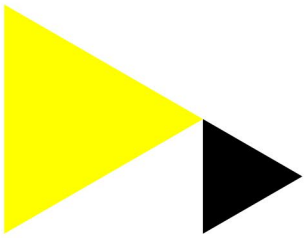
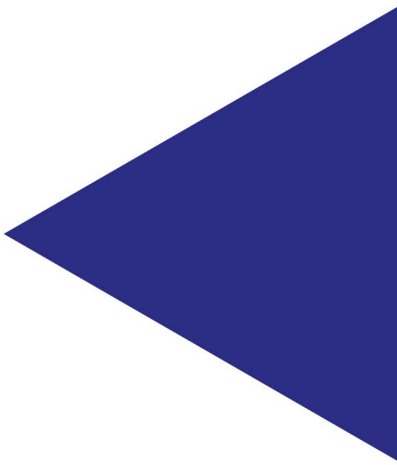
Application and performance of Kestrel sensors for assessing thermal comfort in outdoor built environments





Application and performance of Kestrel sensors for assessing thermal comfort in outdoor built environments

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INTRODUCTION

In face of climate change and urbanization, the need for thermally comfortable outdoor urban spaces is increasing. In the design of the thermally comfortable urban spaces and decision making about interventions that enhance thermal comfort, scientists and professionals that work for cities use meteorological measurements and models. These measurements can be done by professional and accurate meteorological sensors, but also by simpler mobile instruments such as the easy-to-use Kestrel weather meters. In using these simple type of sensors, it is important to know what the performance of these sensors is for outdoor thermal comfort assessments and how they can be used by scientists and professionals in decision making about urban designs that enhance thermal comfort.

To answer these questions, we carried out three experiments in the summer of 2020 in Amsterdam, the Netherlands, in which we tested the 11 Kestrel 5400 heat stress sensors and assessed the performance of this equipment for thermal comfort studies.

Hogeschool van Amsterdam

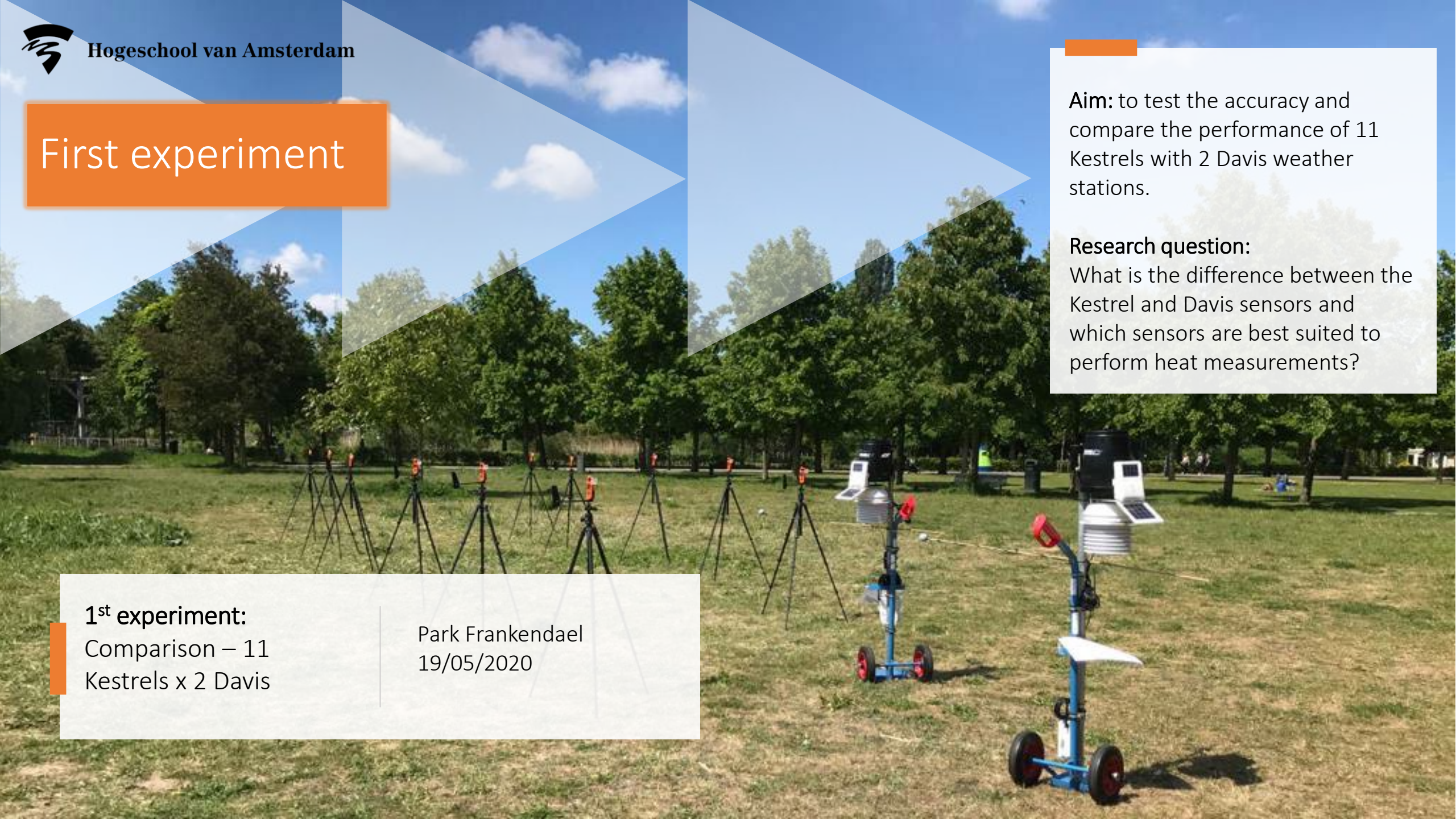
First experiment

Aim: to test the accuracy and compare the performance of 11 Kestrels with 2 Davis weather stations.

Research question:
What is the difference between the Kestrel and Davis sensors and which sensors are best suited to perform heat measurements?

1st experiment:
Comparison – 11 Kestrels x 2 Davis

Park Frankendael
19/05/2020



Location: Park Frankendael

Microclimatic characteristics of the test location:

- Green area: grass
- No shade
- Treeline around test location (distance to treeline ≈ 10 m)
- Ponds around the test location

Dutch weather report

Hogeschool van Amsterdam

Daggegevens van het weer in Nederland

Het weer op dinsdag 19 mei 2020 te Schiphol

Temperatuur		**Normaal**	**Neerslag**		
Gemiddelde	15.5 °C	13.2 °C	Hoeveelheid	0.0 mm	
Maximum	20.2 °C	17.8 °C	Duur	0.0 uur	
Minimum	10.3 °C	8.4 °C			
Zon, bewolking & zicht			**Wind**		
Duur zonneschijn	11.7 uur		Gemiddelde snelheid	3.5 m/s	(3 Bft)
Rel. zonneschijnduur	74 %	47 %	Maximale uurgemiddelde snelheid	7.0 m/s	(4 Bft)
Gem. bedekkingsgraad	5 octa's		Maximale stoot	10.0 m/s	
	Half tot zwaar bewolkt				
Minimaal zicht	9.0 km		Overheersende richting	282 °	(W)
Relatieve luchtvochtigheid			**Luchtdruk**		
Gemiddelde	75 %	75 %	Gemiddelde luchtdruk	1022.3 hPa	

Set up:

Start time: 11:46 h
End time: 16:00 h
Time interval measurements: 1 minute

Parameters

- Air temperature
- Humidity
- Wind speed
- Globe temperature
- Mean Radiant Temperature

$$\text{RMSE} = \sqrt{\frac{\sum_{i=1}^{n}(x_{1,i}-x_{2,i})^2}{n}}$$

Ref = average Kestrels

Thorsson et al. (2007):

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

Walikewitz et al. (2015):
Black globe (Kestrel): $1.1 \times 10^8 V_a^{0.6}$
Grey globe (Davis): $1.335 \times 10^8 V_a^{0.71}$

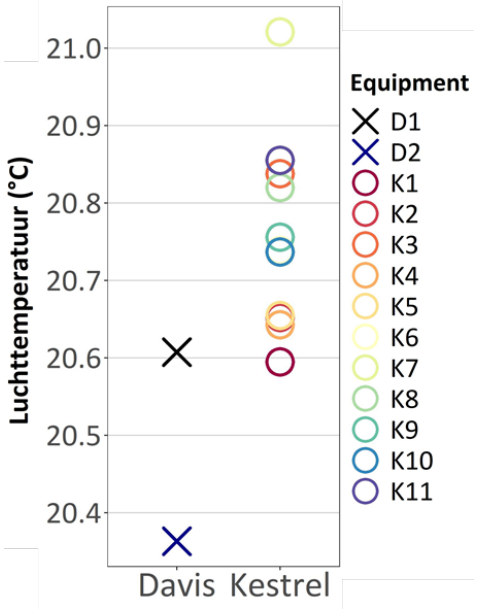
Davis = 38 mm Kestrel = 150 mm

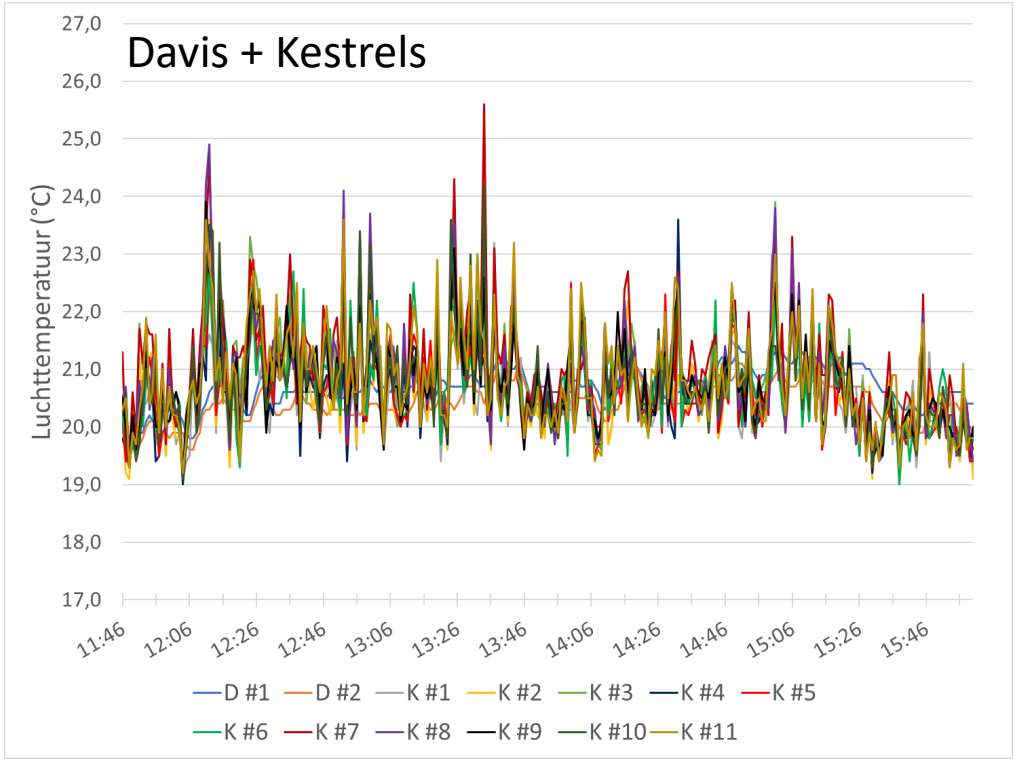
- PET is calculated with Raymann v. 1.2 based om 10-min averages of air temperature, globe temperature, wind speed and TMRT (10 min)
- According to the website of Kestrel, the temperature inside a 1-inch black powder-coated copper globe is converted to Tg equivalent for a standard 6 inches (150 mm) globe.

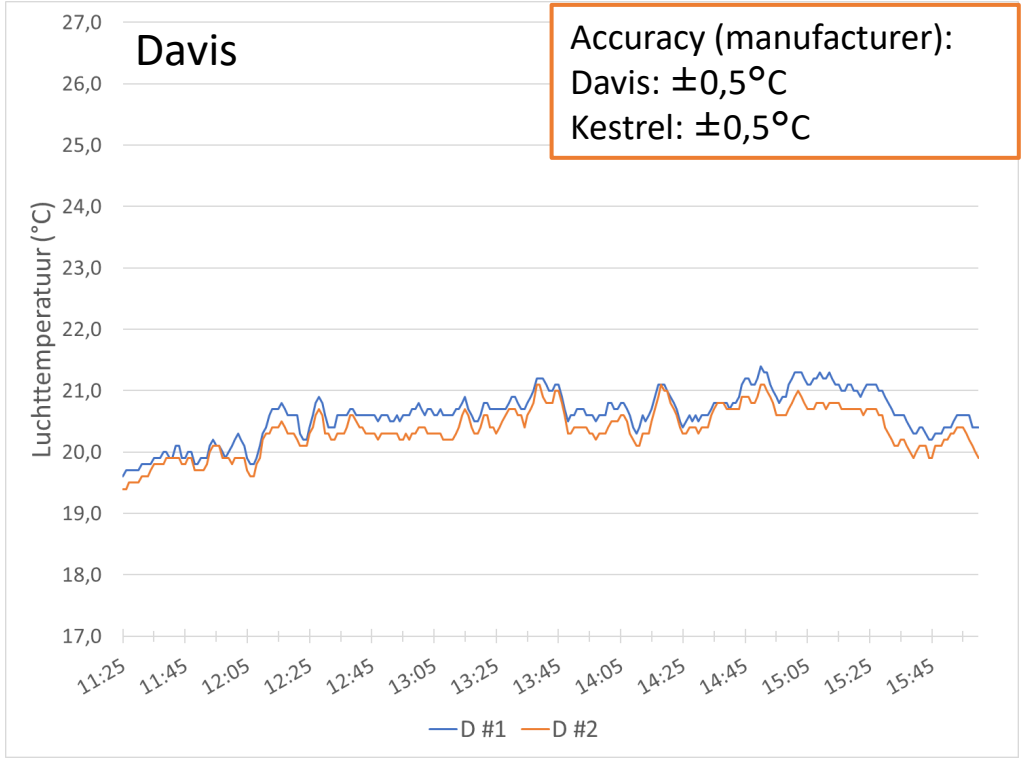
Results – Air temperature

Luchttemperatuur (°C)	D#1	D#2	Ref &Kestrels										
			K#1	K#2	K#3	K#4	K#5	K#6	K#7	K#8	K#9	K#10	K#11
RMSE	0,3		0,4	0,3	0,3	0,3	0,3	0,4	0,5	0,4	0,3	0,4	0,4
GEMIDDELDE	20,6	20,4	20,6	20,7	20,8	20,6	20,7	20,7	21,0	20,8	20,8	20,7	20,9
n	276	276	255	255	255	255	255	255	255	255	255	255	255

