Faculty of Science

How are the Wet Bulb Globe Thermometer components affected by the microclimatic environment?

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Abstract

The Wet Bulb Globe Temperature (WBGT) index is used mostly to assess different types of working environments or sports events where heat stress may arise. However most index users do not reflect upon how the microclimate itself affect the index they measure, which is what this article investigated. To investigate the effect of the microclimate on the WBGT index, measurements were taken during different weather conditions in a private garden using two WBGT monitors. Also a modelled WBGT estimation based on metrological data was preformed, to investigate if metrological data can be used to replicate WBGT measurements. Since metrological data is so widely available and continuous in comparison to the time-consuming process of using WBGT instruments. The experiment result showed that during different weather conditions the microclimate can change the measured index considerably. The modelled WBGT estimations showed a good correlation to the measured WBGT index, indicating that metrological data can be used to *some extent* to model WBGT index. However the modeled estimations could be improved with higher temporal resolution metrological data.

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1. Introduction

This section describes the aim of the study and the research questions of interest. Some background information, in which the history and implementation of the WBGT index and the index equation will be presented. Also a brief explanation of WBGT instruments in general will be presented.

1.1. Aim

The WBGT index is used to estimate the effect of different meteorological parameters on humans, such as air temperature, humidity, wind speed, visible radiation and infrared radiation (Wikipedia, 2020). Most of the users who use the Wet Bulb Globe Temperature (WBGT) index only use the index as a screening tool for heat stress evaluation and are unaware of its limitations (d'Ambrosio Alfano, Malchaire, Palella, & Riccio, 2014). Relatively uncharted is how the index itself is affected by weather conditions, groundcovers, direct sunlight or shade, different times of the day etc. Also outdoor thermal comfort studies is a rather new research field in comparison to indoor comfort studies, according to Johansson, Thorsson, Emmanuel, and Krüger (2014), which is one of the reasons behind this study.

The main aim of this study is to investigate how the measured WBGT and its components is dependent on the microclimatic environment. Another aim is to compare measured WBGT data with modeled WBGT estimations based on metrological data, mainly to explore the possibility to use metrological data as a supplement to instruments for measuring the WBGT index, suggested by Liljegren, Carhart, Lawday, Tschopp, and Sharp (2008). But also because of a generally increasing interest and demand in using metrological data for WBGT forecasts or warning systems. Due to metrological data generally being so widely available and continuous, while WBGT monitoring with instruments are time consuming and ineffective for larger geographical areas. Currently there exists no Heat-Health Warning System (HHWS) at an international level, however a web-based platform is being developed by the EU-project HEAT-SHIELD. HEAT-SHIELD is thought to implement the WBGT index with the use of meteorological data to provide a HHWS for occupational settings across Europe (Morabito et al., 2019). This may be a step in the right direction to prevent heat-stress-risks internationally.

Questions that are of interest in this study are:

- How do different groundcovers, where the instruments are placed, affect the measured parameters?
- How does measurements taken in sunshine or shade differ during the same weather conditions?

- What is the difference in the measurements when the solar radiation is at its highest level in comparison to its lowest?
- Statistically, how good are modelled WBGT estimations in comparison to the WBGT measurements?
- Which of the parameters the WBGT monitors measures can potentially contribute most to the WBGT differences during different weather conditions?

1.2. Background information

1.2.1. History and Implementation of the WBGT Index

The WBGT index was first implemented and used by the United States Army and Marine Corps during the 1950s to monitor outbreaks of heat stress in training camps (Budd, 2008). Today the index is also used during sports events to prevent heat strokes (table 1) or during workplace heat stress risk assessments to improved workers health quality (table 2).

This is also where most of the research have taken place, such as Roberts (2010) who used the index to determine a WBGT temperature at which a marathon should be cancelled due to heat stress risks for the attended runners. Another example is the study by Lemke and Kjellstrom (2012) in which they calculated the WBGT index from metrological data to assess workplace WBGT levels at which workers can experience heat stress.

1.2.2. WBGT index

The WBGT index is calculated by the following equation (1):

$$WBGT = (0.7 \times WB) + (0.2 \times TG) + (0.1 \times TA) \quad (1)$$

Where the WB is the wet bulb temperature, TG is the black globe temperature, and TA is the air temperature. The wet bulb temperature in combination with the dry bulb temperature is an indication of the air humidity. The black globe temperature is the temperature of the black globe (figure 1a), which is a measurement simulating the radiant heat transfer from the human body (ISO, 1998). The air temperature is *almost* equal to the dry bulb temperature, since dry bulb temperature is measured through a half-enclosed housing, it is *not* equal to free air temperature.

Table 1. Recommended physical activity based on WBGT measurement readings. Source: modified version from WeatherOps.

WBGT	Level	Practice Hours
Under 27,8 °C	Green	Resume normal activities
30,5 to 27,8 °C	Yellow	Use discretion for intense or prolonged exercise
32,2 to 30,5 °C	Orange	Maximum practice time is two hours
33,3 to 32,2 °C	Red	Maximum length of practice is one hour
Above 33,4 °C	Black	No outdoor workouts

Table 2. Recommended work intensity based on the WBGT index measured in degrees Celsius. Light work: light hand work and occasional walking. Moderate work: moderate lifting. Heavy work: heavy material lifting. Very heavy work: picking or shoveling. Source: ACGIH "2017 TLVs and BEI"

% Work	**Workload**			
	Light	**Moderate**	**Heavy**	**Very heavy**
Continuous	31,0 °C	28,0 °C	No work heat stress risk to high	No Work heat stress risk to high
50 to 75%	31,0 °C	29,0 °C	27,5 °C	No Work heat stress risk to high
25 to 50%	32,0°C	30,0 °C	29,0 °C	28,0 °C
0 to 25%	32,5 °C	31,5 °C	30,5 °C	30,0 °C

1.2.3. WBGT instruments

The WBGT instruments available on the market vary both in composition, features and size. The predecessor (still used today) of the modern electronic WBGT instrument is the traditional wet bulb thermometer. Which features a thermometer covered up by a water-soaked cloth (also called a wick) measuring the wet bulb temperature (Gupton Jr, 2001), and combined with a regular thermometer measuring air temperature, the humidity can be estimated. Today's WBGT instruments calculates the wet bulb temperature and humidity electronically instead. The features available for the instrument is depending on how expensive the instrument is, more expensive instrument usually have better hardware and most notably better measuring accuracy.

The WBGT instrument consist of a black globe thermometer and usually other sensors placed outside the ball that measures relative humidity and air temperature or other parameters depending on the instrument used. Inside a black globe thermometer a temperature sensor is placed. According to ISO (1998) the sensor can be e.g. a thermocouple, a resistance probe or the bulb of a mercury thermometer, but also other types of temperature sensors can be installed inside the black globe. ISO (1998) also recommends using a ball with the diameter of 150mm, but smaller balls can also be used, if the diameter size is taken into consideration during calculations. It is also very important that the ball is painted black, "so that the external surface of the globe absorbs the radiation from the walls of the enclosure" (ISO, 1998). Another important aspect of the ball diameter is that smaller globes warms up quicker than larger globes. Smaller globes reach equilibrium faster, around 5 minutes for a 75mm ball according to Budd (2008), which is better suited for outdoor measurements. Larger globes warms up slower and reach equilibrium around 20 to 30 minutes for a 150mm ball according to ISO (1998). This leads to them being less suitable for outdoor measurements, since the weather can change rapidly before the instrument finds its equilibrium. However as also pointed out by ISO (1998), the smaller the ball diameters, the greater the influence of both the air temperature and wind speed on the measurement accuracy of the instrument. In other words the ball used should not be either too large or too small. Since smaller balls leads to bigger measurement fluctuations and bigger balls are too unaffected by the weather condition or environment around it. Careful planning is needed depending on what parameters or for how long you are going to measure.

2. Methods

The following section will present measuring site and the instruments used during the different experiments, what specification they have and what parameters they measured and calculated. Also an explanation of how and when the different experiment were performed. As well as a brief description of how the WBGT modelling were done and what parameters the model used.

