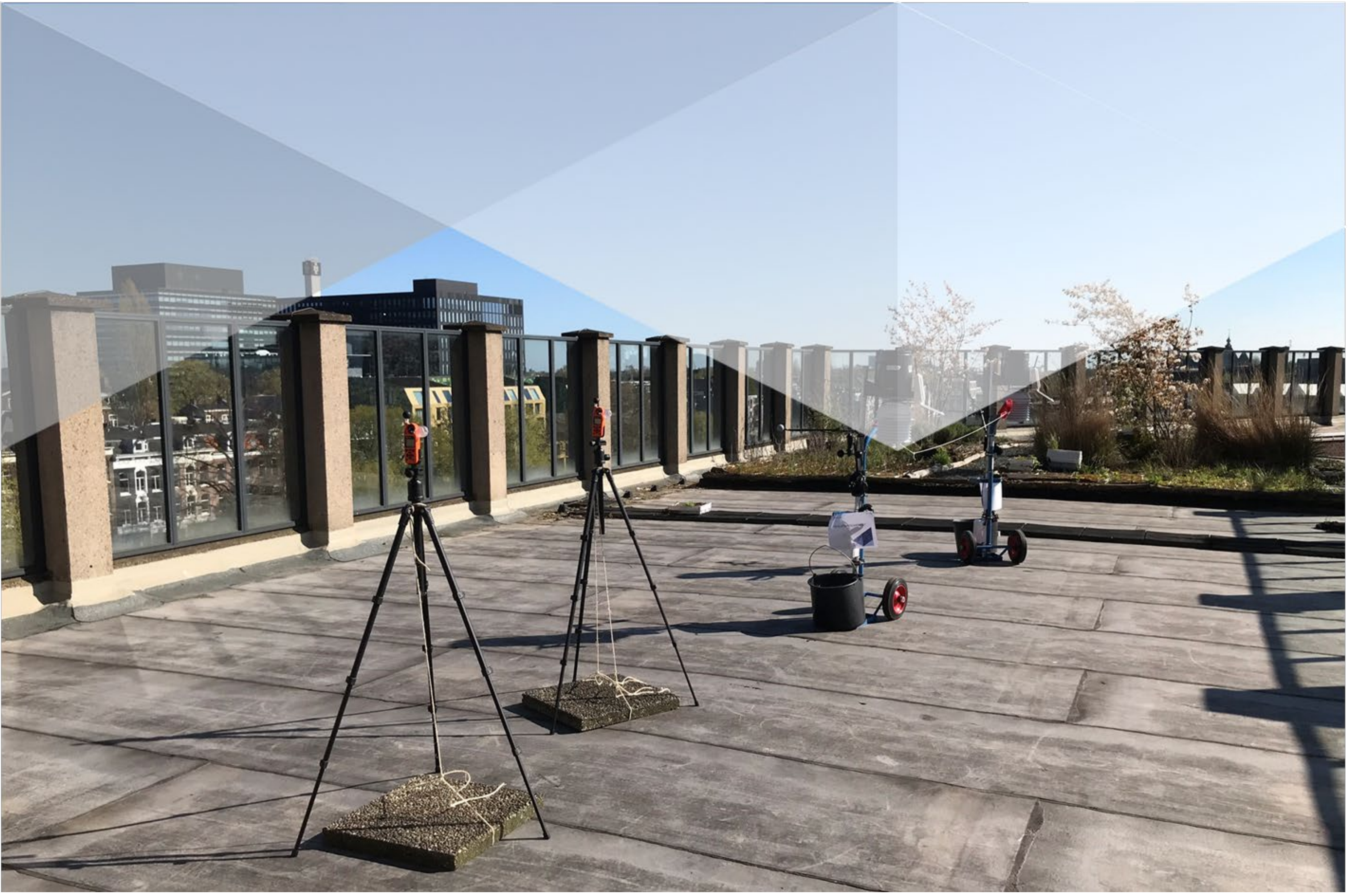

WEATHER STATIONS COMPARISON

Measurement analysis

Abstract

This report summarizes the result of the comparison between 4 weather stations: 2 Kestrels 5400 Heat Stress and 2 Davis Vantage Pro2. The measurements were performed from the 08/04/2019 to 11/04/2019 on the rooftop of the Benno Premselahuis from the Hogeschool van Amsterdam.

Amsterdam, Monday 20 March 2020

Erica Caverzam Barbosa, Lisette Klok

e.caverzam.barbosa@hva.nl; e.j.klok@hva.nl

Hogeschool van Amsterdam

Table of Contents

Summary

Between 08/04/2019 and 11/04/2019, we conducted measurements with 4 weather stations (2 Kestrels 5400 Heat Stress and 2 Davis Vantage Pro2) on the rooftop of the Benno Premselahuis building from the Hogeschool van Amsterdam. These measurements were realized to address the differences between the stations and to determine which one is the most suitable for performing heat stress measurements.

The data collected consists of a 1-minute interval series of air temperature (°C), wind speed (m/s), globe temperature (°C), relative humidity (%), and solar radiation (W/m², only for the Davis). With this data, we calculated the Mean Radiant Temperature (T_{mrt}) and the Physiological Equivalent Temperature (PET). To compare the datasets among the stations, we calculated the Root Mean Square Deviation (RMSD). The RMSD is a measure of accuracy and represents the standard deviation of the individual differences between two datasets. The RMSD was calculated for two periods: (1) entire measurement period, and (2) the period between 11:00 h and 15:00 h (the hottest period of the day).

The intra-comparison analysis revealed that both the Kestrels and Davis are accurate for the main parameters analysed (RMSD < manufacturer's accuracy), except for the Kestrel's wind speed and air temperature. The imprecise wind speed measurements of the Kestrels are related to the fact that the vane mount was not installed on the sensor. The vane mount allows the Kestrels to move in the direction of the wind, and its absence generates inaccurate wind speed readings. The air temperature oscillations of the Kestrels, which did not occur with the Davis's data series, represent the effect of solar radiation on the air temperature sensor of the Kestrel, which is neither shielded nor ventilated.

We also observed a high RMSD for the mean radiant temperature of the Davis. Such a high RMSD can be related to the self-made device of Davis' grey globe. In this sense, the globe's mean convection coefficient may be different for each globe, affecting the mean radiant temperature calculations.

The differences in PET between the sensors achieved a maximum of 4.4°C for the period between 11:00 h and 15:00 h, which is within the range of one PET heat stress class (6°C). Nevertheless, the PET calculation includes the problems mentioned above, what may have affected the final results.

The occurrence of some measurement problems during the experiment does in fact not allow for an accurate comparison among the different stations and a recommendation for one of the sensors specifically. The idea for further research would be to correct these problems in a new experiment. By doing this, we expect to obtain higher accuracy, reduced differences among the stations and lower PET differences between the stations (<4.4°C). With such values, we believe that any of the stations would be appropriate to measure heat stress conditions.

1. Introduction and equipment setup

This report aims to compare the differences between four weather stations: two Davis Vantage Pro2 and two Kestrel 5400 Heat Stress, and to identify if the stations are suitable for performing heat stress measurements. The Davis stations were named Davis S1 and Davis S2, and the Kestrels were identified by the last 3 digits of their serial number, becoming Kestrel 628 and Kestrel 633.

The measurements were taken from the 08/04/2019 until the 11/04/2019 at the rooftop of the Benno Premselahuis building from the Hogeschool van Amsterdam. The rooftop surface is about 15 m x 8 m. The equipment was placed approximately in the center of the area, with a distance of about 4 m from the closest wall. The distance between the equipment is indicated in Figure 1. The sensors were placed in the following order (from left to right in Figure 1 and Figure 2): Kestrel 633, Kestrel 628, Davis S2, and Davis S1. The consoles of the Davis were placed inside a covered box, to avoid direct sunlight (see Figure 3).