Average values

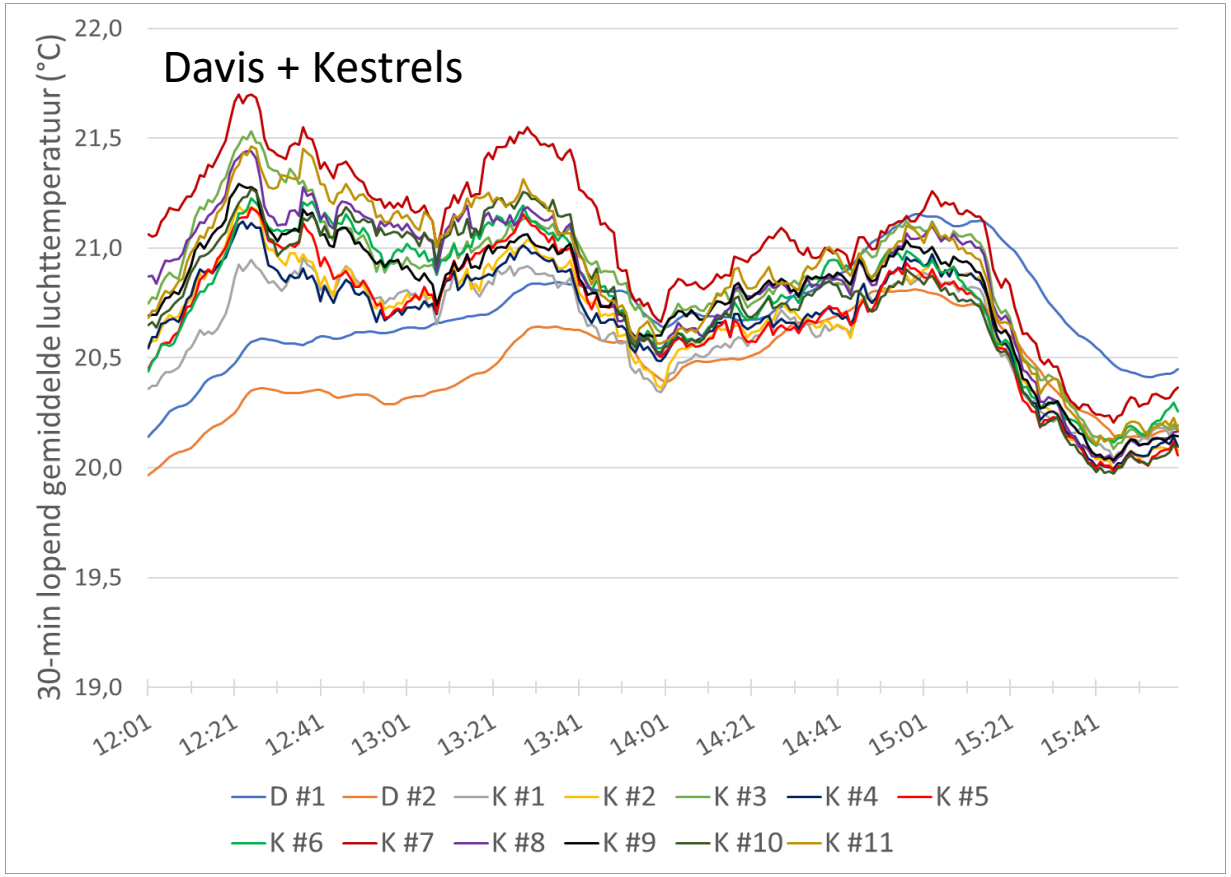


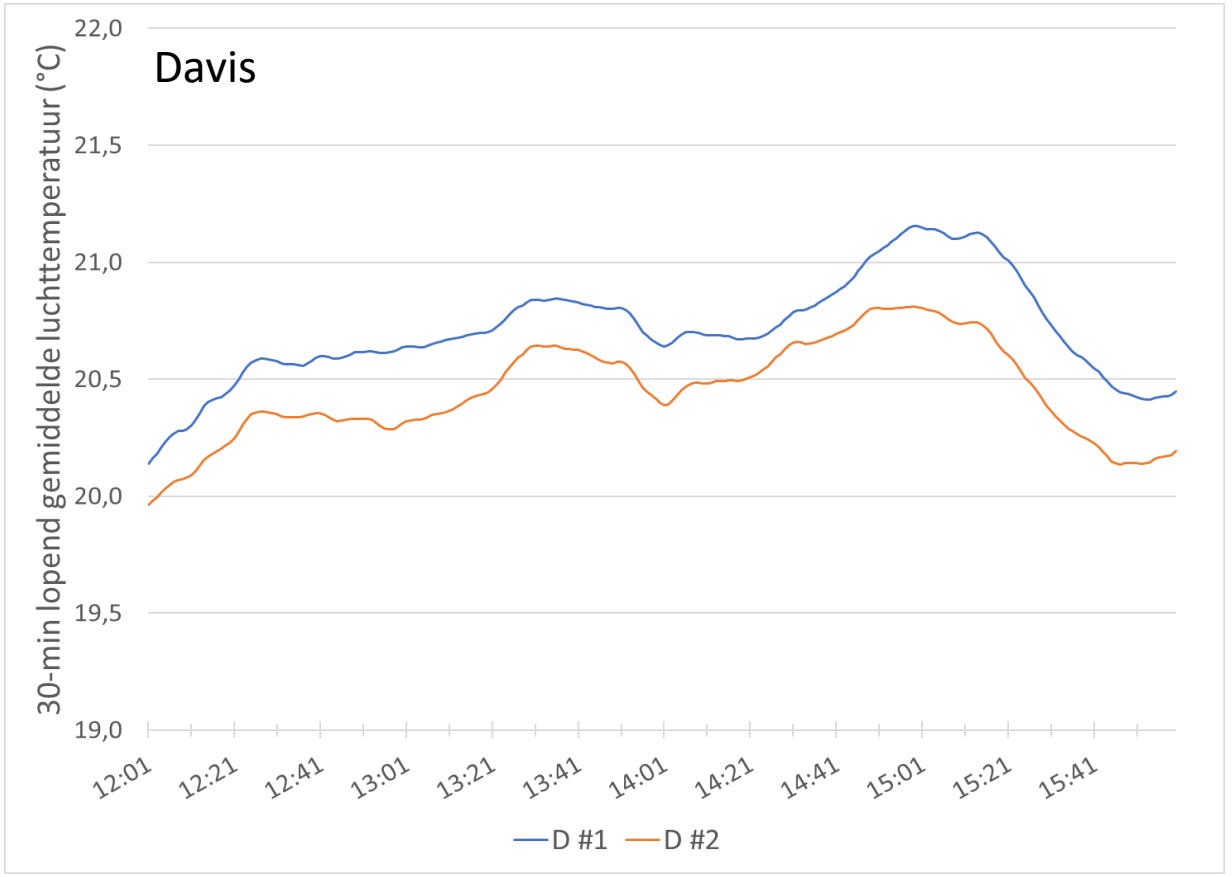




Accuracy (manufacturer):
Davis: ±0,5°C
Kestrel: ±0,5°C

Results – Air temperature – 10 min running average

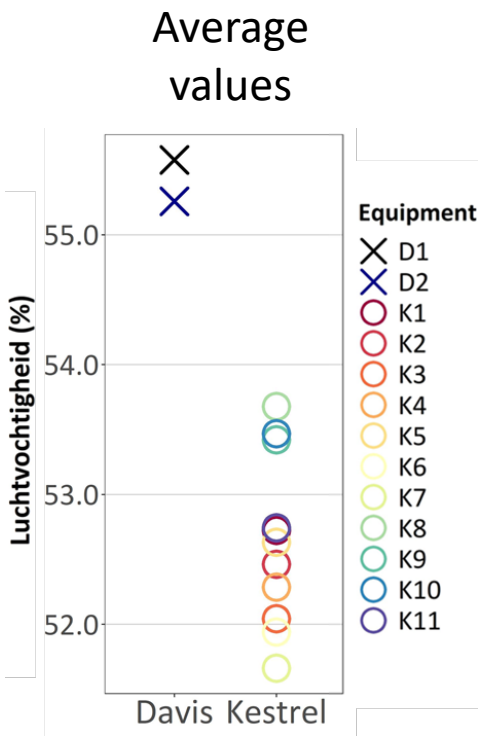


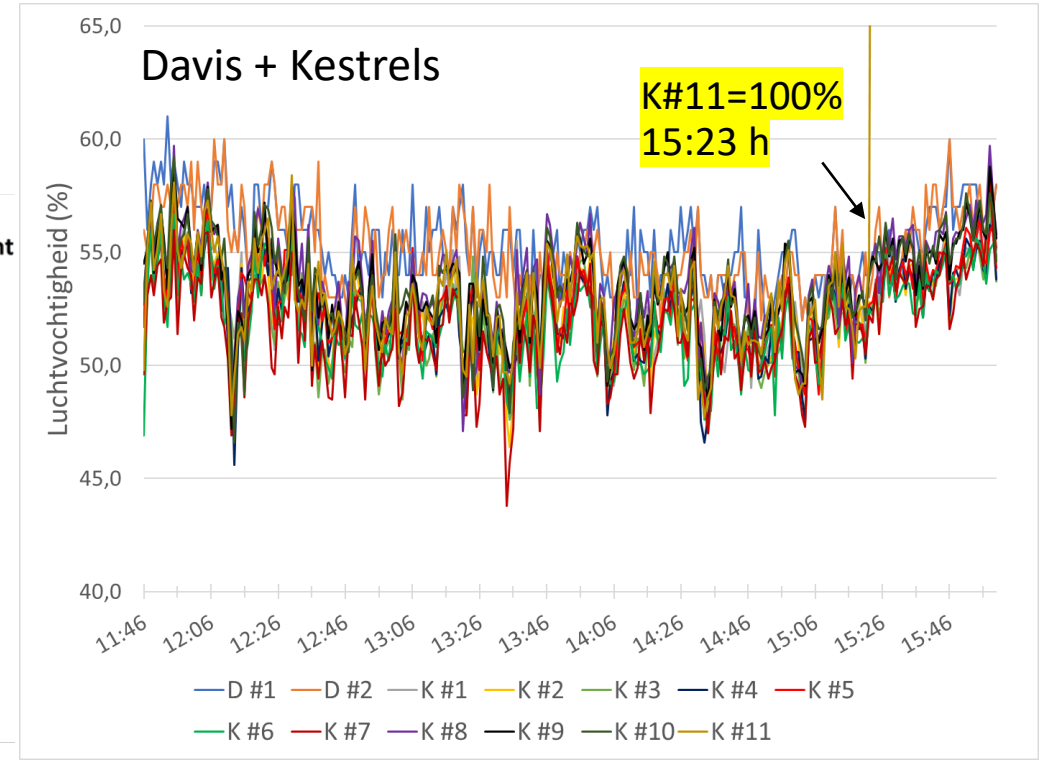


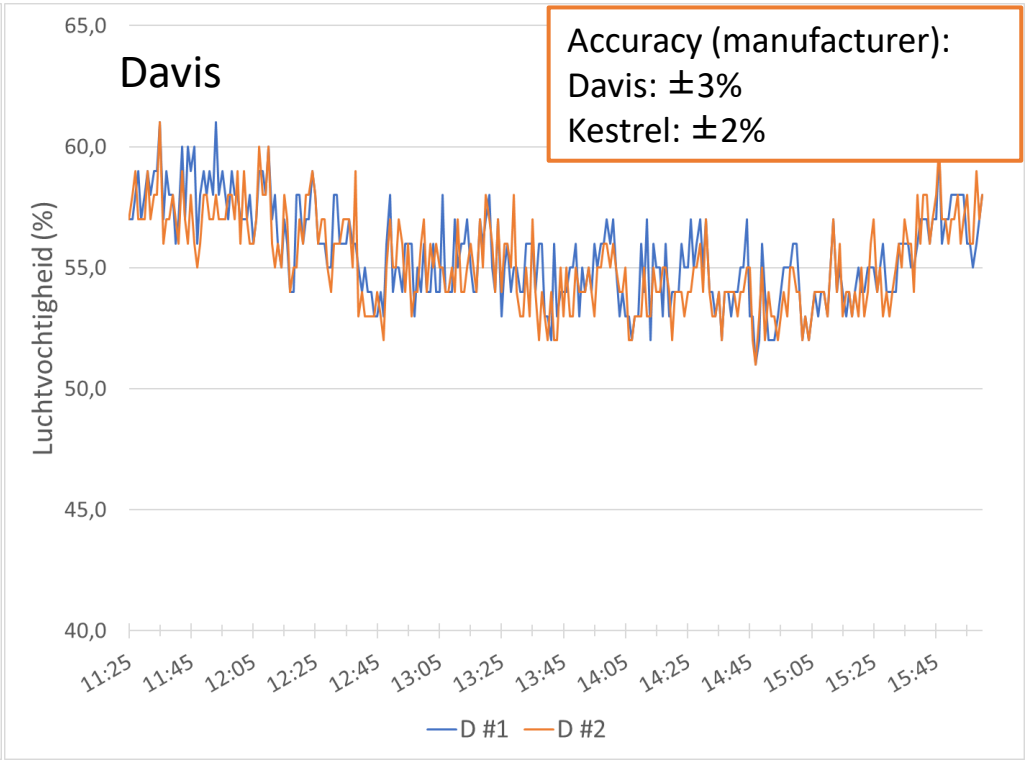
1e proef: Park Frankendael

Results - Humidity

Luchtvochtigheid (%)	D#1	D#2	Ref &Kestrels									
			K#1	K#2	K#3	K#4	K#5	K#6	K#7	K#8	K#9	K#10	K#11
RMSE	1,3		0,8	0,7	0,9	0,7	0,7	1,1	1,3	1,2	1,0	1,1	1,0
GEMIDDELDE	55,6	55,3	52,7	52,5	52,0	52,3	52,6	51,9	51,7	53,7	53,4	53,5	52,7
n	276	276	255	255	255	255	255	255	255	255	255	255	217



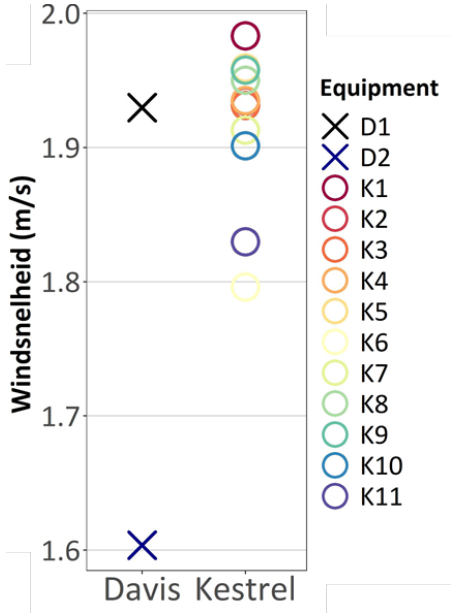


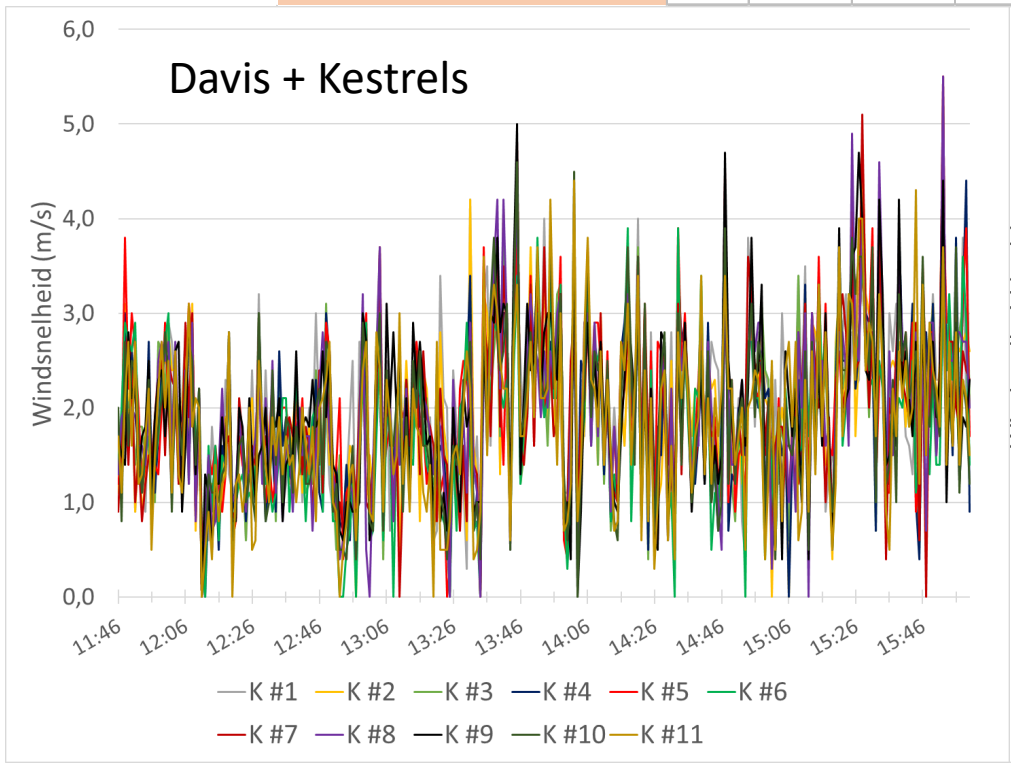


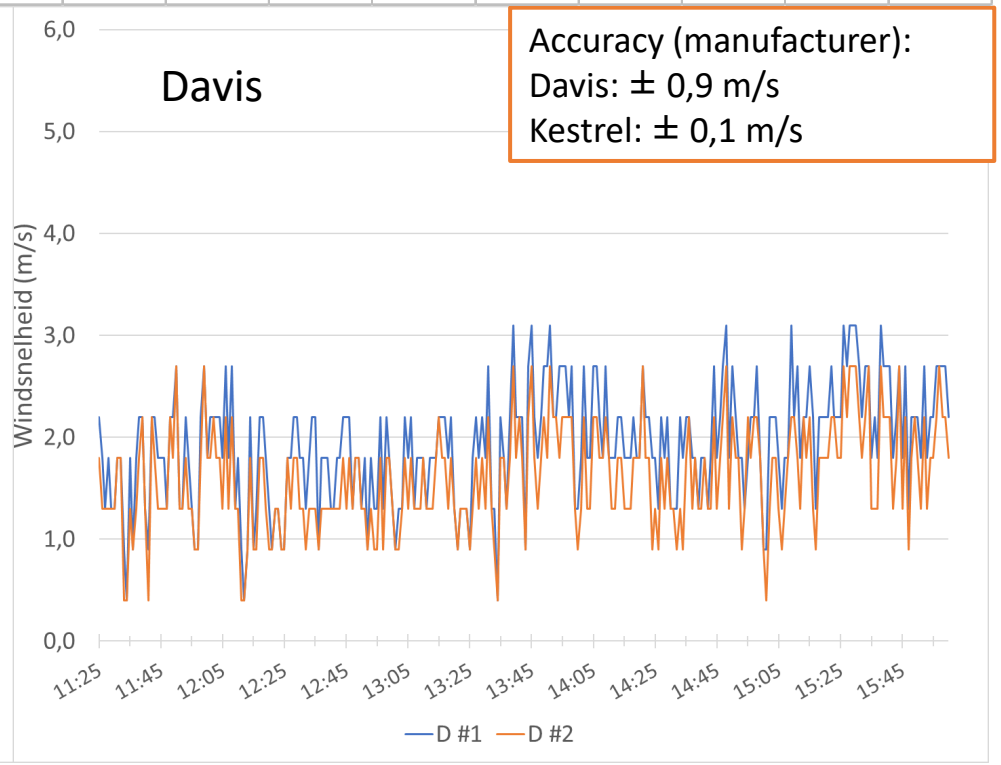
Results – Wind speed

Windsnelheid (m/s)	D#1	D#2	Ref &Kestrels										
			K#1	K#2	K#3	K#4	K#5	K#6	K#7	K#8	K#9	K#10	K#11
RMSE	0,4		**0,6**	**0,4**	**0,3**	**0,4**	**0,4**	**0,5**	**0,4**	**0,4**	**0,5**	**0,4**	**0,5**
GEMIDDELDE	**1,9**	**1,6**	**2,0**	**1,9**	**1,9**	**1,9**	**2,0**	**1,8**	**1,9**	**2,0**	**2,0**	**1,9**	**1,8**
n	276	276	255	255	255	255	255	255	255	255	255	255	255

Average values

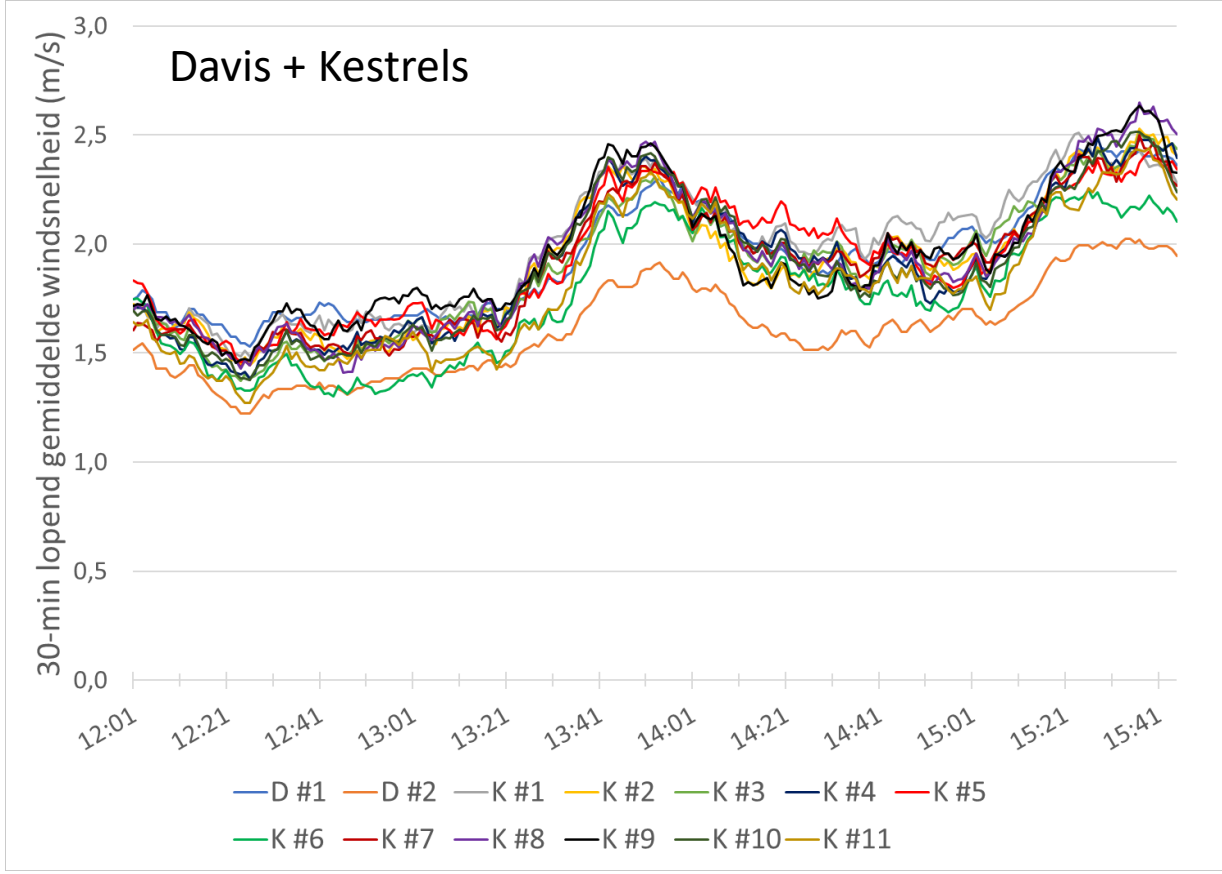


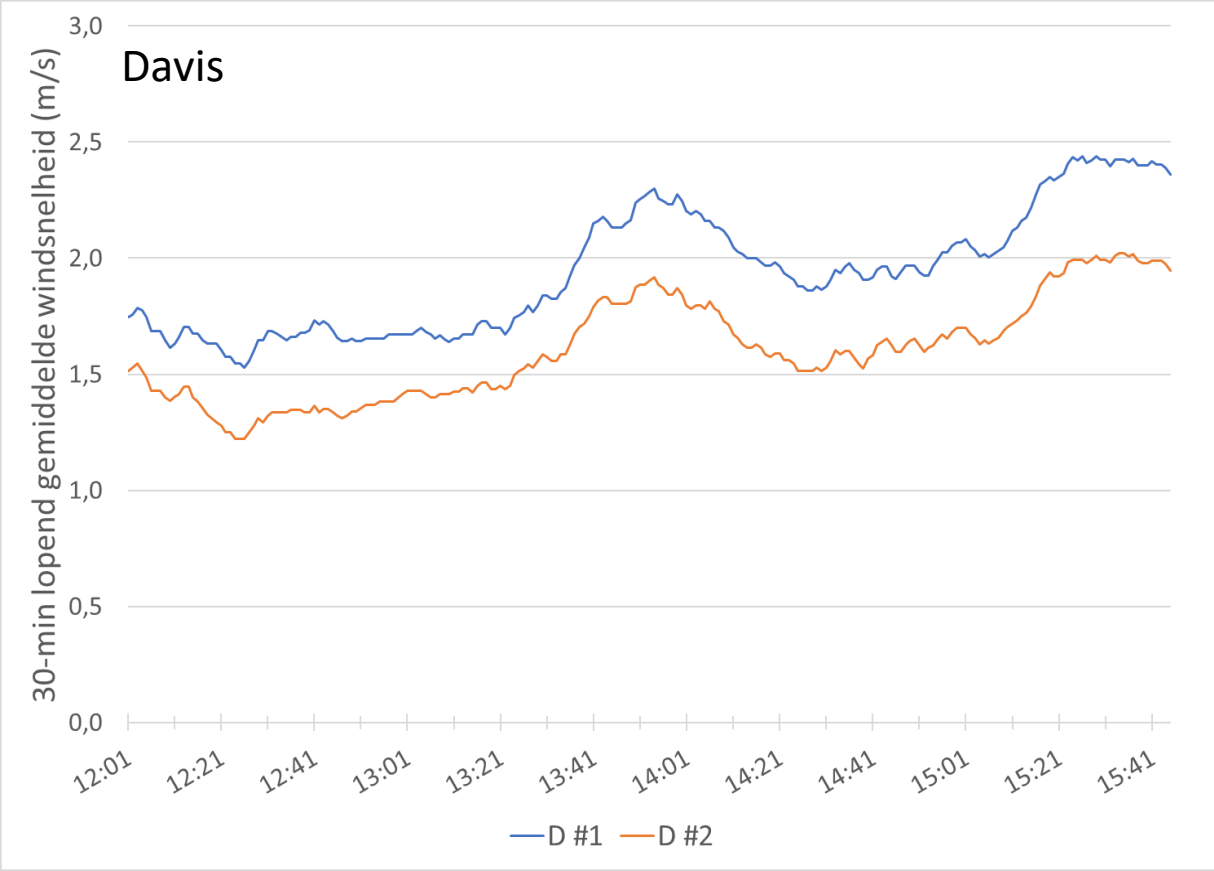




Accuracy (manufacturer):
Davis: ± 0,9 m/s
Kestrel: ± 0,1 m/s

Results – Wind speed– 30 min running average



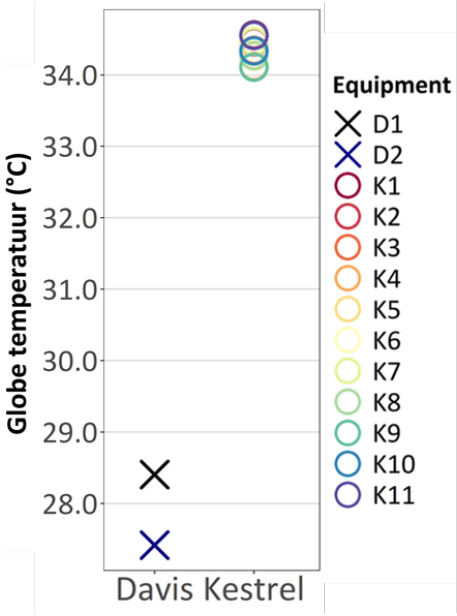


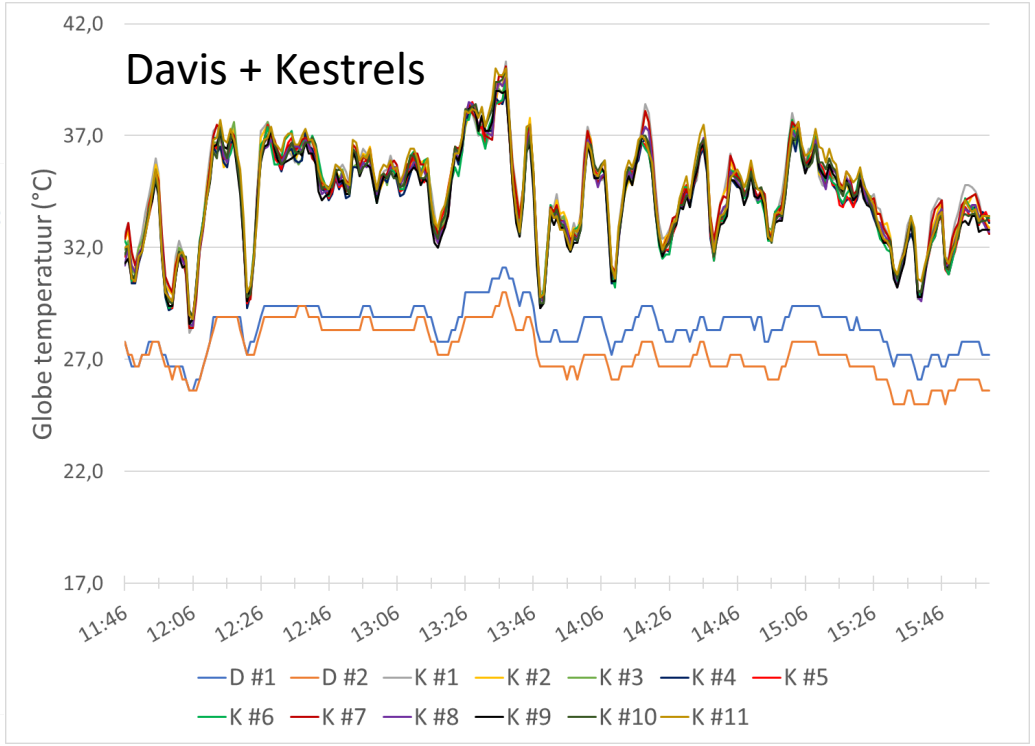
1e proef: Park Frankendael

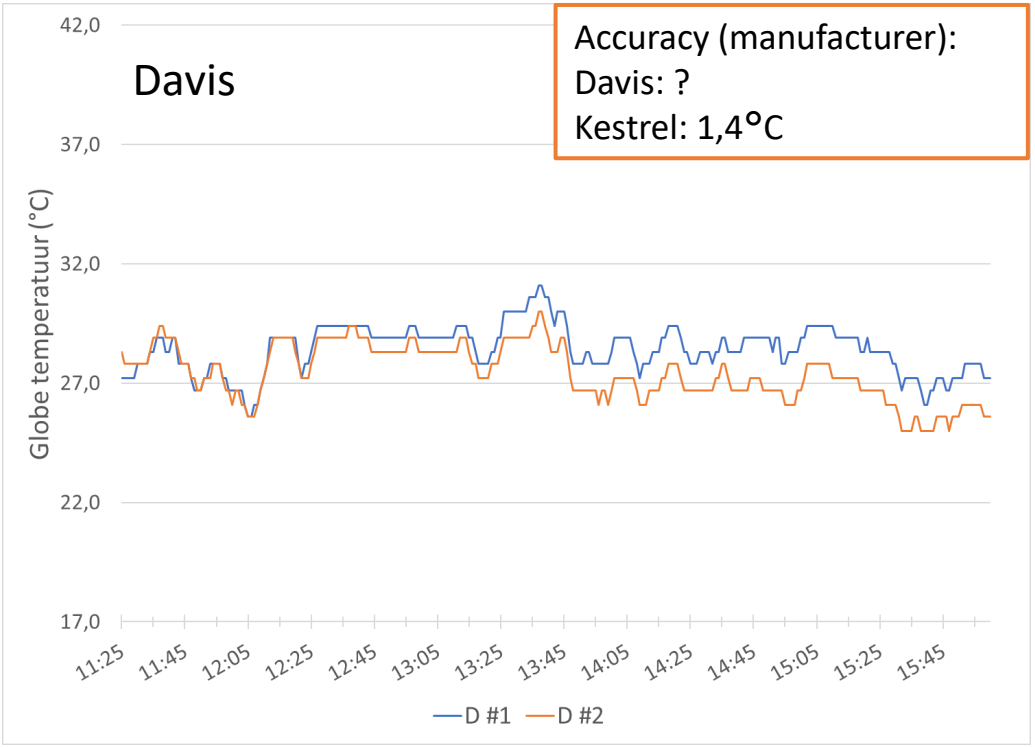
Results – Globe temperature

Globe temperatuur (°C)	D#1	D#2	Ref &Kestrels										
			K#1	K#2	K#3	K#4	K#5	K#6	K#7	K#8	K#9	K#10	K#11
RMSE	1,2		0,4	0,3	0,2	0,3	0,2	0,3	0,3	0,2	0,3	0,2	0,4
GEMIDDELDE	28,4	27,4	34,6	34,5	34,3	34,1	34,3	34,3	34,5	34,3	34,1	34,3	34,6
n	276	276	255	255	255	255	255	255	255	255	255	255	255

