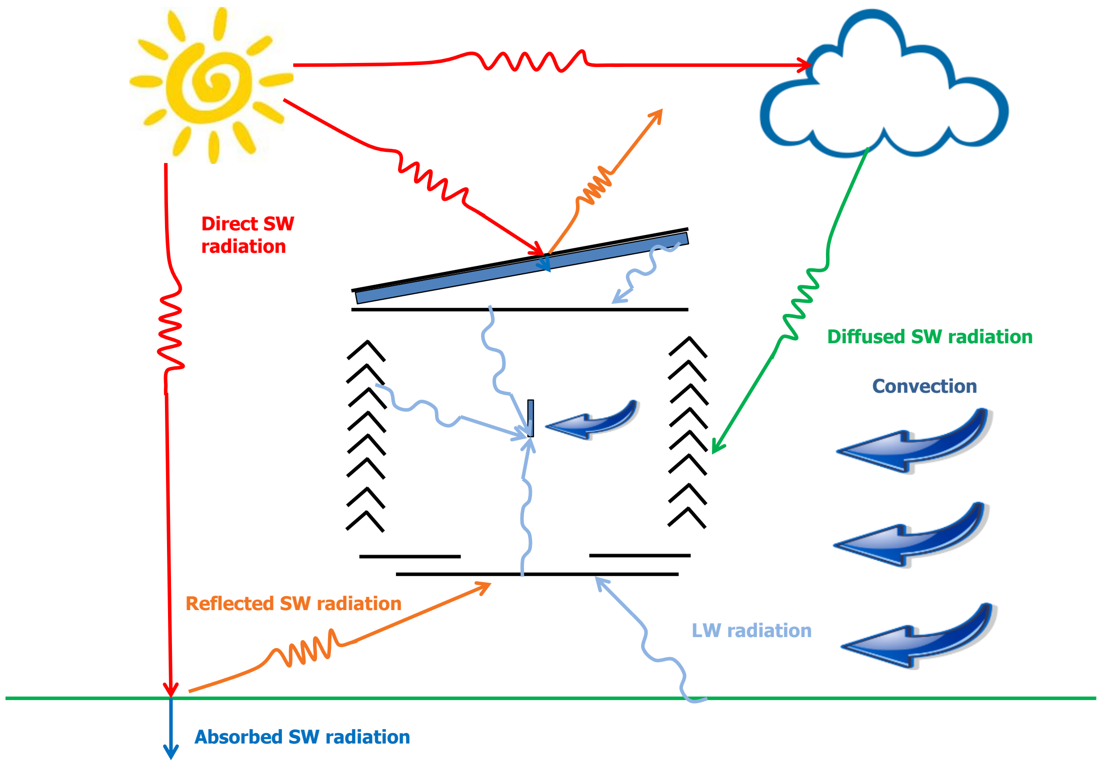


Figure 1. Heat transfer modes involved in modeling the measured temperature inside a meteorological screen.

Simulations are performed using Comsol Multiphysics software which includes a heat transfer module and the possibility to couple flow and heat transfer calculations.

The approach followed in this work is to estimate the magnitude of individual influences that contribute to the uncertainty of meteorological air temperature measurement and derive the uncertainties related to the shield. The measurand is the open field meteorological air temperature (T_{air}). It can be expressed as a function which contains every quantity and correction factors (corrections attributable to that contribute to the uncertainty to the measurement result:

$$T_{air} = T_{sensor} + \Sigma Cor_{\ sensor} + \Sigma Cor_{\ IN\ environ} + \Sigma Cor_{\ OUT\ environ} \quad (1)$$

The measured quantity is fact the temperature recorded by the sensor inside the meteorological shield, T_{sensor}.

The correction factors may be grouped as:

- factors related to the sensor intrinsic characteristics, Cor_{sensor}. This category accounts for sensor self-heating, hysteresis and time constant;
- factors related to the far environment of the sensor, outside the meteorological shield, $Cor_{\ OUT\ environ}$. This category groups factors related to the sitting position of the weather station such as influence of roads, trees or buildings.
- factors related to the near environment of the sensor, inside the meteorological shield, $Cor_{\ IN\ environ}$. This category includes the radiation shield design and the influence of other elements placed inside it (electronics for data transmission, other sensors, ventilation, power supply, etc.)