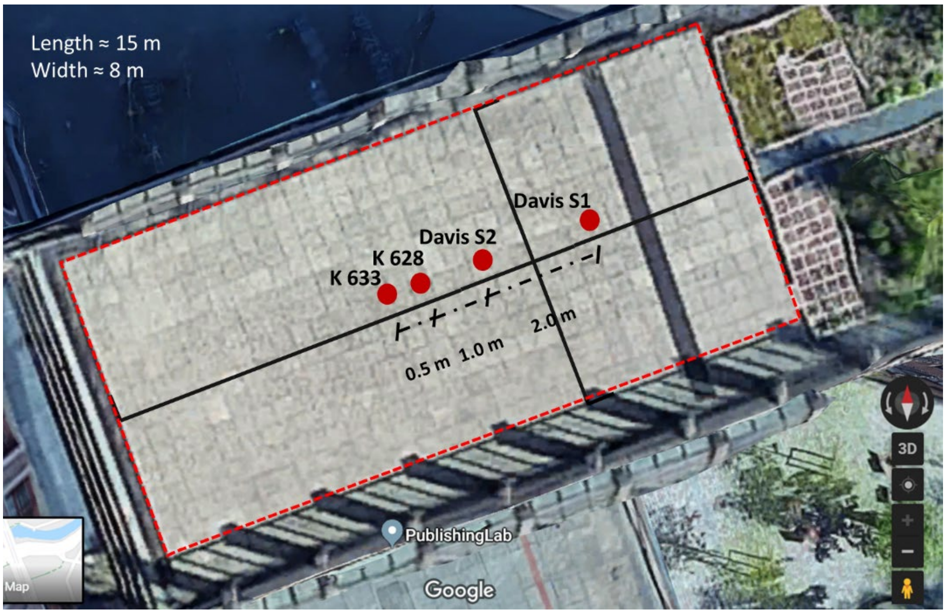

Figure 1: Scheme of the equipment setup in the study area.

Figure 2: Initial setup of the stations (08/04/2019).

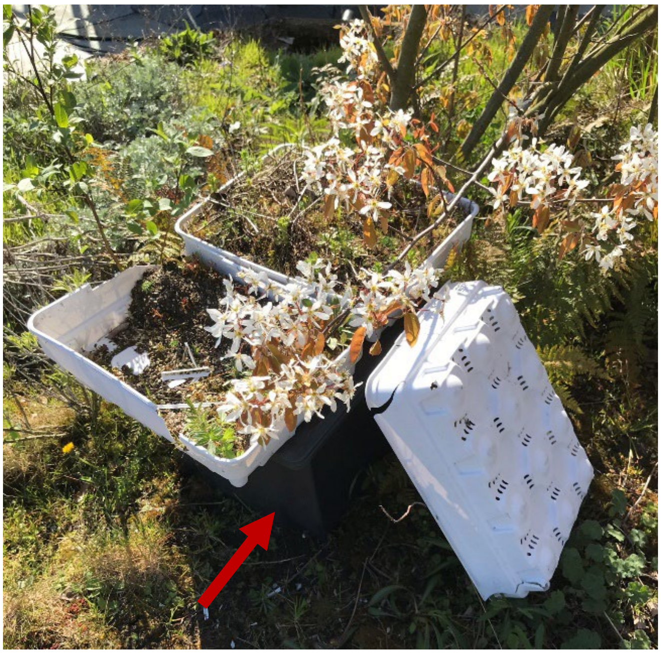

Figure 3: Setup of the console of the Davis stations. The red arrow indicates the location of the console.

2. Learning by doing

Along the measurement days, some problems occurred:

1) When checking the sensors on the second day of measurements (09/04), we found both the Kestrels on the ground. The tripod does not provide sufficient support against strong winds. To continue with the measurements, we attached the tripod to a large block of concrete that was available in the study area (see Figure 4).

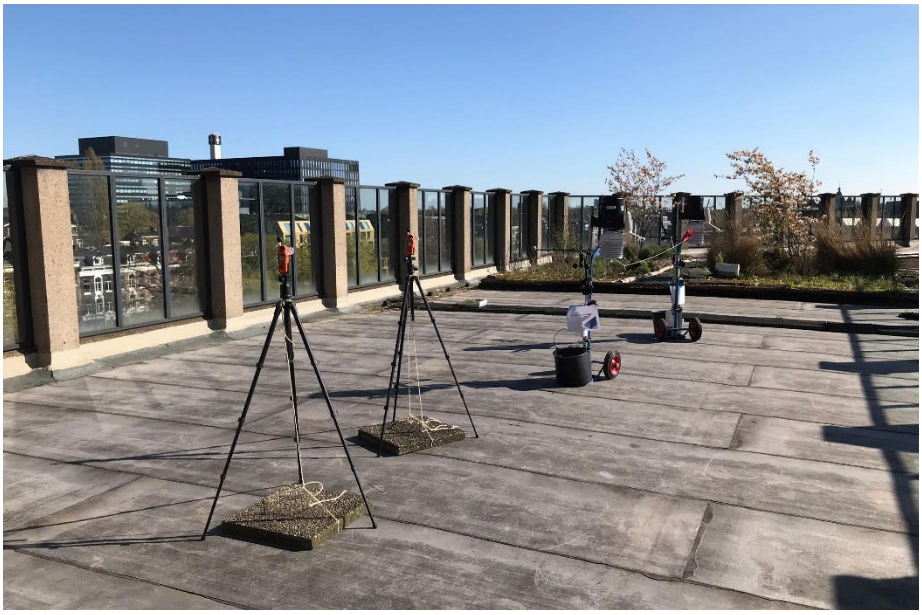

Figure 4: Final setup of the stations (09/04).

2) On the third day of measurements (10/04), we found out that the globe temperature was not being recorded continuously for the Kestrel stations. The data was only recorded during the moments that the Kestrel was with the screen turned on. The problem is that the globe-related parameters (globe temperature, WBGT, naturally ventilated wet-bulb temperature) are not recorded by the station if the measuring interval is lower than 10 minutes and the equipment is OFF, even if the Auto Log function is ON. In the afternoon of 10/04, more precisely at 14:28 h, the Kestrels were turned on and the Auto Shutdown function was disabled. Because of that, we only have continuous data of globe temperature from that moment on.
3) In the afternoon of the 10/04, we also noticed that the setup of the sensors was leading to an irregular shading of the equipment. The shading of the building was moving from the Kestrels towards the Davis stations, perpendicular to the alignment of the sensors (see Figure 5). The data comprising the shading period was excluded from the RMSD calculations.
4) During data analysis, we also found out that the Davis instruments were creating shade on the grey globe. The data of this period were excluded from the RMSD calculations.

Figure 5: Shading pattern coverage on the equipment.

3. Methods

The four stations were programmed to collect data with a 1-minute interval and the units of all the parameters were set to the metric system. Every day the equipment was checked and the data was collected. The data of the Kestrel was exported wireless via the LiNK App for mobile phones, whilst the data of the Davis was collected via USB cable with the WeatherLink software.

The parameters analysed were: air temperature (°C), relative humidity (%), wind speed (m/s), globe temperature (°C), and solar radiation (W/m², only for the Davis). Besides that, the mean radiant temperature (T_{mrt},°C) was calculated using the 10-minutes average values of air temperature, wind speed, and globe temperature, according to the equation proposed by Thorsson et al. (2007):

$$(3.1)\quad T_{mrt} = \left[\left(T_g + 273.15\right)^4 + \frac{1.1\times 10^8 V_a^{0.6}}{\varepsilon D^{0.4}} \times \left(T_g - T_a\right)\right]^{\frac{1}{4}} - 273.15$$

Where:
T_g = (10-minutes average) globe temperature (°C)
V_a= (10-minutes average) wind speed (m/s)
T_a = (10-minutes average) air temperature (°C)
D = globe diameter (m)
ε = globe emissivity

The Kestrel has a black globe with a diameter of 1 inch (0.0254 m). According to the website of Kestrel, the temperature inside a 1-inch black powder-coated copper globe is converted to Tg equivalent for a standard 6 inches (150 mm) globe. Therefore, for the $\mathrm{T_{mrt}}$ formula, the Kestrel diameter was substituted by 0.15 m. The Davis's grey globe was self-made using a 38-mm grey painted table tennis balls using a flat grey paint (RAL 7001) following Thorsson et al. (2007). A temperature probe of Davis (type 6372) was used inside the table tennis ball. The accuracy of this sensor is 0.5°C (Klok et al. 2019).

The calculation of the $\mathrm{T_{mrt}}$ also depends on the globe's mean convection coefficient, which is an empirically derived parameter. In equation 3.1, this is represented by $1.1 \times 10^8 V_a^{0.6}$, which is the globe's mean convection coefficient for a black globe. This value was used for the calculation of the mean radiant temperature of the Kestrel. Since the Davis has a grey globe, a different coefficient was used, $1.335 \times 10^8 V_a^{0.71}$ (Walikewitz et al., 2015; Thorsson et al., 2007).

