Sensor shielding and the temporal & sensor resolution

Introduction

With an objective to create a low-cost and robust network of climate-sensors, it will be important to find a good balance of costs and accuracy. The data has to be accurate enough to provide data about the climate in the area, and especially the extremes that are occurring in different regions and seasons. The costs can be reduced by having a low-cost housing of the sensors, but also by decreasing the labour required. This means being able to use the sensors in the field for a long period without the need to replace or read the sensor-data. Analysing data is another step in which labour can be reduced by creating *e-Agriculture* applications that require limited input to provide useful information to farmers and researchers. A straightforward option to increase the period the sensors can be used in the field is to adjust the resolution at which the sensors make their observations. The iButton Hygrochron (DS1923)[i] can make temperature measurements at 8- or 11-bit resolution (0.5°C or 0.0625°C), and humidity measurements at 8- or 12-bit resolution, which is either 0.6% or 0.04% RH. The readings, however, are either stored in 8- or 16-bit, with the total memory for this sensor being 8192 bytes. According to the specifications, the temperature accuracy is better than ±0.5°C for most of the range (-10°C to +65°C), while the accuracy of the humidity measurements is ±5% RH. By using a lower resolution sensor for both temperature and humidity, the sensor can store double the number of observation at the same time interval as would be possible at the higher resolution (*see table 1*).

Table 1: Number of observations and possible observation period at different resolutions

	Number of observations	*Time covered at 2-hour interval*	*Time covered at 1-hour interval*	*Time covered at 30-min interval*	*Time covered at 15-min interval*
1 unit at low-res	**8192**	683 days	341 days	171 days	85 days
1 unit at high-res or 2 units at low-res	**4096**	341 days	171 days	85 days	43 days
1 unit at low-res & 1 unit at high-res	**2560**[ii]	213 days	107 days	53 days	27 days
2 units at high-res	**2048**	171 days	85 days	43 days	21 days

While changing the sensor resolution has the potential to provide easy gains, a more challenging approach to reduce costs relates to creating low-cost shielding. A large number of recommendations exists (*see box 1*), which relate to issues such as sensor-height, reflectivity and aeration of the sensor-housing. Literature provides data of related experiments that have been conducted to find low-cost sensor shielding[iii, iv, v], in which differences have been found of up to 7.4^{0}C. Most of these studies have focused on natural areas – where additional shading can easily be found. As the network that will be created will ideally be easy to use in different regions, the material that will be used for the shields will have to be very basic. This means only standard (relatively thin) PVC tubes, basic materials for shielding (insulating foil, reflective tape), and basic approaches to increase aeration (drilling holes) will be tested. It is unlikely that these shielding constructions can provide the same accuracy as certified weather stations, but ideally the maximum and minimum will be in a small range that can be reduced by smoothing of the dataset. The steps that will be taken to make the basic sensor shields and resolution accurate will be: **1)** analysing the impact that different sensor accuracy has on the provided data – and especially the extremes (*experiment 1A*); **2)** studying the impact that different temporal resolutions have on the extremes; **3)** testing different sensor shields and analysing how these impact on the provided temperature data (*experiment 2*); and **4)** combining the findings from step 1, 2 & 3 to find a good balance between the costs of the network and the accuracy of the temperature and humidity data.

When assessing trade-offs, the most important factor will be the robustness and accuracy of the data. Having similar data in the created shields as in a certified weather station would be ideal (physical calibration), but this is likely not feasible to a very high extent. This difference between the shields and a certified weather station will have to be the same, so that a computer-based correction can take place. It can be expected that a lower temporal resolution will result in a certain smoothing of the data. This can be corrected by different interpolation techniques, but it will be hard to do this for the extremes, as wind and clouds will play a role at the local level (*see chapter on local climatic factors*). On the other hand, it can be expected that – in line with existing literature – it will be very hard to reduce the impact of midday radiation on temperature. As the shields are projected to result in an exaggeration of temperature extremes. A reduced temporal interval (possibly in combination with additional smoothing), could be used to offset these differences. An important note made in the *WMO Guide to Meteorological Instruments and Methods of Observation*[vi] is that, while it is acknowledged that it might not be economically feasible to work with sensors that directly meet the accuracy requirements, *'it is necessary to limit the size of the corrections to keep residual errors within bounds'*. The maximum difference between the (max- & min-) correction (in the range -30 to +45°C) is 0.2 K, which might not be possible in this network. As it is not an 'official' weather station and has a different objective, this is not a serious limitation, but it should be preferred to work as close to the WMO standards as possible. In addition to this, an important ISO standard that will be taken into account during the comparison of different sensor shields is ISO standard 17714: *Meteorology — Air temperature measurements — Test methods for comparing the performance of thermometer shields/screens and defining important characteristics*[vii].

Box 1: Summary of relevant recommendations for weather stations[vi]

1. For general meteorological work, the observed air temperature should be representative of the free air conditions surrounding the station at a height of between 1.2 and 2.0 m above ground level.
2. A radiation shield or screen should be designed to provide an enclosure with an internal temperature that is both uniform and the same as that of the outside air; it should completely surround the thermometers and exclude radiant heat, precipitation and other phenomena that might influence the measurement.
3. Thermally insulating plastic-based material is preferred as material for the shield over the better performing highly polished, non-oxidized metal, because of its simple maintenance requirements; thermally insulating material must be used if the system relies on natural ventilation.
4. A humidity sensor may be combined with or co-located with a temperature sensor in its radiation shield as long as the sensor thermal output (self-heating) is very low.
5. Direct contact with liquid water will seriously harm sensors using hygroscopic electrolyte as a sensor element. Great care should be taken to prevent liquid water from reaching the sensitive element sensors.
6. Desirably characteristics include reliability & stability, simplicity of design, durability and acceptable cost.
7. Agricultural meteorological stations should be inspected at interval sufficiently short to ensure the maintenance of a high standard of observations and the correct functioning of the sensor.
8. Recording instruments should be compared frequently with instruments of the direct-reading type.
9. The position of a station referred to in the World Geodetic System 1984 (WGS-84) Earth Geodetic Model 1996 (EGM96) must be accurately known and recorded (1/1000 degrees latitude & longitude).
10. It is important that records should be kept not only of the temperature data, but also of the circumstances in which the measurements are taken (metadata).

<u>*Section overview:*</u>

This section will continue with the results of experiments 1 & 2, followed by a discussion of the results and an additional experiment in which the results of the experiments will be combined. The section will conclude with recommendations regarding the sensor/temporal resolution, as well as the preferred sensor shielding.

Sensor & temporal resolution: Experiment 1A

Sensor resolution

An experiment has been done with a total of 30 sensors, making observations at 5-minute interval during one week. The sensors have been placed in a certified weather station - which also houses an official observation instrument, to make sure the conditions would be the same for all sensors. Half the sensors have been set at the highest temperature and humidity resolution, while the other half has been set at the lower resolution. The sensors have been paired throughout the weather station and linear interpolation has been used to get the value at 1-minute intervals. Statistics have been calculated over the dataset at minute-intervals, which contained 30 sensors with 10.080 observations each. Basic temperature graphs are provided in *figure 1*, while more detailed plots from this experiment (including humidity) are provided in *Annex 1*.

Figure 1A: temperature graph at low-resolution

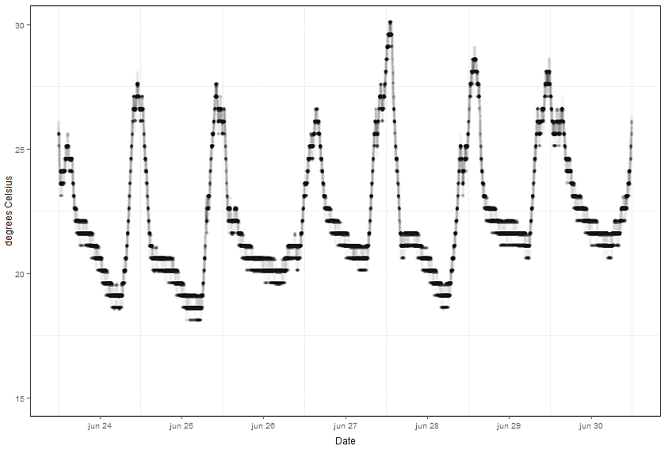
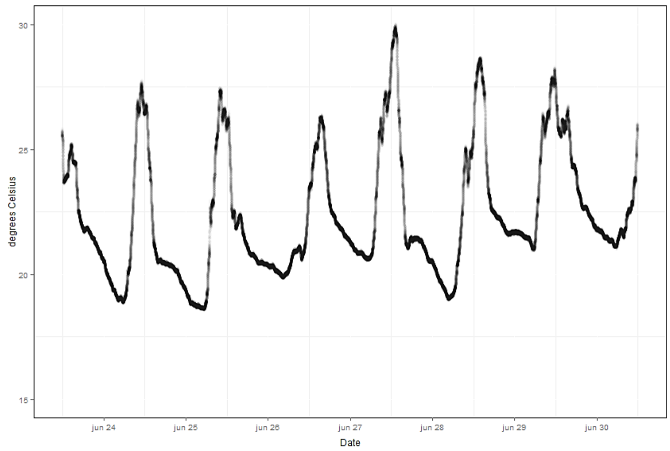


Figure 1B: temperature graph at high-resolution



Analysing the sensors provides more detailed information; the temperature range for the low-res sensors is 18.11 – 30.12°C, while this is 18.54 – 30.02°C for the high-res sensor. For humidity the range is 64.33 – 99.94% RH for the low-res and 63.86 – 100.23% RH for the high-res sensors. The mean temperature and humidity for the low-res sensors are 22.37°C and 90.45% RH; for the high-res sensors these values are 22.35°C and 90.93% RH, which is all within a small range (see *table 1*). Another important issue to take into account is the variability between sensors; a visual analysis shows that this is especially an issue for the low-res temperature observations. The standard deviation has been calculated as the mean of every row of the data-matrix which contains 15 sensors with 10.800 observations. The standard deviation for the low-res temperature sensors is 0.26°C; this is < 0.05°C for the high-res sensors. For humidity, the standard deviation is 1.13% for the low-res sensors, whereas this is slightly higher (1.20%) for the high-res sensors. Correlation between temperature and humidity is -0.91 for the low- and -0.92 for the high-resolution sensors.