2.1. Measuring site description

My garden is an almost equal split of lawn and stone slabs, the lawn is approximately 24,5 square meters and the stone slabs cover approximately 19 square meters. The vegetation around my lawn consist mostly of bushes, but also some lilacs.

Outside my garden there is a relatively big football ground consisting of artificial grass, which may have an effect on the measurements (albedo not the same as for regular grass), however this is much unlikely. Also there is a number of large trees outside the garden which creates most of the shadows in my garden, which can potentially affect some of the measurement results.

2.2. Instruments

Two PCE-WB 20SD WBGT monitors from PCE instruments (figure 1a) were used to measure the WBGT index during the different experiments. The instrument features a 75mm black brass ball, which are relatively small compared to other WBGT instruments available on the market.

An ALMEMO® 2590-2A/-4AS data logger from AHLBORN were used to measure the metrological data used for the modeled WBGT estimations (figure 1b). The data logger were equipped with a combined capacitive air temperature and humidity sensor (FHA646-E1).

Figure 1: a) PCE-WB 20SD WBGT monitor with its 75mm black brass ball (left) and air temperature and humidity sensor (right), SD-card for data extraction next to the monitor. b) ALMEMO® 2590-2A/-4AS data logger connected to the combined capacitive air temperature and humidity sensor (FHA646-E1)(grey connector) and a USB connector to extract data (black connector).

2.2.1. Measured and Calculated Parameters

The two WBGT monitors measures black globe temperature, air temperature and relative humidity (table 3). The monitors also calculates the wet bulb temperature, dew point temperature and WBGT simultaneously during measuring. The wet bulb temperature and dew point temperature is calculated from the measured air temperature and humidity, while the WBGT is calculated based on the parameters in the equation listed in the introduction (1).

The humidity sensor for the data logger measures relative humidity, air temperature, and dew point temperature (table 4).

Table 3: Accuracy table for the calculated WBGT and measured parameters via the WBGT monitor (PCE-WB 20SD). Modified table from operation manual. Measuring intervals based on "tests under the environment RF Field Strength less than 3 V/M & frequency less than 30 MHz only" (cited from operation manual).

Parameter	Accuracy	Measuring interval
WBGT	±1,5ºC	15 to 59ºC
Black globe temperature	±0,6ºC	15 to 40ºC
Air temperature	±0,8ºC	15 to 40ºC
Relative humidity (RH)	±3% reading error + 1% RH (above 70%) ±3% RH (below 70%)	5 to 95% RH

Table 4: Accuracy table for the measured parameters via the humidity sensor (FHA646-E1).

Parameter	Accuracy	Measuring interval
Relative humidity	±2% RH	Nominal temperature
Air temperature	±0,1ºC	0 to 70ºC

2.3. Measurements

All the measurements were taken in my own private garden, with 10 minute measuring intervals for all the experiments and 1 minute intervals for the precision test. The garden receives sunlight from around 14:00 until around 19:30, most of the experiments start at 14:00 for this reason.

The instruments were placed at a measuring height of 1,1 meters (figure 2a), since this height should represent the center of gravity for the human body (ISO, 1998). Also a homemade radiation shield was provided for the combined capacitive air temperature and humidity sensor (figure 2b), to minimize the instruments radiative exchange to its surrounding environment (ISO, 1998). The shield also had proper ventilation to circumvent warm air formation and maximize convection inside the shield recommended by WMO (2008). During the measurements each 30 minutes the solar position and shadows presence were also estimated.

Parameters not measured by the data logger but needed for the WBGT modelling, was provided by the metrological data from Svergies Meteorologiska och Hydrologiska Institut (SMHI) weather stations 71415 and 71420.

Figure 2: a) Improvised measuring stands composed of an old camera tripod (instrument 1 during experiments) and a note stand (instrument 2 during experiments), b) radiation shield composed of aluminium foil, and c) frame of the radiation shield.

2.3.1. Precision test

To estimate the precision for each of the WBGT instruments, a precision test was performed. The instruments were placed in direct sunlight close to each other (approximately 0,5 meters apart), the measurement lasted approximately from 14:50 to 15:50 the 23rd of April.

The data logger were not used during the test, since I wanted to examine the precision for the two WBGT monitors.

2.3.2. Groundcover experiment

The first experiment were to compare how different groundcovers affected the measured parameters. For this experiment one of the WBGT monitors were therefore placed on moss (partly grass) (figure 3a) and the other one on stone slabs (figure 3b), both in direct sunlight.

The weather during this experiment were sunny with medium cloud cover, later into the experiment the weather got clearer, some weak winds were also present. The first measurement were logged at 14:05 and the last one at 17:05 the 5th of May.

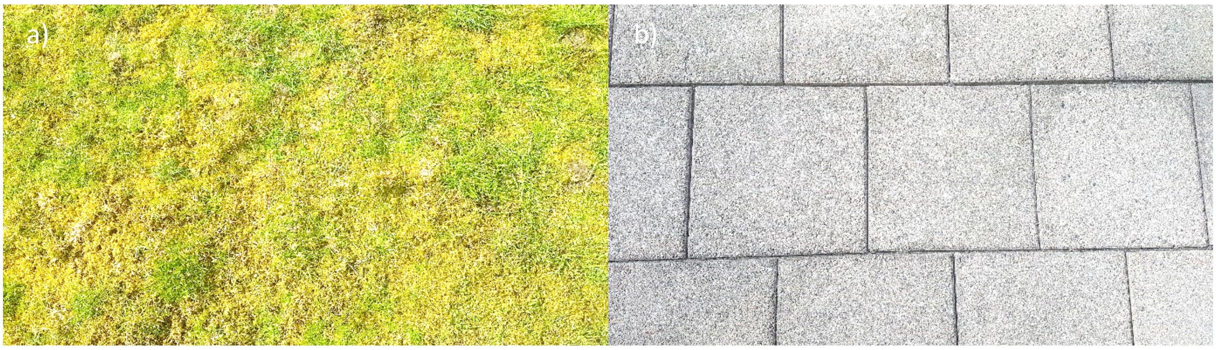


Figure 3. The different groundcovers a) lawn consisting mostly of moss and partly grass and b) garden stone slabs.

2.3.3. Shade and sun experiment

The second experiment were to analyze how measurements taken in the shade differs in contrast to measurements taken in direct sunshine. Therefore one of the WBGT monitors were placed in direct sunshine and the other one in the shadow, both instruments were placed on the stone slabs.

The weather during the experiment were clear and sunny with low cloud cover, a little windier than in the previous experiment. First logged measurements at 14:12 and the last one at 16:02 the 6th of May.

2.3.4. Solar radiation level experiment

The third experiment were to investigate how measurements taken during strong solar radiation in comparison to weak solar radiation differs from each other. Only one of the WBGT monitors were placed on the stone slabs, also the data logger were used to acquire data needed for the WBGT estimation model.

The weather during the experiment were clear with low (almost absent) cloud cover, some consistent winds were also present. The measurement started at 14:09 and stopped at 21:18 (sunset around 21:10) the 7th of May. This time interval were chosen since the solar radiation were relatively strong at 14:00 and after sunset weak or almost absent.

2.4. Estimation model

For the modelled WBGT estimation, a R-code were downloaded from GitHub (2017) (Appendix 1) which were based on the principles suggested by Liljegren et al. (2008). Where the WBGT index was dependent on following parameters: global radiation (W/m^2), air temperature (^{o}C), relative humidity (%), wind speed (m/s) and air pressure (hPa). The global radiation were measured by weather station 71415, wind speed and air pressure were measured by weather station 71420, both downloaded from SMHI (2020). The air temperature and relative humidity were measured by the data logger during the third experiment (extracted measurements taken each hour from the experiment). The estimation model were then compared to hourly data from the third experiment as a comparison.