Every quantity in equation 1 has its own associated uncertainty which contributes to the combined measurement uncertainty.

In this work we focused on $Cor_{IN\ environ}$ factors. For this first study only the influence of effects related to the radiation shield design is investigated but effects of additional elements placed in the same shield can be added to the model using a similar heat and flow modeling approach.

Figure 2 shows the factors that are included in our model: solar irradiance, screen material, screen geometry, wind speed, screen surface finishing (emissivity, albedo), ground characteristics (emissivity, albedo). This factors are input constants that can be varied to quantify, for example, the ground cover effect (grass, snow, concrete).

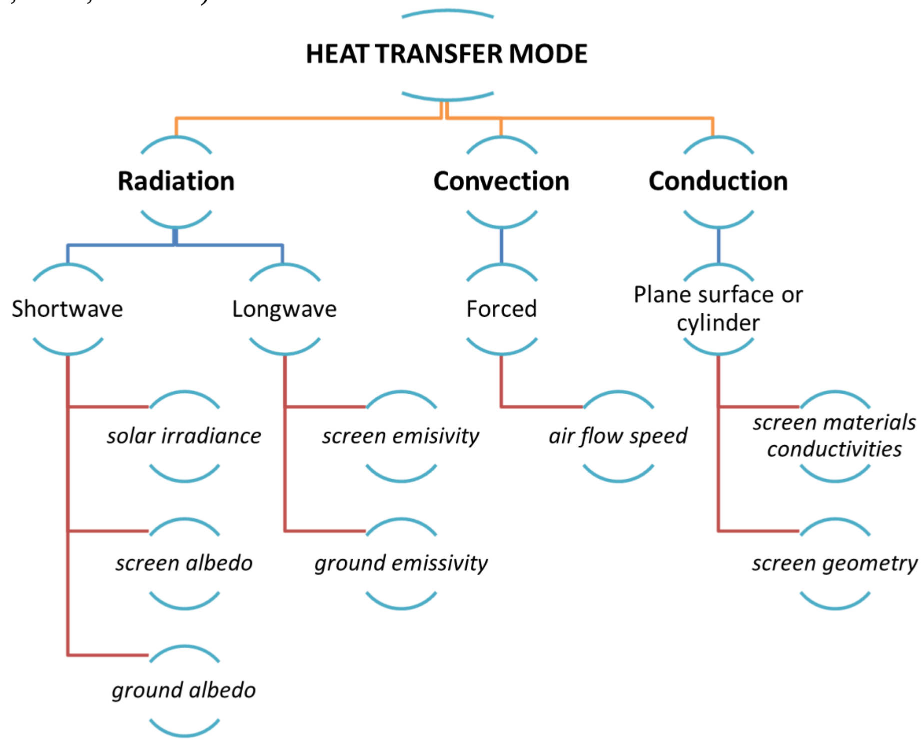


Figure 2. Ambient parameters contributing to heat transfer inside a meteorological shelter

2. Building the numerical model

The 3D model of the Stevenson screen with temperature sensor is based on the real wooden screen, installed in Brussels, at Royal Meteorological Institute of Belgium. The screen is approximately 1060 mm wide, 580 mm long and 740 mm high. In all performed simulations, screen bottom is fixed at 1.5 m above the ground. The screen accommodates the thermometer which is modeled as a simple cylinder of 6 mm in diameter and 36 mm long. Being mounted in the centre of the screen, thermometer measures air temperature at the height of 1.85 m above the ground. After performing preliminary simulations, the dimension of the ground area was set to 200 x 200 m, with screen positioned in its center. The air domain was set to 3.5 m on each side except in front of the screen where air inlet length was 7.5 m. Symmetry was not used as the direction of the sun radiation was not symmetrical on the radiation shield.

Figure 3 shows the mesh chosen for final simulations. It consists of 1.6 million elements, most of which are tetrahedral. The greatest set of elements is used to describe the air in proximity to the screen. Two boundary layers were used on all shield surfaces that are in contact with air, and eight layers are used on the ground.