Table 1: temperature statistics of the sensors at low- and high-resolution

	Minimum	*1^{st} Quartile*	*Median*	*Mean*	*3^{rd} Quartile*	*Maximum*	*Standard deviation*	*Maximum difference*
Type 1 (low-res):	18.11	20.61	21.61	22.37	24.06	30.12	0.26	1.02
Type 2 (high-res):	18.54	20.58	21.64	22.35	23.96	30.02	0.05	0.65

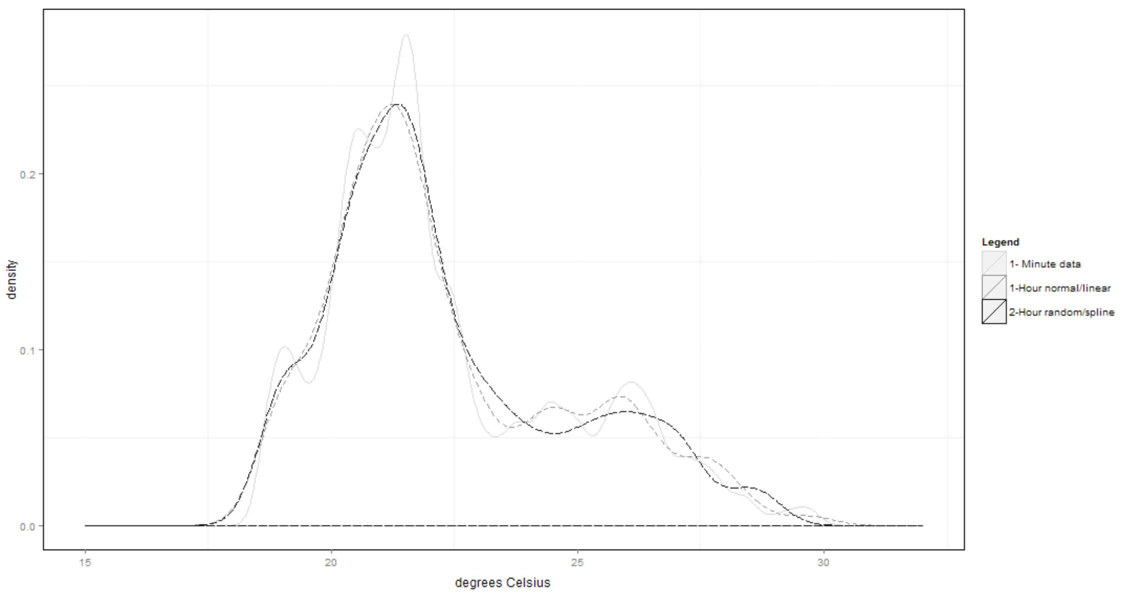
Sensor & temporal resolution: Experiment 1B

Temporal resolution

This experiment will initially use the high-resolution dataset that has also been used in experiment 1A, and after this the most promising interpolation techniques will also be applied to the low-resolution dataset to see whether it will provide sufficiently similar results to be able to work with only the low-resolution sensors. The original data-set (5-min interval) will be used, in which the start-moment will be chosen at random. This means no average will be taken, but only one value from the original data-set will be used and the rest will be ignored. Different interpolation techniques are available in the R-package {zoo}[viii], which is developed especially for irregular time-series. The techniques available here include linear (*na.approx*) and cubic spline (*na.spline*) techniques, which have limited room for adjustment. As there are many different forms of splines available[ix], alternatives could be tested to see if they work better on the sensor data at 1 & 2-hour intervals.

When the data is reduced to only have observations at the hour, instead of every minute, the graph continues to have the same complexity and very little data will be lost (*Annex 2 - 1*). The range for the temperature observations with the high-resolution sensor will be 18.59 – 29.85°C, while the mean will be 22.36°C. While measurements, when interpolated to 1-minute intervals, surpass 30°C (which might be a common threshold), this was only the case at two observations out of the total of 151,200, which makes this negligible. The overall density plot does not change a lot (*figure 2*), which would result in similar conclusions that will be drawn from these datasets. Although most conclusions that will be drawn from this data-set will be similar to those which can be drawn from the original data-set, a reduction in range could be a problem, as the extremes will change. When only using one value for each hour, randomly selected from the original dataset (*Annex 2 – 2*), and using a linear interpolation approach to get the value at the exact hour, the resulting plot shows even more smoothing of the data. The range for this dataset is 18.59 – 29.66°C, while the mean remains almost the same (22.35°C). The standard deviation in this experiment is still only ±0.09°C.

Figure 2: Density plots of temperature observations selected by two different approaches

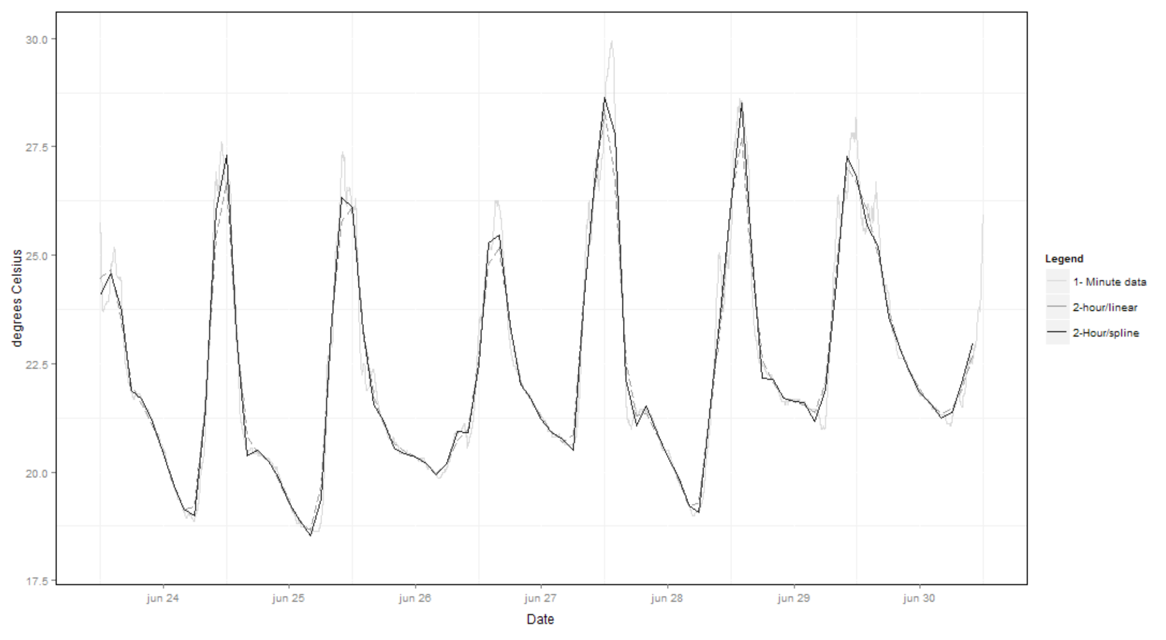


When using the low resolution, the range and mean become 18.11 - 30.11°C and 22.38°C when using the closest observation, while it will be 18.11 – 29.85°C and 22.37°C for the random start-moment (*Annex 2 – 3 & 4*). The maximum difference between any two sensors at a certain moment (exact hour) is lowest when using the closest observation with the high-res sensor (0.65°C), followed by the low-res sensor with the closest value (1.02°C), the high-res sensor with a random start-moment (1.14°C) and finally the low-res sensor with random moment of start (1.69°C). The difference was 0.65/1.02°C (low/high-res) in the original dataset, which shows that the difference does not change when using the closest value. Taking a random starting point increases the maximum difference by ±0.5 degrees Celsius for both types of sensors.

At this moment only the built-in cubic-spline approach in the {zoo} package will be tested, but in the case more adjustment would be required (e.g. if the construction results in a certain temperature/humidity bias), advanced interpolation techniques will be triea, such as can be found in the {crs}[x], {pastecs}[xi] and {quantreg}[xii] packages.

The graphs resulting from the built-in cubic spline function *na.spline* in the package {zoo} can be seen in *Annex 2 – 5:8*. The range, when taking the closest measurement, is 18.59-29.89 for the high-res sensors and 18.11-30.16 for the low-res sensors. The means is 22.36 for the high-res and 22.38 for the low-res sensors. The maximum difference at any hour is 0.34 for the high-res and 1.10 for the low-res sensors. With a random starting point, the range for the high-res sensor is 18.57-30.27°C and the mean is 22.35°C. The maximum difference at the hour, however, has gone up from 1.14 to 1.43°C. For the low-res sensor, the range becomes 18.06-30.52°C, with a mean of 22.37°C. The difference between rows stays quite similar with 1.75°C. A summary of the differences caused by these different techniques can be seen in *Annex 3*. A 2-hour interval is also included in these tables to show how different techniques impact at this larger interval. The mean of al 15 sensors at high-resolution over the week of measurement for the 1-min compared to 2-hour observations (random start-point, linear and spline interpolation) is shown in *figure 3*. Splines provide a closer match to the original data-set, which is especially clear at higher temperatures. While splines give a good match on most days, it still results in a large difference on June 27th, when the temperature is highest.