Average values







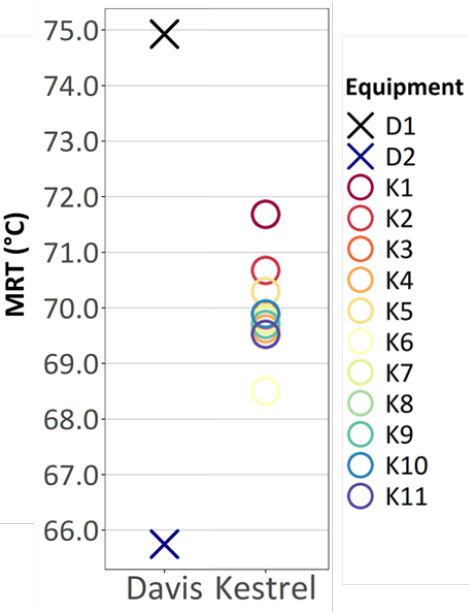
Accuracy (manufacturer):
Davis: ?
Kestrel: 1,4°C

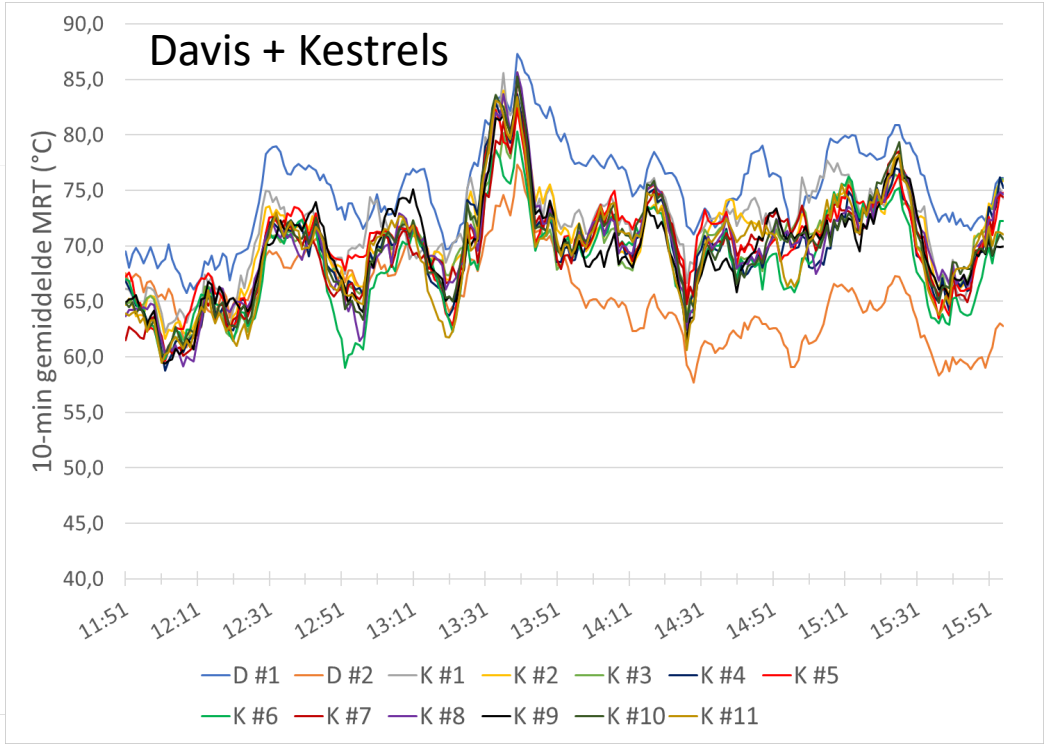
1e proef: Park Frankendael

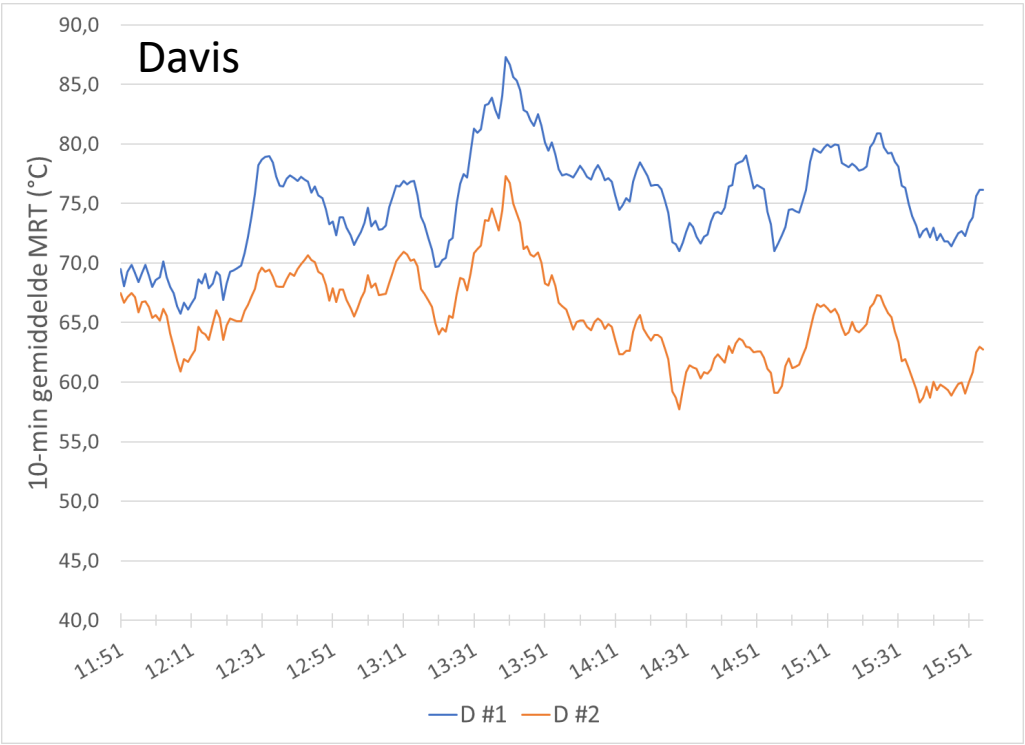
Results – Mean Radiant Temperature

MRT (°C)	D#1	D#2	Ref &Kestrels										
			K#1	K#2	K#3	K#4	K#5	K#6	K#7	K#8	K#9	K#10	K#11
RMSE	10,1		**2,2**	**1,3**	**1,1**	**1,0**	**1,3**	**2,1**	**1,1**	**1,1**	**1,4**	**1,0**	**1,4**
GEMIDDELDE	**74,9**	**65,7**	**71,7**	**70,7**	**69,9**	**69,6**	**70,3**	**68,5**	**69,8**	**69,9**	**69,7**	**69,9**	**69,5**
nn	266	266	245	245	245	245	245	245	245	245	245	245	245

Average values



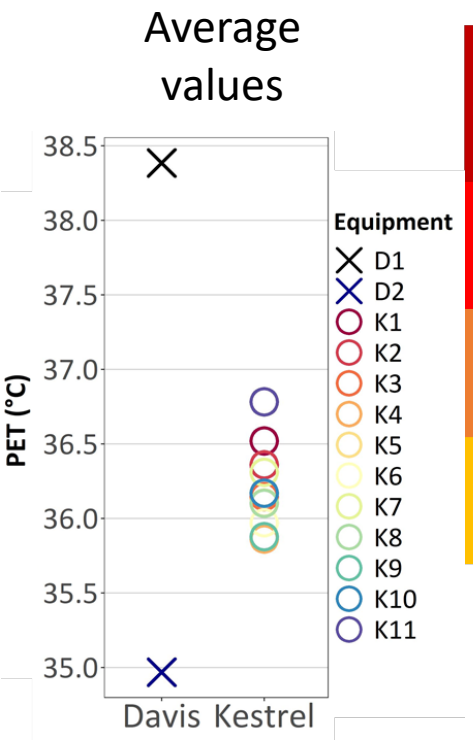


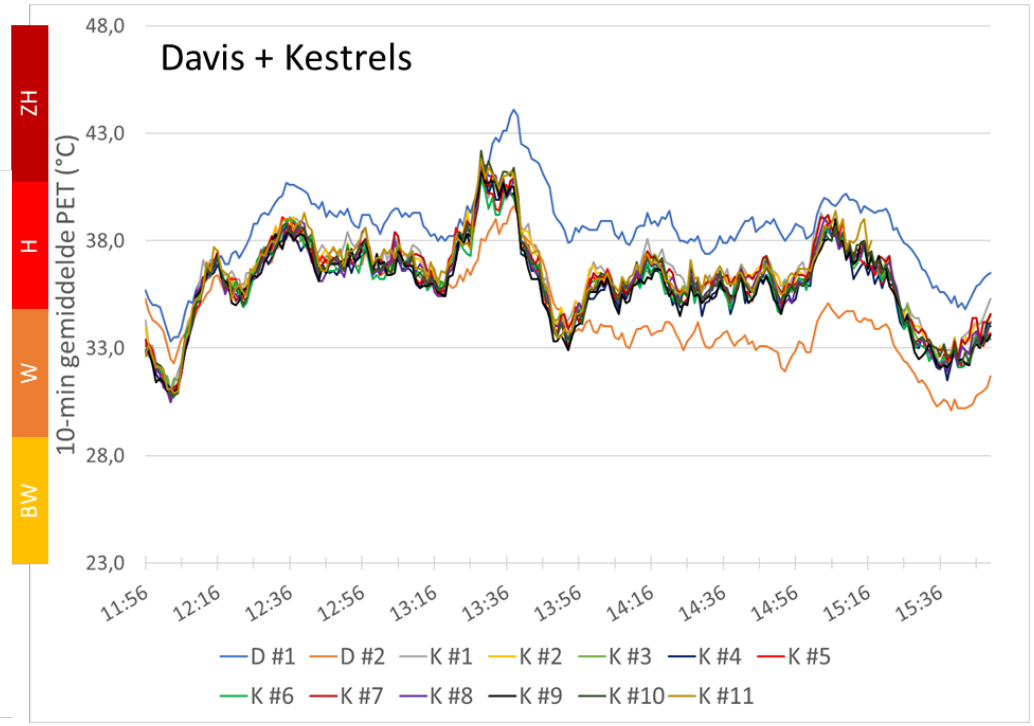


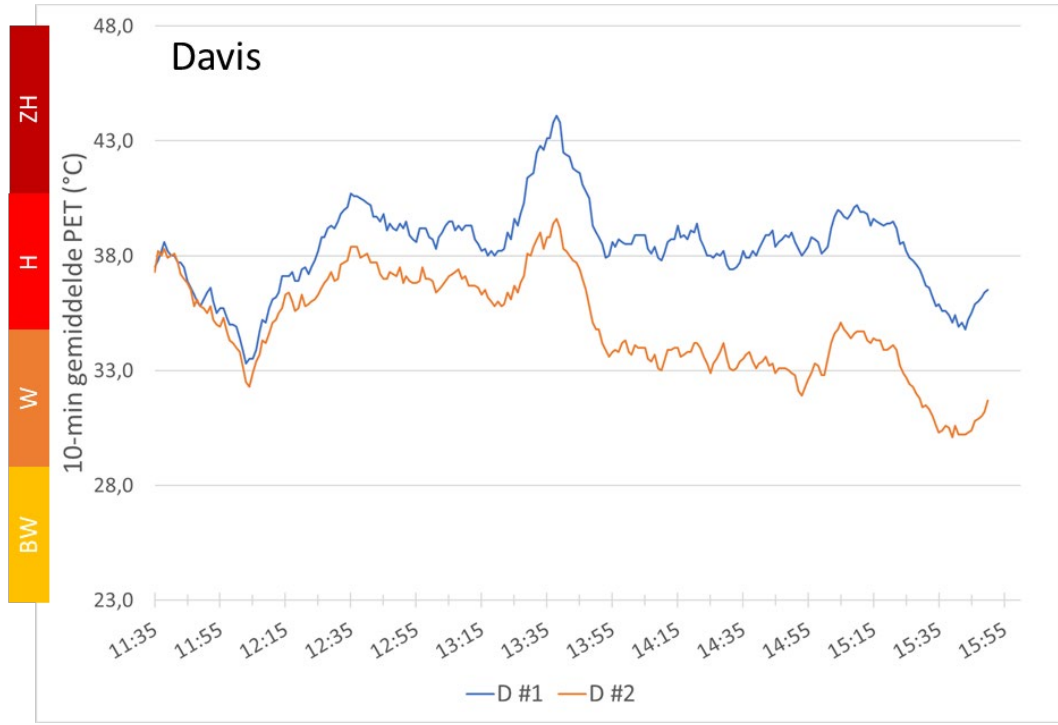
1e proef: Park Frankendael

Results – PET (10-min average)

PET(°C)	D#1	D#2	Ref &Kestrels										
			K#1	K#2	K#3	K#4	K#5	K#6	K#7	K#8	K#9	K#10	K#11
RMSE	3,9		0,5	0,3	0,2	0,4	0,3	0,4	0,3	0,3	0,4	0,3	0,4
GEMIDDELDE	38,4	35,0	36,5	36,4	36,1	35,9	36,1	36,0	36,3	36,1	35,9	36,2	36,8
n	256	256	235	235	235	235	235	235	235	235	235	235	202



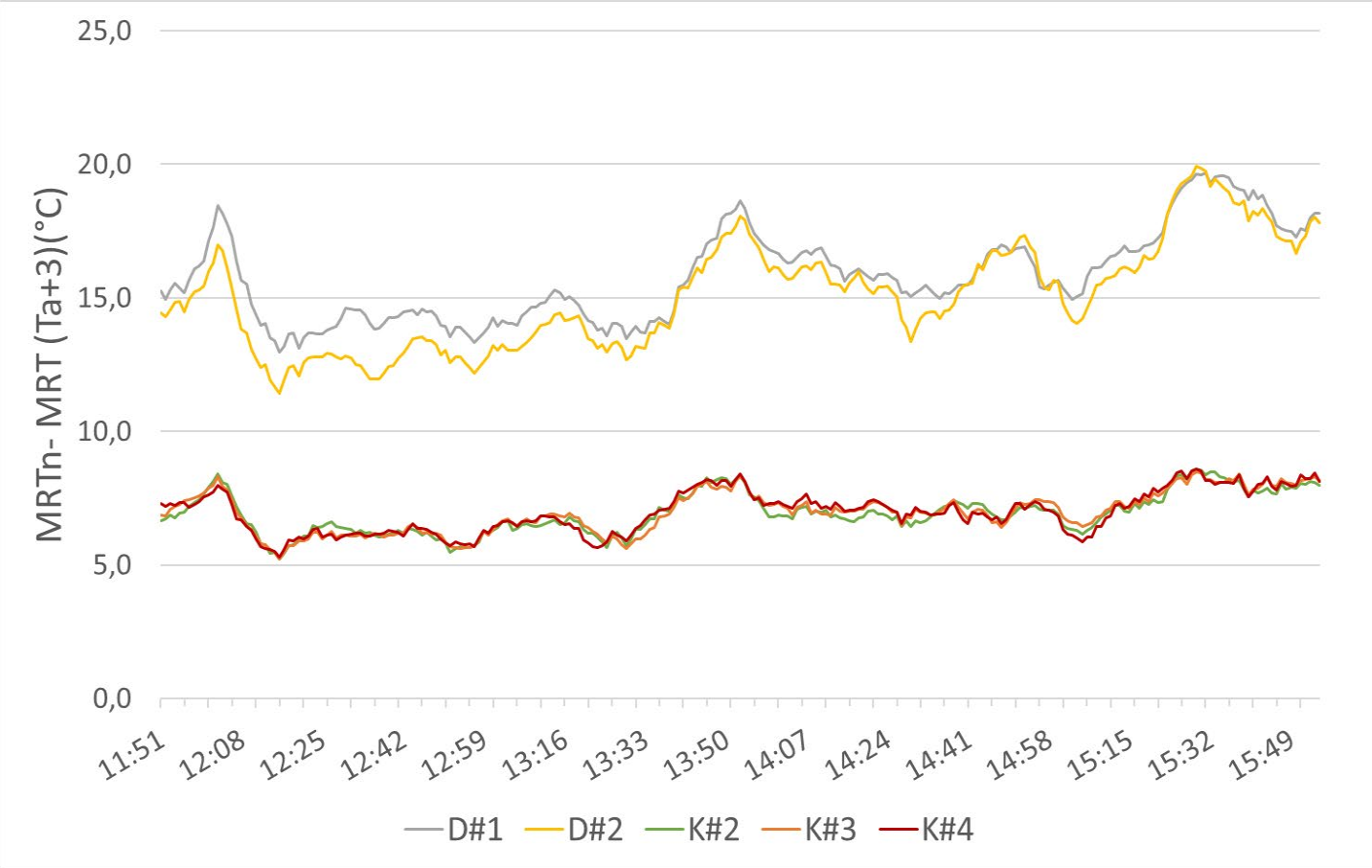




PET classification: Very Hot (>41 C), Hot (41-35 C), Warm (35-29 C), Slightly warm (29-23 C), Comfortable (23-18 C), Slightly Cool (18-13 C), Cool (13-8 C), Cold (8-4 C), Extremely Cold (<4 C). (Coccolo et al., 2016).

1e proef: Park Frankendael

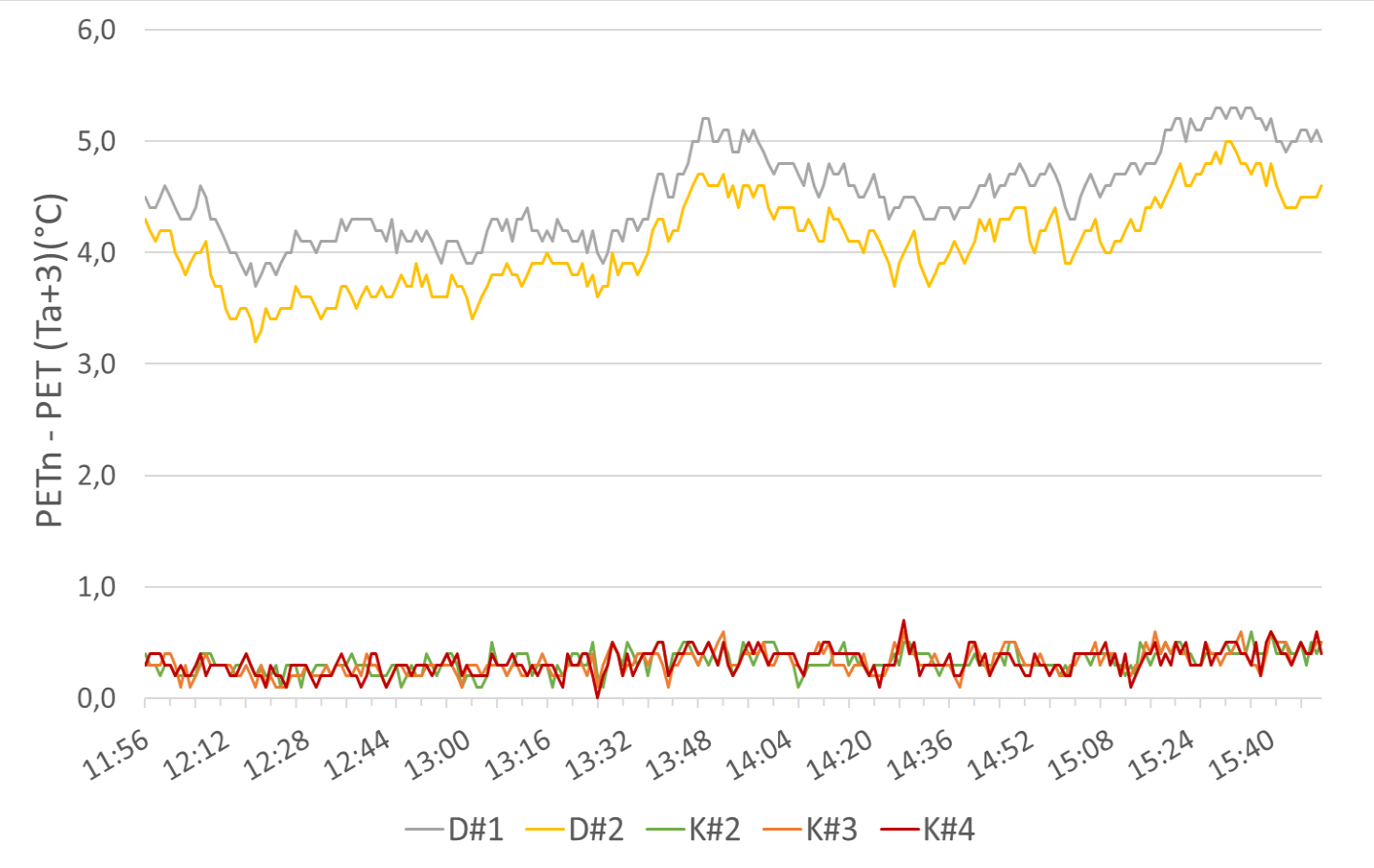
Results – sensitivity of MRT-calculation with respect to air temperature



- D#1, D#2, K#2, K#3, and K#4 were selected for a sensitivity analysis with respect to air temperature.
- Air temperatures of these sensors were increased by 3°C. The other variables were kept the same.
  - MRTn -> normal MRT (see previous slides).
  - MRT(Ta+3) -> MRT calculated with an increase of 3°C for the air temperature.
- Result: The MRT calculation of the Davis is more sensitive for a difference in air temperature than the Kestrel. A higher air temperature leads to lower MRT, which is a consequence of the equation (Thorsson et al., 2007)).