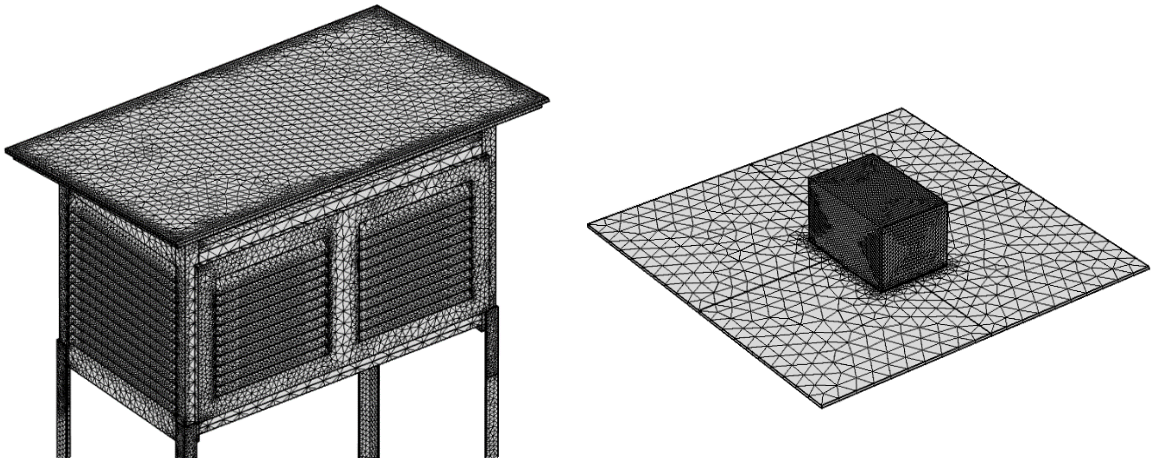


Figure 3. Screen and domain mesh.

The simulation was solved using Comsol's Non-Isothermal Flow and Conjugate Heat Transfer Interfaces. The interface solves fully compressible formulation of the continuity and momentum equations as well as heat equation. The turbulent incompressible air flow is simulated using k-ε turbulence model.

For thermal radiation, the wavelength dependence of emissivity is taken into account by using two spectral bands, a solar band for wavelengths shorter than of 2.5 µm and ambient band for wavelengths above mentioned value. For each surface participating in radiation heat exchange, properties are defined in terms of a solar absorptivity and an emissivity. The model is solved for steady state conditions.

The component materials with corresponding properties used in the simulations are shown in Table 1. As values for material properties are varying, depending on the information source, additional study of their influences on the simulation results is planned in the future research. The properties of the air are excluded from the table as they are provided by Comsol's built-in material library.

Table 1. Material properties

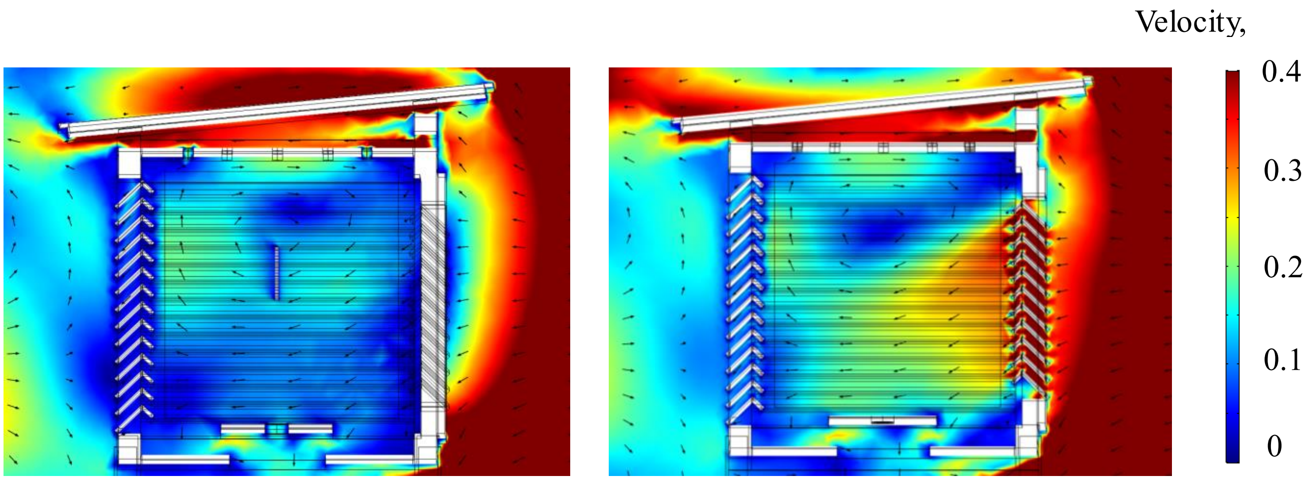
Component	**Material**	**Densitykg/m^3**	**Thermal conductivity W/m*K**	**Heat capacity at constant pressure J/kg*K**
Shield - wood	Oak	700	0.19	2390
Shield - roof	Asbestos	700	0.36	1050
Thermometer	Copper	8960	400	385
Component	**Material**	**Emissivity**	**Absorptivity**	
Ground	Grass	0.986	0.77	
	Snow	0.82	0.13	
Shield painting	White paint	0.96	0.2	
Sensor	Galvanized metal new	0.65	0.13	
	Stainless steel	0.37	0.05	
	Copper	0.4-0.65	0.2-0.3	