Figure 3: Temperature extremes using a 2-hour interval (random starting-point)

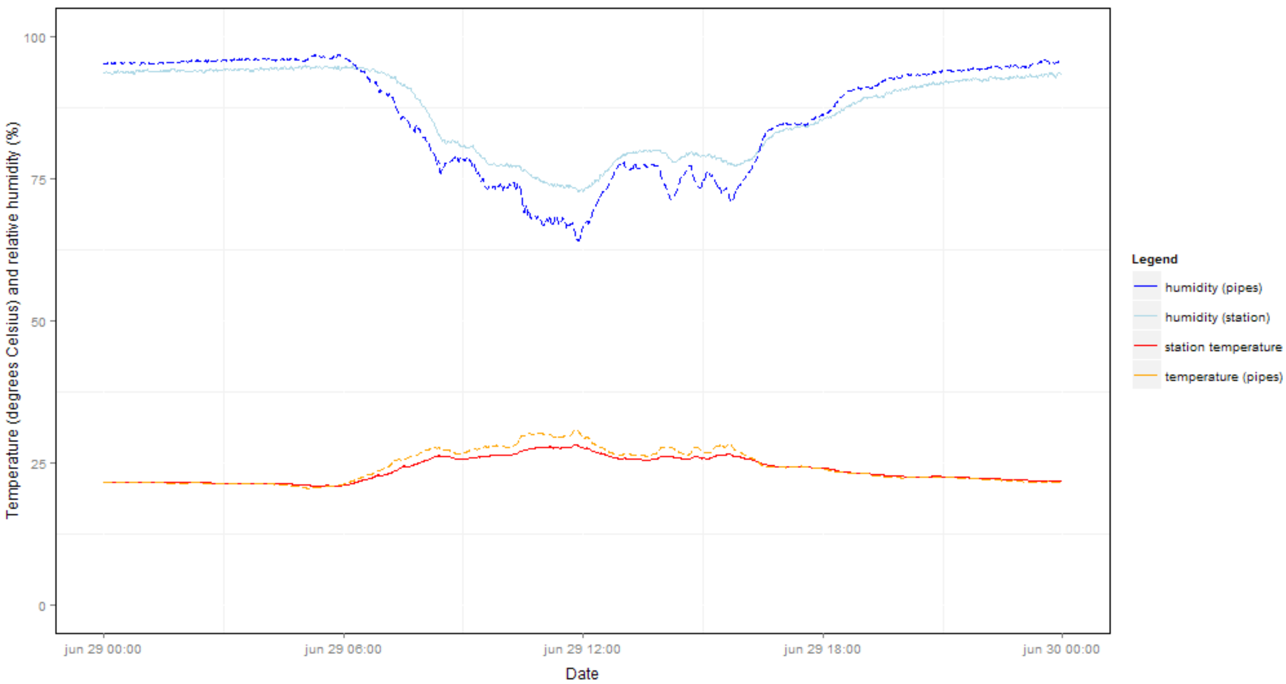


Sensor housing: Experiment 2

This experiment has been conducted on several days on the meteorological station at CATIE (Turrialba, Costa Rica). The first tests have been done with a larger (50mm diameter) PVC tube, after which a smaller version (25mm) has also been tested. All tubes have been thin white PVC tubes existing of several parts: 1) a 1.75m main tube (25cm to place in the ground); 2) a PVC elbow attached to the main tube; 3) a small (20cm) second tube that will be attached horizontally to the elbow; 4) a second elbow that will be attached to the horizontal section and that will point down again; 5) a final 5cm tube that will be attached to the elbow and in which the sensor will be placed. The sensor will be placed on plastic mesh (mosquito net) that will be located between the elbow and the final part. The material of this net might also have an influence on the sensor, but testing different material to place the sensor on has not been done due to time restrictions.

As only a relatively short time was available for these experiments, the different shields that have been tested have been based on literature[iii, iv, v]. Main WMO recommendations have also been taken into account where possible, but have mainly related to the height of the sensor. Another important document has only been discovered after most of the experiments had been conducted (ISO standards on test methods for comparing the performance of thermometer shields). Some of the ISO standards that have been used include: using a test site with a range of meteorological conditions that will also be encountered at the actual field sited; the test site meets the standards of a meteorological station at a height between 1.25 and 2 m; and the shield will be tested under different conditions (in this case only predominantly sunny and cloudy days). The shields were mainly designed to limit the radiation-errors, by increasing the aeration and/or reflectivity. All experiments include at least a 'control' blank tube, a tube with holes (aeration), a tube with foil (reflectivity) and a tube with foil & holes. The experiments with 50mm tube also include reflective tape, but these were too difficult (thick) and expensive to also try on the smaller tubes. The graph of the first experiment, with 6 blank 50mm tubes (2 sensors each) and 6 sensors in the official weather station, is shown in *figure 4*.

Figure 4: Temperature and humidity in the tubes vs. the official weather station



The first experiment already showed that the peaks in temperature during the peak sun-hours (around noon) are much steeper in the station than in the station. There is a strong correlation between the temperature and humidity (-0.98), so the peaks in humidity are similar to the peaks in temperature. For this reason, only temperature statistics have been studied in the different structures, and correlation has also been provided to show how significant these results will be for the humidity data. The graphs of the four experiments (50mm vs. 25mm, 'sunny' vs. 'rainy' day) are provided in *Annex 4*. All graphs – except for the 4th graph, have observed 1-minute intervals from midnight to midnight (1440 observations), the final graph has the same number of observations, but has been measuring the temperature and humidity from 3pm to 3pm due to the weather conditions. A visual analysis of these graphs already gives the impression that sun will be the biggest problem for the accuracy. The first experiment (50mm with no further adjustment) provides a mean of 24.32°C, compared to a mean of 23.81°C in the station. The minimum is also quite similar, with 20.94°C in the tubes and 20.50°C in the station; the main problem, however, is the maximum: 28.33°C in the station and 31.71°C in the tubes. The standard deviation in the tubes was 0.25°C, compared to 0.06°C in the station. The results from the experiments with different constructions are provided in tables 2A & B.

Table 2A: temperature statistics in different sensors shields (50 mm PVC) vs. station

	Sunny day				*Cloudy day*			
	Mean	Min	Max	St. dev	Mean	Min	Max	St. dev
Station	23.92	19.68	28.94	0.04	21.92	20.48	27.40	0.05
White paint	24.61	19.08	33.78	0.25	21.81	20.23	30.87	0.10
Holes (+- 30%)	24.38	19.16	32.47	0.21	21.68	20.20	31.82	0.24
Insulating foil	24.61	19.48	32.17	0.22	21.92	20.27	30.20	0.08
Holes + foil	24.76	19.36	33.24	0.24	21.80	20.23	30.31	0.12
Reflective tape	24.70	19.20	34.42	0.42	21.77	20.27	30.17	0.20

Table 2B: temperature statistics in different sensors shields (25 mm PVC) vs. station

	Sunny day				*Cloudy day*			
	Mean	Min	Max	St. dev	Mean	Min	Max	St. dev
Station	23.23	20.42	28.12	0.04	21.40	20.68	22.53	0.04
Nothing	23.94	20.05	34.07	0.17	21.29	20.55	22.70	0.05
Holes (+- 30%)	23.80	19.95	33.14	0.13	21.24	20.52	22.59	0.02
Insulating foil	23.72	20.24	32.27	0.10	21.31	20.55	22.89	0.09
Holes + foil	23.82	20.12	33.30	0.12	21.30	20.56	22.62	0.04

The experiments show that sensor housing will not make any different on a fully cloudy day (2B), but even on a cloudy day with very limited sun (2A), the peaks can be very significant. Very limited adjustments (nothing, white paint, or tape) result in the largest differences in the maximum value – almost 6°C on a sunny day in a 25mm PVC tube without adjustment. The lowest differences on sunny days are found for the insulating foil (without holes). Although holes alone perform quite acceptable in both 25 & 50mm tubes on the sunny days (2nd after the insulating foil), this approach is quite labour intensive and will create the risk that water will reach the sensor. Combining holes and foil is providing higher maximum values for the sunny days in both types of sensor shields. More detailed discussion will follow later in the *discussion* section. A next step will be to combine experiments 1 and 2, to see whether a reduced temporal interval (possibly in combination with additional smoothing) has the potential to provide better results on the sunny days.

Data smoothing: Experiment 3

As it will be very difficult to increase the performance of the sensor shielding without also significantly increasing the costs of the shields, data smoothing could be performed on the resulting dataset. As is already shown in experiment 1B, increasing the temporal interval from 1 minute to 1- or 2-hours, will result in data-smoothing. Smoothing is a solution if the shields cannot reduce the impact of strong radiation during the day, but is not preferred for many reasons. Approaches to remove outliers are of limited use, as only a small number of observations (generally 24) are made during the day, and removing the highest value might remove a valid high observation. Smoothing by running median (Turkey's) is one of the easiest approaches to 1-dimensional smoothing, as no additional parameters have to be provided. Smoothing will have to be 1-dimensional, as there is no clear relation with time that can be assumed over longer periods. This approach does not work well with minute-data, as many high values will be found close together, which results in a running median that will also remain very high. Smoothing splines and LOWESS smoothing include smoothing parameter that can be used to adjust smoothing to different temporal intervals. LOWESS smoothing is a non-parametric regression method in which the 'window' of nearest neighbours can be selected. In smoothing splines a cubic spline is fitted to the original data, smoothing can be adjusted. Other approaches exists as well, but these are three of the most common approaches to smooth 1-dimensional data.

The main issue that has to be taken into account that smoothing should not decrease the complexity of the data by too much, as otherwise all sensors in the study area might provide the same information and local differences will not be visible. Smoothing will only be performed over the dataset once, so no smoothing of smoothed data will take place. Preferably the main peaks will remain clear, but the very short extremes will be avoided. A running median will be ideal to remove the extremes, but will only provide limited smoothing. Different test will be conducted with 1-hour data, in which the closest value to the exact hour is taken and *na.spline* is used to predict this value (which does not change data a lot, as the closest value is always 1 second past the minute – e.g. 13:00:01). Only 25mm PVC tubes are studied, as these provided the largest differences and are also used in the field. As most shields provide relatively similar information, the default shield is studied (largest differences on the sunny day). Adjusting parameters to closely fit daily values is easy (*table 3*), but the parameters should also work on longer datasets. The default value Turkey's smoothing has been used ("3RS3R"), the smooth parameter that has been used for the spline is *spar = 0.62*, while the smoother span for the LOWESS smoothing has been set at 0.45, which indicates a time span of 10 hours.