1e proef: Park Frankendael

Results – sensitivity of PET-calculation with respect to air temperature



- D#1, D#2, K#2, K#3, and K#4 were selected for a sensitivity analysis with respect to air temperature.
- Air temperatures of these sensors were increased by 3°C. The other variables were kept the same.
  - PETn -> normal PET (previous slides).
  - PET(Ta+3) -> PET calculated with an increase of 3°C for the air temperature.
- Result: Differences in air temperature almost have no effect on the PET-calculation of the Kestrels, but it does for the Davis.

Results - overview

RMSE - 2020	Davis	Ref &Kestrels										
		K#1	K#2	K#3	K#4	K#5	K#6	K#7	K#8	K#9	K#10	K#11
Luchttemperatuur (°C)	**0,3**	**0,4**	**0,3**	**0,3**	**0,3**	**0,3**	**0,4**	**0,5**	**0,4**	**0,3**	**0,4**	**0,4**
n	276	255	255	255	255	255	255	255	255	255	255	255
Luchtvochtigheid (%)	**1,3**	**0,8**	**0,7**	**0,9**	**0,7**	**0,7**	**1,1**	**1,3**	**1,2**	**1,0**	**1,1**	**1,0**
n	276	255	255	255	255	255	255	255	255	255	255	217
Windsnelheid (m/s)	**0,4**	**0,6**	**0,4**	**0,3**	**0,4**	**0,4**	**0,5**	**0,4**	**0,4**	**0,5**	**0,4**	**0,5**
n	276	255	255	255	255	255	255	255	255	255	255	255
Globe temperatuur (°C)	**1,2**	**0,4**	**0,3**	**0,2**	**0,3**	**0,2**	**0,3**	**0,3**	**0,2**	**0,3**	**0,2**	**0,4**
n	276	255	255	255	255	255	255	255	255	255	255	255
Zonnestraling (W/m²)	**135**	**-**	**-**	**-**	**-**	**-**	**-**	**-**	**-**	**-**	**-**	**-**
n	276	-	-	-	-	-	-	-	-	-	-	-
MRT (°C)	**10,1**	**2,2**	**1,3**	**1,1**	**1,0**	**1,3**	**2,1**	**1,1**	**1,1**	**1,4**	**1,0**	**1,4**
n	266	245	245	245	245	245	245	245	245	245	245	245
PET(°C)	**3,9**	**0,5**	**0,3**	**0,2**	**0,4**	**0,3**	**0,4**	**0,3**	**0,3**	**0,4**	**0,3**	**0,4**
n	256	235	235	235	235	235	235	235	235	235	235	202

Comparing RMSE with experiments carried out in 2019 and accuracy given by manufacturer and

RMSE – 2019 & 2020	2019			2020		Nauwkeurigheid (fabrikant)	
	11:00-15:00 h			11:40-16:00h			
	Davis x Davis	2 Davis x 2 Kestrels	2 Kestrels	DavisxDavis	11 Kestrels	Davis	Kestrel
Luchttemperatuur (°C)	**0,3**	**0,6-0,7**	**0,2**	**0,3**	**0,3-0,5**	**0,5**	**0,5**
N	865	215	215	276	255		
Luchtvochtigheid (%)	**0,7**	**3,9-4,2**	**0,2**	**1,3**	**0,7-1,3**	**2,0**	**3,0**
N	865	215	215	276	255*		
Windsnelheid (m/s)	**0,6**	**0,8**	**0,4**	**0,4**	**0,3-0,6**	**0,9**	**0,1**
N	865	215	215	276	255		
Globe temperatuur (°C)	**0,4**	**-**	**0,3**	**1,2**	**0,2-0,4**	**?**	**1,4**
N	671	-	215	276	255		
Zonnestraling (W/m²)	**88**	**-**	**-**	**135**	**-**	**50**	**-**
N	865	-	-	276	-		
MRT (°C)	**3,7**	**3,1-7,1**	**1,6**	**10,1**	**1,0-2,2**	**-**	**-**
N	671	149	215	266	245		
PET (°C)	**0,8**	**1,0-1,7**	**0,6**	**3,9**	**0,2-0,5**	**-**	**-**
N	671	149	215	256	235*		

1e proef: Park Frankendael

Conclusions based on experiment 1

- **Air temperature:**
  - Kestrel and Davis sensors both deviate less than the accuracy specified by the manufacturer.
  - However, the 1-minute time interval measurements of the Kestrel show large fluctuations. These might be caused by the increase in temperature of the Kestrel-casing (see next experiment). It is discouraged to use the Kestrel to determine the 1-minute temperature values.

- **PET**:
  - Based on this research the Kestrels seem to determine the PET more accurate than the Davis. This might have been caused by problems with the wind sensor and the grey globe of the Davis. It is possible that the wind sensor of the Davis 2# needs maintenance. The different grey balls of the globe temperature sensor of the Davis might explain the big differences in PET between the two Davis stations.
  - The strong variation in measured Kestrel-temperatures has a low influence on the calculated PET-value, as is proven in a sensibility study.

Second experiment

Aim: to investigate the influence of the heating of the Kestrel casing on air temperature measurements by sun radiation.

Research question:
Does the heating of the casing has an influence on the air temperature measurements of the Kestrels?
How does this influence the PET?

2nd experiment: Kestrel air temperature

Stadionplein
26/05/2020

Hogeschool van Amsterdam

Location: Stadionplein

Microclimatic characteristics of the test location:

- Grey area (square)
- Impermeable pavement
- Large building west of test location
- Not much green present (small garden east of test location)

Dutch wheater report

Daggegevens van het weer in Nederland

Het weer op dinsdag 26 mei 2020 te Schiphol

© KNMI

Temperatuur		**Normaal**
Gemiddelde	16.2 °C	13.7 °C
Maximum	23.2 °C	18.1 °C
Minimum	8.0 °C	9.0 °C

Zon, bewolking & zicht		
Duur zonneschijn	14.0 uur	
Rel. zonneschijnduur	86 %	45 %
Gem. bedekkingsgraad	5 octa's	
	Half tot zwaar bewolkt	
Minimaal zicht	10.0 km	

Relatieve luchtvochtigheid		
Gemiddelde	70 %	77 %

Neerslag		
Hoeveelheid	0.0 mm	
Duur	0.0 uur	

Wind		
Gemiddelde snelheid	2.6 m/s	(2 Bft)
Maximale uurgemiddelde snelheid	5.0 m/s	(3 Bft)
Maximale stoot	7.0 m/s	
Overheersende richting	309 °	(NW)

Luchtdruk		
Gemiddelde luchtdruk	1035.2 hPa	

Set up 1

Start time: 10:56 h

Time interval measurement: 1 minute

6 Kestrel sensors

K#5

K#1

K#7

K#4

K#2

K#6

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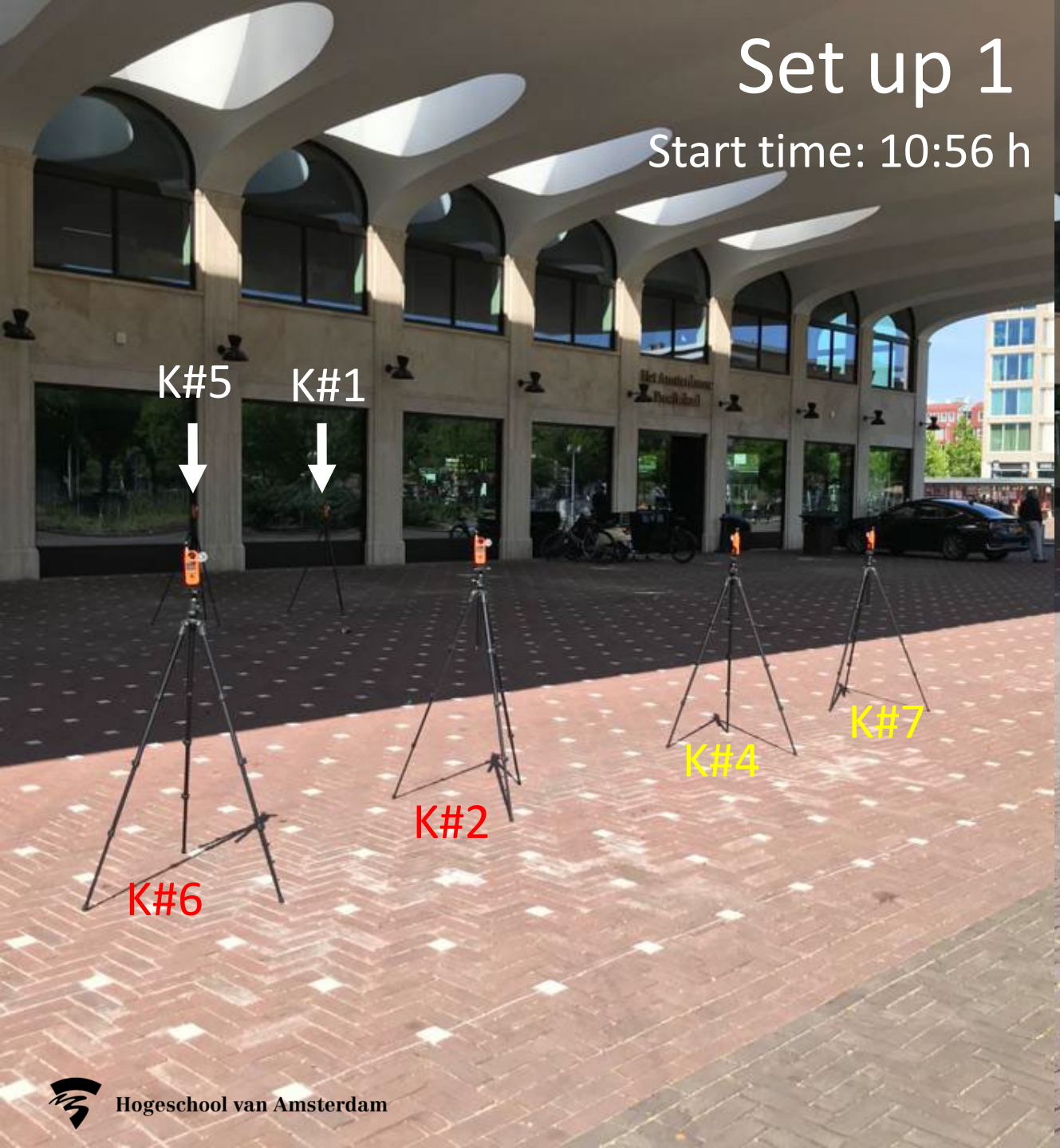
K#5 & K#1: shadow

K#4 & K#7: shadowed by itself

K#6 & K#2: direct sun

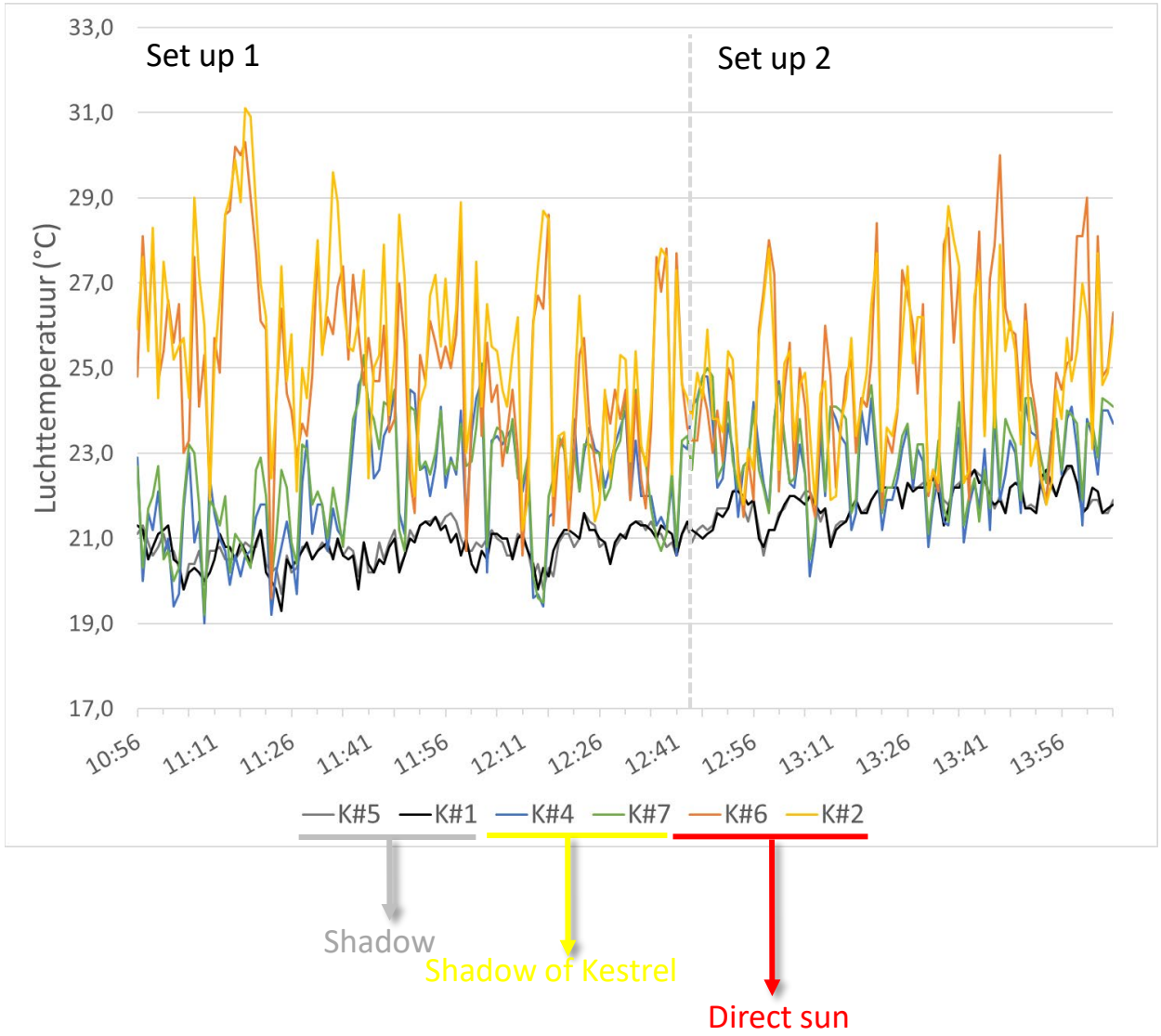

Set up 1
Start time: 10:56 h
K#5
K#1
K#6
K#2
K#4
K#7
Hogeschool van Amsterdam


Set up 2
Start time: 12:49 h
End time: 14:07 h
K#5
K#1
K#6
K#2
K#4
K#7

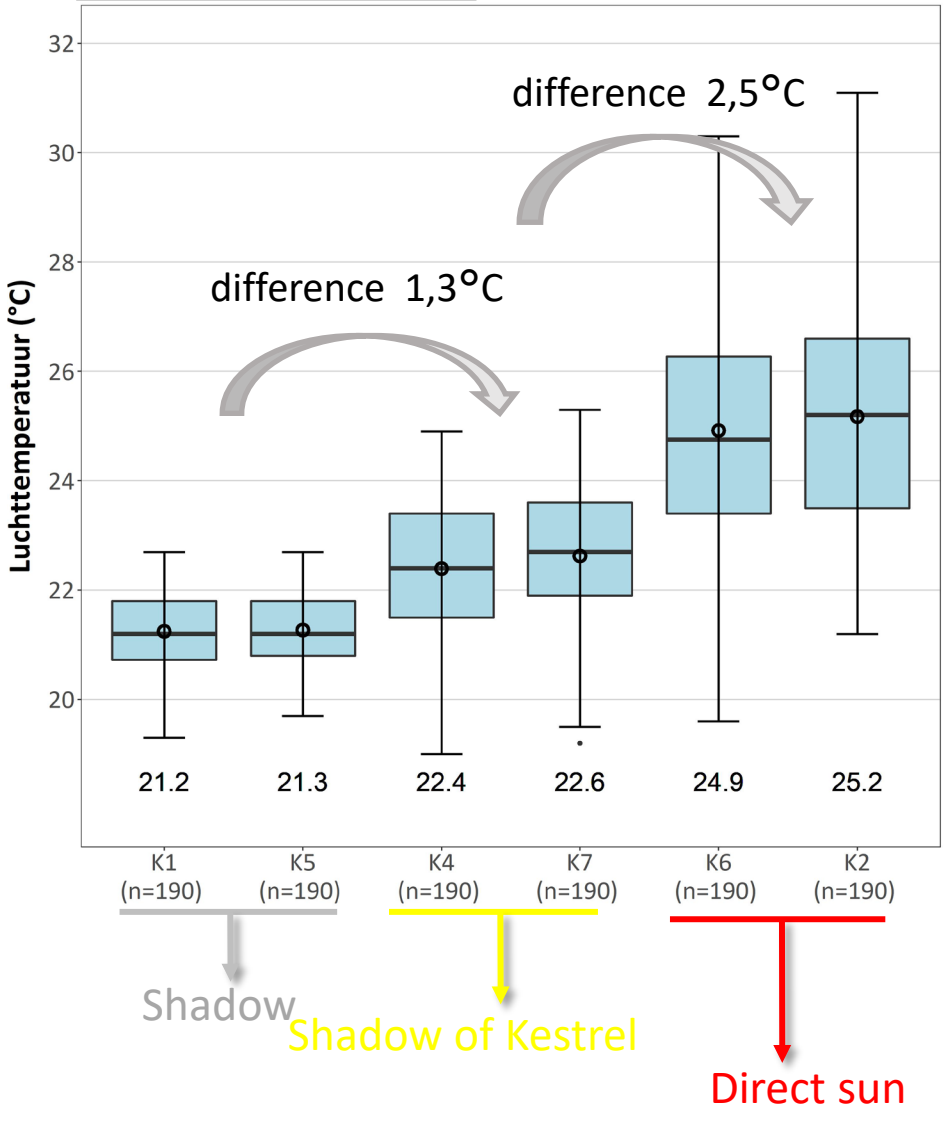
Results – Air temperature

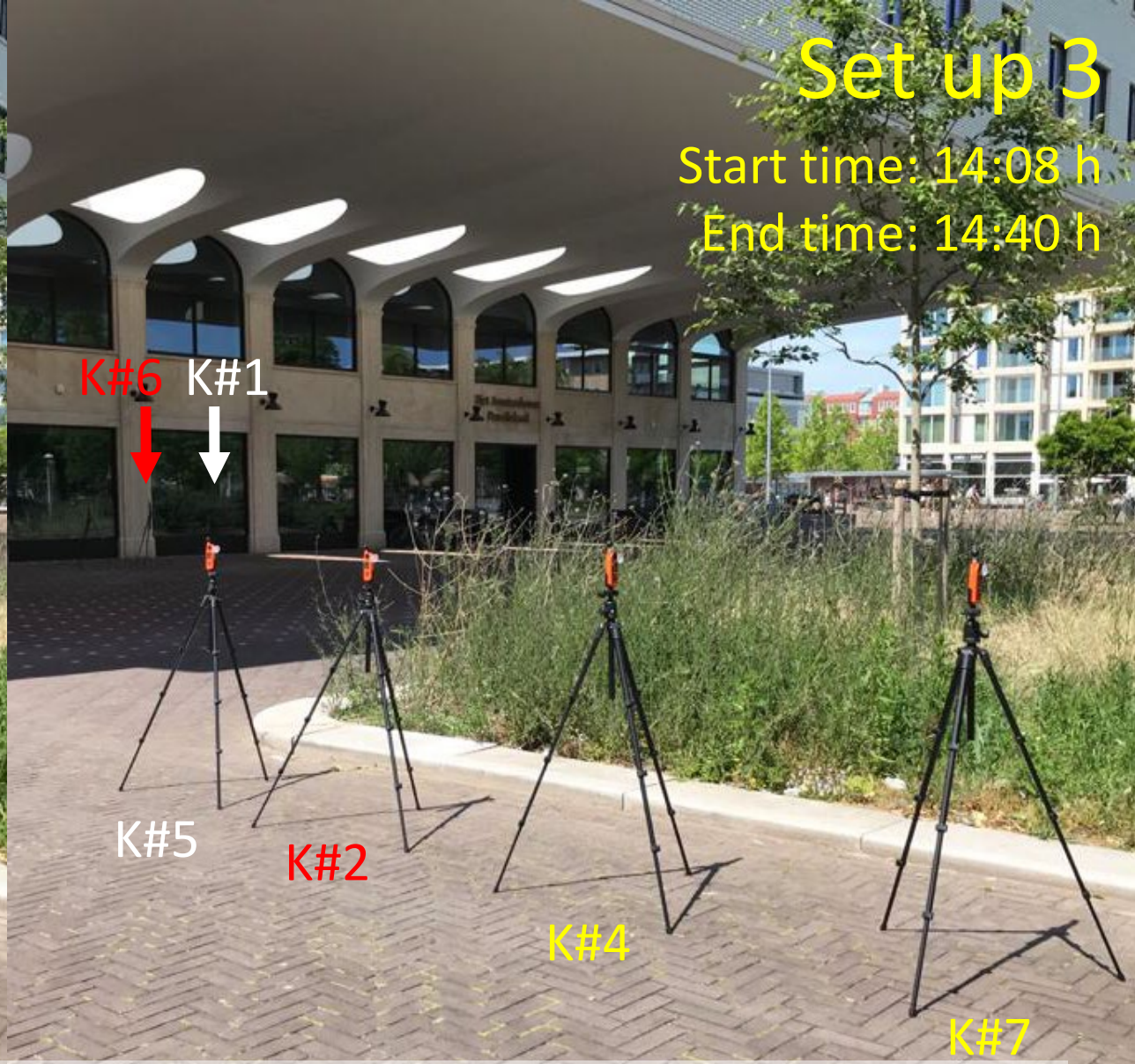
Hogeschool van Amsterdam

2nd experiment: Stadionplein



Period: 10:56-14:06 h





In set up 3, a Kestrel in the shade (# 5) and a Kestrel in full sun (# 6) are mixed up. The purpose of this was to understand how long it takes for the air temperature measurements to stabilize if the sensor is placed in the sun from the shade and vice versa. How long does it take for the case of the Kestrel to cool / warm up, causing a temperature effect on the measurement?