With the $\mathrm{T_{mrt}}$ values, we calculated the Physiological Equivalent Temperature (PET). The PET was calculated via the software Rayman version 1.2. The personal data, clothing, and activity were kept as default: male, 35 years, 75 kg, 1.75 m, 0.9 clo, and 80 W, as a light activity. Due to the large fluctuations of PET caused by the variable conditions at 1-minute interval, the PET values were calculated twice. First, the program was run with an input data file with the actual values (1-minute interval) of air temperatures (°C), relative humidity (%), wind speed (m/s) and the 10-minutes average $\mathrm{T_{mrt}}$. In the second time, the input file consisted of the 10-minutes average of all the aforementioned parameters. The averaging of all the parameters aimed to create a smoother PET series by representing the thermal conditions of a location over a short period.

The comparison among the stations was made through the analysis of the Root Mean Square Deviation (RMSD) of all the parameters. The RMSD is a measure of accuracy and represents the standard deviation of the individual differences among two datasets. In this report, the RMSD was used to obtain the average difference between two stations regarding a certain parameter. The lower the RMSD, the higher the accuracy of the sensors. The RMSD was calculated for two different periods. The first comprises the entire measurement period, whilst the second comprises only the period between 11:00 h and 15:00 h. This was done to compare the RMSD for the 24 h-period and the hottest period of the day (11:00 h to 15:00 h).

$$(3.2) \quad \mathrm{RMSD} = \sqrt{\frac{\sum_{i=1}^{n}(x_{1,i} - x_{2,i})^2}{n}}$$

Where $x_{1,n}$ and $x_{2,n}$ are the values of a certain parameter for two different stations an n is the number of observations.

As previously explained, there were some setbacks along the measurement period. As a consequence, the following data was excluded from the RMSD calculations:

1) Due to the **shading** of the building, the calculation of the RMSD did not consider the period between 14:30 h and 15:45 h for the Kestrels and the period between 15:00 h and 15:45 h for the Davis. These periods were determined by globe temperature and solar radiation data. The first (14:30 h – 15:45 h) comprises the moment of shading of the first Kestrel and the last Davis. The second (15:00 h – 15:45 h) refers to the period of shading of the Davis weather stations (see Figure 10).
2) Due to the **lack of globe temperature data**, the calculation of the RMSD with the Kestrels considered only the data after 10/04 14:33h. In combination with the setback mentioned above, the RMSD calculations for the Kestrel included only the data after 10/04 15:45 h (see Figure 10).

3) Due to the **shading of the Davis on the grey globe**, the calculation of the RMSD for globe temperature, PET and MRT did not consider the period between 08:30 h (in practice 08:25 h due to the 10 min average) to 12:00 h (in practice 12:05 h due to the 10 min average). This is the period was determined by the globe temperature and comprises the moment when the grey globe is shaded by the Davis (see Figure 10).

4. Results and discussion

4.1. Air temperature

As shown in Figure 6, the air temperature values registered by the Davis and Kestrel seem to correlate well for the 24 hours period (RMSD = 0.4°C, Table 1). During the period between 11:00 h and 15:00 h, the values registered by the Kestrels show a great oscillation, whilst the Davis ones result in a smoother line. As a consequence, the RMSD for this period increased to 0.6-0.7°C (see Table 1). Such oscillations may be explained by the fact that the temperature sensor of the Kestrel does not have a radiation and fan-aspired shield as the Davis. As such, the air temperature measurements may be more sensitive to sunlight and wind speed. Thus, being more likely to suffer fluctuations during the periods when the sun is shining. Due to the fall of the Kestrels, a clear difference between air temperature can be observed between the 08/04 and 09/04 (see Figure 6). As explained above, these period was not included in the calculations.

Both the Kestrel and Davis have an accuracy provided by the manufacturer of ±0.5°C for air temperature. The RMSD calculated for both instruments is lower than the accuracy (see Table 1), indicating that the sensors are following their specifications.

Figure 6: Air temperature (°C) for the entire measurement period. The grey area represents the moment when the Kestrels fell.

Table 1: RMSD of air temperature (°C).

	Davis 1 Davis 2	Davis 1 Kestrel 628	Davis 1 Kestrel 633	Davis 2 Kestrel 628	Davis 2 Kestrel 633	Kestrel 628 Kestrel 633
24 hours period (excluding shaded moments)	0.2 (n=4352)	0.4 (n=1398)	0.4 (n=1398)	0.4 (n=1398)	0.4 (n=1398)	0.1 (n=1398)
From 11:00 h to 15:00 h	0.3 (n=865)	0.6 (n=215)	0.6 (n=215)	0.7 (n=215)	0.6 (n=215)	0.2 (n=215)

4.2. Relative humidity

The relative humidity values registered by the Kestrels were slightly lower than those registered by the Davis during the majority of the measurement period (see Figure 7). The RMSD between the Davis and Kestrel varied from 3.5% to 4.2%, with slightly higher values for the period of 11:00 h and 15:00 h (see Table 2).

According to the Kestrel's and Davis's manufacturers, their accuracy regarding relative humidity is of ±2% and ±3%, respectively. The RMSD calculated for both instruments is lower than their accuracy, indicating that both sensors are following their specifications.

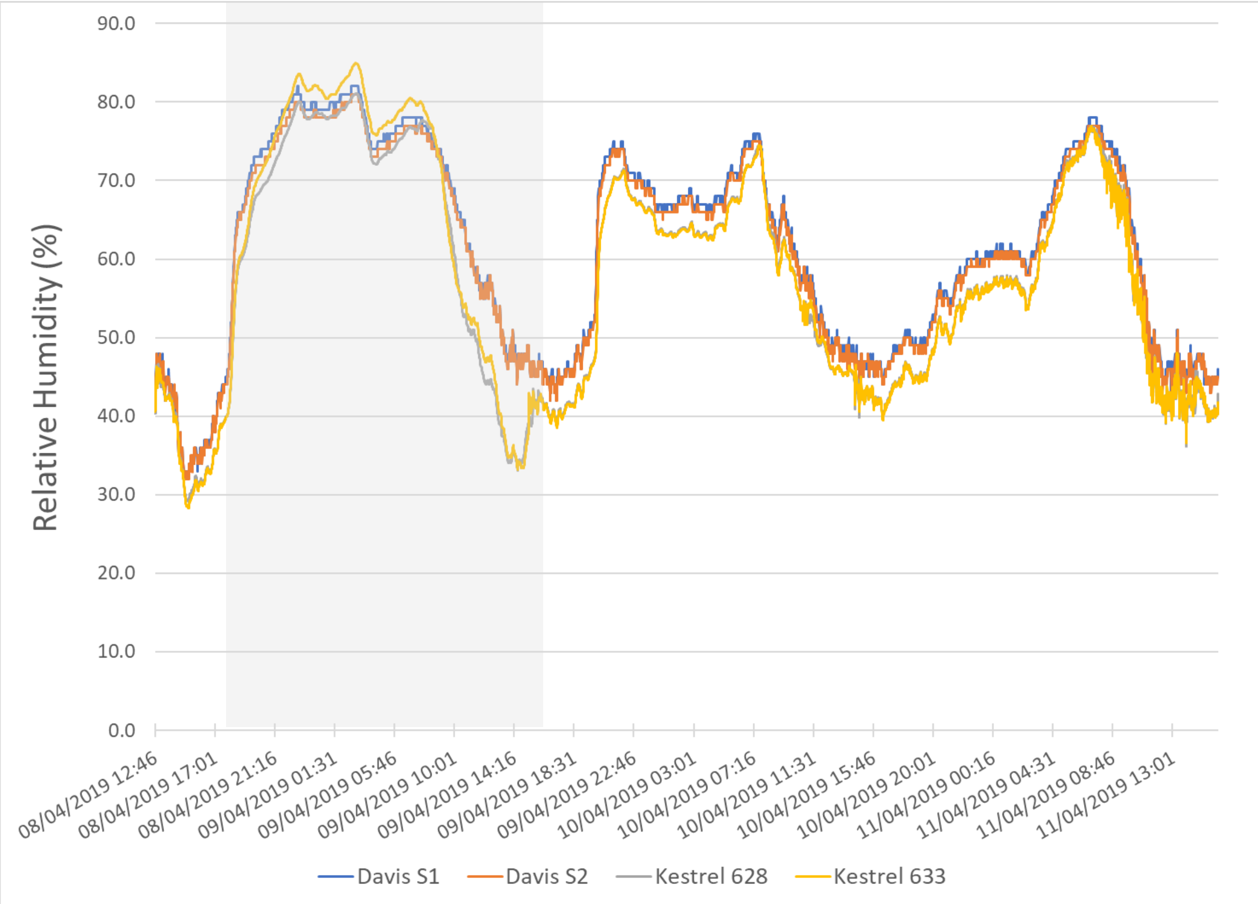

Figure 7: Relative humidity (%) for the entire measurement period. The grey area represents the moment when the Kestrels fell.