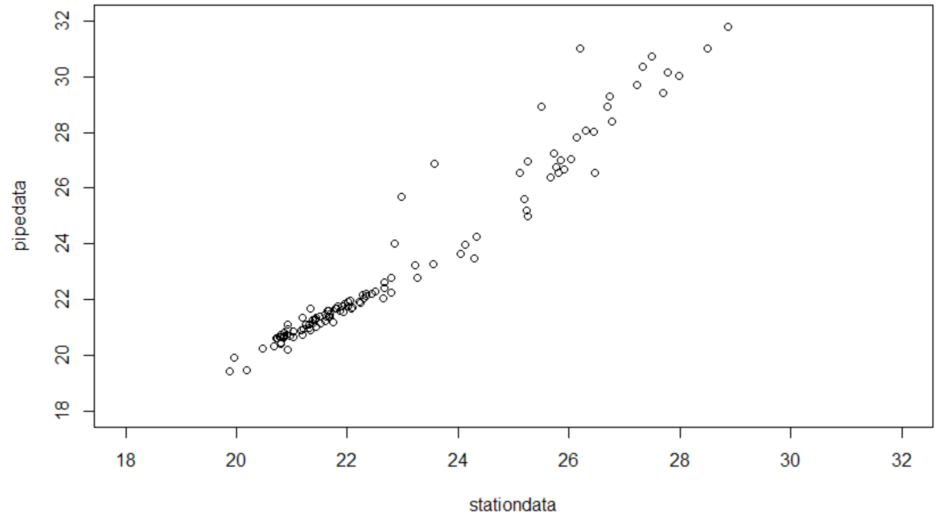
Table 3: Smoothed temperature statistics in different sensors shields (25 mm PVC – no adjustment) vs. station

	Station data			***Shield data***		
Sunny day	*Mean*	*Minimum*	*Maximum*	*Mean*	*Minimum*	*Maximum*
No adjustment	23.20	20.47	27.33	23.86	20.25	31.02
Turkey's smoothing	-	-	-	23.89	20.86	30.36
Smoothing spline (0.62)	-	-	-	23.85	20.81	28.15
LOWESS smoothing (0.45)				23.75	21.07	28.17
Rainy day						
No adjustment	21.39	20.72	22.49	21.27	20.60	22.59
Turkey's smoothing	-	-	-	21.28	20.66	22.22
Smoothing spline	-	-	-	20.63	21.27	22.23
LOWESS smoothing	-	-	-	20.70	21.23	22.17

While smoothing can perform well on a 1-day dataset, the impact on more days will have to be analysed as well. This will first be done on a dataset that combines the 5 separate 1 day experiments, resulting in a five-day period (one of these days starts at 3pm, causing a strange graph) Different types of sensors are used, but the difference is always quite high between the shields and the station, while this is quite limited between the different shields.

As using similar smoothing parameters as have been used in table 1 would result in strange values in longer data-sets, they will have to be adjusted to values that make more sense. As the problematic temperature peak is during midday, a window (time-span) that would make sense ranges of a few hours. For the smoothing spline, values that are considered acceptable would range between 0 and 1 (1 is smooth). The default for the running median can remain similar. Decreasing the peak without causing changes in other parts of the curve will be the objective. Both smoothing splines and LOWESS has the potential to smooth the peaks without causing changes at the minimum levels. The problem is that no data is data is available in the shields during longer period. For this reason a week has been recreated by adding the five separate days that blank tubes have been used together – 2 days with 25mm tubes and 3 days with 50mm tubes (2 days with white paint).

Figure 5: Correlation between temperature in the station and in the tubes during the five experiment days



Smoothing can be used to correct the days with a constant error between the station and shield-data. These are days with a lot of sun and days that are fully cloudy. The main problem is to correct days with a short period of sun, as smoothing will take the neighbouring values, which - in the case of a short peak – will be low, resulting in an over-smoothing of the data. The best fits (visual adjustment) of different smoothing techniques is provided in *Annex 5*. The original correlation between the station-data and the data in the shields during the five days is 0.98; and remains similar for the Turkey's and spline smoothing – it, however, drops to 0.90 for the LOWESS smoothing. The original station range has been 19.71-28.9°C, with a mean of 22.87°C, while the original range in the shields has been 19.15-33.31°C (mean = 23.19). The range and mean of the three smoothing techniques are: 19.15-33.27°C (23.19°C) for Turkey's smoothing; 19.33-31.03°C (23.19°C) for smoothing splines; and 20.40-29.41°C (23.12) for LOWESS smoothing. The visual analysis for LOWESS smoothing looks best, and only fails to follow the minimum on the first day and reach the peak on the third day. Smoothing splines and LOWESS smoothing will both be used in further analysis to see how they perform on larger datasets with more different types of days. Smoothing could give different outputs at other time-intervals, but working at 1-hour is the most likely in the intended projects.

Sensor shielding and the temporal & sensor resolution

Discussion

A preliminary conclusion which can be drawn from experiment 1 will be that working at a higher-resolution would not make a lot of sense for both temperature and humidity, as the reduced interval at which observations can be made will likely reduce the quality of the data-set more than this can be increased by the higher accuracy of the higher resolution. Especially for relative humidity a high-resolution would not contribute meaningfully. The range of these observations, as well as the standard deviation between the sensors, is higher than for the low-res sensors. In this case, the low-resolution sensor seems to be better. For temperature, the mean is very similar (within 0.02°C), while there is a large difference between the standard deviation in both datasets. This is not necessarily a big problem, as the maximum standard deviation at any moment is less than 0.4°C. While it is already quite clear that measurements at low-res would be fine for relative humidity, the impact of the low-resolution on temperature would require more study. In the case that measurements would only be made at a low-interval (1 or 2 hours), the differences might be exaggerated when using interpolation techniques to estimate the temperature at lower (e.g. 15 min) intervals. Another option that will be studied in a different experiment will be whether using the humidity sensors on all the iButtons would be useful at all; an alternative would be to only use this in one out of every *x* sensors, to be able to make more temperature measurements, while not losing a lot of information about the humidity. A 1-hour interval will allow to measure some of the crops that are provided in *table 4*.

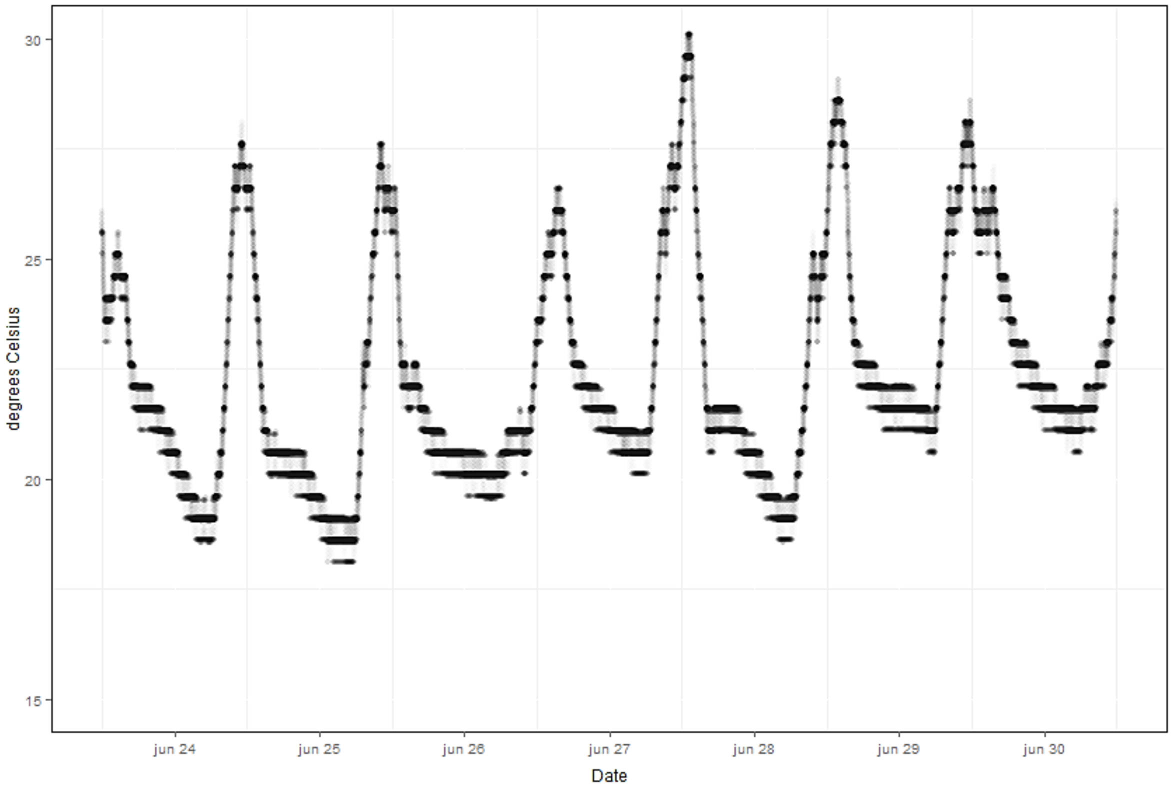
Table 4: Minimum and maximum duration of some important food crops[xiii]

Crop	*Species*	*Minimum duration*	*Maximum duration*
Barley	*Hordeum vulgare L.*	90	240
Cassava	*Manihot esculenta Crantz.*	180	365
Chickpea	*Cicer arietinum L.*	90	180
Common bean	*Phaseolus vulgaris L.*	50	270
Cowpea	*Vigna unguiculata Walp.*	30	240
Maize	*Zea mays L.*	65	365
Potato	*Solanum tuberosum L.*	90	160
Rice	*Oryza sativa L.*	80	180
Sorghum	*Sorhum bicolor Moench.*	90	300
Wheat	*Triticum aestivum L.*	90	250