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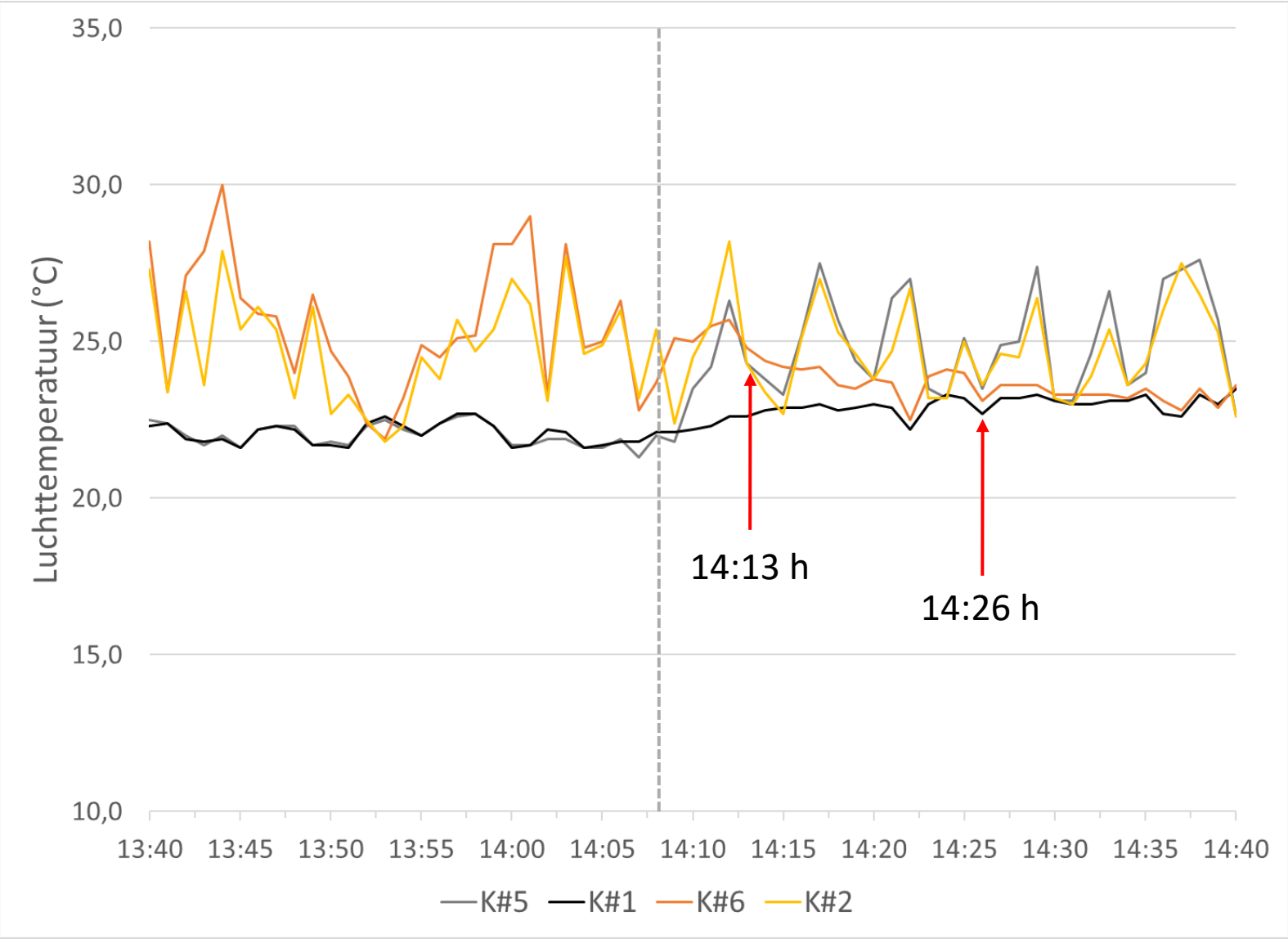
Results – Air temperature



Time for stabilization:

- **From shadow to sun:** 5 min before the difference between K#5 & K#2 becomes < 0,5°C
- **From sun to shadow:** 20 min before the difference between K#6 & K#1 becomes 0,5°C

2e proef: Stadionplein

Knowledge Base

CATEGORY

- Manuals and Downloads
- Kestrel LiNK Software and Apps
- Kestrel 5 Series
- Kestrel Ballistics
- Kestrel 4 Series

How do I get the most accurate measurements from my Kestrel?

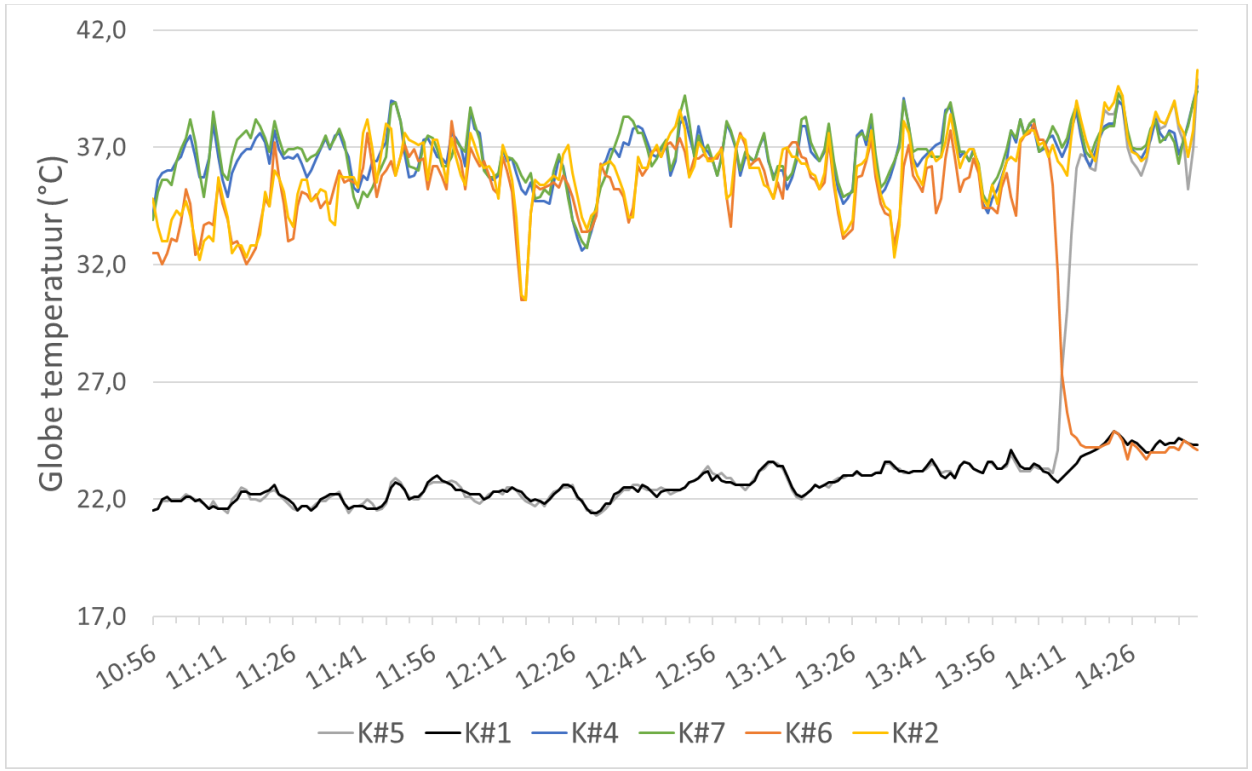
"All measurements not available in all units"

Temperature Functions

For best accuracy when taking temperature measurements you must keep the air moving around the temperature sensor and keep the Kestrel out of prolonged, direct sunlight. If there is a strong breeze, just point the Kestrel into the wind. If there is no wind, swing the Kestrel around in a circle on its lanyard or rapidly wave it back and forth in hand. This ensures that the sensor measures the temperature of the air rather than the temperature of the case. Alternatively, if you have time, allow the Kestrel to rest where you want to measure the air temperature (NOT in your hand or in direct sunlight if there is no wind) until the case temperature equalizes with the air temperature. When equalized, the display will read a constant value. Be aware that this could take a few minutes, particularly if there is no wind.

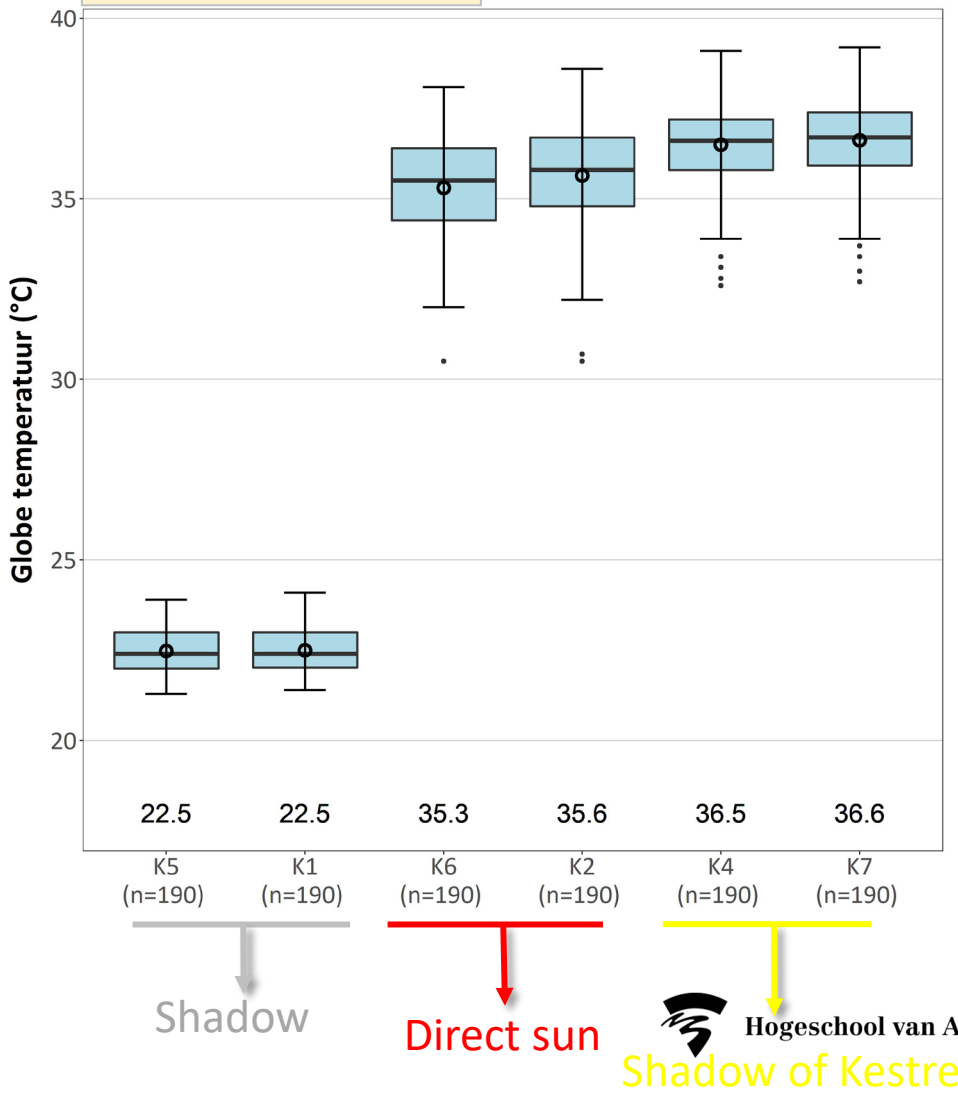
Results – Globe temperature

2nd experiment: Stadionplein



K#5 & K#1: shadow
K#6 & K#2: direct sun
K#4 & K#7: shadowed by itself

Period: 10:56-14:06 h



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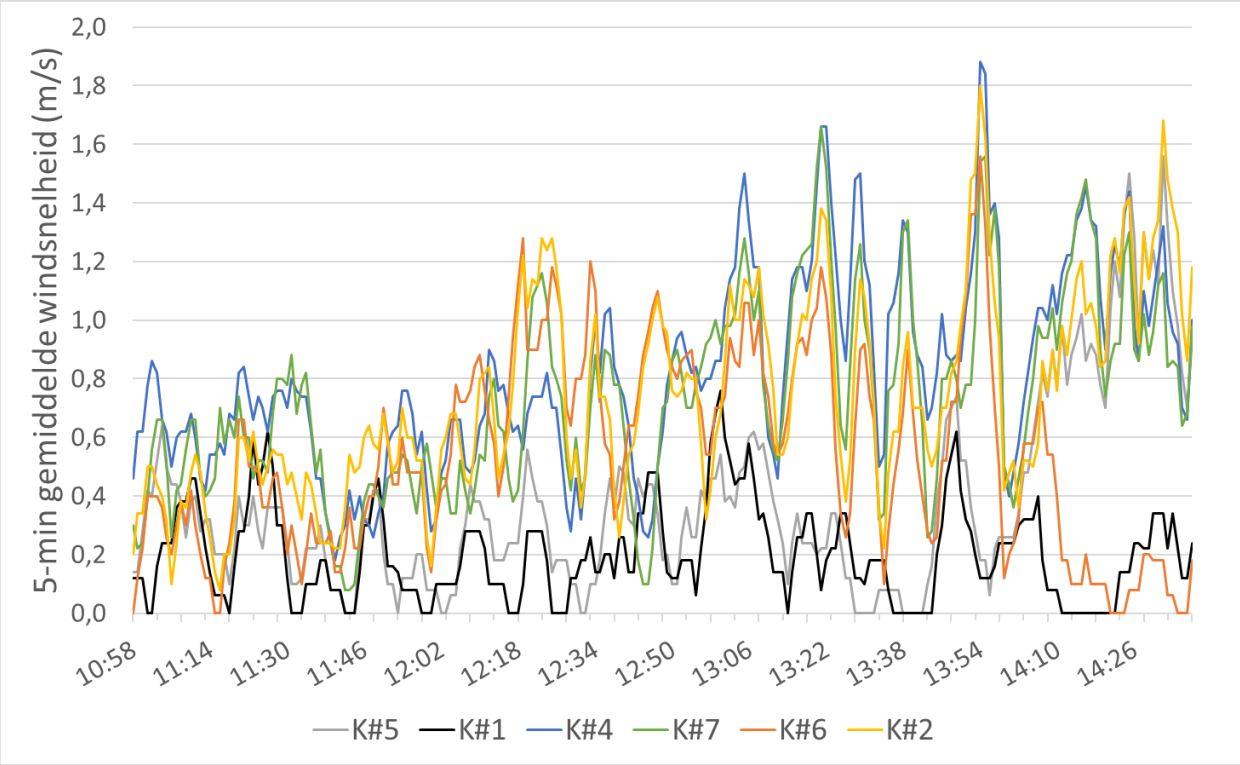
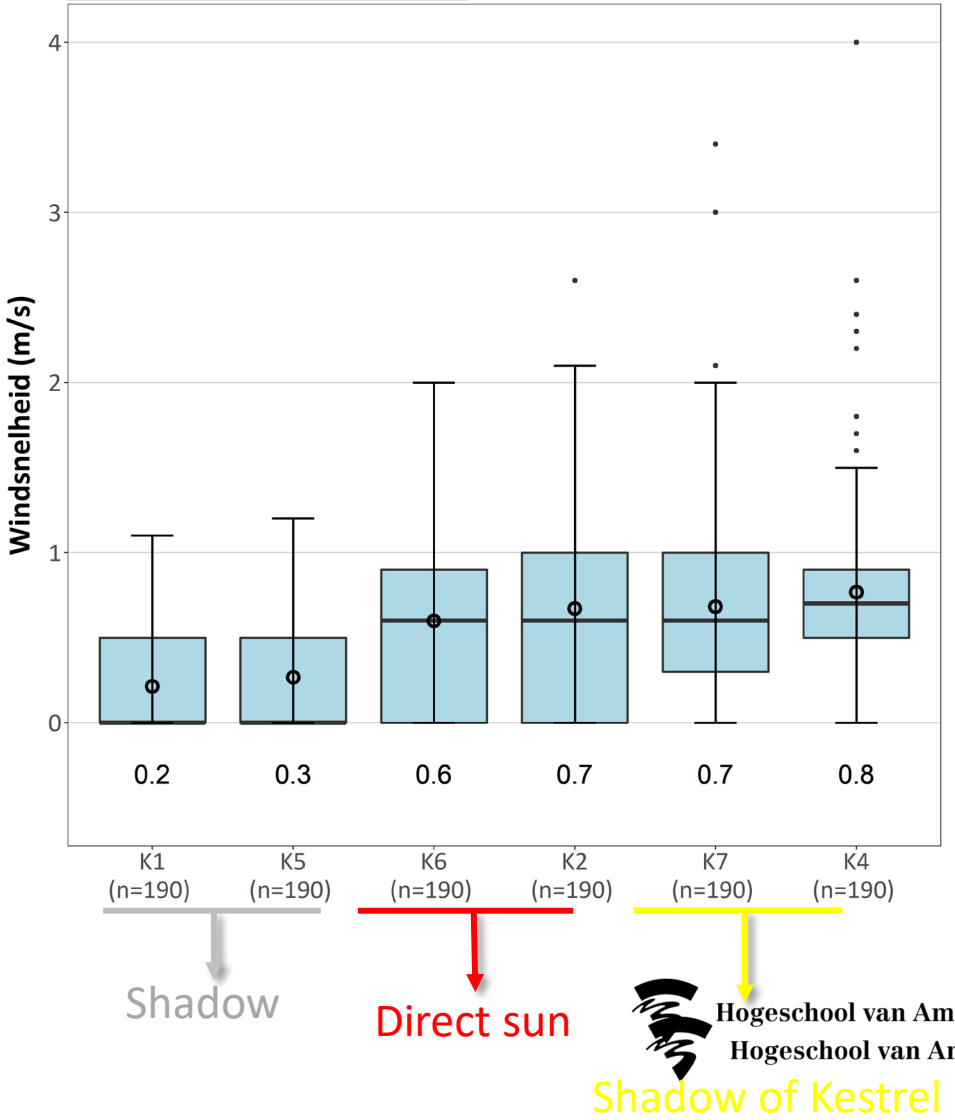
Results – Wind speed

2nd experiment: Stadionplein



K#5 & K#1: shadow
K#4 & K#7: shadow of Kestrel
K#6 & K#2: direct sun

Period: 10:56-14:06 h



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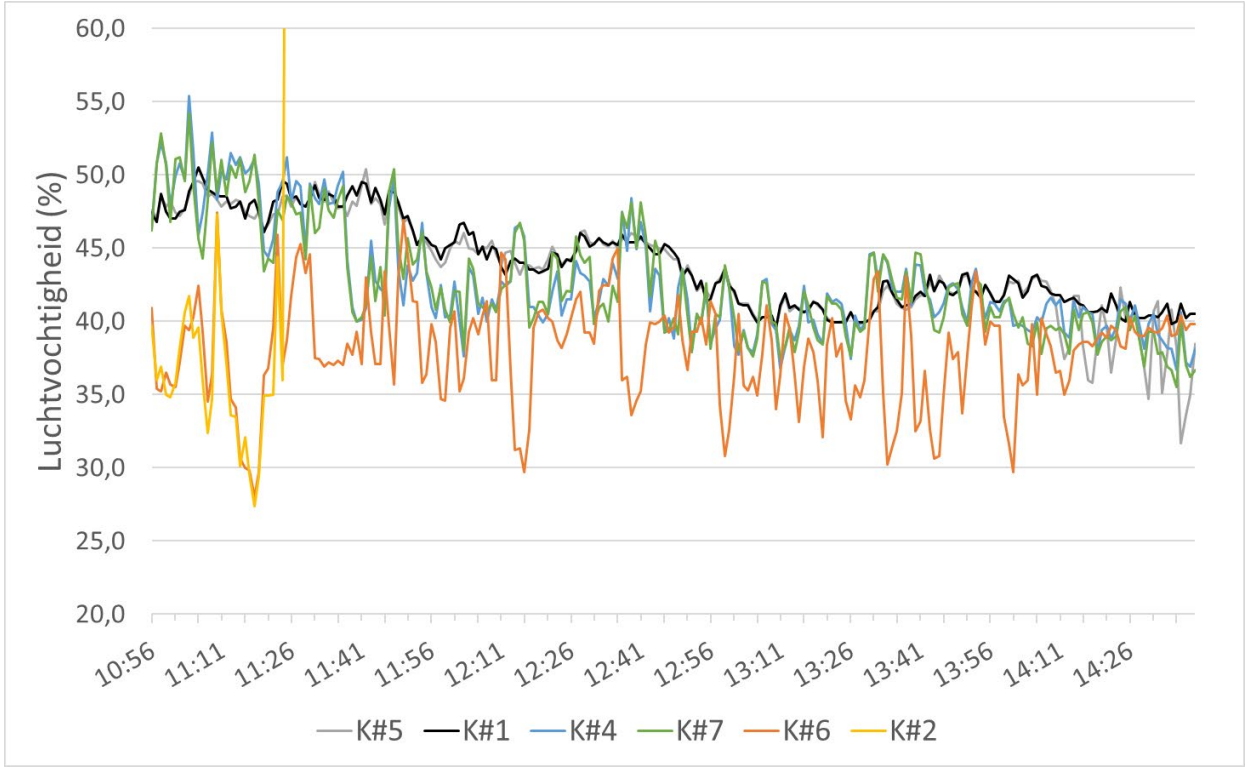
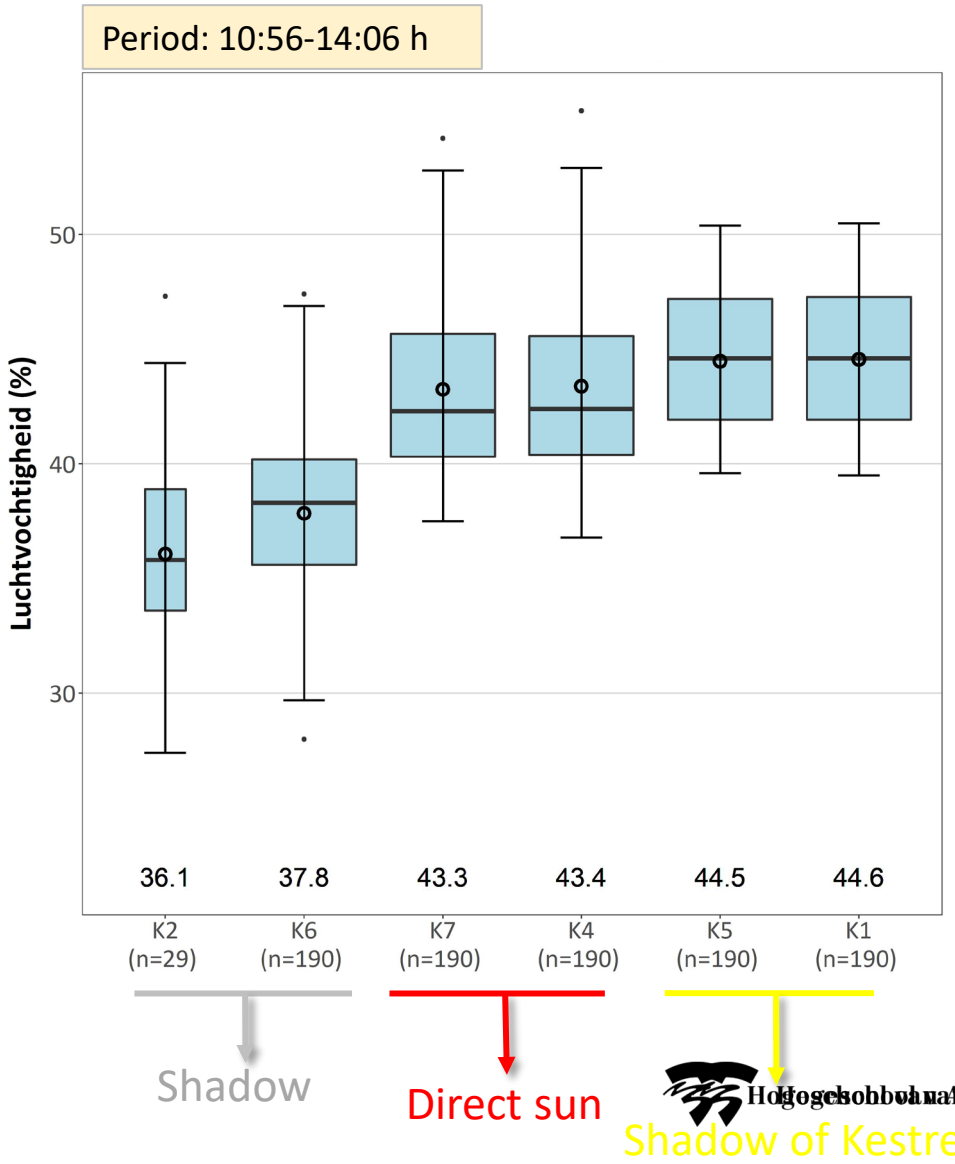
Results - Humidity