Table 2: RMSD of relative humidity (%).

	Davis 1 Davis 2	Davis 1 Kestrel 628	Davis 1 Kestrel 633	Davis 2 Kestrel 628	Davis 2 Kestrel 633	Kestrel 628 Kestrel 633
24 hours period (excluding shaded moments)	0.9 (n=4352)	4.0 (n=1398)	4.1 (n=1398)	3.5 (n=1398)	3.6 (n=1398)	0.3 (n=1398)
From 11:00 h to 15:00 h	0.7 (n=865)	4.2 (n=215)	4.2 (n=215)	4.0 (n=215)	3.9 (n=215)	0.2 (n=215)

4.3. Wind speed

Figure 8 shows the 30 minutes average wind speed values for the entire measurement period. Between the 08/04 and the 09/04, there is a significant drop in the wind speed for the Kestrels. This drop of the values is associated with the moment when the equipment felt.

The graph also shows that the wind speed values registered by the Kestrel were usually lower than the ones registered by the Davis. This difference may be caused by the fact that the Kestrels were not coupled with their vane mount at the time of the measurements. Because of this, the sensor did not move towards the wind direction, which may result in inaccurate measurements. This is likely to be the cause for the higher differences among the Kestrels, resulting in an RMSD of 0.4 m/s (see Table 3). **This is above the Kestrel's accuracy for wind speed, which is of ±0.1 m/s**. The RMSD values between the Davis and Kestrel varied from 0.8 to 1.1 m/s. **Among the Davis, the RMSD is 0.6 m/s, which is below Davis's accuracy of wind speed (±0.9 m/s).**

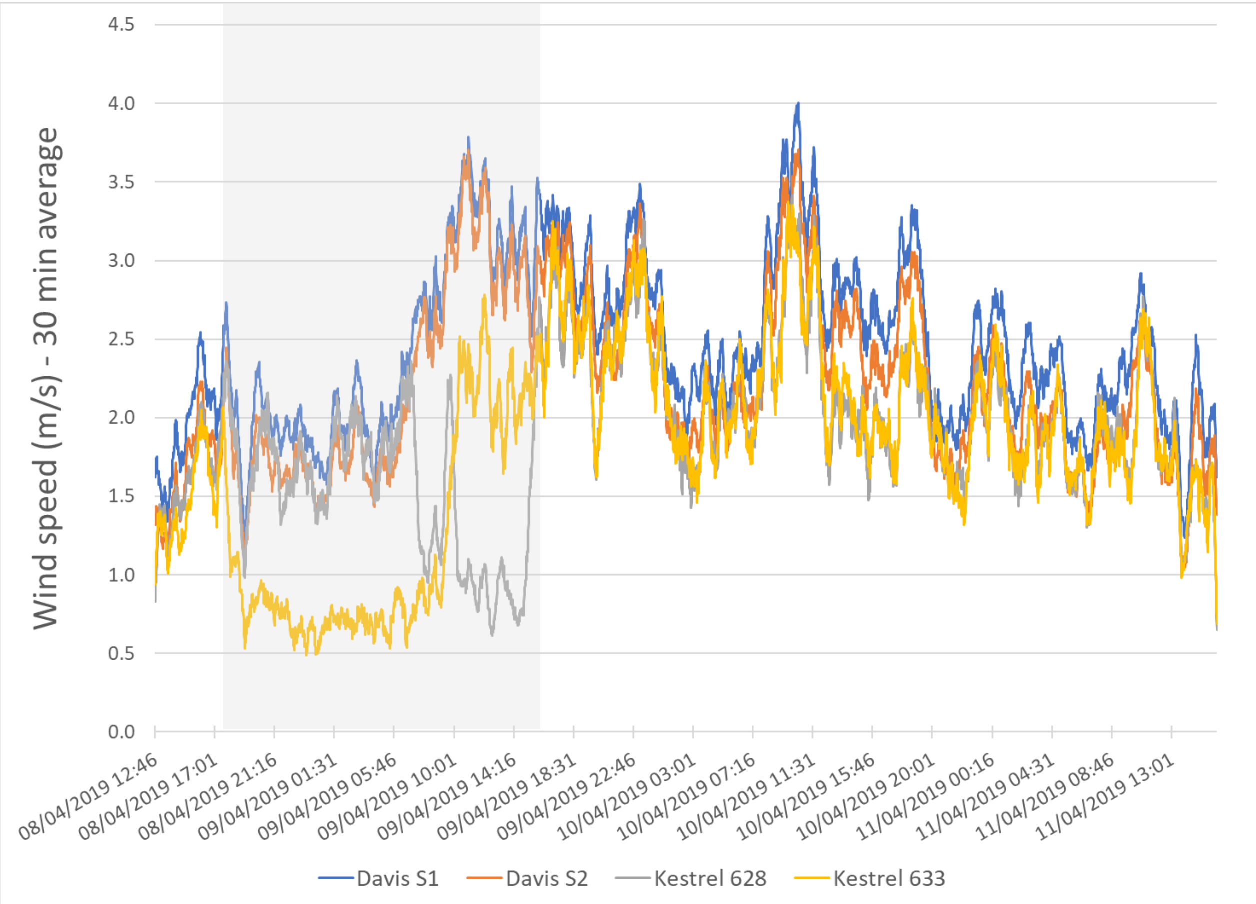

Figure 8: 30 min average wind speed (m/s) for the entire measurement period. The grey area represents the moment when the Kestrels fell.

Table 3: RMSD of wind speed (m/s).

	Davis 1 Davis 2	Davis 1 Kestrel 628	Davis 1 Kestrel 633	Davis 2 Kestrel 628	Davis 2 Kestrel 633	Kestrel 628 Kestrel 633
24 hours period (excluding shaded moments)	0.6 (n=4352)	1.1 (n=1398)	1.1 (n=1398)	1.0 (n=1398)	1.0 (n=1398)	0.4 (n=1398)
From 11:00 h to 15:00 h	0.6 (n=865)	0.8 (n=215)	0.8 (n=215)	0.8 (n=215)	0.8 (n=215)	0.4 (n=215)

4.4. Solar radiation

The Kestrels do not measure solar radiation and thus values are only available for the Davis stations. As shown in Figure 9, the values registered by the two Davis are very well correlated. Through this graph, we can also see the effect of the shade of the building: at approximately 15:15 h, there is a drop in the solar radiation of the Davis S2. For the Davis S1, this drop occurs about 25 min later.

A large oscillation can be observed on the last day, which can be explained by the presence of intermittent clouds, not present in the previous days. The RMSD of solar radiation for the 24 hours period (39.6 W/m²) is much lower than the one for the period between 11:00 h and 15:00 h (88.0 W/m²). The decrease of RMSD for 24 hours period occurs because at night both sensors register solar radiation equal to 0 W/m². During day time, the RMSD exceeds the value provided by the manufacturer, which is 50 W/m² (5% of the full scale, Ref: Eppley PSP at 1000 W/m²).

Table 4: RMSD of solar radiation (W/m²) for the Davis stations.