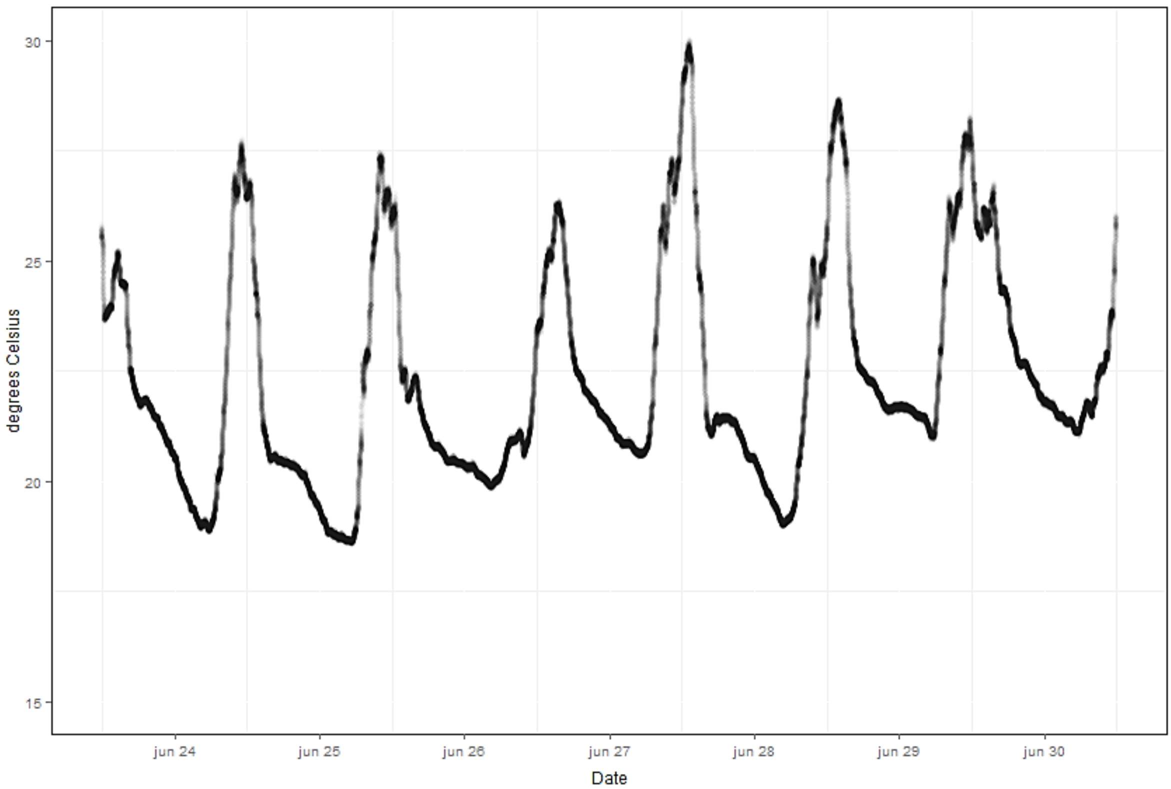
While increasing the temporal interval from 1 minute to 1 hour will result in some smoothing of the data, there does not seem to be a lot of difference between using random start-points or the closest value in the original dataset. The smoothing that results from increasing the temporal interval is negligible compared to the increased range of the data that results from working with PVC sensor –shields. Using a 2-hour interval in the PVC shields will still provide a larger temperature range than a 1-minute interval in the weather station will provide, but a 2-hour interval has the potential to miss peaks during the day, and for that reason is not recommended. The main recommendation is to create a script that launches all the sensors at the same moment, while more research into sensor shields that can reduce the effect of midday radiation without adding too much costs is also something that would provide a lot of benefits to similar projects. Smoothing can be performed in different ways, but smoothing splines and LOWESS smoothing provide the best results on the available data-set. All of the results from these experiments will have to be re-evaluated with the field-data, which spans a longer time-period (different types of day) and also deals with a more diverse terrain.

Annex 1: Temperature & humidity observations

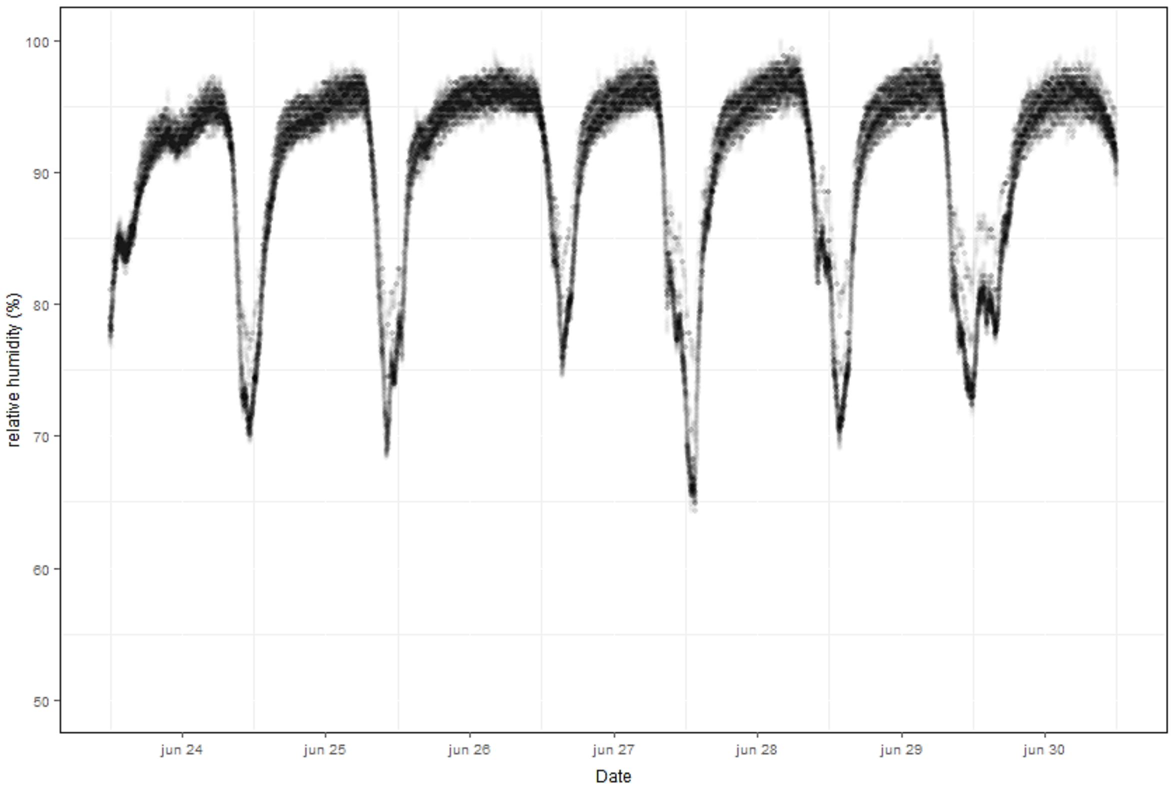
1A. Type 1 (lower resolution) temperature observations at minute interval



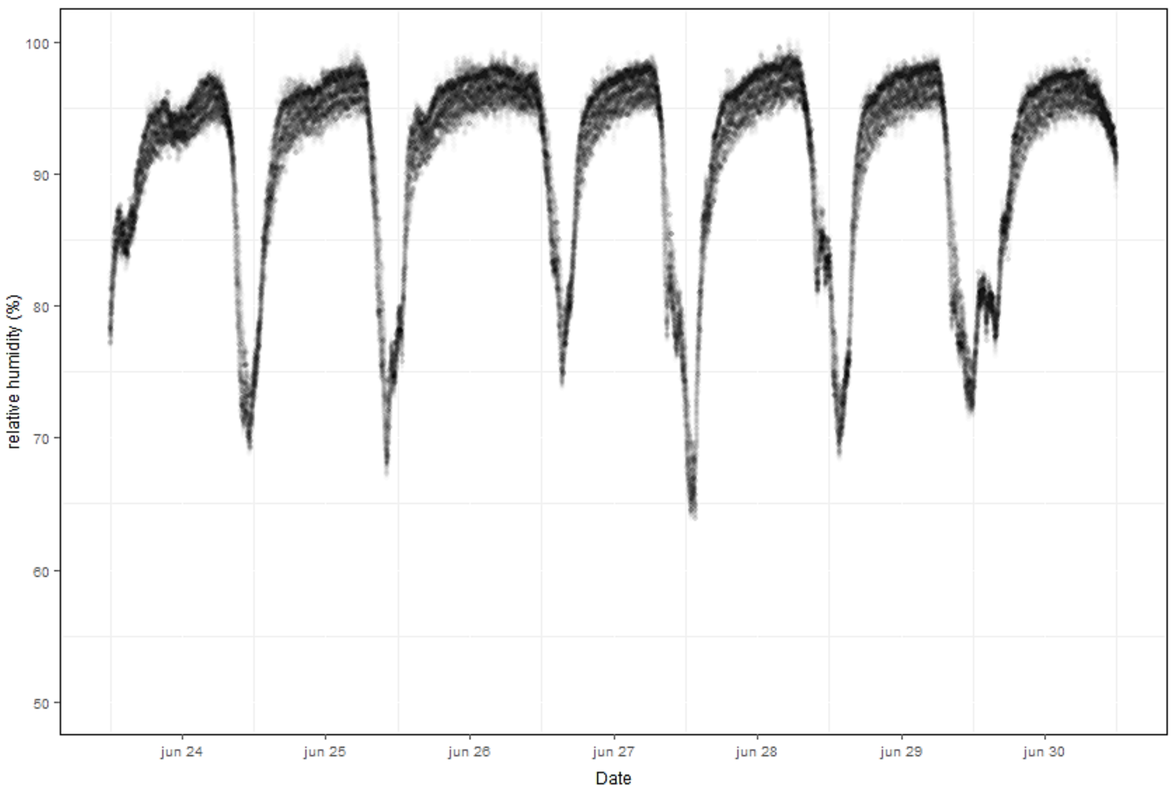
1B. Type 2 (higher resolution) temperature observations at minute interval