3. Simulation results

The first set of simulations where performed with the following parameter settings:

- Inlet air speed of 1 m/s
- Surrounding air temperature 20 °C
- Grass ground
- White screen painting
- Screen made of stainless steel
- Solar irradiance 800 W/m^2
- Ground and ambient temperature 20 °C

Inside the shield, air velocity does not exceed 0.35 m/s, as shown in figure 4. This value is in very good agreement with experimental air speed measurements performed inside a similar meteorological screen [2]. It can be observed that the air velocity around the thermometer is lower in comparison to the areas behind the door louvers, as the door frame in front of the thermometer obstructs the air flow.



a. Plane through the screen center (behind the door frame).

b. Plane located 250 mm on the left of the screen center (behind the door louvers).

Figure 4. Velocity profile inside the shield.

The differences of temperatures inside the shield and temperature of the environmental air are shown in figure 5. Similarly, as in the case of velocity profiles, it can be observed that the door frame protects the thermometer from the warm air stream being heated by the louver surfaces.

For the given conditions and for an open field air temperature of 20 °C, calculated average thermometer temperature is 21.13 °C, while the air temperature inside the shield varies from 20.23 to 24.34 °C. By analyzing the simulation results, it was determined that the present temperature difference could be reduced to approximately 0.23 °C by placing the thermometer closer to the upper door louvers. In this way, the airflow around the thermometer would be increased. On the other hand, in this area, the air receives less heat from the door louvers as they are cooler since they are in the shadow provided by the shield roof. The results are in agreement with experimental measurements performed with a similar screen design [2,3].

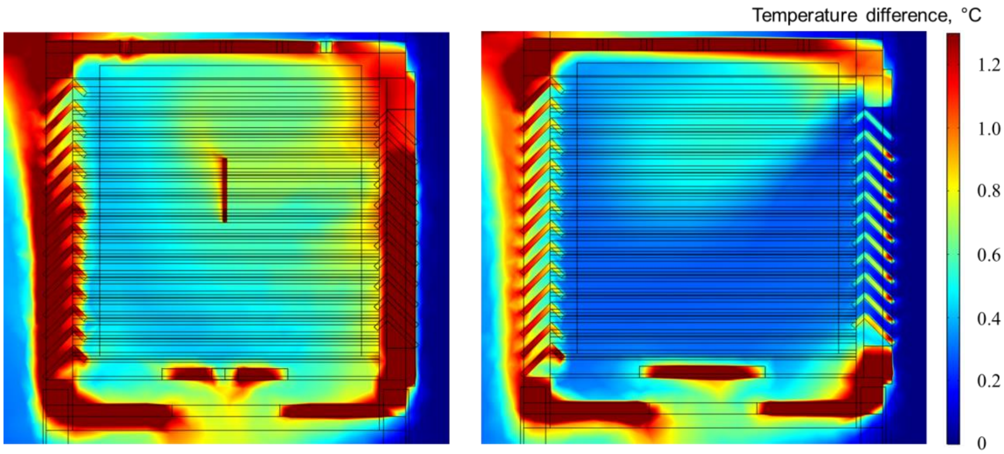


Figure 5. Temperature difference of the air inside the shield and surrounding air. Left: the plane cutting through the thermometer center (behind the door frame). Right: the plane located 250 mm to the left of the thermometer (behind the door louvers).