2nd experiment: Stadionplein

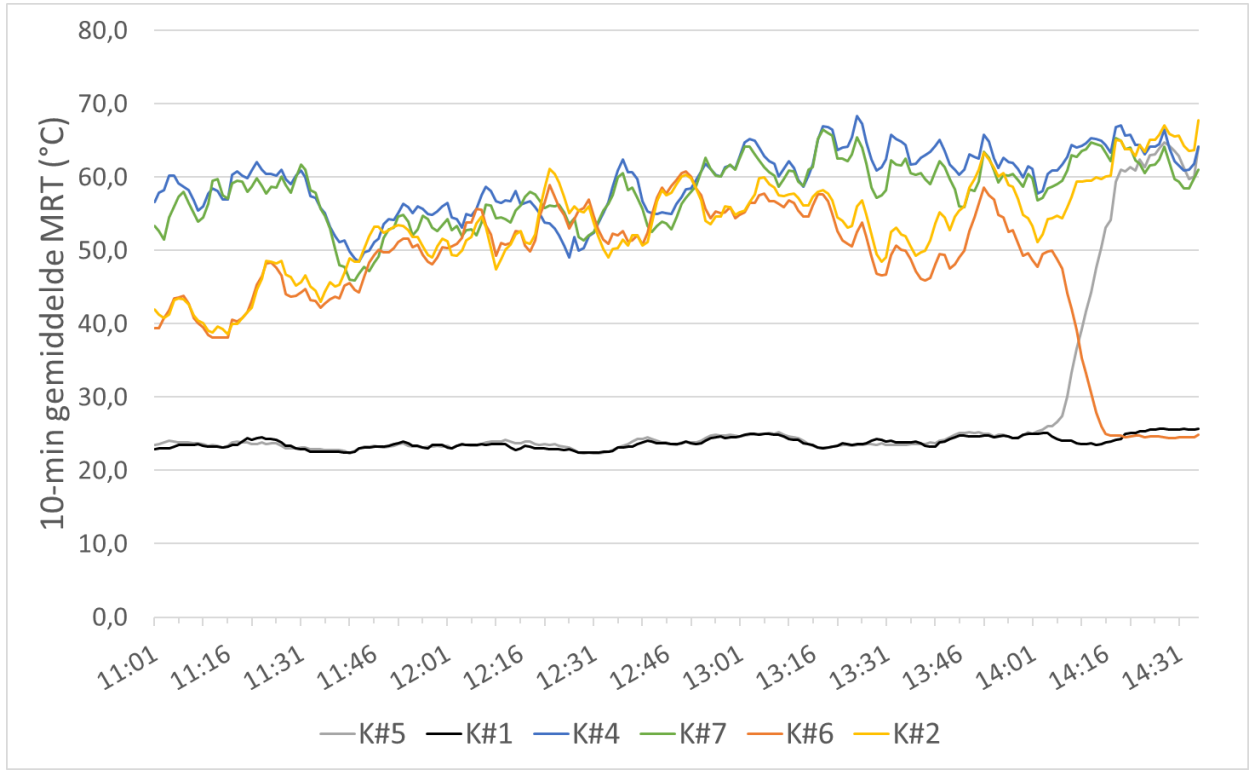


K#5 & K#1: shadow
K#4 & K#7: shadow of kestrel
K#6 & K#2: direct sun

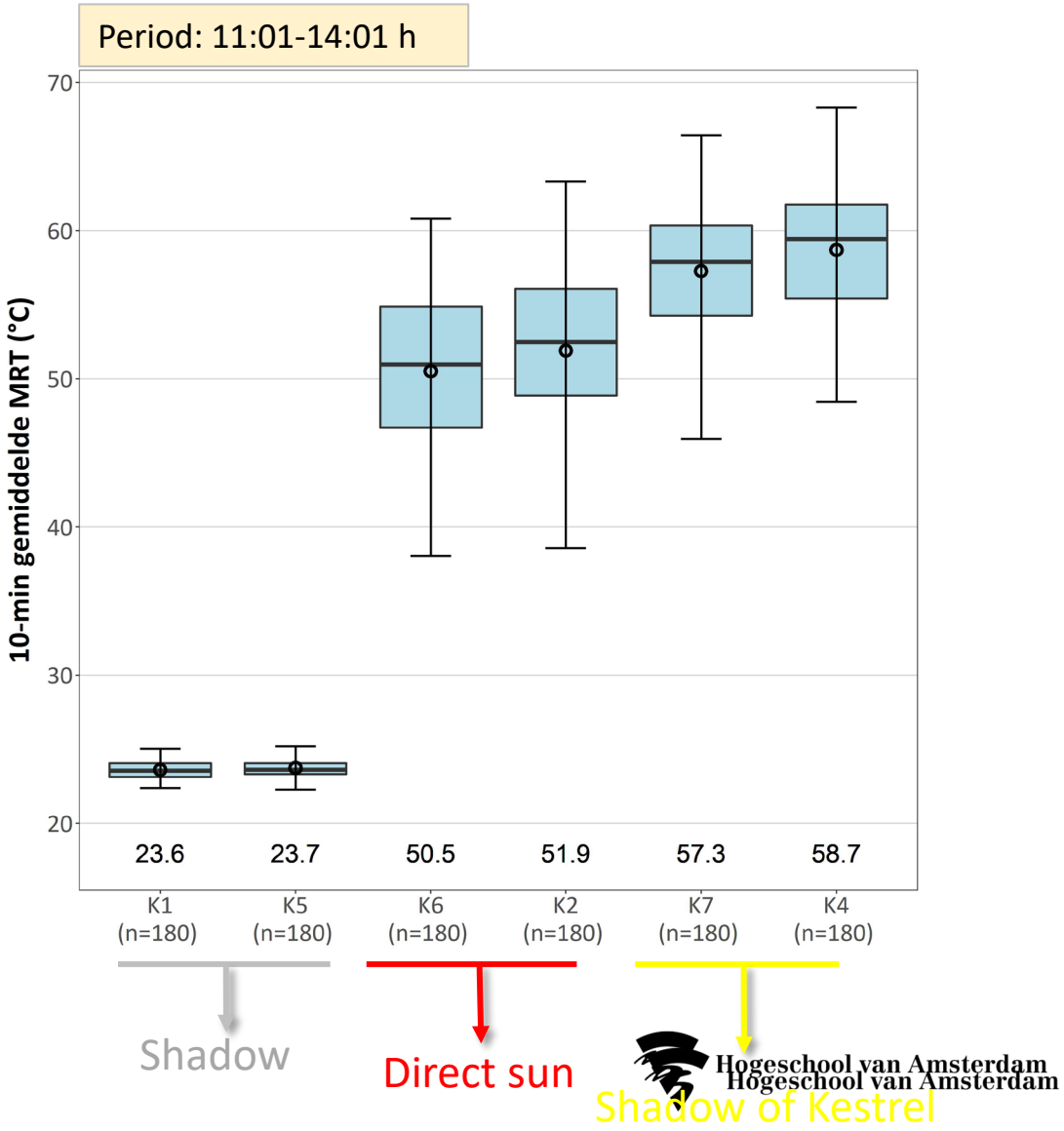


Results – 10-min average MRT

2nd experiment: Stadionplein



K#5 & K#1: shadow
K#4 & K#7: shadow of kestrel
K#6 & K#2: direct sun



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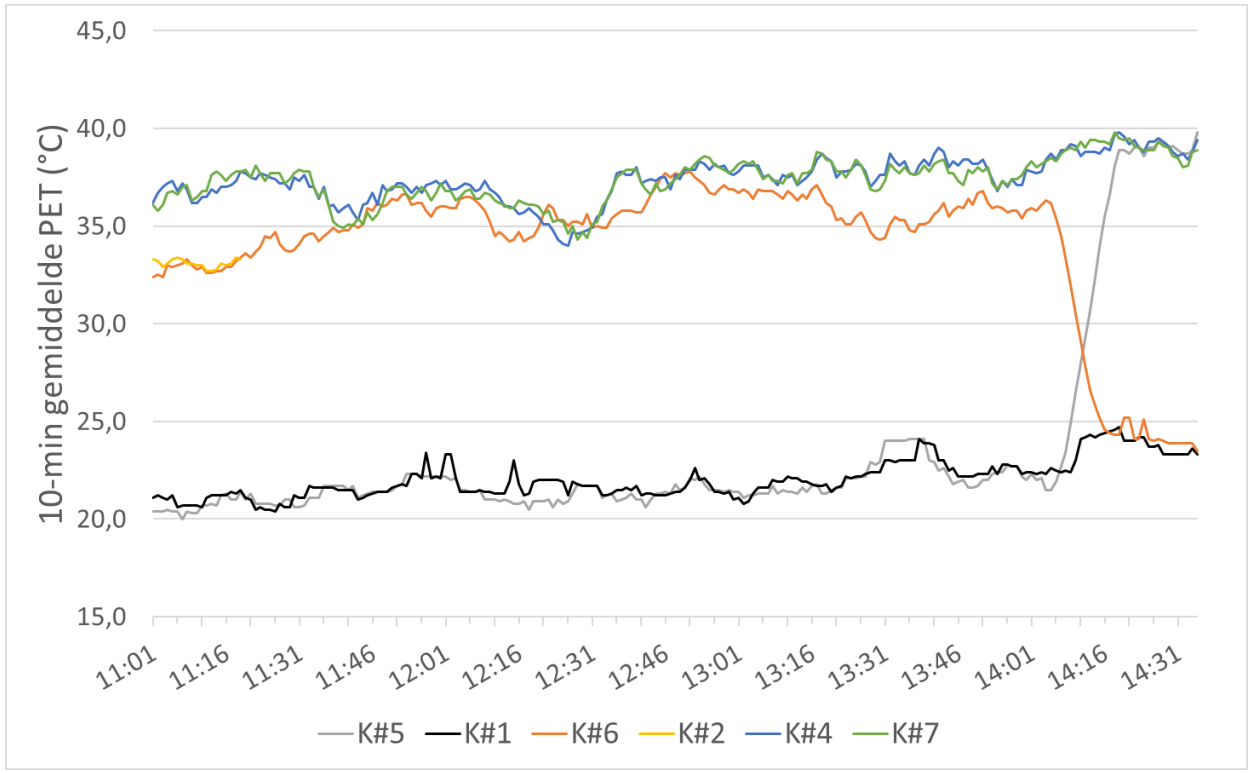
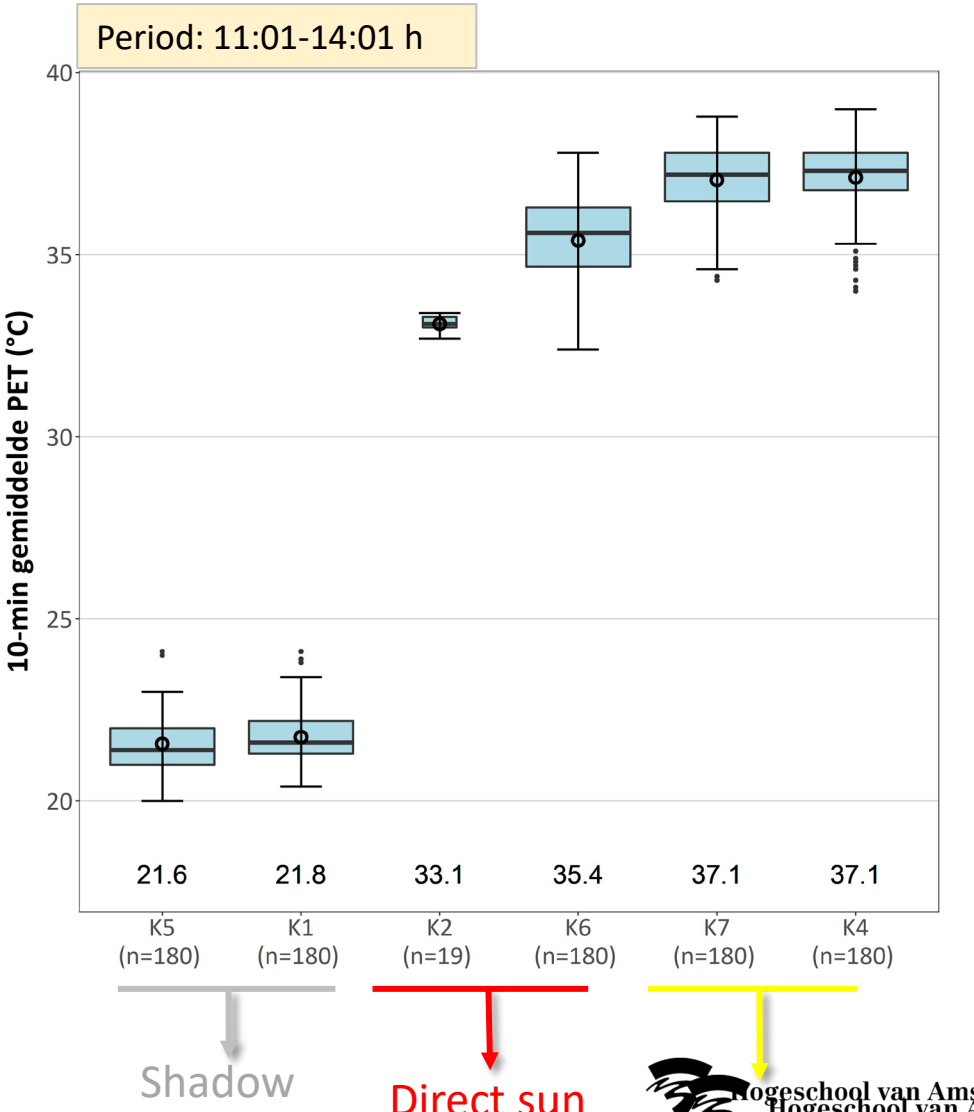
Results – 10-min average PET

2nd experiment: Stadionplein



K#5 & K#1: shadow
K#4 & K#7: shadow of kestrel
K#6 & K#2: direct sun



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Results

2nd experiment proef: Stadionplein

		Luchttemperatuur (°C)	Luchtvochtigheid (%)	Windsnelheid (%)	Globetemperatuur (°C)	5-min MRT (°C)	10-min MRT (°C)	5-min PET (°C)	10-min PET (°C)
Shadow	Kestrel #5	21,3 ± 0,7	44,5 ± 2,9	0,3 ± 0,3	22,5 ± 0,6	23,7 ± 1,0	23,7 ± 0,8	21,6 ± 0,9	21,6 ± 0,8
	Kestrel #1	21,2 ± 0,7	44,6 ± 2,9	0,2 ± 0,3	22,5 ± 0,6	23,6 ± 1,0	23,6 ± 0,7	21,9 ± 0,9	21,8 ± 0,7
Shadow of Kestrel	Kestrel #4	22,4 ± 1,3	43,4 ± 3,9	0,8 ± 0,6	36,5 ± 1,1	58,5 ± 5,7	58,7 ± 4,3	37,0 ± 1,3	37,1 ± 1,0
	Kestrel #7	22,6 ± 1,2	43,3 ± 3,7	0,7 ± 0,6	36,6 ± 1,2	56,9 ± 6,1	57,3 ± 4,1	36,9 ± 1,4	37,1 ± 1,0
Direct sun	Kestrel #6	24,9 ± 2,1	37,8 ± 3,8	0,6 ± 0,5	35,3 ± 1,5	50,2 ± 7,1	50,5 ± 5,4	35,3 ± 1,6	35,4 ± 1,3
	Kestrel #2	25,2 ± 2,1	36,1 ± 4,5	0,7 ± 0,5	35,6 ± 1,5	51,7 ± 7,0	51,9 ± 5,7	33,3 ± 0,8	33,1 ± 0,2

Conclusions based on experiment 2

- According to the manufacturer, Kestrels are not suitable for measuring the air temperature when the Kestrel is being exposed to direct sunlight for a longer period of time. This is confirmed by our results: we concluded a difference in measured air temperature of 3,8 °C for Kestrels in direct sunlight and in the shade.

- For an accurate measurement with the Kestrels it seems to be important to create a radiation screen (see next experiment) or to swing the Kestrels like the manufacturer mentioned in the FAQ.

- We also seem to conclude a difference in measured globe temperatures between Kestrels positioned in direct sunlight compared to those that are in direct sunlight but cast shade on their own temperature sensor. The globe temperature of the sensors that are in direct sunlight have a slightly lower globe temperature of 1 °C, and a lower humidity, causing the PET-values toe be 2 °C lower on average. This lower globe temperature is caused by the conversion of the 1-inch to 6-inch globe temperature values made by the Kestrels. In this calculation the Tmrt equation of Thorsson is used. Therefore, the globe temperature is influenced by the air temperature values: the higher the air temperature, the lower the globe temperature will be.

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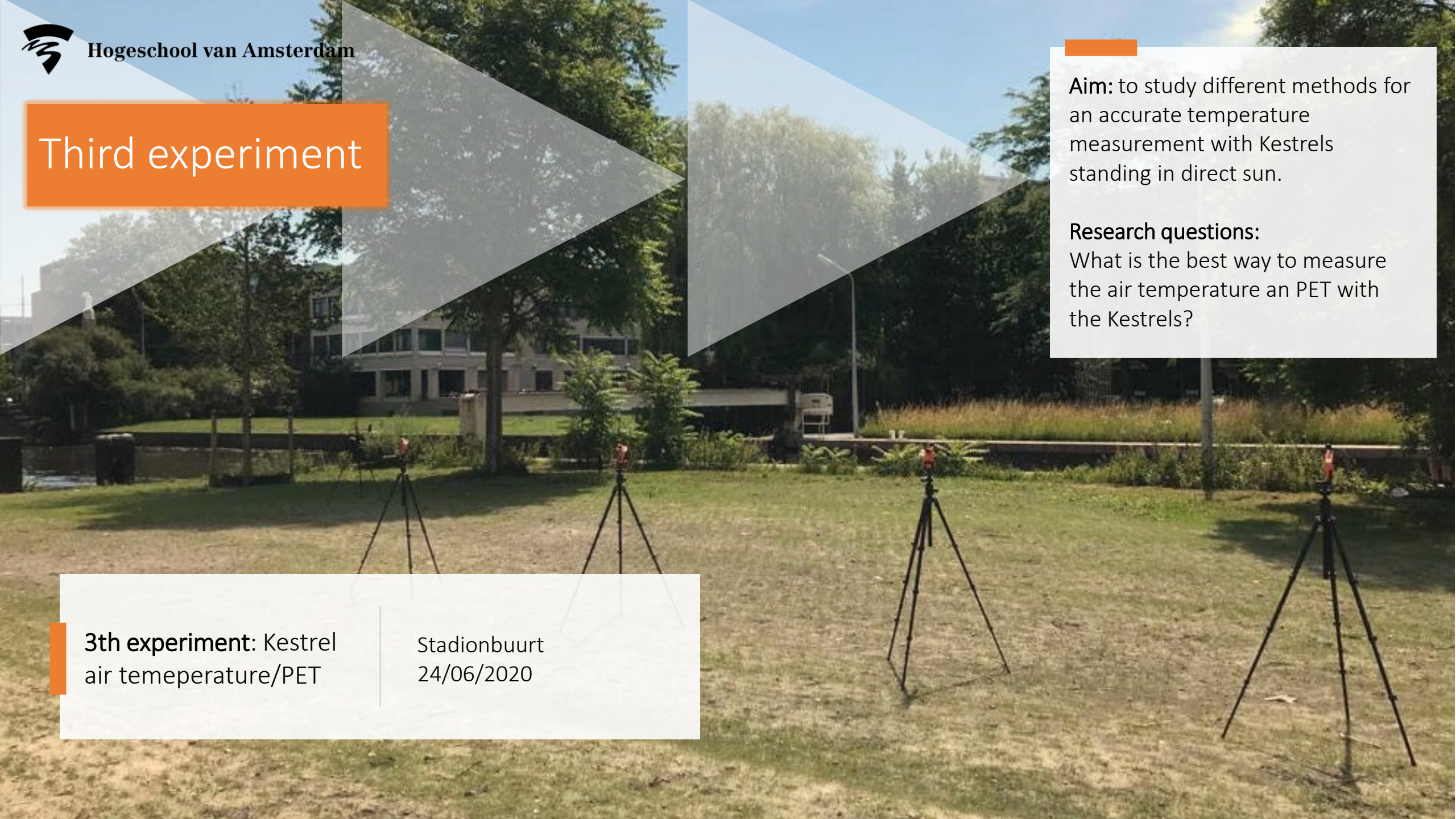
Third experiment

Aim: to study different methods for an accurate temperature measurement with Kestrels standing in direct sun.