2A. Type 1 (lower resolution) humidity observations at minute interval

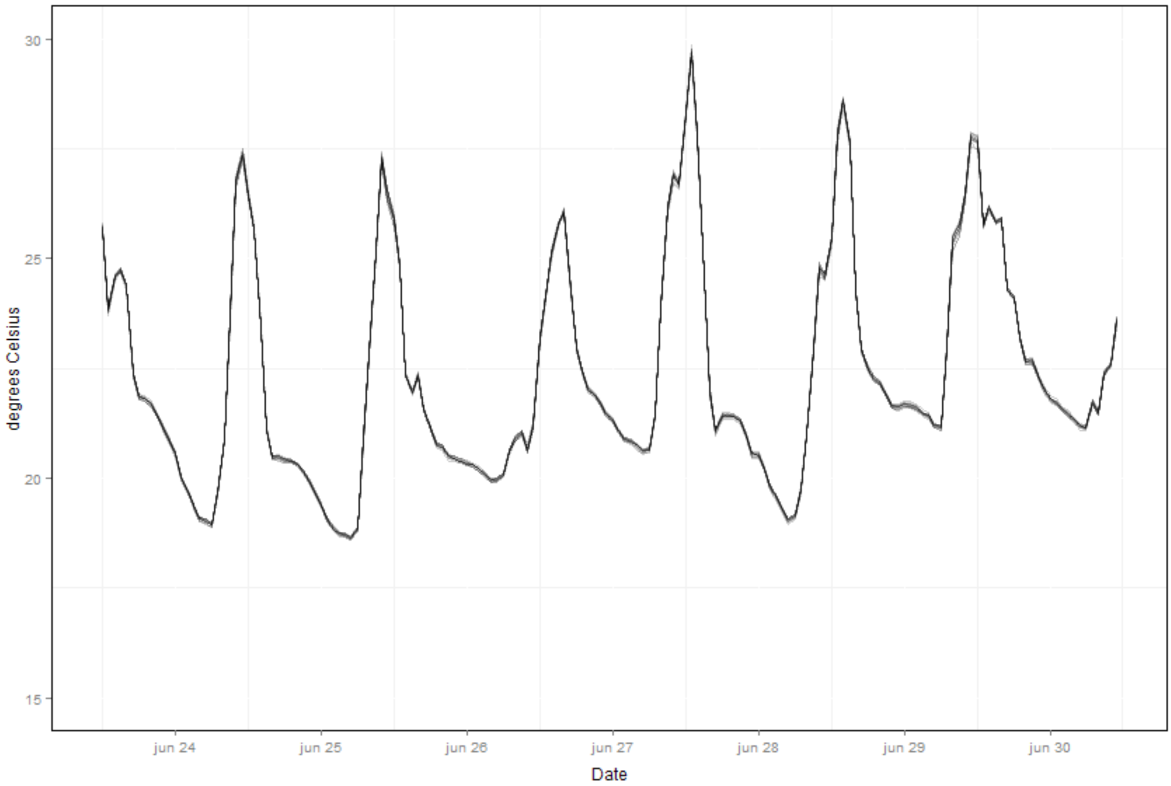


2B. Type 2 (higher resolution) humidity observations at minute interval

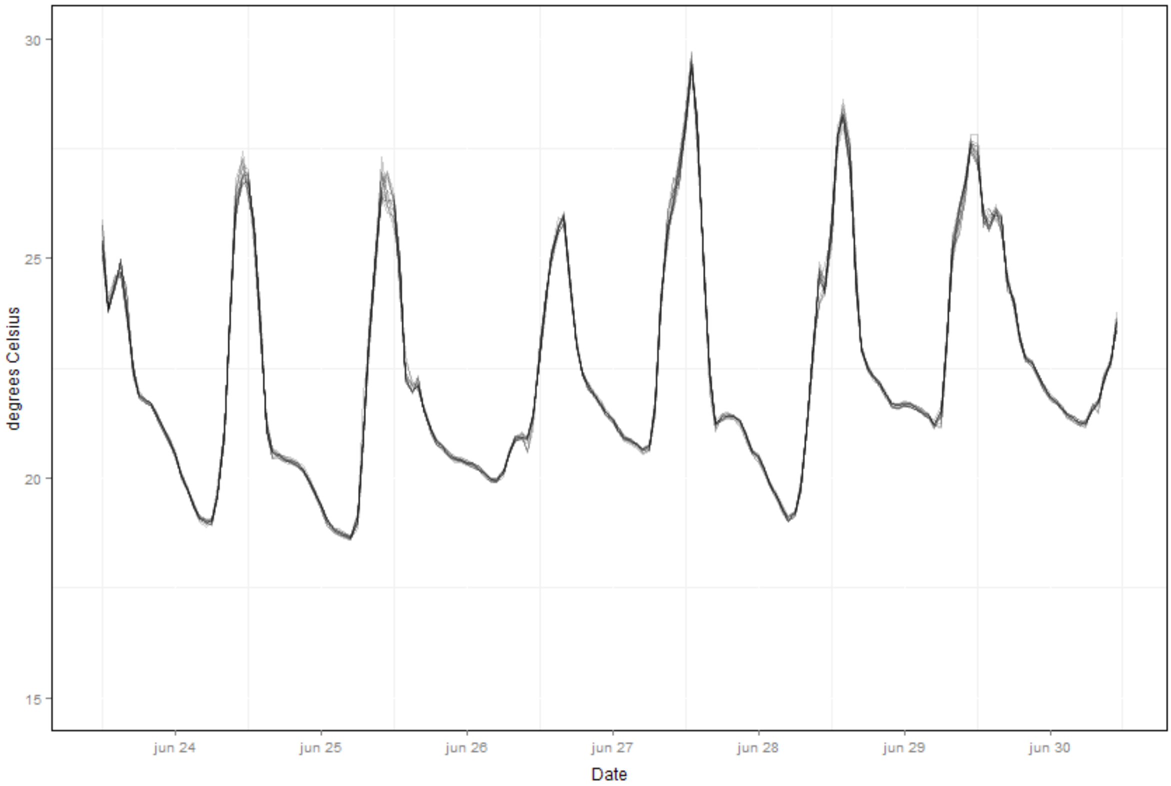


Annex 2: Different interpolation &time-selection techniques

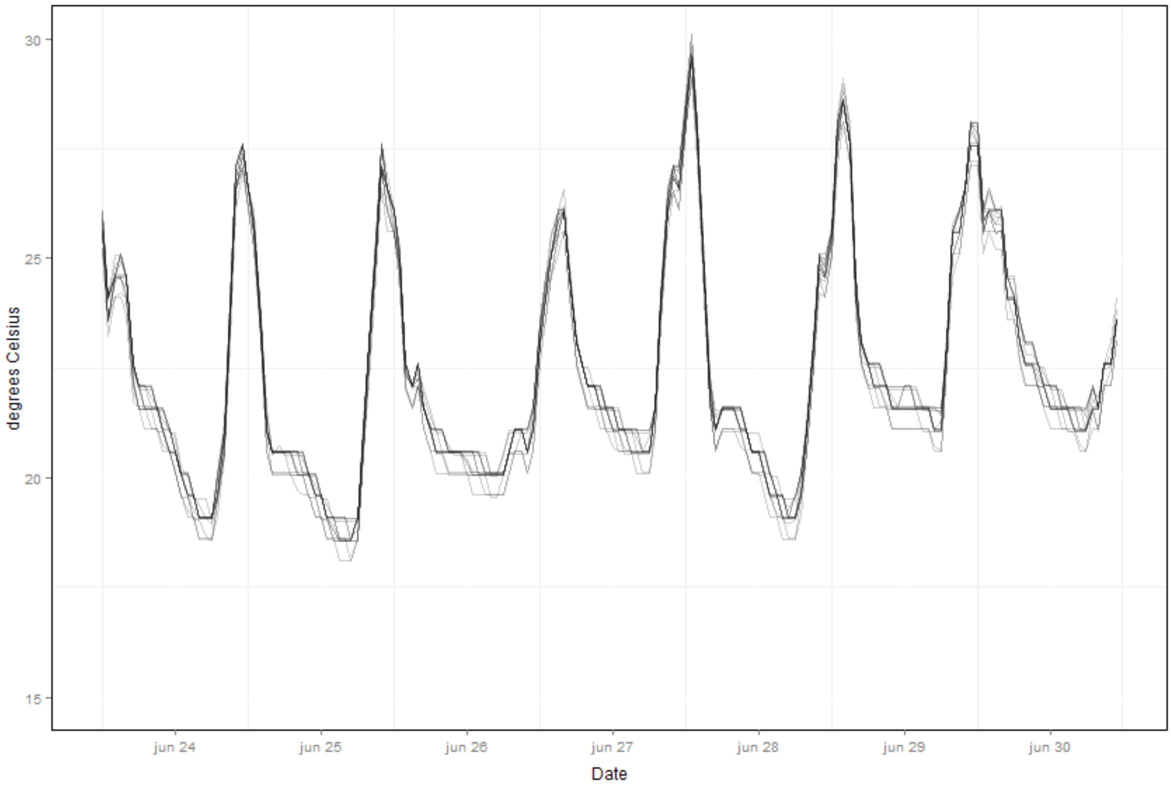
1. Type 2 (higher resolution) temperature observations at hourly interval (normal)



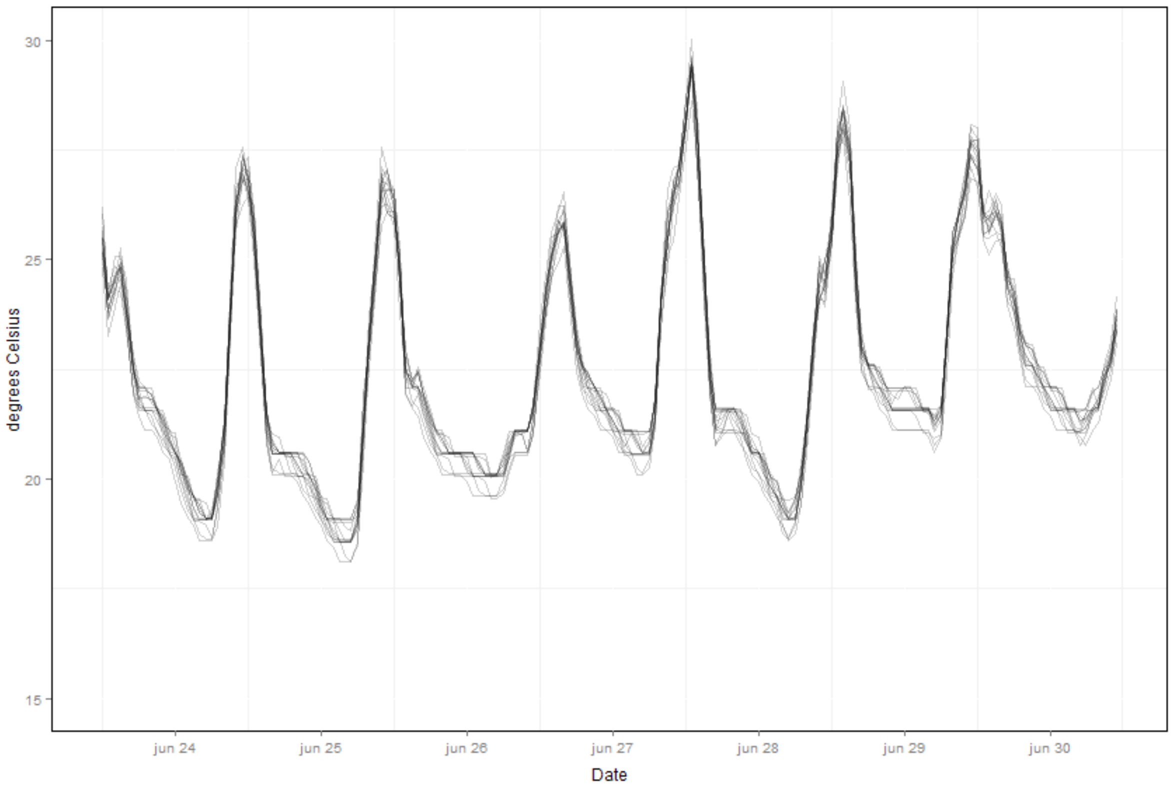
2. Type 2 (higher resolution) temperature observations at hourly interval (random)