4. Uncertainty in air temperature measurement

If no correction is made to the temperature measured by the sensor in the meteorological shield the value will differ from the real air temperature in open field. The difference can be translated into a measurement uncertainty value.

We simulated different ambient conditions in order to calculate the range of the expected differences. In a simple approximation, without further information about the distribution of values inside this range, we can use a square distribution to translate these differences into uncertainty values for individual factors.

First, the wind speed influence is assessed by varying both wind speed and solar radiation values. At maximal solar irradiation we can see in figure 6 that the temperature difference between sensor and air temperature decreases exponentially with wind speed increase.

As the **wind speed influence** is very important **a correction is more suitable** than including this effect into the measurement uncertainty. For the configuration shield/sensor considered in our simulations the correction equation is:

$$\Delta T = 1.5 \cdot V^{-0.8} \tag{2}$$

With ΔT the temperature difference between sensor and open air expressed in °C and V the wind speed expressed in m/s.

Figure 7 presents the combined influence of wind speed and solar irradiation. We can see that except for the case of very low wind, the meteorological shield considered here is a very good protection against sun and wind effects.

The other factors considered in this work are grouped in table 2. For example, the ground around a meteorological shield is usually grass. But depending on the type and humidity of the grass the absorptivity values found in literature varied from 0.7 to 0.84.

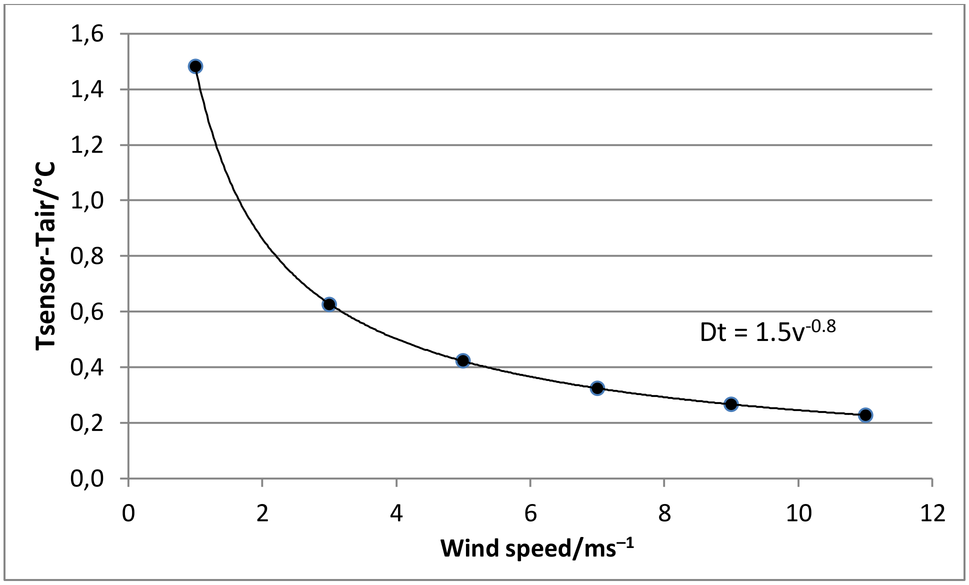


Figure 6. Temperature difference of the air inside the shield and surrounding air for different wind speed at maximum solar irradiation (1000 Wm^{-2}).