	Davis 1 Davis 2
24 hours period (excluding shaded moments)	39.6 (n=4352)
From 11:00 h to 15:00 h	88.0 (n=865)

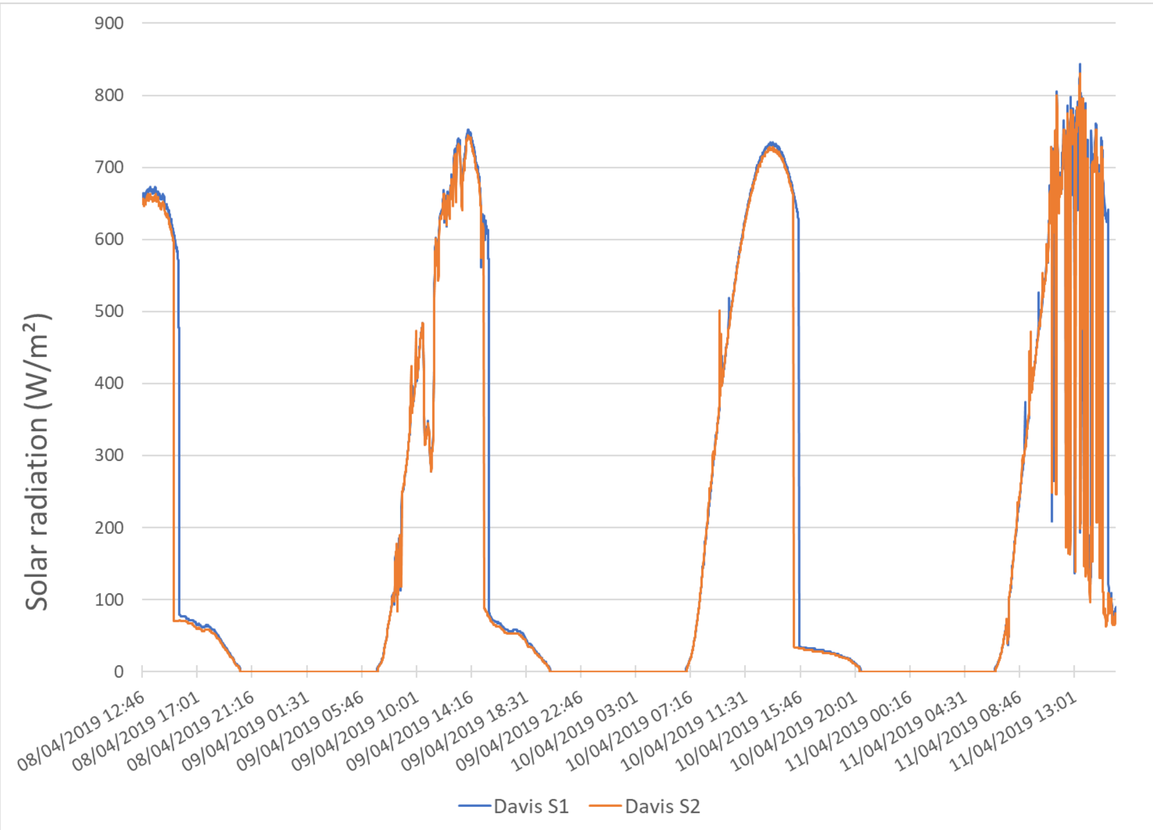

Figure 9: Solar radiation (W/m²) for the Davis weather stations for the entire measurement period.

4.5. Globe temperature

The Davis stations show a good correlation of globe temperature (RMSD of 0.3°C and 0.4°C) (see Table 5). These values do not take into account the period between 08:30h and 12:00h. During this time, there is a drop of Davis S1 globe temperature, followed by a drop of Davis S2 (see Figure 10). This drop was caused by the shade of the own station on the grey globe during the morning period. For further measurements that require whole day exposure of the Davis, it is recommendable to extend the 'arm' where the grey ball is located to avoid this type of error.

Continuous Kestrel readings for globe temperatures at low interval rates (<10 min, see pages 2-3), are available only after 10/04 (see Figure 10). The globe temperature values were well correlated among the Kestrels, resulting in a RMSD of 0.3°C, which is far below its accuracy which is 1.4°C. During the day, the globe temperatures registered by the Kestrels were usually higher than the ones registered by the Davis. This may be explained by the difference in the globe colours, as the grey globe tends to underestimate short-wave radiation (Thorsson et al., 2007). Since the type of globe temperature sensors differs between Davis (grey globe) and Kestrel (black globe), their readings were not compared and the RMSD between the Davis and Kestrels was not computed.

Table 5: RMSD of globe temperature (°C).

	Davis 1 Davis 2	**Kestrel 628 Kestrel 633**
24 hours period (excluding shaded moments)	0.3 (n=3693)	0.3 (n=1398)
From 11:00 h to 15:00 h	0.4 (n=671)	0.3 (n=215)

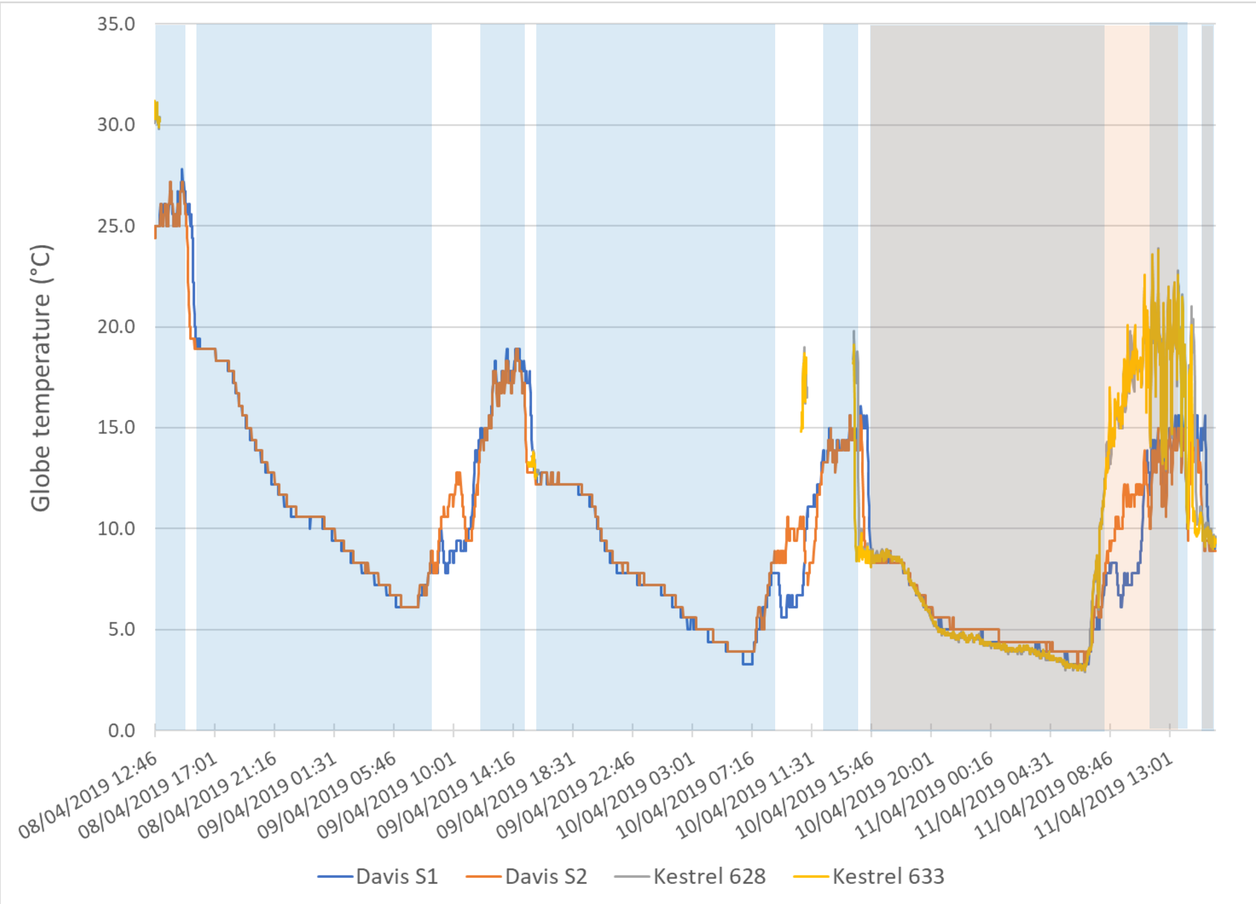

Figure 10: Globe temperature (°C) for the entire measurement period. The blue parts comprise the data used for the RMSD calculations between the Davis, and the orange parts represent the data used for the Kestrels.

4.6. Mean Radiant Temperature

Similar to the globe temperature, the mean radiant temperature also showed a gap in the morning period for the Davis. For the Kestrels, continuous data is only available after the 10/04.