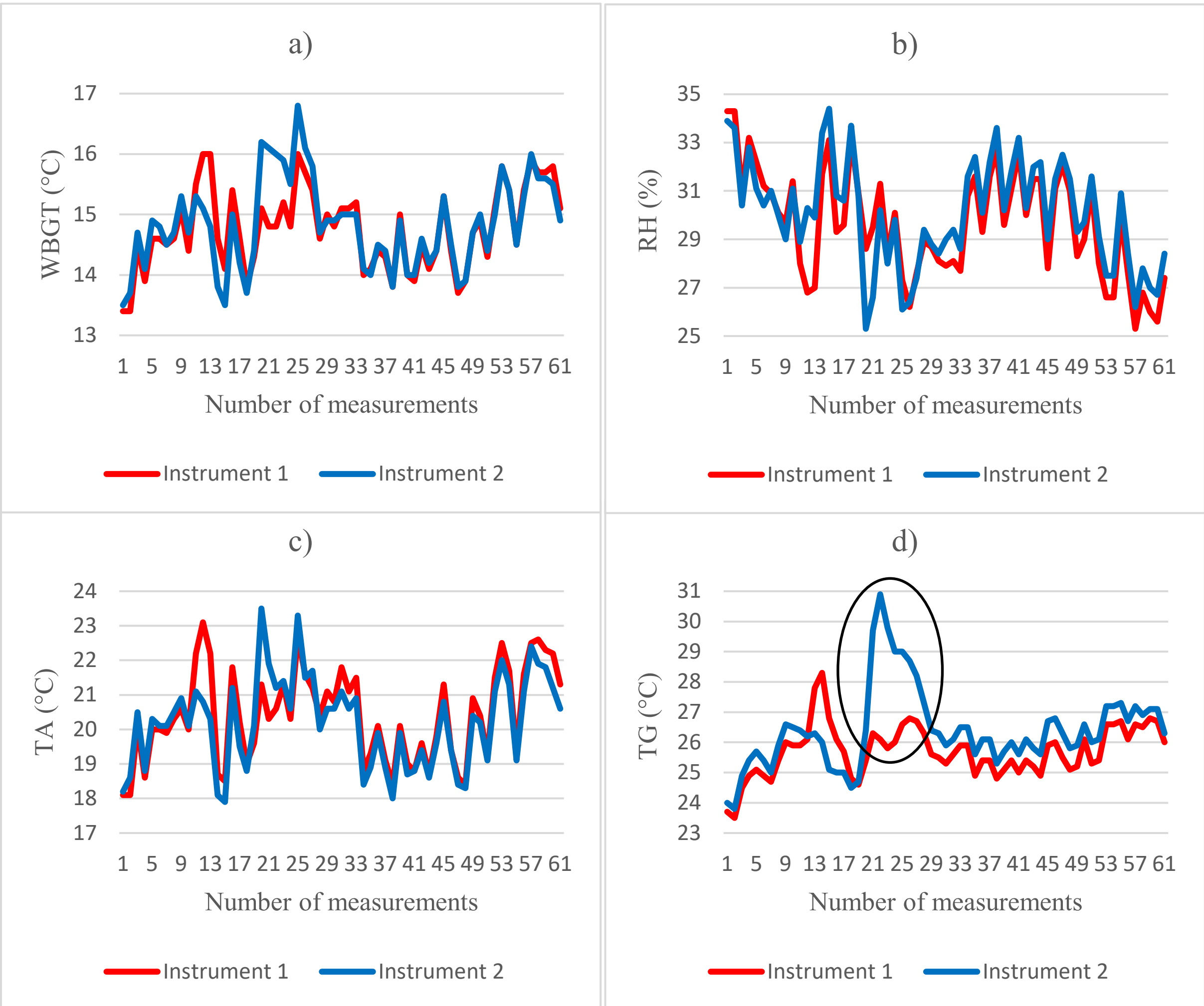
3. Results and Discussion

In this section the experiment result will be presented and discussed in the order they were performed, and lastly the WBGT model result will be presented and discussed.

Legend description: for all the experiments the red line is instrument 1 and blue line instrument 2 measurements. Instrument 1 and 2 are the two WBGT monitors (PCE-WB 20SD).

3.1. Precision test

The precision of the two monitors were good throughout most of the test, only during some stages of the test, differences can be visualized (figure 5). The Root Mean Square Error (RMSE) and difference in averages for the different parameters are relatively low, except for the relative humidity and black globe temperature (table 7, table 8). The RMSE values for most parameters are between the intervals enlisted in the operation manual (table 3), which proves that the precision test were successful.



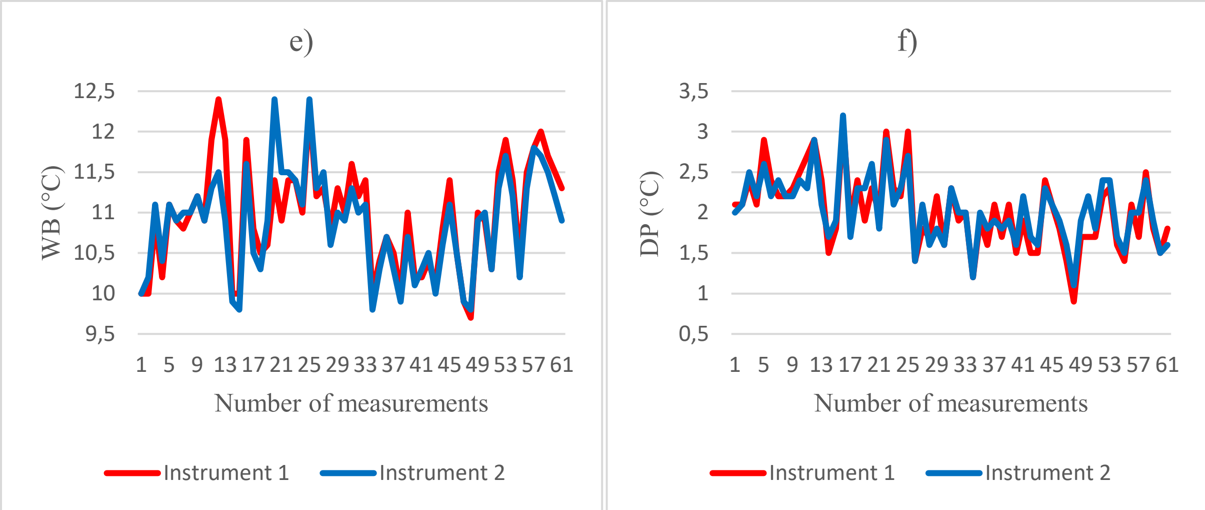


Figure 4: The precision test results for a) wet bulb globe temperature (WBGT), b) relative humidity (RH), c) air temperature (TA), d) black globe temperature (TG), e) wet bulb temperature (WB), and f) dew point temperature (DP). Measurements each minute, starting from 14:50 to 15:50 the 23rd of April.

The RMSE may be high for the relative humidity (table 7), but keep in mind that this parameter is measured in percent compared to the other parameters (measured in degrees Celsius). Meaning that a RMSE of 1,12 % is a sign of good precision for the relative humidity. Also the difference in relative humidity averages between the instruments are barely noticeable (table 8).