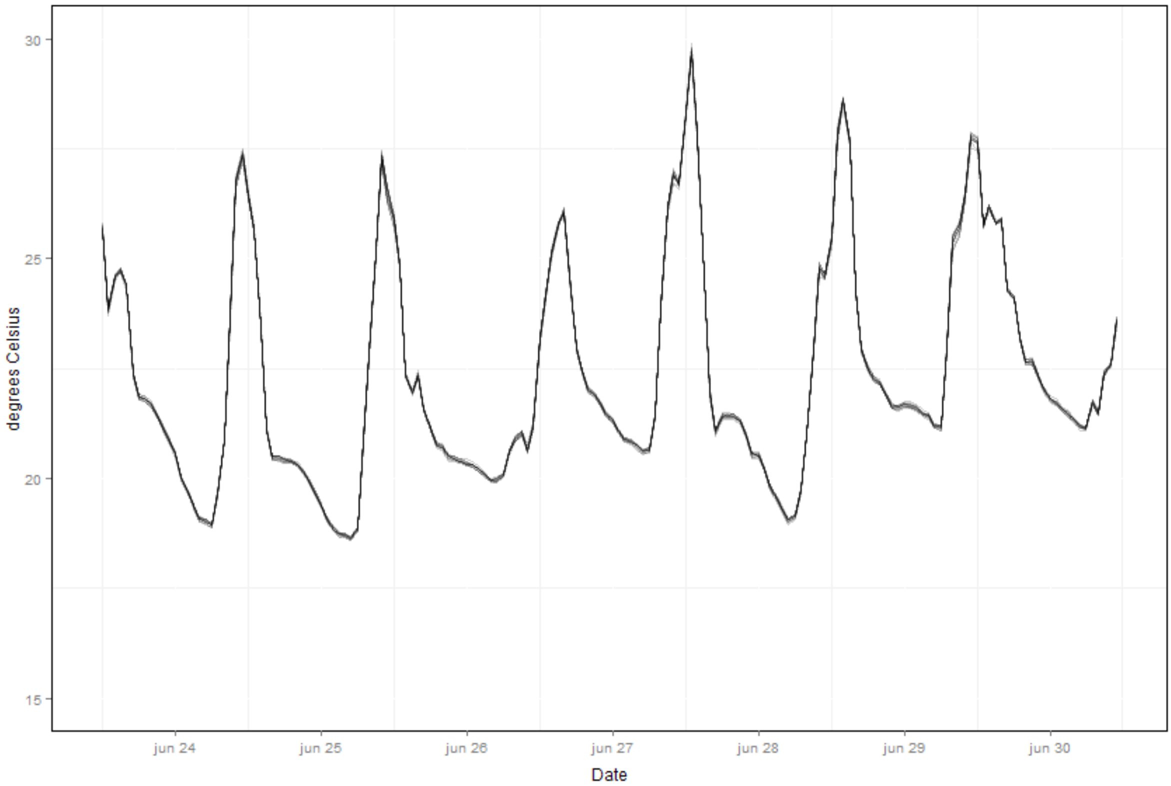
3. Type 1 (lower resolution) temperature observations at hourly interval (normal)



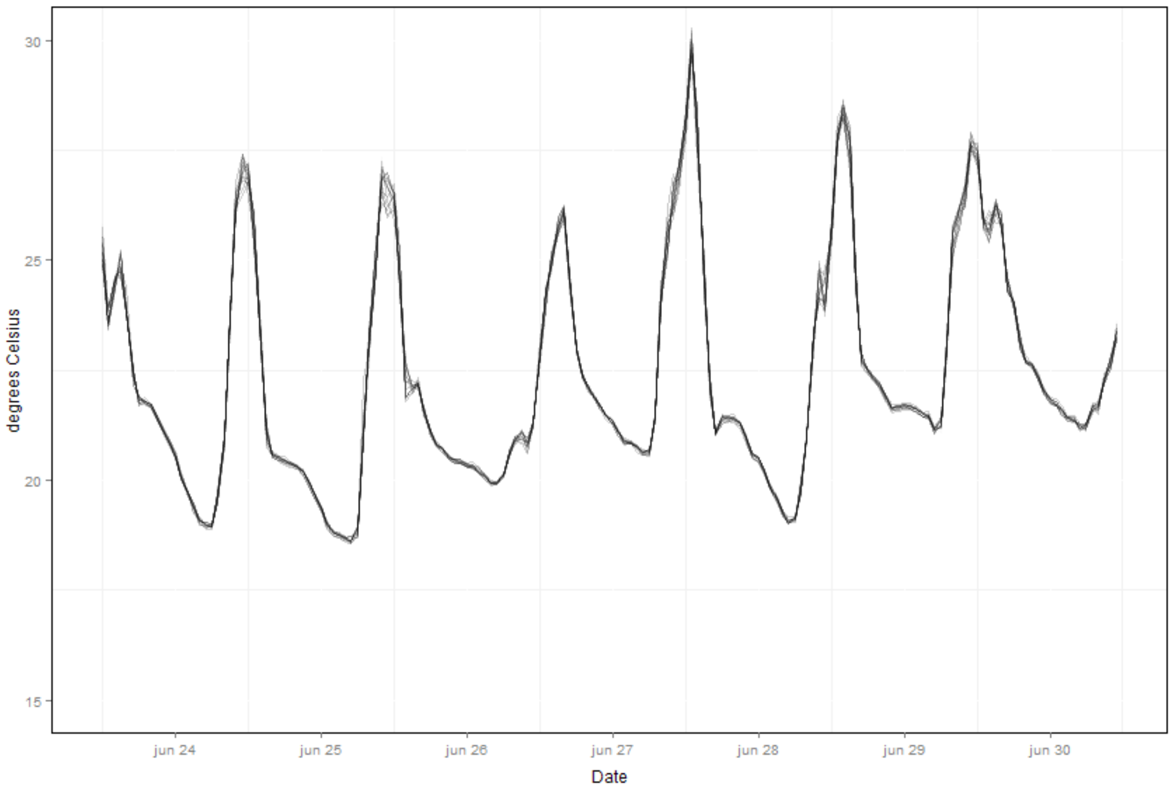
4. Type 1 (lower resolution) temperature observations at hourly interval (random)



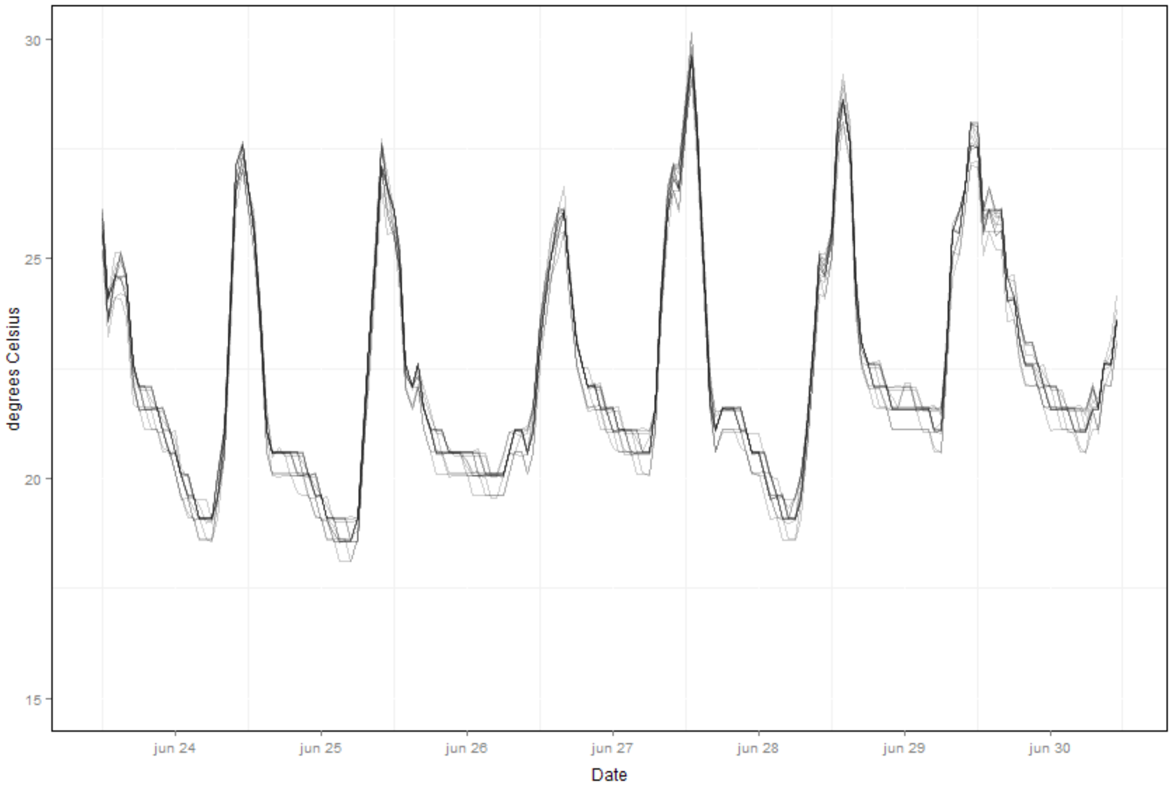
5. Type 2 (higher resolution): cubic spline of temperature observations at hourly interval (normal)