The Davis's RMSD was 4.9°C for the 24-hours period and 3.7°C for the afternoon period (see Table 6). For the Kestrels, these values were 0.9°C and 1.6°C, respectively. We believe that the higher RMSD for the Davis is associated with the fact that the Davis's grey globe is a self-made device. Despite following the requirements presented in Thorsson et al. (2007), the production of the globe is not fully standardized. Differences in the globe material, paint type, paint thickness or even paint age might result in a different globe's mean convection coefficient, other than specified by Thorsson et al. (2007). As such, the globe's mean convection coefficient may be different for each globe and different from the one presented by Thorsson et al., 2007. The RMSD calculations excluded the shaded times in the morning for the Davis (08:30 h to 12:00 h), and in the afternoon for the Davis (15:00 h to 15:45 h) and the Kestrels (14:30 h to 15:45 h) (see Figure 10). The RMSD between the two instruments was much higher, reaching up to 7.1°C. This can be explained by two reasons. First, the wind speed recorded by the Kestrels is inaccurate, since the vane mount was not coupled to the stations. As a consequence, the mean radiant temperature may have been affected. Second, as stated above, the Davis's grey globe may require a different globe's mean convection coefficient. To achieve higher accuracy, an individual calibration of each globe thermometer would be necessary (Thorsson et al., 2007).

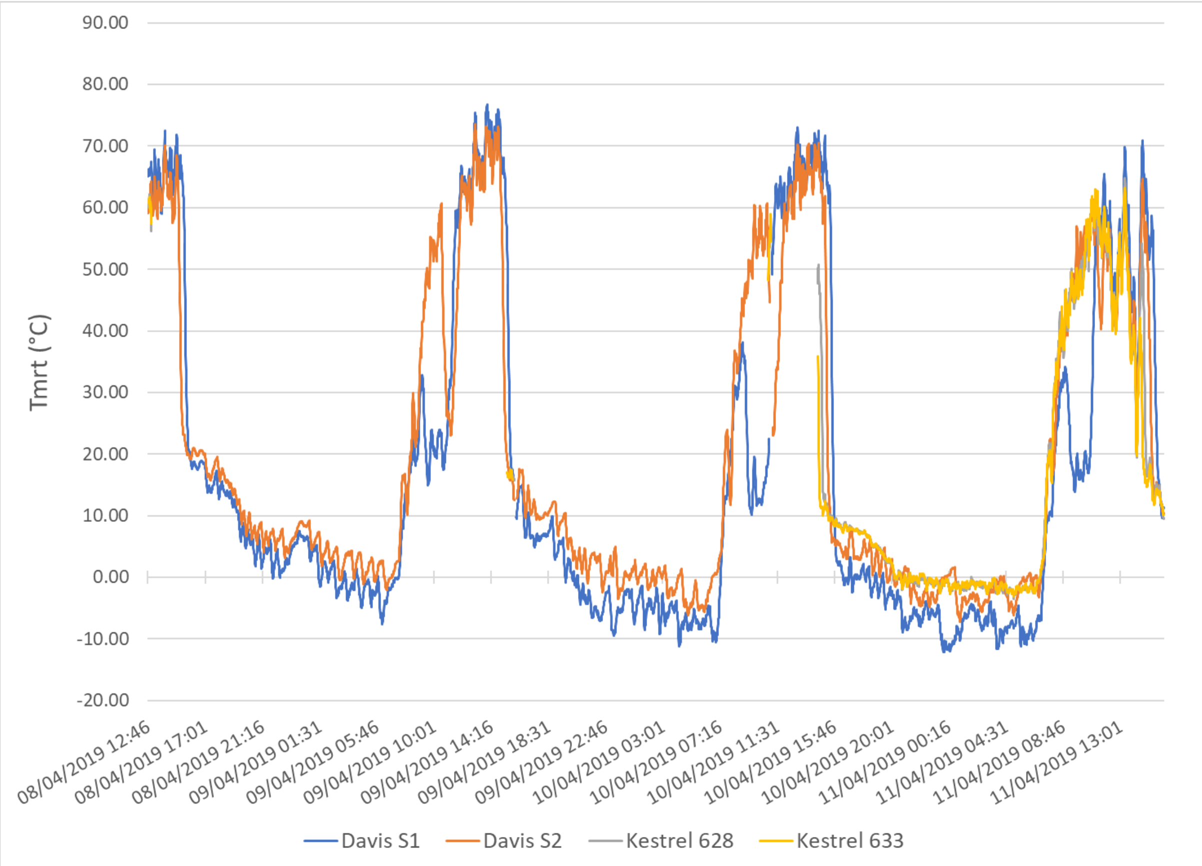

Figure 11: Mean Radiant Temperature (°C) for the entire measurement period.

Table 6: RMSD of Mean Radiant Temperature (°C).

	Davis 1 Davis 2	Davis 1 Kestrel 628	Davis 1 Kestrel 633	Davis 2 Kestrel 628	Davis 2 Kestrel 633	Kestrel 628 Kestrel 633
24 hours period (excluding shaded moments)	4.9 (n=3680)	6.6 (n=1177)	6.7 (n=1177)	2.8 (n=1177)	2.9 (n=1177)	0.9 (n=1398)
From 11:00 h to 15:00 h	3.7 (n=671)	6.1 (n=149)	7.1 (n=149)	3.1 (n=149)	4.0 (n=149)	1.6 (n=215)

4.7. PET

Figure 12 shows the results of the PET calculations using the T_{mrt} as the only parameter 10-minutes averaged, and Figure 13 shows the results of the PET calculations considering the 10-minutes average of all the parameters. The main distinction is a smoother result, as evidenced by the graphs.

Overall, the PET values calculated for the Kestrels were higher than those calculated for the Davis. When PET is calculated using only the T_{mrt} as a 10-minutes average parameter, the accuracy of both instruments is very similar. For the Davis, the RMSD of the 24-hours period was 1.4°C and for the afternoon period, 2.2°C (see Table 7). For the Kestrels, these values were 1.4°C and 2.4°C, respectively. The RMSD between the two stations reached up to 4.4°C during the hottest hours of the day. By averaging all the parameters before the PET calculation, we obtained lower RMSD values. For the Davis, these values were 1.0°C for the 24-hours period and 0.8°C for the afternoon (see Table 8). For the Kestrels, these values changed to 0.4°C and 0.6°C, respectively. The RMSD between the two instruments also decreased, achieving a maximum of 1.7°C in the hottest hours of the day. The averaging procedure smooths out large differences in some parameters (e.g. wind speed) and reduces the RMSD.