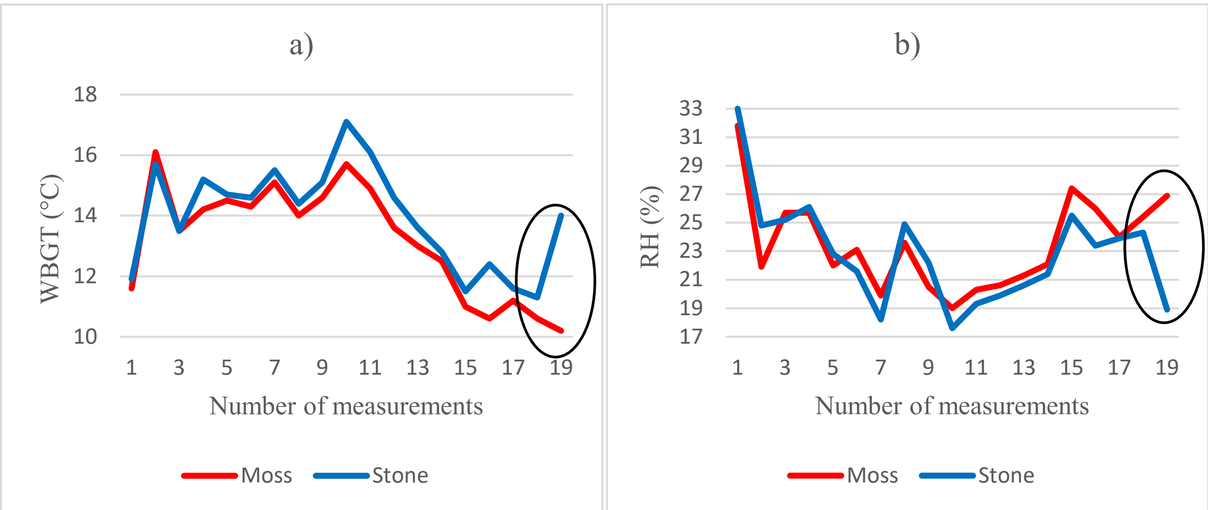
However a RMSE of almost 1,3 °C for the black globe temperature is not a good sign of precision, since all the other parameters had a lower RMSE in comparison (table 7). The difference in black globe temperatures averages between the instrument is also relatively high (table 8).

Why the RMSE for the black globe temperature were high can have several reasons. One possible explanation could be that one of the instruments got shadowed during some measuring intervals of the experiment, especially during the big differences in temperature between measurements 20 to 29 (figure 4d, oval). However under further investigation (estimating the solar position another day), shadows were not the reason behind this difference, since no shadows were present at that time in my garden. Another possibility could be that the convective heat transfer around the globe vary as a function of the ball diameter (d'Ambrosio Alfano et al., 2014). Meaning that globes with larger diameters tends to have smaller fluctuations in temperature, while smaller globes have higher fluctuations. Since the globe are only 75mm in diameter for the monitors, it can potentially lead to large fluctuations during measuring, which is what could have happened during the precision test. However it is uncertain if this would explain the big differences between measurements 20 to 29, since all other measuring points almost match (figure 4d). Also for the convective heat transfer to be a factor, the instruments need to have been exposed to different wind conditions, which is unlikely since they were placed next to each other. A more plausible explanation to the difference between the measurements given by Kerslake (1972) is that cheaper WBGT instruments, which have globes with smaller diameters than the standard 150mm globes, leads to a larger convection coefficient and therefore different measurement readings. However it is still unclear why this would largely affect the black globe temperature and not the other parameters in the same extent. The cause of the large difference between measurements 20 to 29 may also have other explanations, such as one of the instrument being affected by reflections from something else at the measuring site. Since radiation fluxes are highly affected by urban structures that can both *reflect*, absorb, and emit solar radiation both in the shortwave and longwave spectrum (Gulyás, Unger, & Matzarakis, 2006). Which in return could potentially have affected the measurements.

One positive aspect of using globes with smaller diameters is that they have shorter response times, which explains why the different monitors almost instantly founded an equilibrium in relation to each other (figure 4).

3.2. Groundcover experiment

It seems that the instruments were not affected by which groundcover they were placed on (according to my results), only small differences could be seen in the measurements, mostly in the WBGT (figure 6a) and black globe temperature (figure 6d). The RMSE for the different parameters and the differences between averages are very low, except for the black globe temperature (table 7, table 8), further suggesting that the instruments were unaffected by which ground cover they were placed on.