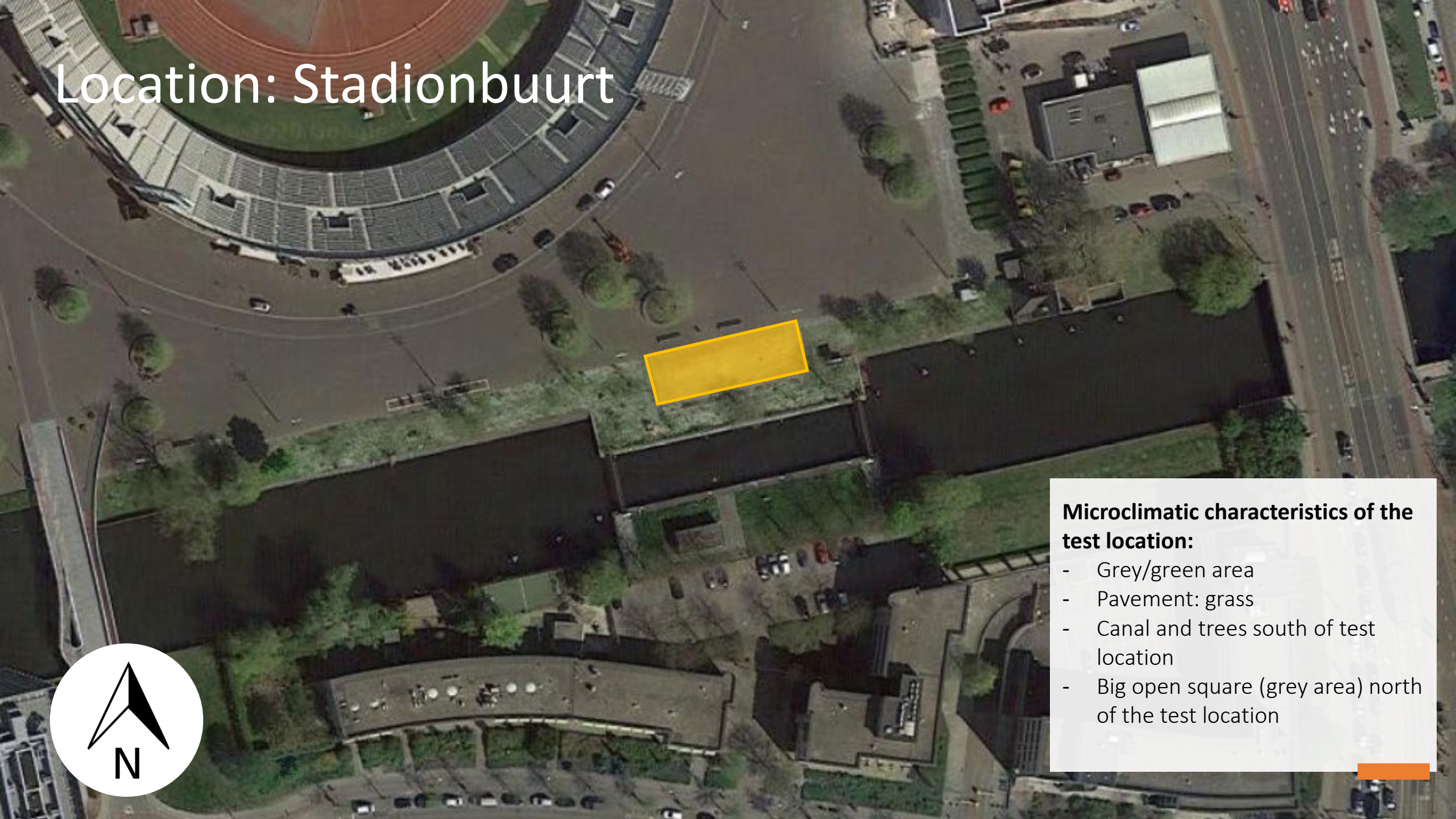
Research questions:
What is the best way to measure the air temperature an PET with the Kestrels?



3th experiment: Kestrel air temeperature/PET

Stadionbuurt
24/06/2020

Location: Stadionbuurt



Microclimatic characteristics of the test location:

- Grey/green area
- Pavement: grass
- Canal and trees south of test location
- Big open square (grey area) north of the test location

Dutch weather report

Daggegevens van het weer in Nederland

Het weer op woensdag 24 juni 2020 te Schiphol

Temperatuur		**Normaal**
Gemiddelde	23.5 °C	16.1 °C
Maximum	28.9 °C	20.5 °C
Minimum	15.7 °C	11.4 °C

Zon, bewolking & zicht		
Duur zonneschijn	14.7 uur	
Rel. zonneschijnduur	88 %	41 %
Gem. bedekkingsgraad	6 octa's	
	Zwaar bewolkt	
Minimaal zicht	20.0 km	

Relatieve luchtvochtigheid		
Gemiddelde	54 %	78 %

Neerslag		
Hoeveelheid	0.0 mm	
Duur	0.0 uur	

Wind		
Gemiddelde snelheid	4.4 m/s	(3 Bft)
Maximale uurgemiddelde snelheid	6.0 m/s	(4 Bft)
Maximale stoot	9.0 m/s	
Overheersende richting	75 °	(O)

Luchtdruk		
Gemiddelde luchtdruk	1022.4 hPa	

Set up

Start time: 12:30h
End time: 16:00 h

K#5: shadow + vane mount

K#5

K#6

K#6: sun + vane mount

K#4: sun + vane mount + 'roof'

K#4

K#7: direct sun

K#7

K#2: Shadow of the Kestrel

K#2

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Set up

Start time: 12:30 h
End time: 16:00 h
Time interval measurement: 1 minute

K#5

K#6

K#4

K#7

K#2

Hogeschool van Amsterdam

K#5: shadow + vane mount

K#6: sun + vane mount

3rd experiment: Stadionbuurt

Set up

Start time: 12:30 h
End time: 16:00 h
Time interval measurement: 1 minute

K#5

K#6

K#4

K#7

K#2

Hogeschool van Amsterdam

K#4: sun + vane mount + ‘roof’

K#7: direct sun

Set up

Start time: 12:30 h
End time: 16:00 h
Time interval measurement: 1 minute

K#5

K#6

K#4

K#7

K#2

Hogeschool van Amsterdam

K#2: shadow of the Kestrel

Results – air temperature

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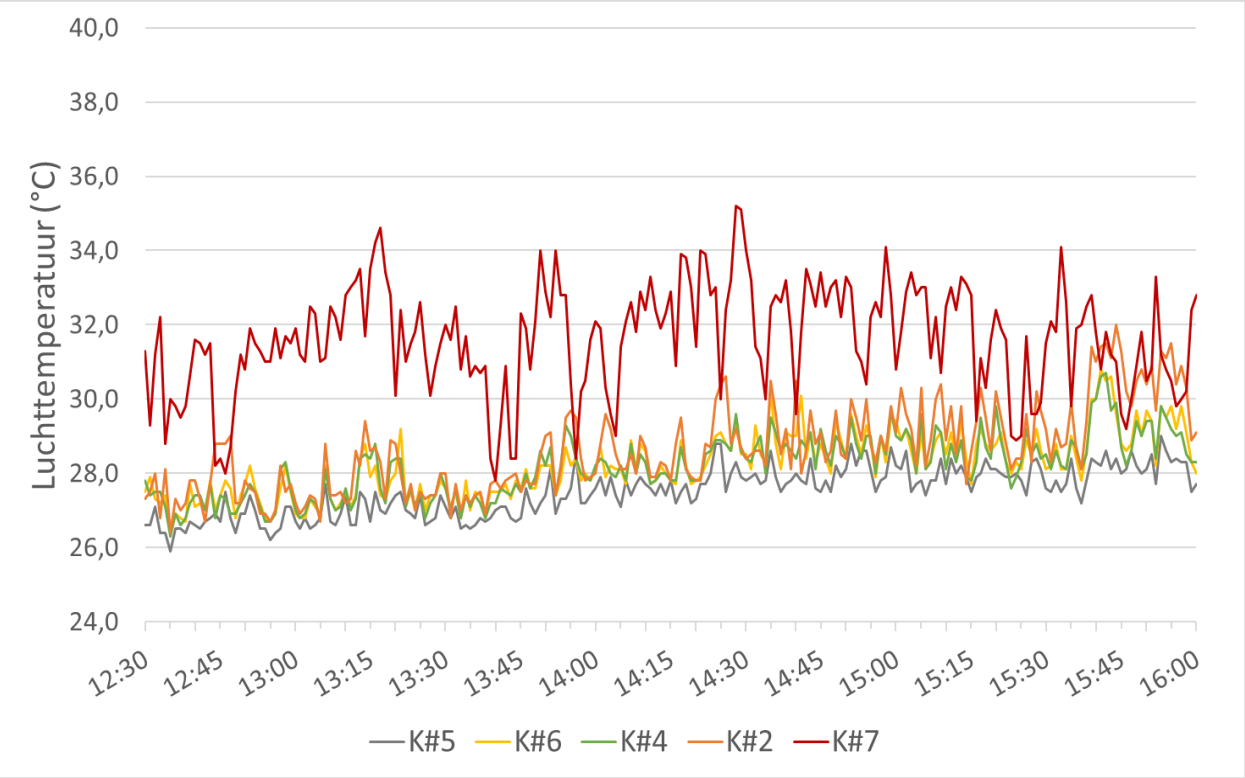
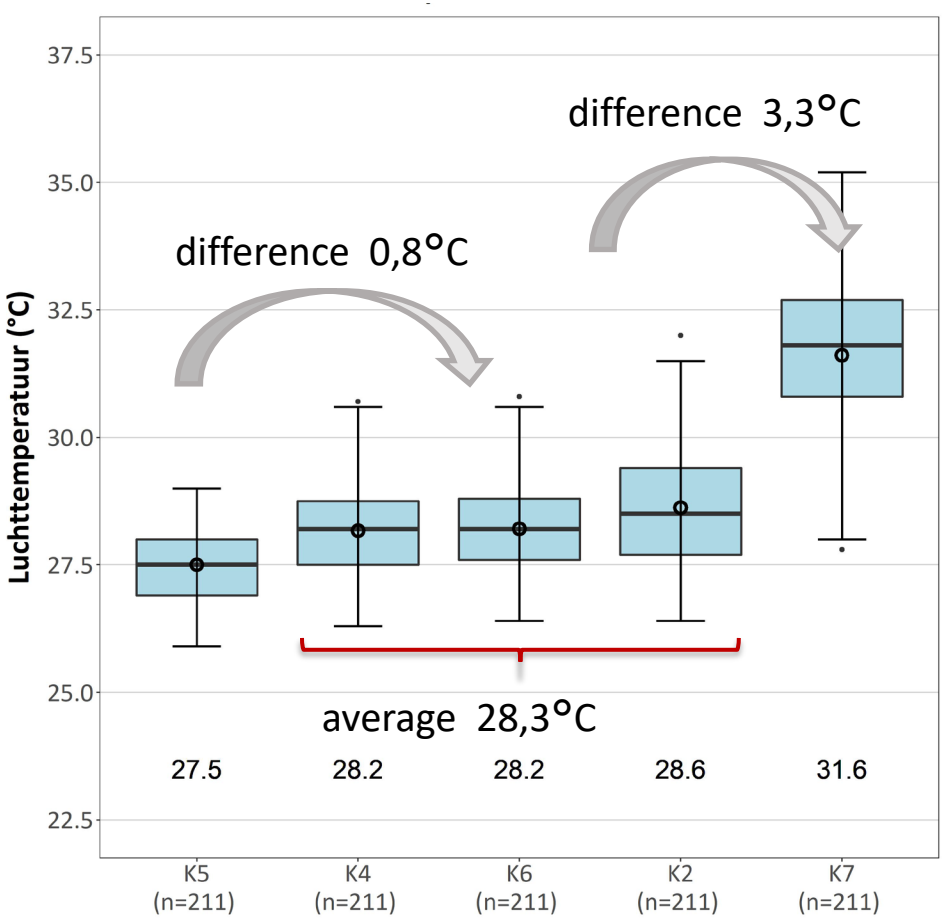
3rd experiment: Stadionbuurt



K#5: shadow + vane mount
K#6: sun + vane mount
K#4: sun + vane mount + roof
K#2: sun + shadow of Kestrel
K#7: direct sun



Results - windspeed

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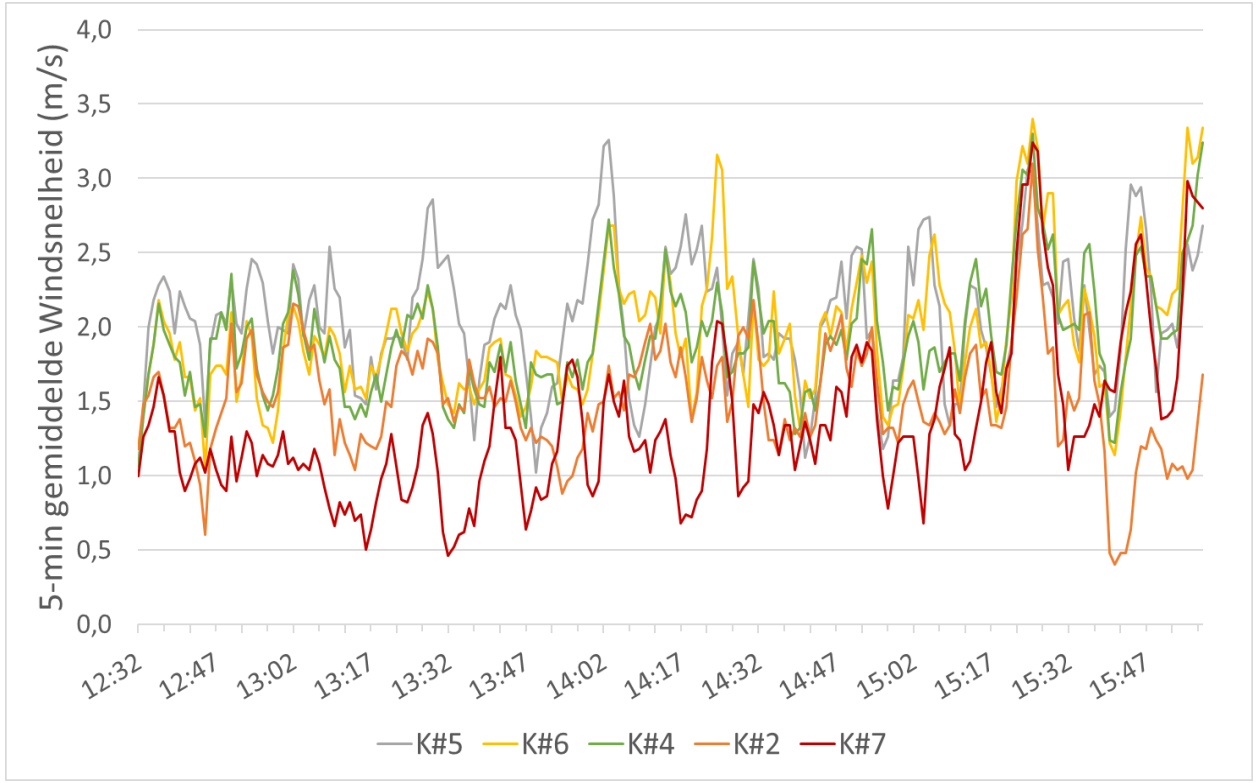
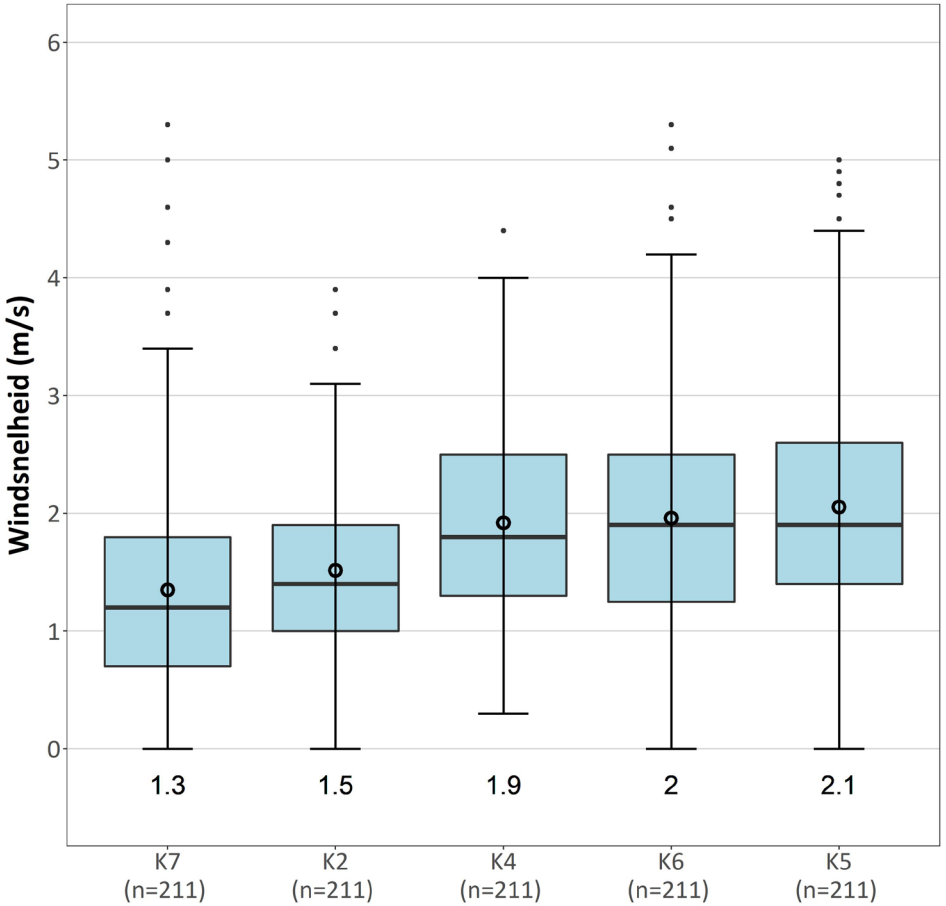
3rd experiment: Stadionbuurt





K#5: shadow + vane mount
K#6: sun + vane mount
K#4: sun + vane mount + roof
K#2: sun + shadow of Kestrel
K#7: direct sun

Results - humidity

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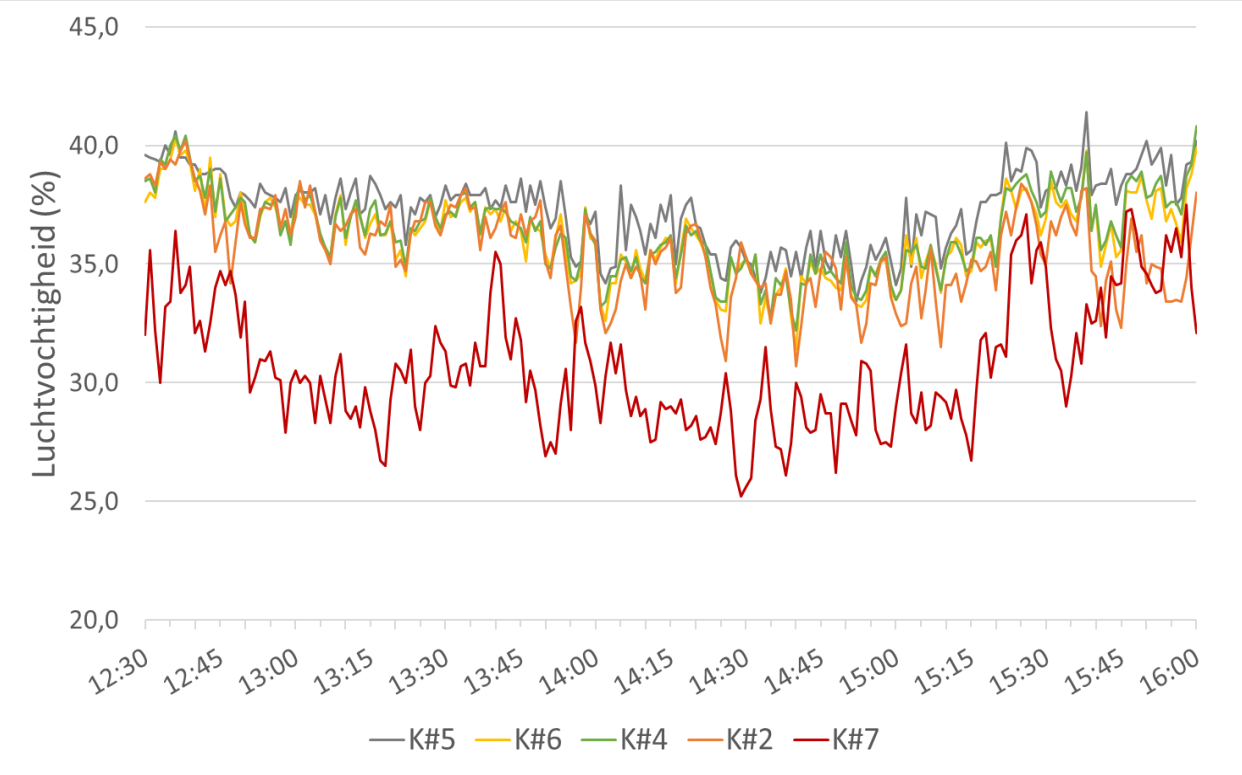
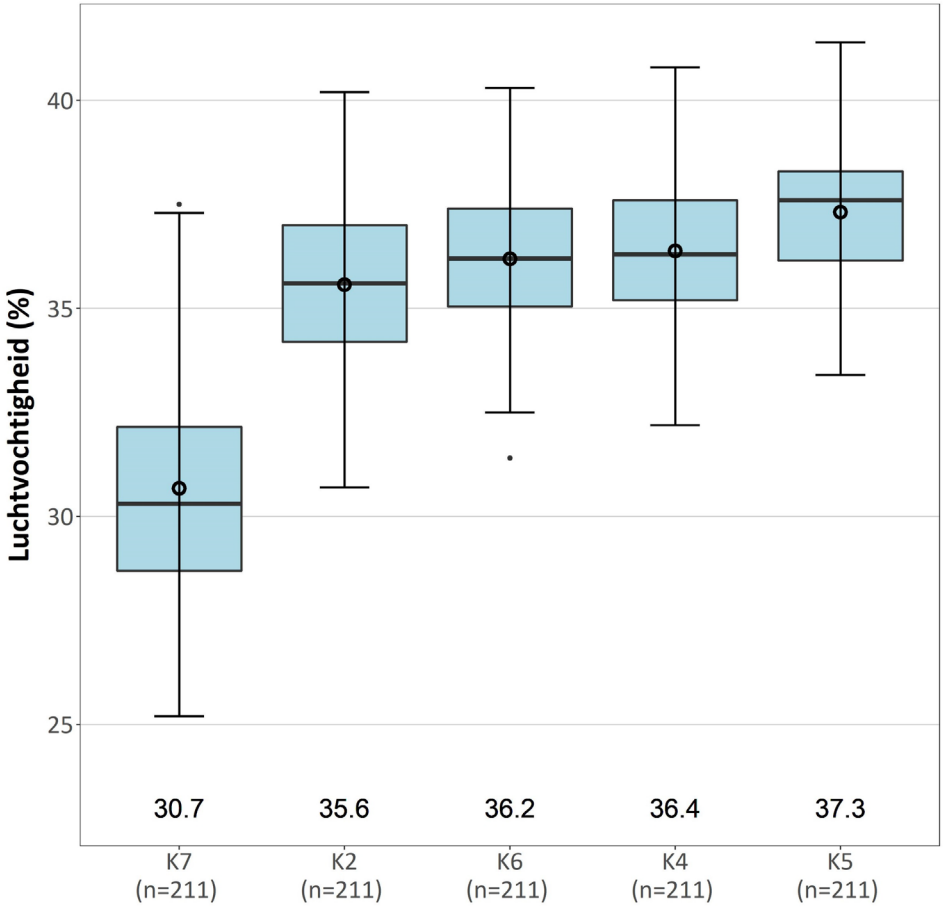
3rd experiment: Stadionbuurt