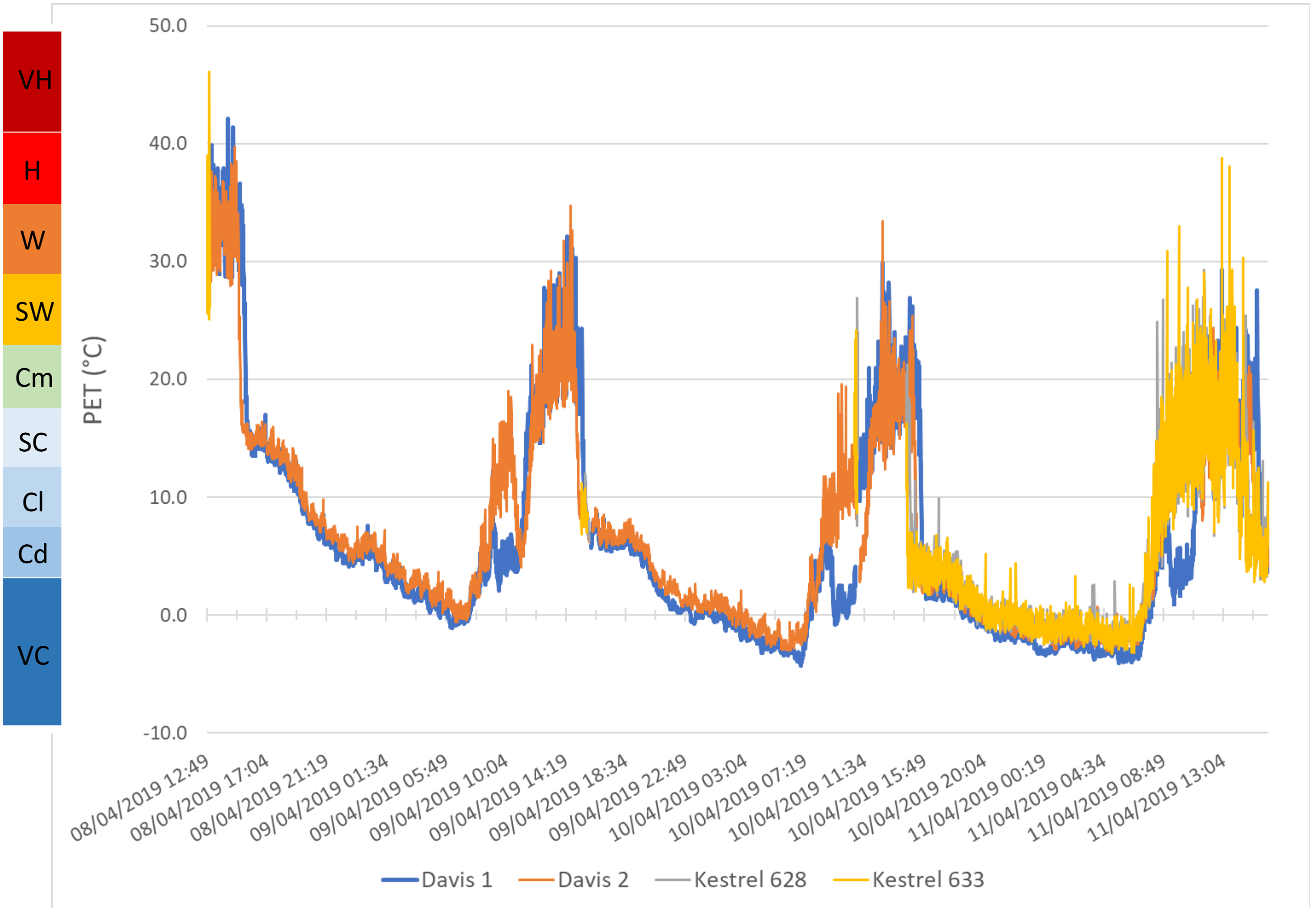

Figure 12: PET (°C) using only the Mean Radiant Temperature averaged. Left bar represents the PET scale (from up to down): Very Hot (>41°C), Hot (41-35°C), Warm (35-29°C), Slightly Warm (29-23°C), Comfortable (23-18°C), Slightly Cool (18-13°C), Cool (13-8°C), Cold (8-4°C), and Extremely Cold (<4°C). Source: Matzarakis et al. (1999).

Table 7: RMSD of PET (°C) calculated only with the Mean Radiant Temperature averaged.

	Davis 1 Davis 2	Davis 1 Kestrel 628	Davis 1 Kestrel 633	Davis 2 Kestrel 628	Davis 2 Kestrel 633	Kestrel 628 Kestrel 633
24 hours period (excluding shaded moments)	1.4 (n=3680)	2.3 (n=1177)	2.4 (n=1177)	1.8 (n=1177)	2.0 (n=1177)	1.4 (n=1398)
From 11:00 h to 15:00 h	2.2 (n=671)	3.3 (n=149)	4.1 (n=149)	3.5 (n=149)	4.4 (n=149)	2.4 (n=215)

Note that the calculated RMSD values between the two instruments may include errors originated from some of the parameters. As indicated in section 4.1, the air temperature of the Kestrels showed larger oscillations during the day, in comparison to the Davis ones. This may be related to the fact that the air temperature sensors of the Kestrels are not shielded nor ventilated and may thus be influenced by solar radiation. As a consequence, the PET is likely to be affected. Besides that, the wind speed recorded by the Kestrels is not accurate, since the vane mount was not coupled to the sensor. This may also have affected the PET outcome. Last but not least, the grey globe of the Davis is not standardized, which might require a further calibration of the globe's mean convection coefficient. Ultimately, this may affect the final PET calculations. All these observations must be acknowledged when using both sensors in one single experiment.

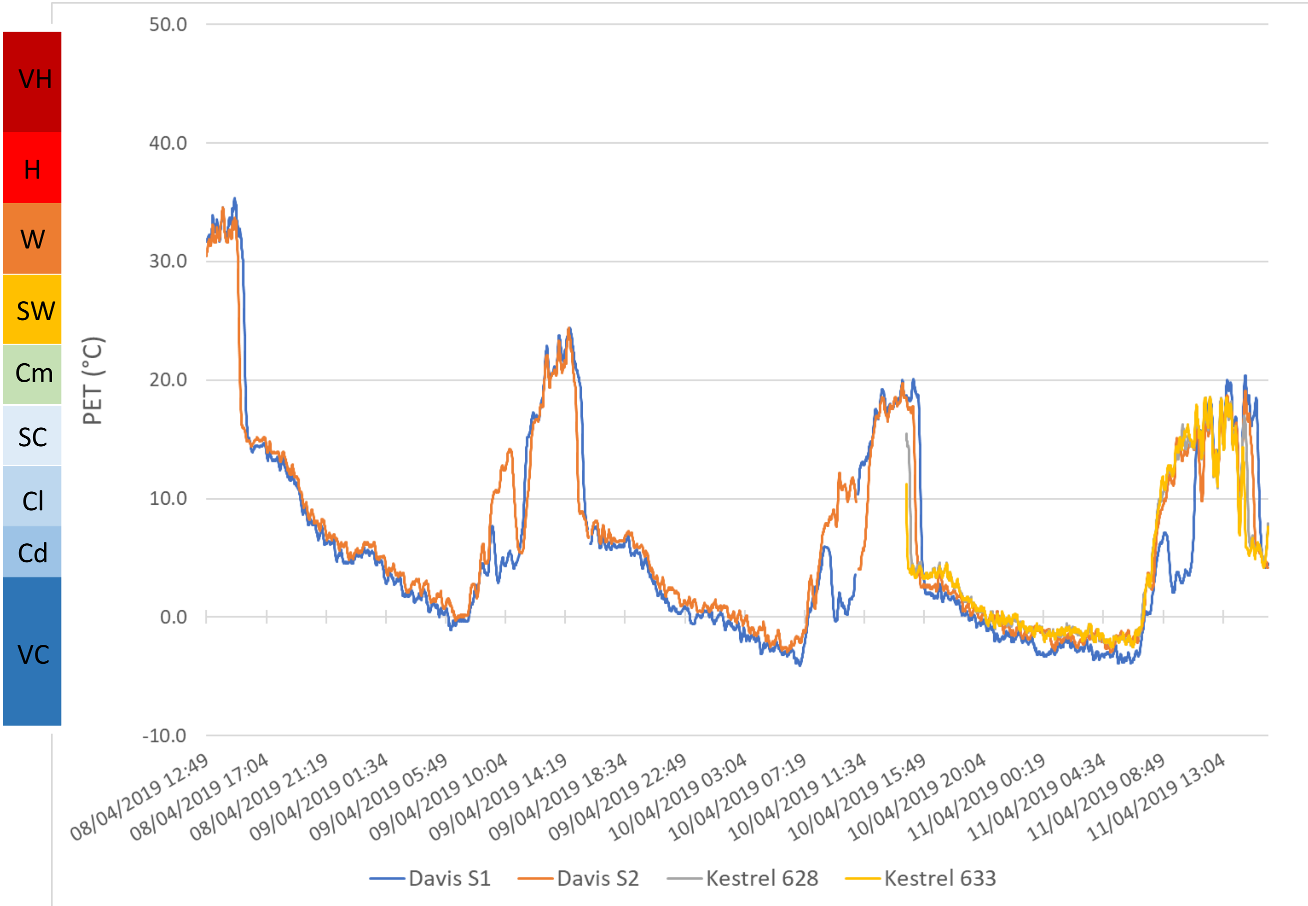

Figure 13: PET (°C) using all the parameters averaged. Left bar represents the PET scale (from up to down): Very Hot (>41°C), Hot (41-35°C), Warm (35-29°C), Slightly Warm (29-23°C), Comfortable (23-18°C), Slightly Cool (18-13°C), Cool (13-8°C), Cold (8-4°C), and Extremely Cold (<4°C). Source: Matzarakis et al. (1999).

Table 8: RMSD of PET (°C) calculated all the variables averaged.

	Davis 1 Davis 2	Davis 1 Kestrel 628	Davis 1 Kestrel 633	Davis 2 Kestrel 628	Davis 2 Kestrel 633	Kestrel 628 Kestrel 633
24 hours period (excluding shaded moments)	1.0 (n=3680)	1.5 (n=1177)	1.6 (n=1177)	0.8 (n=1177)	0.9 (n=1177)	0.4 (n=1398)
From 11:00 h to 15:00 h	0.8 (n=671)	1.4 (n=149)	1.7 (n=149)	1.0 (n=149)	1.2 (n=149)	0.6 (n=215)

4.8. Overview of RMSD values

Table 9: Overview of RMSD calculations for the 24 hours period (excluding shaded moments).