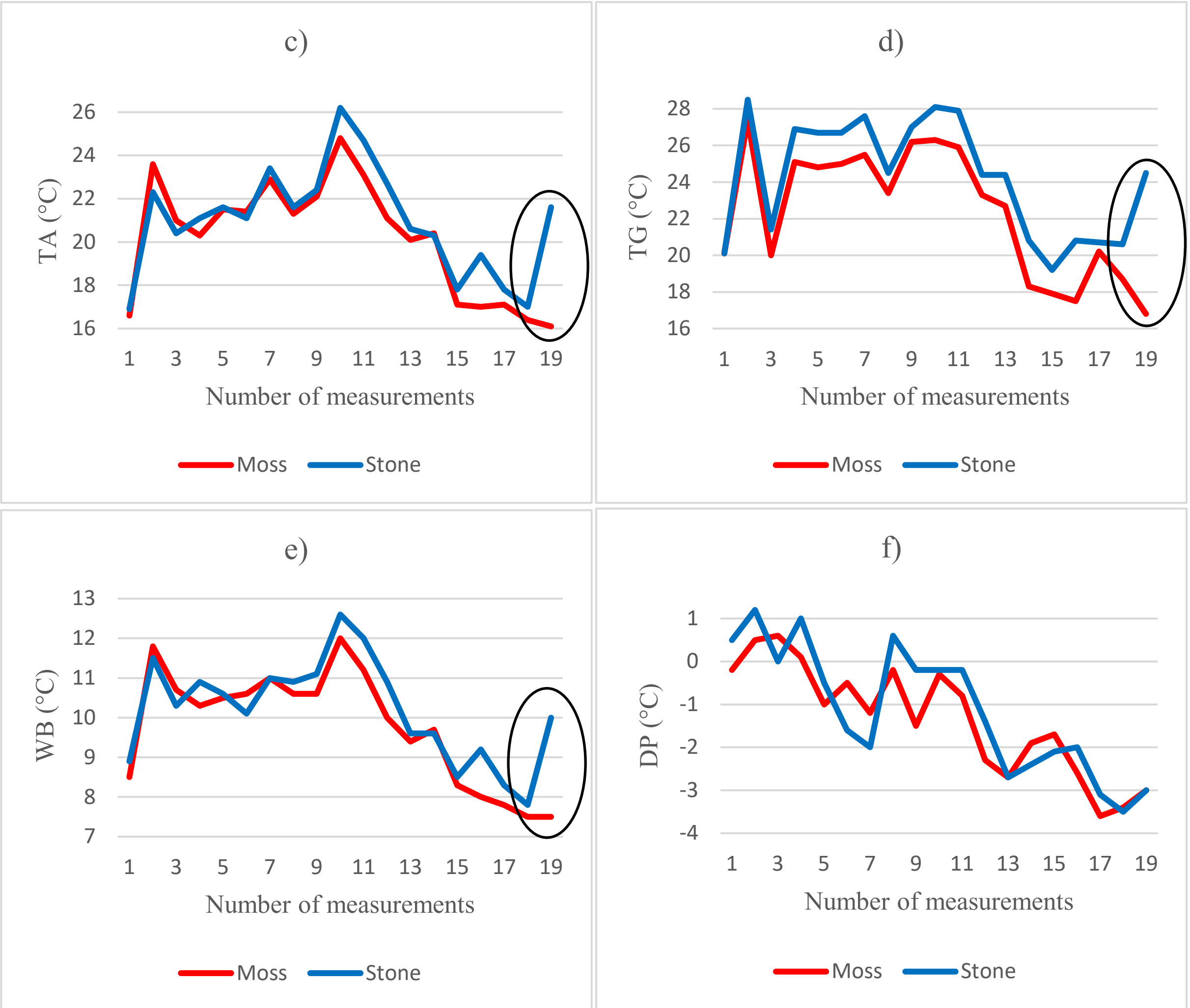


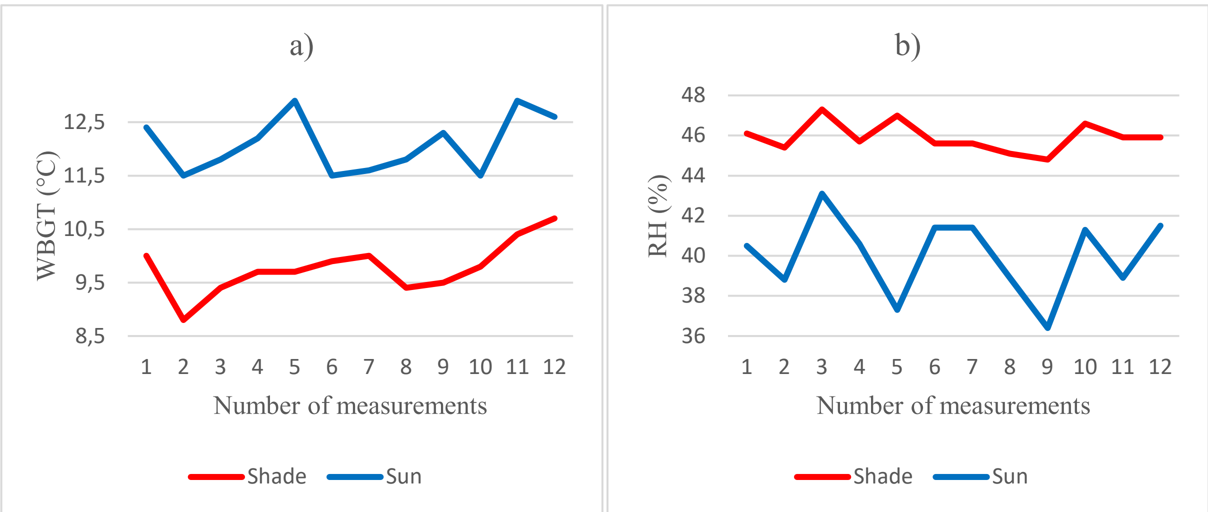
Figure 5: The groundcover experiment results for a) wet bulb globe temperature (WBGT), b) relative humidity (RH), c) air temperature (TA), d) black globe temperature (TG), e) wet bulb temperature (WB), and f) dew point temperature (DP). Measurements each 10 minutes, starting from 14:06 to 17:06 the 5th of May.

The big difference in black globe temperature between the instruments could depend on multiple factors, most definitely shadows, which could also explain the large difference between measurements 18 to 19 for most of the parameters (figure 6, ovals). It especially makes sense when observing the difference in air temperature between the two instruments (21,6 ºC and 16,1 ºC respectively), which most likely could been a reflection of one instrument measuring temperature in the shadow and the other one measuring temperature in the sun (figure 6c, oval). This is the most likely explanation for the large difference, since I observed shadows starting to appear on in my garden at approximately 16:00. Measurements 18 and 19 were taken at 16:46 and 16:56 respectively, by then my garden were most likely covered with periodic shadows. Shadows may also have affected other black globe temperature measurements throughout the experiment, since there were a slight difference between them for most of the experiment (figure 6d). Another explanation could be that the different groundcovers *actually* affects the black globe temperature. In theory the stone slabs should become hotter than the moss, due to the stone slabs having lower albedo and higher emissivity than the moss. Causing higher solar radiation absorption and thus an increased surface temperature (Alghoul, Sopian, Lahimer, & Elayeb, 2017) in comparison to the moss. This would explain why the black globe temperature is slightly higher for the stone slabs in comparison to the moss. Therefore a t-test was made for both the WBGT and the black globe temperature, which both showed a statistically significant difference (p-values; WBGT ≈ 0,002 and black globe temperature ≈ $6{,}63 \times 10^{-5}$). Further suggesting that the black globe temperature and WBGT index *differ* between different groundcovers.

Why there were no obvious differences for most parameters between the instruments can also have other reasons. One could had been that the instruments were placed too close to each other (only 3-4 meters apart), to maybe achieve a better result would need more spacing between the two instruments. Also to claim that instruments are independent by different groundcovers there are measuring over, would need more measurements on different groundcovers. For example the difference between measurements taken above hot tarmac compared to grass, would probably be much higher compared to the difference in my results. In other words more research is needed to draw any relating conclusions.

3.3. Shade and sun experiment

There were definitely a big difference between the instruments in almost all of the measured parameters (figure 7). The RMSE and difference in averages for the different parameters are all very high, except for the wet bulb temperature and dew point temperature (table 7, table 8). The big differences in all parameters were somewhat expected, and most of the differences makes sense under further investigation.



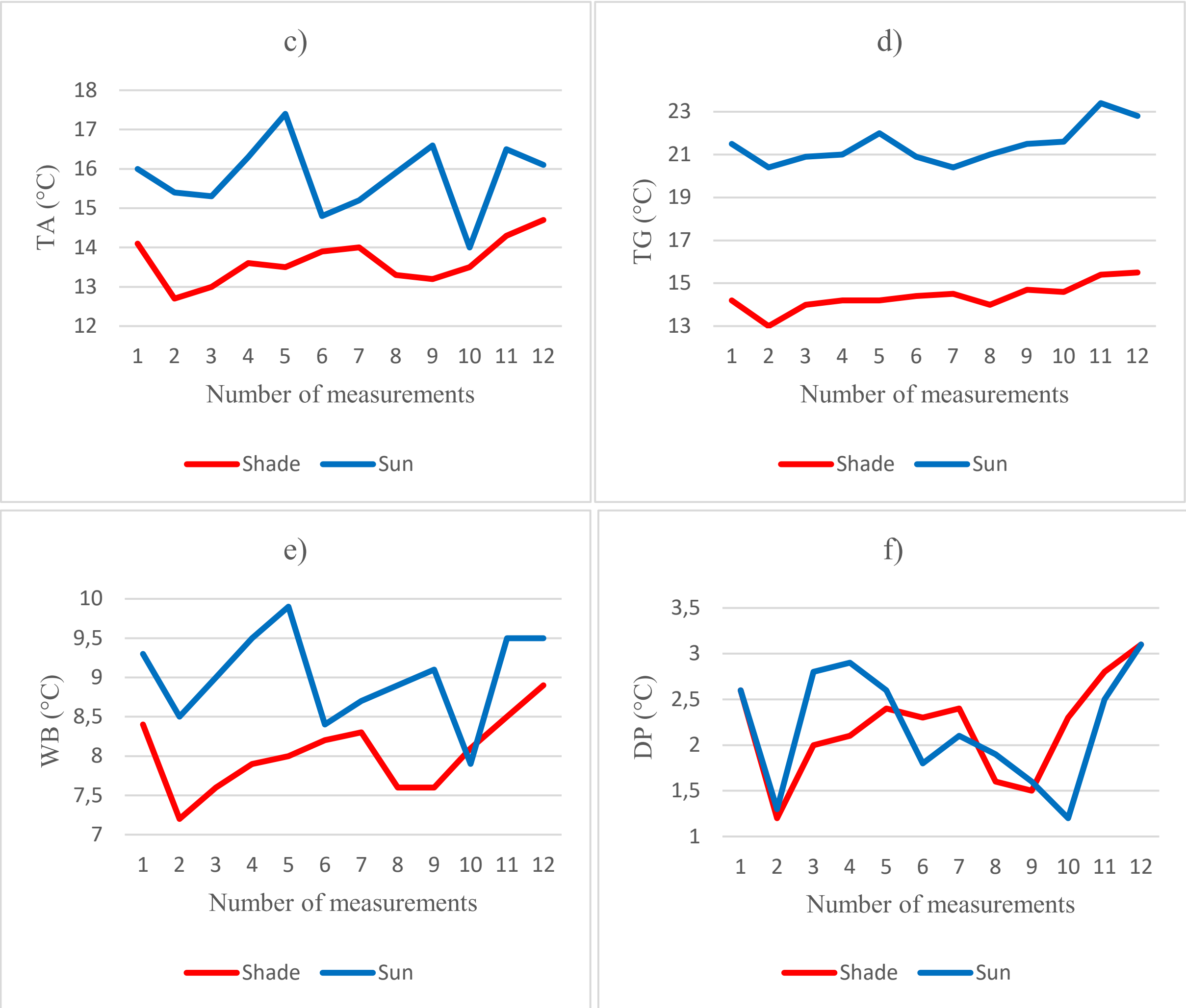


Figure 7: The shade and sun experiment results for a) wet bulb globe temperature (WBGT), b) relative humidity (RH), c) air temperature (TA), d) black globe temperature (TG), e) wet bulb temperature (WB), and f) dew point temperature (DP). Measurements each 10 minutes, starting from 14:12 to 16:02 the 6th of May.