K#5: shadow + vane mount
K#6: sun + vane mount
K#4: sun + vane mount + roof
K#2: sun + shadow of Kestrel
K#7: direct sun



Results – globe temperature

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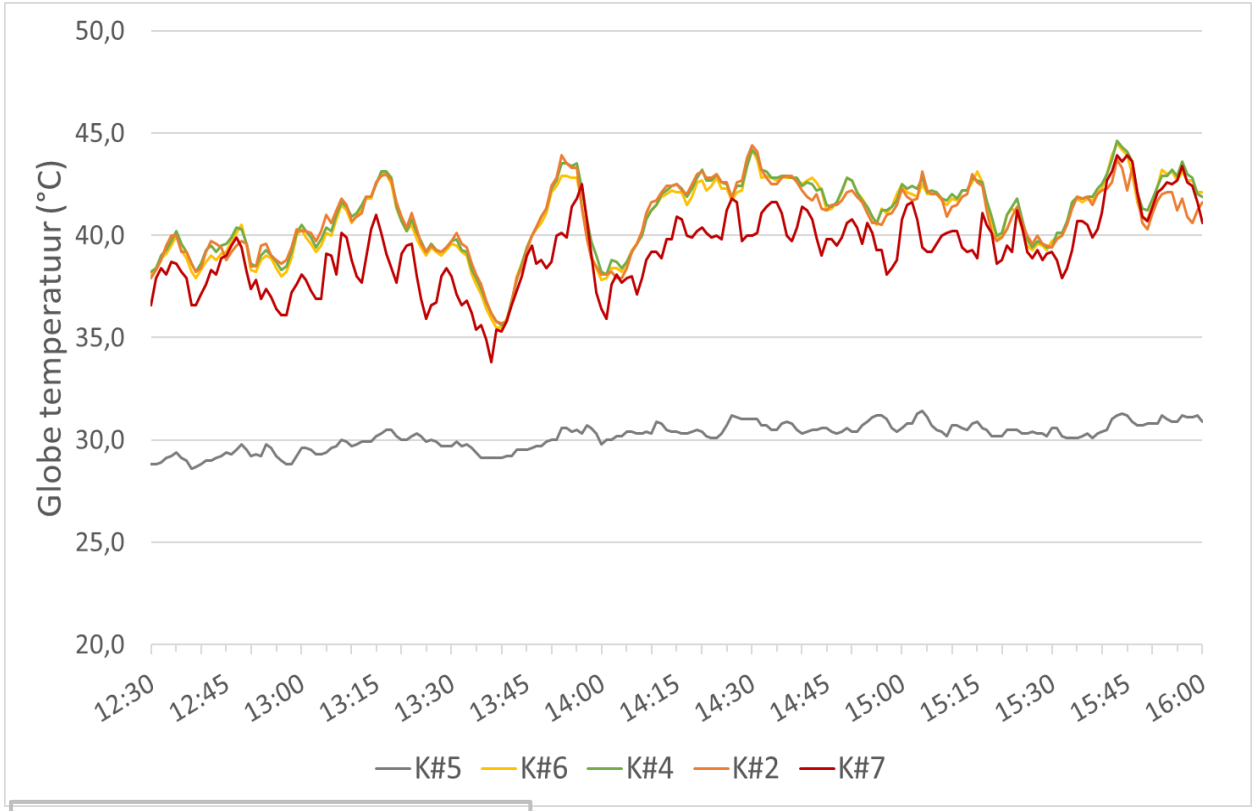
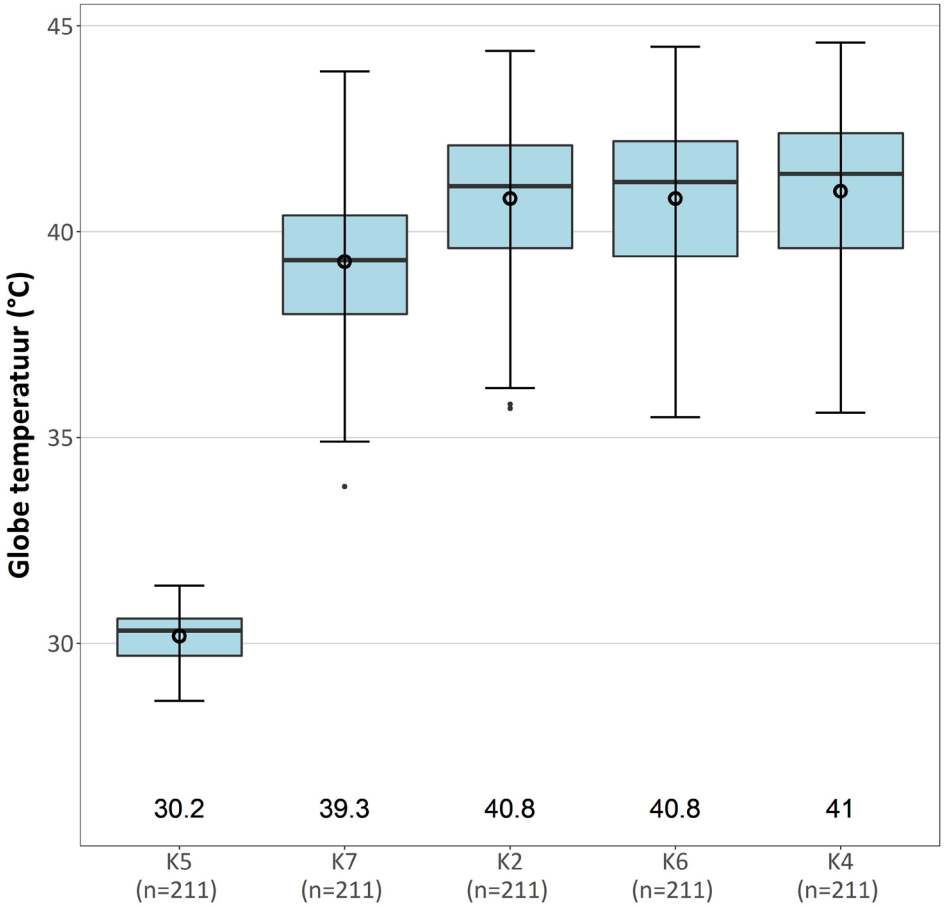
3rd experiment: Stadionbuurt

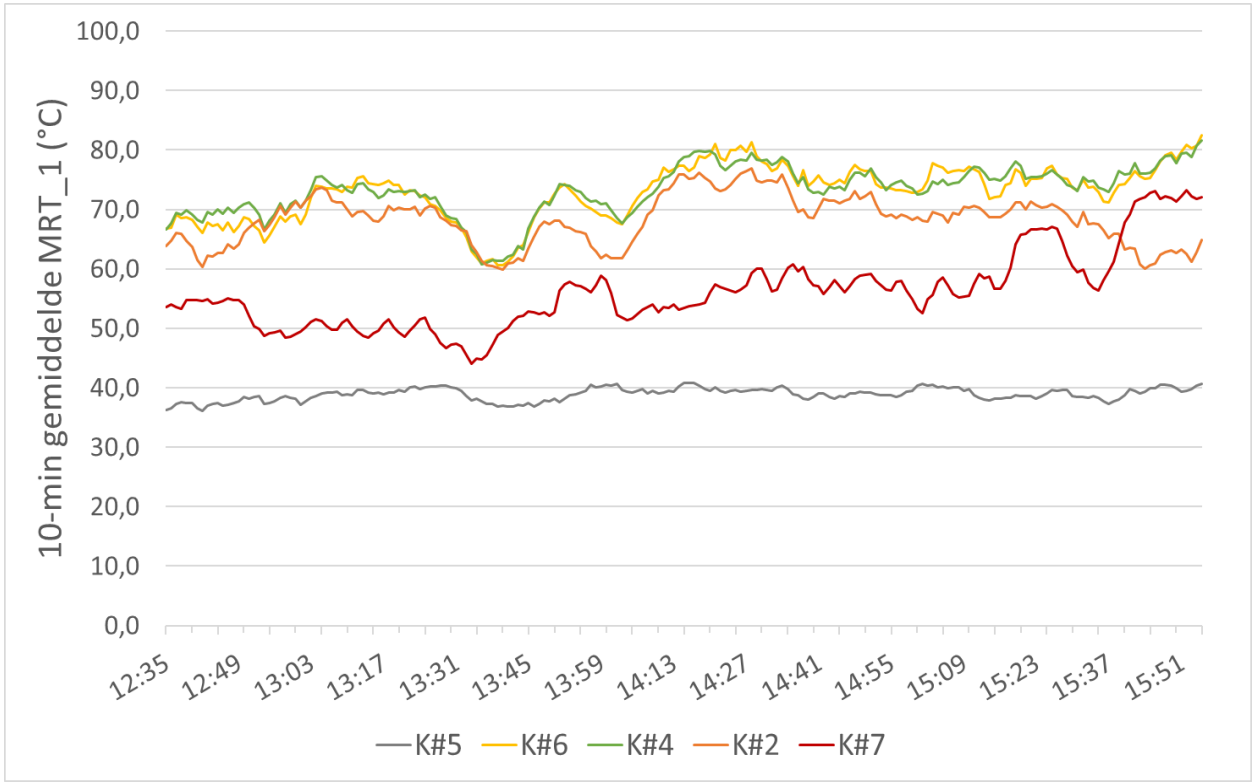


K#5: shadow + vane mount
K#6: sun + vane mount
K#4: sun + vane mount + roof
K#2: sun + shadow of Kestrel
K#7: direct sun

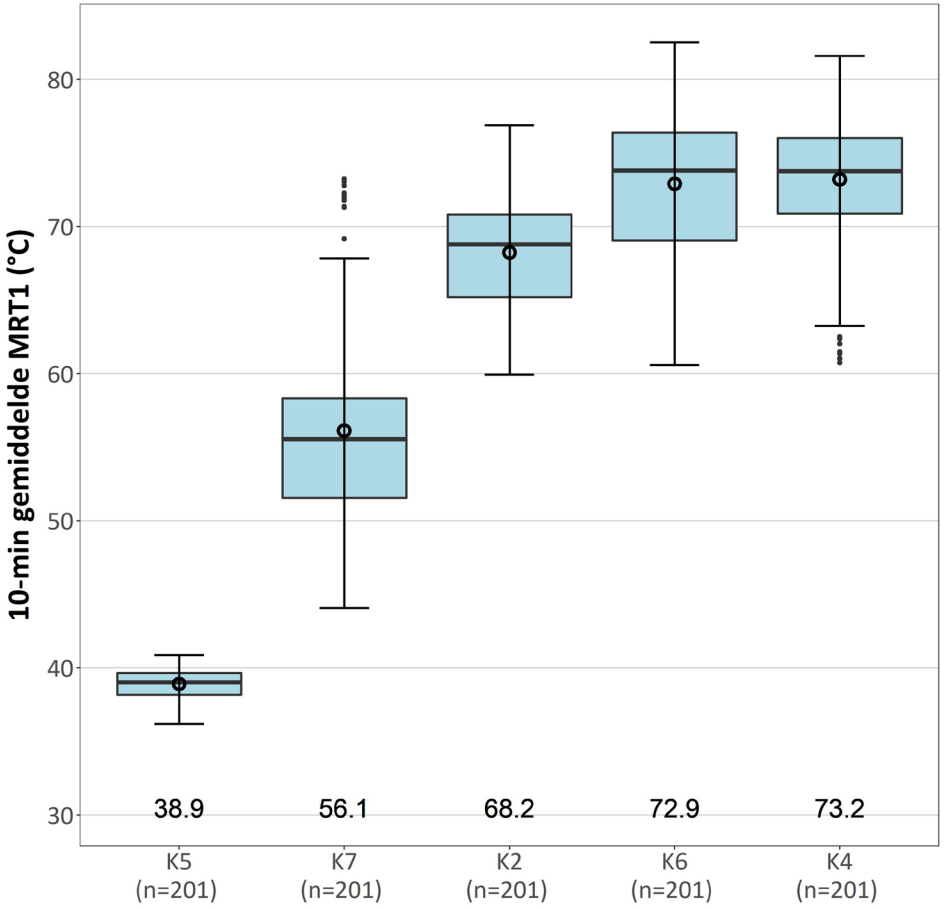


Results – 10-min average MRT

3rd experiment: Stadionbuurt



K#5: shadow + vane mount
K#6: sun + vane mount
K#4: sun + vane mount + roof
K#2: sun + shadow of Kestrel
K#7: direct sun



Results – 10-min PET

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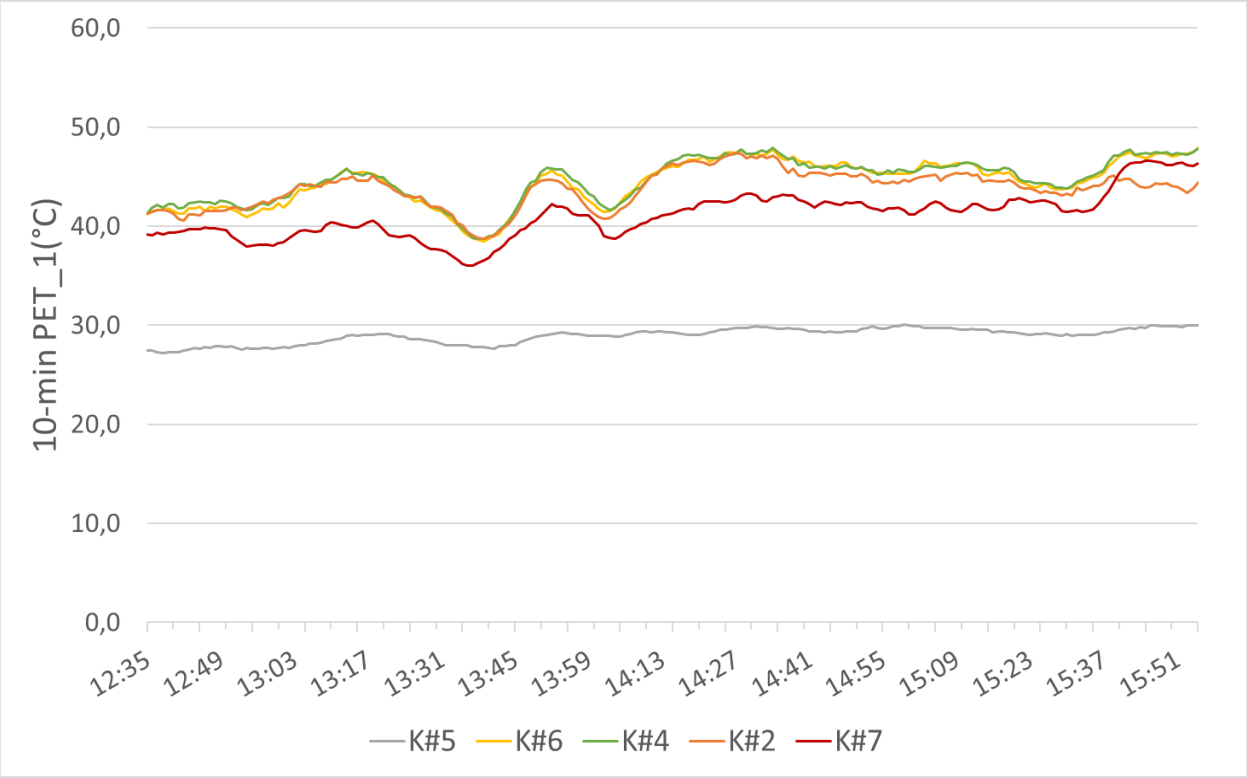
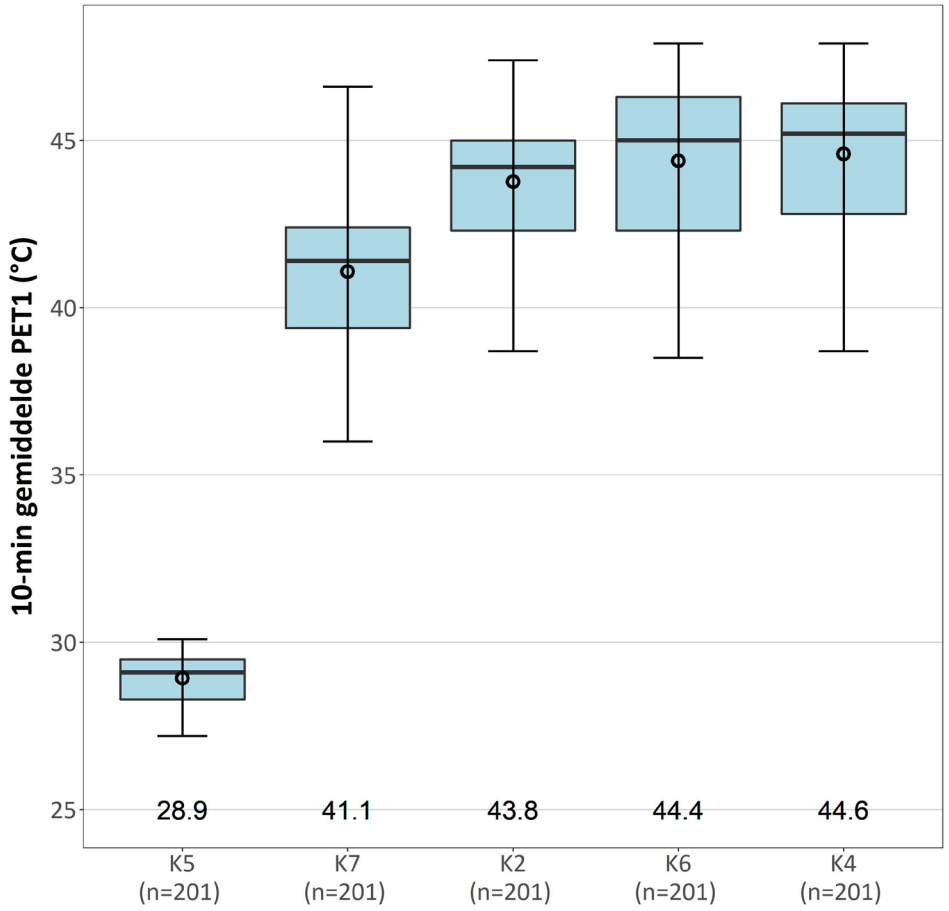
3rd experiment: Stadionbuurt



K#5: shadow + vane mount
K#6: sun + vane mount
K#4: sun + vane mount + roof
K#2: shadow of Kestrel
K#7: direct sun



Results

Hogeschool van Amsterdam

Average results ± standard deviation

	K#5	K#6	K#4	K#7	K#2
Luchttemperatuur (°C)	27,5 ± 0,6	28,2 ± 0,9	28,2 ± 0,8	31,6 ± 1,5	28,6 ± 1,2
Luchtvochtigheid (%)	37,3 ± 1,6	36,2 ± 1,6	36,4 ± 1,7	30,7 ± 2,7	35,6 ± 1,9
Windsnelheid (m/s)	2,1 ± 1,0	2,0 ± 0,9	1,9 ± 0,8	1,3 ± 0,9	1,5 ± 0,7
Globe temperatuur (°C)	30,2 ± 0,6	40,8 ± 1,8	41,0 ± 1,8	39,3 ± 1,9	40,8 ± 1,7
~~MRT1 (5 min) (°C)~~	~~38,9 ± 1,6~~	~~72,9 ± 5,8~~	~~73,2 ± 5,4~~	~~56,4 ± 8,0~~	~~68,0 ± 5,4~~
MRT1 (10 min) (°C)	38,9 ± 1,1	72,9 ± 4,7	73,2 ± 4,2	56,1 ± 6,5	68,2 ± 4,2
~~MRT2 (5 min) (°C)~~	~~38,9 ± 1,6~~	~~74,4 ± 6,0~~	~~74,6 ± 5,5~~	~~64,1 ± 7,5~~	~~70,1 ± 5,2~~
~~MRT2 (10 min) (°C)~~	~~38,9 ± 1,1~~	~~74,4 ± 4,9~~	~~74,7 ± 4,4~~	~~64,0 ± 6,2~~	~~70,3 ± 4,0~~
~~PET1 (5 min) (°C)~~	~~28,9 ± 0,8~~	~~44,4 ± 2,6~~	~~44,6 ± 2,5~~	~~41,1 ± 2,6~~	~~43,7 ± 2,1~~
PET1 (10min) (°C)	28,9 ± 0,8	44,4 ± 2,3	44,6 ± 2,2	41,1 ± 2,3	43,8 ± 1,9
~~PET2 (5 min) (°C)~~	~~28,9 ± 0,8~~	~~44,5 ± 2,6~~	~~44,7 ± 2,5~~	~~41,4 ± 2,7~~	~~43,8 ± 2,2~~
~~PET2 (10 min) (°C)~~	~~28,9 ± 0,8~~	~~44,5 ± 2,3~~	~~44,7 ± 2,2~~	~~41,4 ± 2,4~~	~~43,9 ± 1,9~~

K#5: shadow + vane mount
K#6: sun + vane mount
K#4: sun + vane mount + roof
K#2: sun + shadow of Kestrel
K#7: direct sun

Conclusions based on experiment 3

- A Kestrel in direct sunlight can measure an air temperature that's 4,1 °C higher than when it's placed in the shadow.
- But when the vane mount is mounted on the Kestrel and the Kestrel can rotate freely, this difference decreases to 0,8 °C. By using the vane mount, the air temperature sensor on the Kestrel is always directed in the wind direction causing the sensor not to heat. Because of that placing a vane mount is the most important tip when preforming accurate temperature measurements with a Kestrel in direct sunlight.
- Mounting an extra paper roof on top of the radiation screen does not make a difference in measured air temperature.
- As was concluded in the experiment on the Stadionplein (experiment 2), Kestrel also measures a lower globe temperature when it is placed in direct sun without a wind vane. Therefore, a Kestrel in direct sunlight without a wind vane is not suited for estimating the MRT.
- Even though the Kestrel sensors do measure air temperatures and globe temperatures correctly in sunlight, the influence of this on the calculation of PET is minimal, being 0,6 °C. This is caused by the higher air temperatures measured by the Kestrels that are compensated by the lower MRT values.

CONCLUSIONS

We concluded that Kestrel sensors can be used very well for assessing differences in air temperature and PET (Physiological Equivalent Temperature) between outdoor built environments. For both air temperature and PET, the RMSE between the 11 Kestrel sensors was 0.5 °C maximum when measuring the same conditions.

However, Kestrel sensors that were placed in the sun without a wind vane mounted to the equipment showed large radiation errors. In this case, temperature differences up to 4 °C were observed compared to Kestrels that were shaded. The effect of a higher air temperature on the PET calculation is, however, surprisingly small. A sensitivity analysis showed that an increase of 3 °C in the air temperature results in a maximal PET reduction of 0.5 °C.

We concluded that Kestrel sensors can very well be used for assessing differences between air temperatures and PET between two locations and assessing the thermal effects of urban designs, but care should be taken when air temperature measurements are carried out in the sun.

We always recommend using the wind vanes to deviate from high radiant input orientations for the temperature sensor. Always place the stations next to each other at the beginning and at the end of the measurements to check whether the stations actually measure the same values. Any differences can be corrected afterwards.