	Davis 1 Davis 2	Davis 1 Kestrel 628	Davis 1 Kestrel 633	Davis 2 Kestrel 628	Davis 2 Kestrel 633	Kestrel 628 Kestrel 633
Tair	0.2 (n=4352)	0.4 (n=1398)	0.4 (n=1398)	0.4 (n=1398)	0.4 (n=1398)	0.1 (n=1398)
RH	0.9 (n=4352)	4.0 (n=1398)	4.1 (n=1398)	3.5 (n=1398)	3.6 (n=1398)	0.3 (n=1398)
Wind speed	0.6 (n=4352)	1.1 (n=1398)	1.1 (n=1398)	1.0 (n=1398)	1.0 (n=1398)	0.4 (n=1398)
Mean radiant temp	4.9 (n=3680)	6.6 (n=1177)	6.7 (n=1177)	2.8 (n=1177)	2.9 (n=1177)	0.9 (n=1398)
Tg	0.3 (n=3693)	-	-	-	-	0.3 (n=1398)
PET only Tmrt averaged	1.4 (n=3680)	2.3 (n=1177)	2.4 (n=1177)	1.8 (n=1177)	2.0 (n=1177)	1.4 (n=1398)
PET all Tmrt averaged	1.0 (n=3680)	1.5 (n=1177)	1.6 (n=1177)	0.8 (n=1177)	0.9 (n=1177)	0.4 (n=1398)

Table 10: Overview of RMSD calculations for the period of 11:00 h to 15:00 h.

	Davis 1 Davis 2	Davis 1 Kestrel 628	Davis 1 Kestrel 633	Davis 2 Kestrel 628	Davis 2 Kestrel 633	Kestrel 628 Kestrel 633
Tair	0.3 (n=865)	0.6 (n=215)	0.6 (n=215)	0.7 (n=215)	0.6 (n=215)	0.2 (n=215)
RH	0.7 (n=865)	4.2 (n=215)	4.2 (n=215)	4.0 (n=215)	3.9 (n=215)	0.2 (n=215)
Wind speed	0.6 (n=865)	0.8 (n=215)	0.8 (n=215)	0.8 (n=215)	0.8 (n=215)	0.4 (n=215)
Mean radiant temp	3.7 (n=671)	6.1 (n=149)	7.1 (n=149)	3.1 (n=149)	4.0 (n=149)	1.6 (n=215)
Tg	0.4 (n=671)	-	-	-	-	0.3 (n=215)
PET only Tmrt averaged	2.2 (n=671)	3.3 (n=149)	4.1 (n=149)	3.5 (n=149)	4.4 (n=149)	2.4 (n=215)
PET all Tmrt averaged	0.8 (n=671)	1.4 (n=149)	1.7 (n=149)	1.0 (n=149)	1.2 (n=149)	0.6 (n=215)

5. Conclusion & discussion points

Intra comparison analysis:

The results of the measurements show that both sensors have good accuracy for the majority of the parameters analysed (see Table 11). We conclude that (see also Tables 9 and 10):

Davis sensors:

- The RMSD between the two Davis stations is lower than the manufacture's specifications for air temperature, relative humidity, and wind speed.
- The RMSD of globe temperature is also relatively low, but we couldn't infer about its accuracy as the globe temperature does not have an accuracy value provided by the manufacturer (the grey globe is a self-made device).
- For solar radiation, the RMSD is higher than the accuracy of the manufacturer during the period between 11:00 h and 15:00 h.
- The RMSD of PET varied between 0.8°C for the PET calculated with all the parameters averaged and 2.2°C for the PET calculated with the T_{mrt} as the only averaged parameter (for the period between 11:00 h and 15:00 h).

Kestrel sensors:

- The RMSD values are below the accuracy of the manufacturer for air temperature, relative humidity, and globe temperature.
- For wind speed, the RMSD is higher than the accuracy of the manufacturer. This can be attributed to the fact that the vane mount was not coupled to the sensor during the measurements, leading to inaccurate wind speed measurements.
- The RMSD of PET varied from 0.6°C for the PET calculated with all the parameters averaged and 2.4°C for the PET calculated with the T_{mrt} as the only averaged parameter (for the period between 11:00 h and 15:00 h).

Table 11: Summary of the accuracy for each station based on the RSMD values and the manufacturer's accuracy.

	RMSD below manufacture's accuracy			
	Air temp	Wind speed	Globe temp	RH
Kestrel	✓	×	✓	✓
Davis	✓	✓	-	✓

Inter comparison analysis:

When comparing Davis with Kestrel, the air temperature was the only parameter with a RMSD below the manufacturer's accuracy (see Table 12). The wind speed comparison was affected by the Kestrel's measurements, which was inaccurate due to the absence of the vane mount. The globe temperature could not be directly compared because both instruments have different globes (size, colour, paint colour, paint thickness).

Table 12: Summary of the comparison between the stations based on the RSMD values and the manufacturer's accuracy.

	RMSD below manufacture's accuracy			
	Air temp	Wind speed	Globe temp	RH
Kestrel	✓	×	-	×
Davis	✓	×	-	×

The results of the measurements show that, by using Davis and Kestrel in a single experiment, one can expect PET values slightly higher for the Kestrels with differences up to 1.7 or 4.4°C (depending on the input values used for the PET calculation, either 1-minute or 10-minutes average) during the hottest hours of the day. In both cases, the RMSD values are still within the range of one PET heat stress class, which is 6°C. The choice of using either 1-minute or 10-minutes average values will depend on the research aim, whether the interest lies on the average or the short term fluctuation values.

In this comparison study, some problems may have influenced the results of the RMSD analysis. For a more accurate comparison, the aspects mentioned below should be acknowledged and a second experiment should be performed. The main problems and their corrections are:

(1) The **Kestrels high fluctuations in air temperatures**, which was likely caused by the non-ventilated and non-shielded air temperature sensor. To obtain more accurate air temperature values, it is recommended to shield the Kestrel's temperature sensor and not use the measurement values when the sensor is exposed to solar radiation.

(1) The wind speed values recorded by the Kestrels are inaccurate, as the vane mount was not connected to it. The **installation of the vane mount** should be one of the first steps during the setup of the Kestrel. It allows for the free movement of the sensor, so it can rotate according to the wind direction and measure the correct wind speed.

(2) Due to the high RSMD observed for the Davis stations, we believe that the **globe's mean convection coefficient** suggested by Thorsson et al. (2007) may be inadequate for the grey globes used in our experiment. This may be due to the incompatibility regarding the manufacturing of the grey globe. Despite following the same globe's characteristics from Thorsson et al. (2007), it is possible that the globes used in the present study present differences regarding the thickness of the paint, the age of the paint, etc. Such differences would influence the globe's mean convection coefficient. To address this problem, a more sophisticated experiment should take place. This would consist of testing again the globe temperature sensor of the Davis system and possibly adjusting the Davis's globe's mean convection coefficient based on the mean radiant temperature measured via integral radiation measurements and angular factors.

The occurrence of these problems does not allow for an accurate comparison among the different stations and, therefore, we cannot recommend one of the sensors specifically. The idea is to repeat the measurement setup, addressing the corrections mentioned above. By doing this, we expect to obtain higher accuracy and reduced differences among the stations. Since the PET depends on parameters affected during the first measurement round, we expect lower PET differences with the corrections (<4.4°C). With such values, we believe that any of the stations would be appropriate to measure heat stress conditions.

6. References

Coccolo et al. (2016). Outdoor human comfort and thermal stress: a comprehensive review on models and standards. *Urban Climate*. 18:33-57.

Klok, L., Rood, N., Kluck, J., & Kleerekoper, L. (2019). Assessment of thermally comfortable urban spaces in Amsterdam during hot summer days. *International Journal of Biometeorology*. 63:219-141.

Matzarakis, A., Mayer, H., & Iziomon, M.G. (1999). Applications of a universal thermal index: physiological equivalent temperature. *Int. J. Biometeorol*, 43, 76-84.

Thorsson, S., Lindberg, F., Eliasson, I., and Homer, B. (2007). Different methods for estimating the mean radiant temperature in an outdoor urban setting. *International Journal of Climatology.* 27:1983-1993.

Walikewitz, N., Jänicke, B., Langner, M., Meier, F., & Endlicher, W. (2015). The difference between the mean radiant temperature and the air temperature within indoor environments: A case study during summer conditions. *Building and Environment.* 84:151-161.