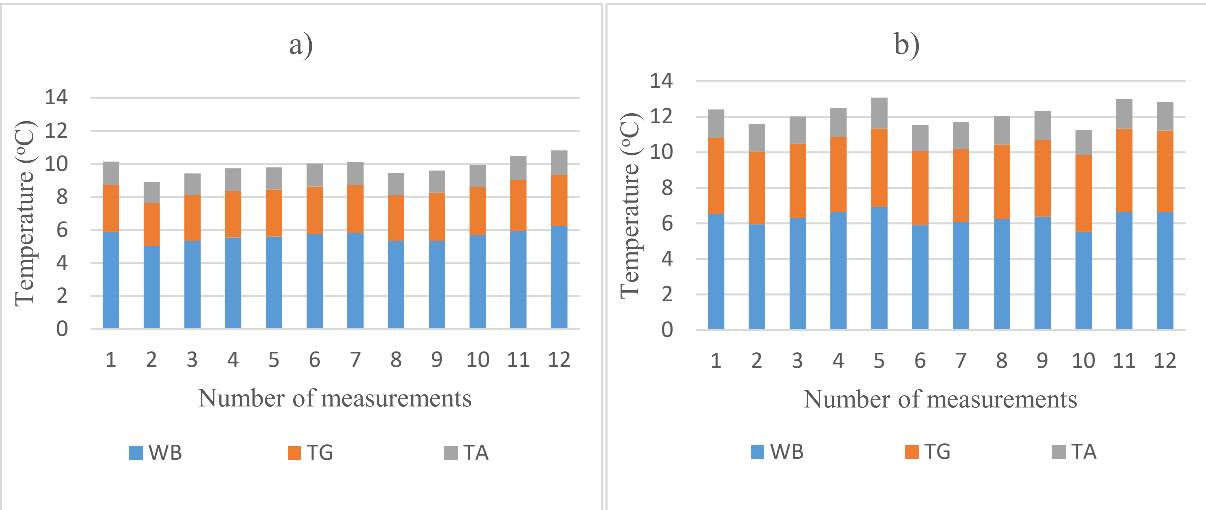


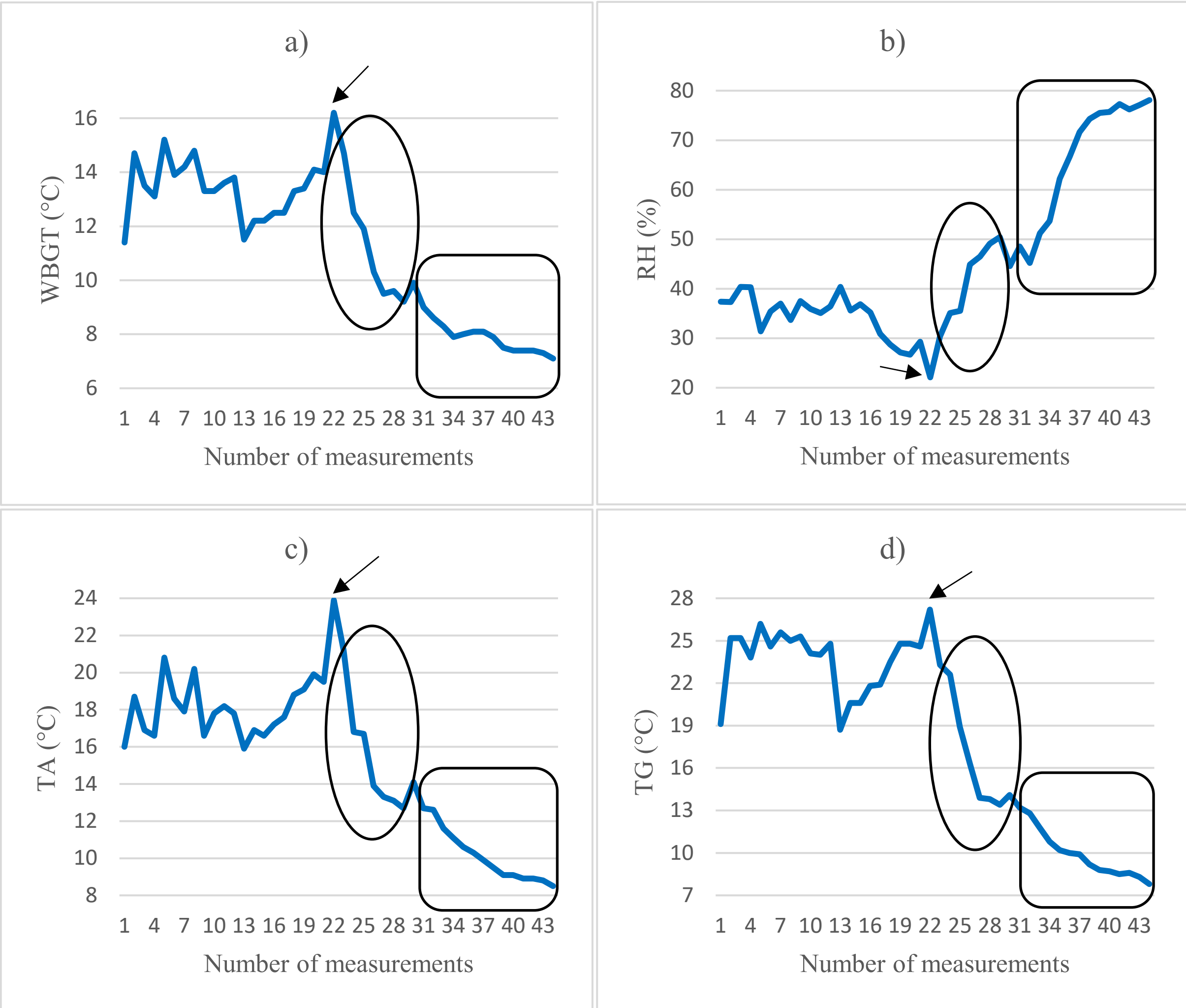
Figure 8: The different WBGT parameters calculated based on the equation (1), for a) the shade instrument and b) the sunlit instrument. The different parameters are wet bulb temperature (WB), black globe temperature (TG), and air temperature (TA). Note the big difference between the black globe temperatures. Measurements each 10 minutes, starting from 14:12 to 16:02 the 6th of May.

The WBGT index is mostly dependent on the wet bulb temperature, but also black globe temperature and air temperature (equation 1). Therefore the large difference in black globe temperature (figure 7d) between the shade and sun will result in a big difference in the WBGT index (figure 7a). This difference can be seen even clearer if all the WBGT parameters are plotted in the same graph (figure 8). The relative humidity between the instruments should be at the same water vapor level, higher for cool air and lower for warm air. Which could explain the big difference in relative humidity (figure 7b) between the shade (cooler air) and sun (warmer air). The big difference in air temperature (figure 7c) were expected, due to sunlit air receiving more solar radiation (energy) the air mass heats up to a greater extent than the shaded air mass, which receives less solar radiation. The black globe temperature (figure 7d) is a measurement of the radiant heat transfer, which explains why the sunlit instrument had higher heat transfer (air receives more solar energy) and therefore also higher black globe temperature, than the shaded instrument (air receives less solar energy). Why the difference between wet bulb temperature and the dew point temperature were relatively low compared to the other parameters can also easily be explained. The wet bulb temperature is a combined measurement of dry bulb temperature (which is *similar* to air temperature) and relative humidity. Since warmer air has higher temperature and lower relative humidity, while cooler air has lower temperature and higher relative humidity. The difference in wet bulb temperature should in theory be minimal, which could explain the relatively small difference in wet bulb temperature between the two instruments (figure 7e, figure 8). The almost nonexistent difference in dew point temperature (figure 7f) between the instruments are probably because both instruments were placed on the stone slabs, reflecting the same humidity environment. Why there existed a small difference in dew point temperature could also be because the sunlit instrument were placed close to a bush while the shaded instrument stood next to a shed.