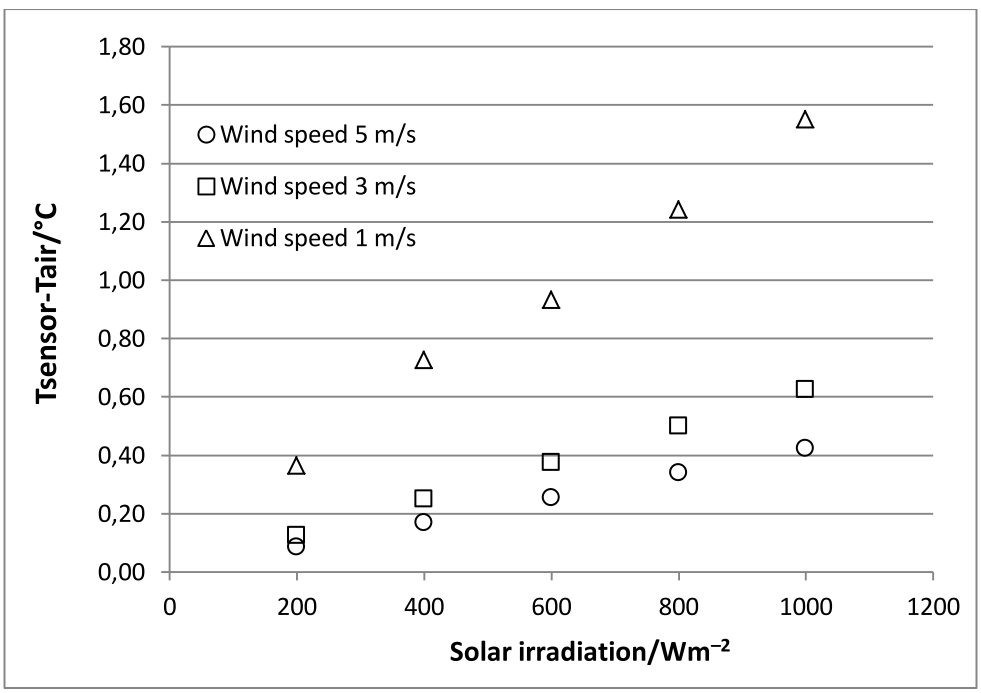


Figure 7. Temperature difference of the air inside the shield and surrounding air for different solar irradiations at different wind speeds

In our simulations we used a value of 0.77 but to account for the effect of different types of grass we varied the value and obtained a maximum difference of 1.79 °C at the sensor level from air (set at 20 °C) and a minimum of 1.17 °C. The difference between upper and lower limit is therefore 0.62 °C.

The uncertainty estimation for grass condition influence in the worst case of low wind speed and maximum sun is 0.36 °C.

In a similar manner we evaluated the influence of paint absorptivity for values ranging from 0.2 white new paint to 0.45 (dirty white paint). This range contains also all values found in literature for different types of white commercial paint.

The uncertainty estimation for paint condition influence in the worst case of low wind speed and maximum sun is 0.05 °C.

All uncertainty values presented hereafter are calculated for a worst case of very low wind speed (1 m/s) and very high solar irradiation (1000 W/m^2).

Table 2. Uncertainty contributions related to ambient parameters at low wind speed (1 m/s and high solar irradiation 1000 W/m^2)

Factor	Parameter	Range of parameter	Range of difference Tsensor-Tair °C	Uncertainty °C
Grass	Absorptivity	0.7 – 0.84	0.62	0.36
Paint	Absorptivity	0.2 – 0.45	0.09	0.05
Ground temperature	Temperature	10 – 20 °C	0.28	0.16
Air temperature	Temperature	10 – 20 °C	0.27	0.16
Sensor material	Copper, steel		0.24	0.14
Sun position	Hour	12:00 – 19:00	0.34	0.20
			Combined uncertainty	**0.49**

The other parameters investigated in this first study are ground and air temperature, sensor material (brass, copper, stainless steel) and sun elevation.

All those factors, if not corrected and in the worst case of low wind and maximum sun irradiation generate a combined uncertainty of 0.5 °C. This value assumes a correction is made for the wind speed influence. If not the combined uncertainty is 0.9 °C. This value is dependent on the shield geometry and sensor characteristics.

5. Conclusion

In this paper, methods and preliminary results of numerical simulation of airflow and heat transfer in a wooden meteorological screen have been presented. The model allows changing the following input parameters: surrounding air (temperature and velocity), sun (irradiance and position), meteorological screen (design, materials and painting properties; emissivity and absorptivity), thermometer (design, material properties and position), and ground surface (temperature and properties; emissivity and absorptivity). The model has proven to be suitable for detailed analysis of the influence of above parameters on the error in air temperature measurements. The error obtained for extreme conditions of low wind speed and high solar irradiation is in very good agreement with asessment performed through experimental in-field comparisons of screens. Quantifying the errors is a step towards calculating real in-field measurement uncertainties. An example is given here for the case of Stevenson screen where the influence of painting condition, of grass type, of ground and air temperature, of sun position and of sensor material are investigated in order to calculate a worst case combined uncertianty in low wind and maximum sun conditions.

Planned future work will include fan aspirated radiation shields and transient phenomena, particularly for low environmental air velocity conditions where significantly higher errors typically occur.

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