The saw-tooth like fluctuation pattern seen for most of the sun-measured parameters is probably due to the wind (figure 7a, b, and c), however this is uncertain since no wind-measuring instruments were used during the experiment. But according to Zare et al. (2020) WBGT instruments are relatively sensitive to wind speed, which suggests that wind could be the reason behind the fluctuation pattern. Furthermore the sunlit instrument were placed in such a way that it were affected by the wind, while the shaded instrument were placed in lee, the sunlit black globe is also much hotter than the shaded black globe. So even if both instruments would have been affected by the wind, the wind would have cooled down the sunlit globe to a greater extent than the shaded one, due to its higher temperature. Clouds could also explain the pattern, since some cloud cover were present during the experiment. Since the shaded instrument is already shaded, the cloud cover shading would have little effect on the shaded instrument. Instead only the sunlit instrument would be affected by the cloud cover, which also explains why only the sunlit instrument show the saw-tooth pattern. A weather condition alternating between cloudy to clear conditions can also cause high variations in shortwave radiation fluxes (Alghoul et al., 2017), which further could explain the saw-tooth pattern.

3.4. Solar radiation level experiment

There were definitely big fluctuations for all the measured parameters throughout the experiment (figure 9), which are thought to have several reasons.



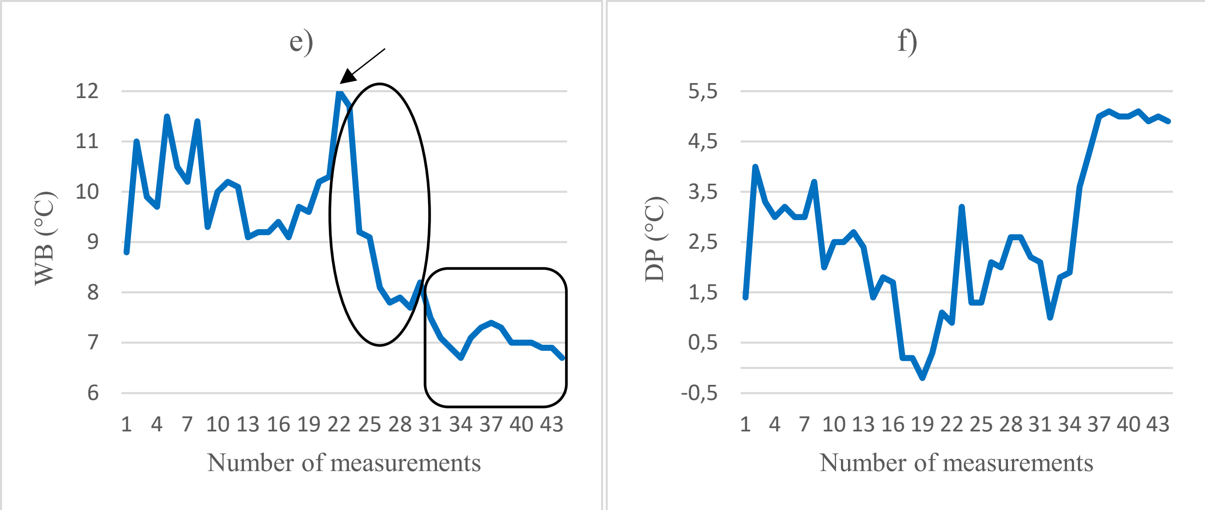


Figure 6: The solar radiation level experiment results for a) wet bulb globe temperature (WBGT), b) relative humidity (RH), c) air temperature (TA), d) black globe temperature (TG), e) wet bulb temperature (WB) and f) dew point temperature (DP). Measurements each 10 minutes, starting from 14:09 to 21:18 the 6th of May.

The fast fluctuations in the parameters were thought to be caused by the wind, much like the fluctuations in my previous experiment. Due to the fast nature of the fluctuations this were thought to be the most promising explanation, since harsh winds can change an environments temperature (and the human body) rapidly if the wind speed and wind duration is high and long enough. The fast decrease for most of the parameters (figure 9a, c, d, and e) and increase (figure 9b) around measuring point 22 (figure 9, arrows) could be due to a fast decrease in solar radiation. The fast decrease in solar radiation were because my garden at approximately 17:30 were mostly covered by shadows (measurement 22 taken at 17:29). Between 17:40 to 18:30 there were some sun present in the garden still, which could explain why the decrease and increase slopes in some parameters between measurements 23 to 29 were slowed down (figure 9, ovals). But after 18:30 (measurement 30 and forward, (figure 9, rectangles)) my garden did not receive any more sun (solar radiation) and as a consequence the decrease and increase slopes amplified even faster.

My results indicates that most parameters that the WBGT monitor measures are dependent on solar radiation fluctuations throughout the day, which corresponds to Yaglou and Minaed (1957) findings, that small increases in both sunlight and wind speed can change the WBGT index (and the associated parameters of the index) rapidly.

3.5. Modelled estimations

Visually there seems to be relatively high correlations between the estimated and measured parameters (figure 10) and not surprisingly the coefficient of determination test for the WBGT, black globe temperature and wet bulb temperature all had high positive correlations (table 6). The RMSE and the differences in averages were surprisingly low, except for the black globe temperature RMSE (table 7), suggesting that the model works.

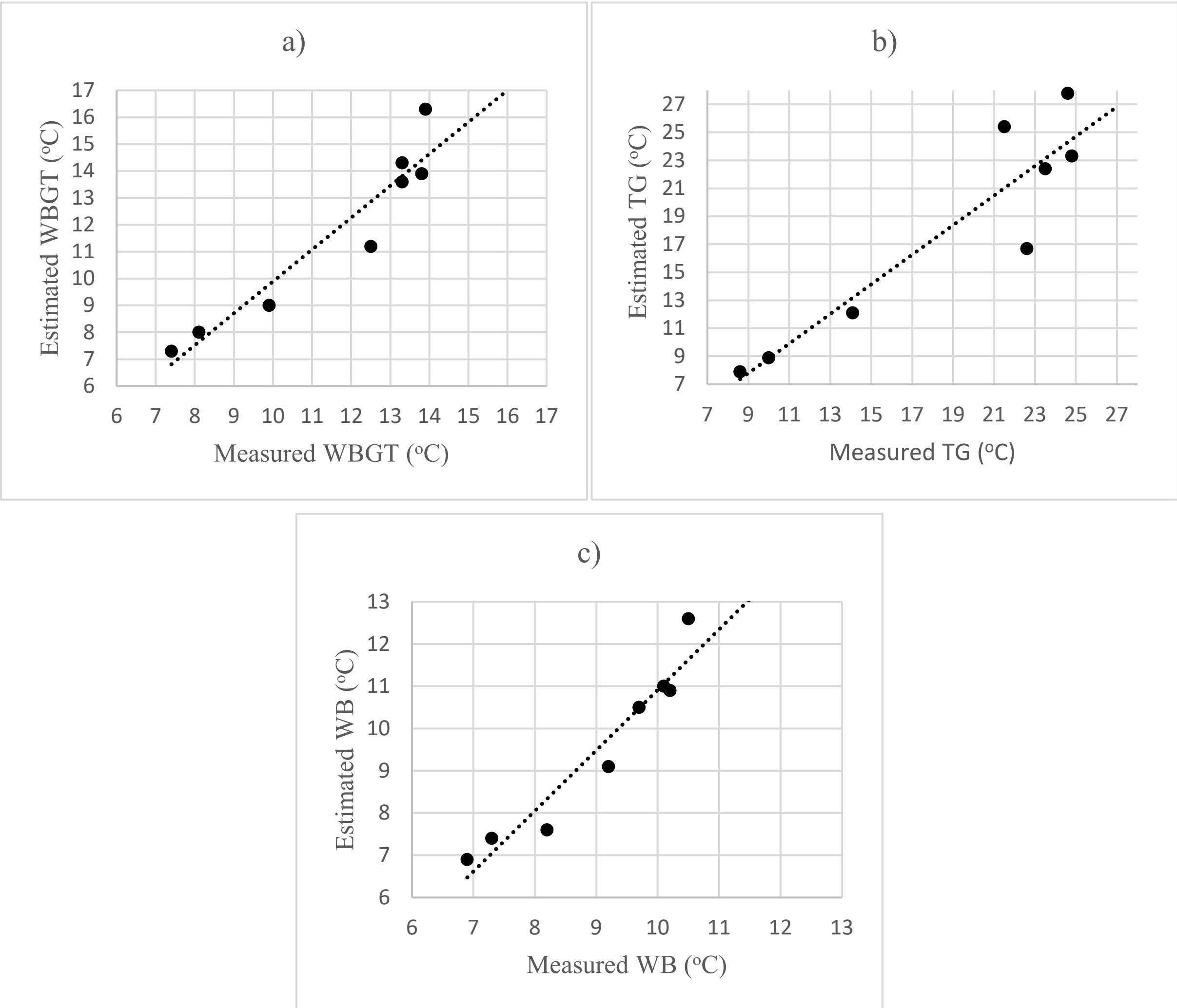


Figure 7: Measured and modelled results for a) wet bulb globe temperature (WBGT), b) black globe temperature (TG), and c) wet bulb temperature (WB). Hourly measured data starting from 14:00 to 21:00 the 6th of May.

Table 5: Coefficient of determination for the different parameters. All values are rounded off.

WBGT	0,90
Black Globe Temperature	0,84
Wet Bulb Temperature	0,92

Why the difference between the RMSE for the black globe temperature were fairly high could have a number of reasons. One being that the measuring instruments had different measuring heights, the metrological data used in the model comes from instruments with measuring heights of approximately 3 (measured the wind speed and air pressure) and 94 meters (measured the global radiation), while my instrument had a measuring height of 1,1 meters. However the measuring height differences would not explain why the difference between the estimated and measured black globe temperature RMSE were rather large. Another plausible explanation are regional climate differences between the measuring sites, the weather stations are located close to Gothenburg city center and thus were more likely affected by the urban heat island effect. While my garden are located in the outskirts of the city and thus were not likely affected by the urban heat island to the same extent. This may had an effect on the black globe temperature RMSE, but to what extent is hard to evaluate. Also geographical distance may explain the differences between the globe temperature RMSE, the different weather stations are located approximately 4,33 kilometers (weather station 71420) and 7,35 kilometers (weather station 71415) from my garden. Within this distances from my garden the weather could had been different, which in return cloud result in different black globe temperature RMSE values. Elevation difference may also be an explanation to the difference between the black globe temperature RMSE, my garden are located approximately 60 meters above sea level, while the weather station instruments are located 3 meters and 94 meters above sea level. The elevation difference could explain why there exists *some* difference between the black globe temperature RMSE. Also as discussed in previous experiments, both differences in wind speed, wind direction and cloud cover between measuring sites could explain the globe temperature RMSE difference. This may have had an effect since only the weather condition present at my garden could be observed, while the weather condition present at the weather stations could not be studied.

Other problems with using weather forecast data explained by Petersson, Kuklane, and Gao (2019) is the difficulty of properly predicting microclimate. Because weather stations usually are positioned to be as unaffected by microclimate as possible. Since the measuring instruments used in my garden are affected by the microclimate around them, this would most certainly explain why there exists differences between the globe temperatures and the other parameters. Also noted by Johansson et al. (2014) are that both temporal and spatial variations of meteorological variables in an microclimatic environment usually are very large.

To achieve a better accuracy for the modelled black globe temperature RMSE would need metrological data with higher temporal resolution, since hourly data usually leads to inaccuracies in microclimate predictions (Petersson et al., 2019). From the beginning I was planning to use data from a weather station with 10 minute temporal resolution, but due to some sensors malfunctioning, the metrological data were as a result rendered useless. As a follow-up study it would be interesting to run the same estimation model with higher temporal resolution metrological data, to see if the modelled parameters can be improved further. It would also be interesting to do the WBGT measurements closer to the weather stations or use a personal weather station in my garden to examine if the modelled accuracy could be improved.

3.6. RMSE and difference in averages

It seems that the RMSE is highest for the shade and sun experiment compared to the other experiments (table 7). This indicates that the instruments are mostly affected by if they measure in the shadow or sunlight, which may not come as a surprise. The WBGT monitors are developed and meant to measure how the human body is affected by hot weather conditions in the *sun*. The RMSE for the groundcover experiment were slightly higher compared to the precision test for all the measured parameters (table 7), indicating that the instrument is *somewhat* affected by the groundcover it measures over. However as previously stated more measurements on different groundcovers are needed to draw any relating conclusions. The RMSE for the modelled estimations were relatively low for most parameters (table 7), indicating that the model could accurately estimate the measured parameters. However with higher temporal resolution metrological data the model would likely be able to create even better estimations.

Table 6: The Root Mean Square Error (RMSE) for the different experiments. All values are rounded off.

Parameters	Precision test	Groundcover	Shade and sun	Modelled estimations
WBGT (ºC)	0,42	0,80	2,36	1,08
Relative Humidity (%)	1,13	1,49	6,15	3,34
Air Temperature (ºC)	0,67	1,03	2,35	1,2
Black Globe Temperature (ºC)	1,29	1,76	7,08	2,94
Wet Bulb Temperature (ºC)	0,30	0,54	1,16	0,92
Dew Point Temperature (ºC)	0,19	0,73	0,50	0,43

Similar results as for the RMSE can be seen in the difference in averages between the different experiments (table 8). Where the highest differences can be seen for the shade and sun experiment, followed by the groundcover experiment and the modelled estimations. The modelled estimations had surprisingly low difference in averages for the different parameters, almost as on par with the precision test for some of the parameters. Which further suggest that the estimation model could accurately predict measurements.

Table 7: The Difference between averages for the different experiments. All values are rounded off.

Parameters	**Precision test** (*instrument 1 – instrument 2*)	**Groundcover** (*moss – stone)*	**Shade and Sun** (*shade – sun)*	**Modelled estimations** (*measured – estimated*)
WBGT (ºC)	-0,06	-0,76	-2,31	-0,17
Relative Humidity (%)	-0,41	0,71	5,91	-1,84
Air Temperature (ºC)	0,19	-0,79	-2,14	0,27
Black Globe Temperature (ºC)	-0,68	-1,88	-7,06	0,65
Wet Bulb Temperature (ºC)	0,08	-0,41	-1,00	-0,49
Dew Point Temperature (ºC)	-0,02	-0,21	-0,01	-0,37

4. Conclusion

In this section conclusions will be drawn based on the research questions presented in the introduction.

- According to my results it would seem that most parameters the WBGT monitors measures are *unaffected* by groundcover, however more measurements in different environments and on different groundcovers are needed before any conclusion can be drawn.
- My results indicates that there is a *big* difference between measurements taken in the sun in comparison to measurements taken in the shadow, especially in the WBGT index, black globe temperature, wet bulb temperature and air temperature.
- The difference between the measurements when the solar radiation were at its highest in comparison to its lowest level were *large*, usually more than twice as high.
- My modelled estimations were a success since estimated and measured values showed a *strong* correlation to each other. The modeled results indicates that metrological data can to *some extent* be used as a supplement to WBGT measurements with instruments. However metrological data with higher temporal resolution would result in an even better WBGT estimation model.
- The parameter that causes *most* variation in the measured WBGT index according to my results would be the *black globe temperature*. Which does not corresponds to the most important theoretical parameter, the wet bulb temperature, according to the WBGT equation (1).

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7. Appendix

7.1. R-code for the estimation model

```
#
md = read.csv("climate_data_model.csv")

latitude=57.6879
longitude=11.9797

outputs<-data.frame()

for (i in 1:nrow(md))
{
L <-
wbgt::wbgt(md[i,'YYYY'],md[i,'MM'],md[i,'DD'],md[i,'HH'],0,1,0,latitude,lon
gitude,
               md[i,'Grad'],md[i,'Pres'],md[i,'Ta'],
               md[i,'RH'],md[i,'Ws_1m'],10,0,1)
outputs = rbind(outputs,L)
}

write.table(outputs, "WBGT_outdata_.csv", sep=",")
```