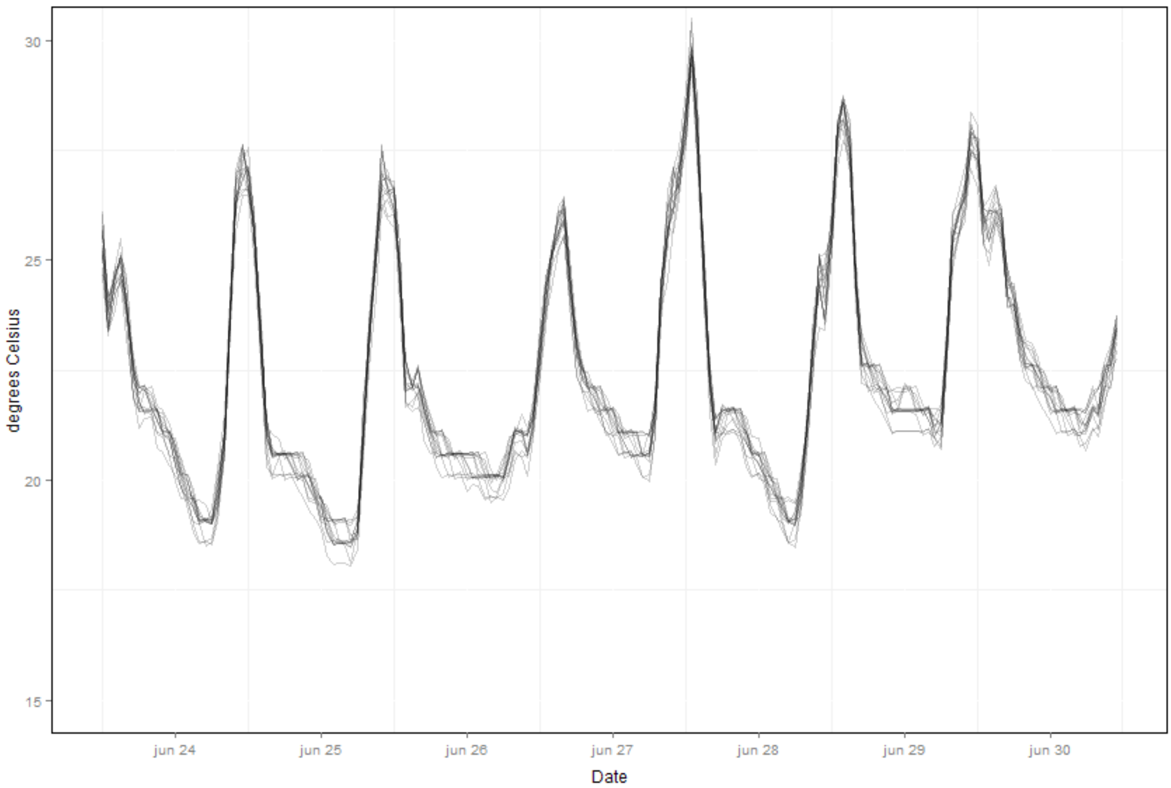
6. Type 2 (higher resolution): cubic spline of temperature observations at hourly interval (random)



7. Type 1 (lower resolution): cubic spline of temperature observations at hourly interval (normal)



8. Type 1 (lower resolution): cubic spline of temperature observations at hourly interval (random)



Annex 3: Temperature statistics

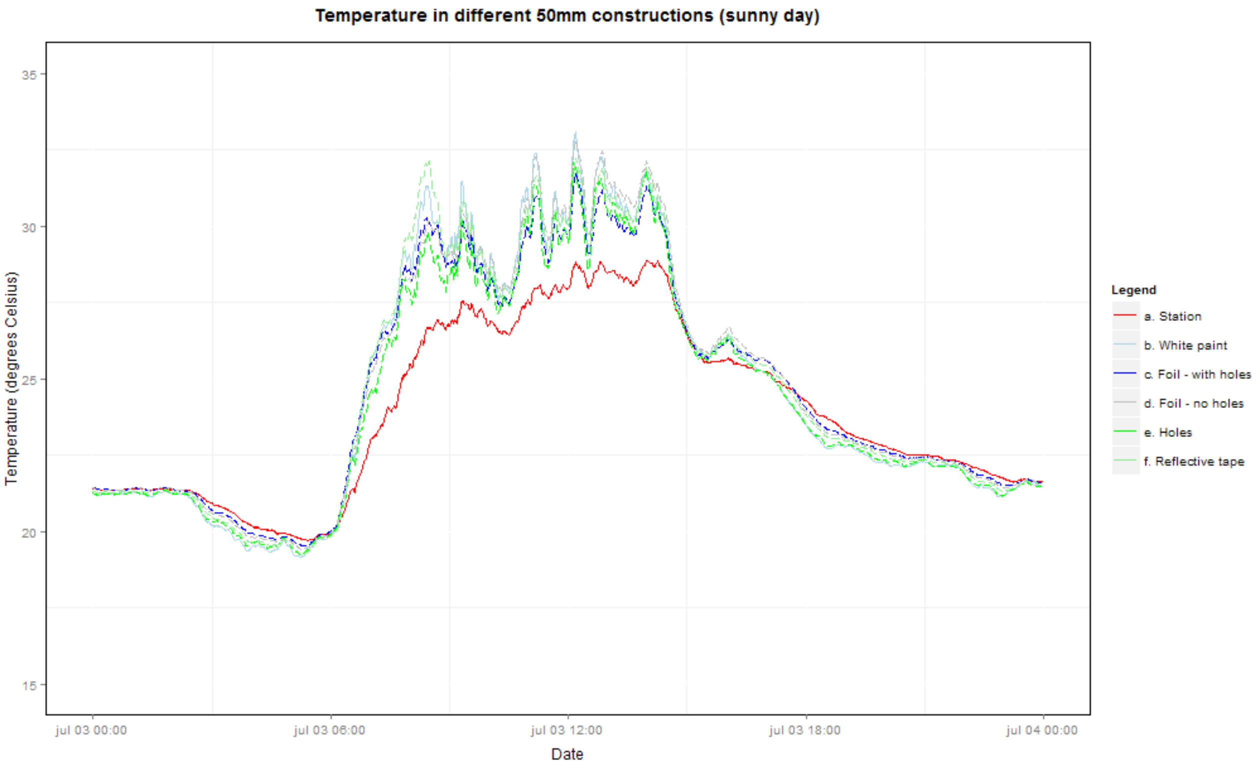
1. Main temperature statistics resulting from different interpolation techniques for all different resolutions

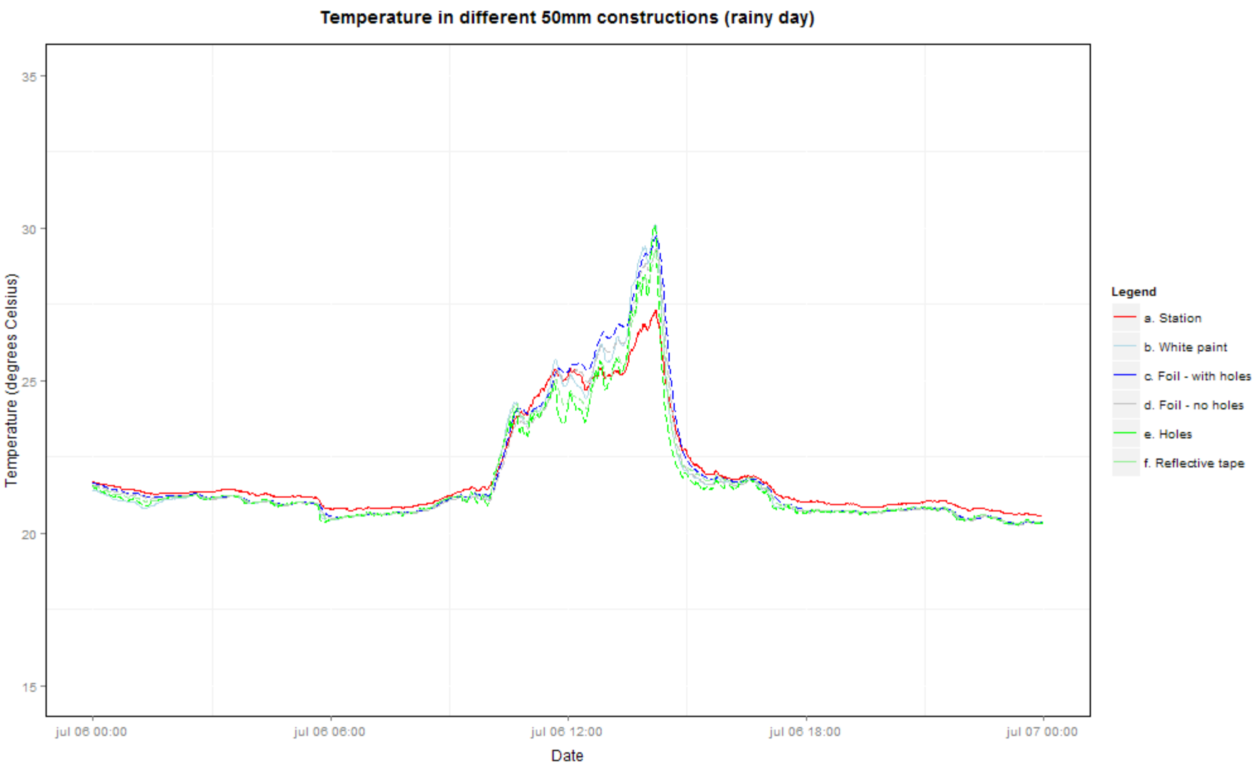
	Minimum	*1st Quartile*	*Median*	*Mean*	*3rd Quartile*	*Maximum*	*Standard deviation*	*Maximum difference*
Type 1 (low-res):								
1-minute interval	18.11	20.61	21.61	22.37	24.06	30.12	0.26	1.02
Closest observation								
1 hour interval (linear)	18.11	20.61	21.61	22.38	24.11	30.11	0.26	1.02
1 hour interval (spline)	18.11	20.60	21.61	22.38	24.10	30.16	0.27	1.10
2 hour interval (linear)	18.11	20.61	21.61	22.40	24.12	29.09	0.26	0.92
2 hour interval (spline)	18.11	20.61	21.61	22.40	24.12	29.18	0.26	1.03
Random start-moment								
1 hour interval (linear)	18.11	20.61	21.61	22.37	24.05	29.85	0.27	1.49
1 hour interval (spline)	17.99	20.61	21.61	22.37	24.00	30.41	0.29	1.59
2 hour interval (linear)	18.11	20.61	21.61	22.38	24.10	28.65	0.27	1.52
2 hour interval (spline)	18.07	20.60	21.63	22.39	24.10	28.81	0.29	1.64
Type 2 (high-res):								
1-minute interval	18.54	20.58	21.64	22.35	23.96	30.02	0.05	0.65
Closest observation								
1 hour interval (linear)	18.59	20.59	21.61	22.36	24.12	29.85	0.04	0.35
1 hour interval (spline)	18.59	20.59	21.61	22.36	24.13	29.89	0.05	0.34
2 hour interval (linear)	18.65	20.59	21.62	22.38	24.17	28.67	0.04	0.35
2 hour interval (spline)	18.65	20.59	21.62	22.39	24.17	28.69	0.05	0.34
Random start-moment								
1 hour interval (linear)	18.59	20.61	21.64	22.35	23.99	29.66	0.09	1.03
1 hour interval (spline)	18.55	20.60	21.62	22.35	23.96	30.15	0.11	1.23
2 hour interval (linear)	18.63	20.64	21.64	22.37	24.02	28.61	0.10	0.73
2 hour interval (spline)	18.62	20.60	21.64	22.37	24.10	28.64	0.11	0.88

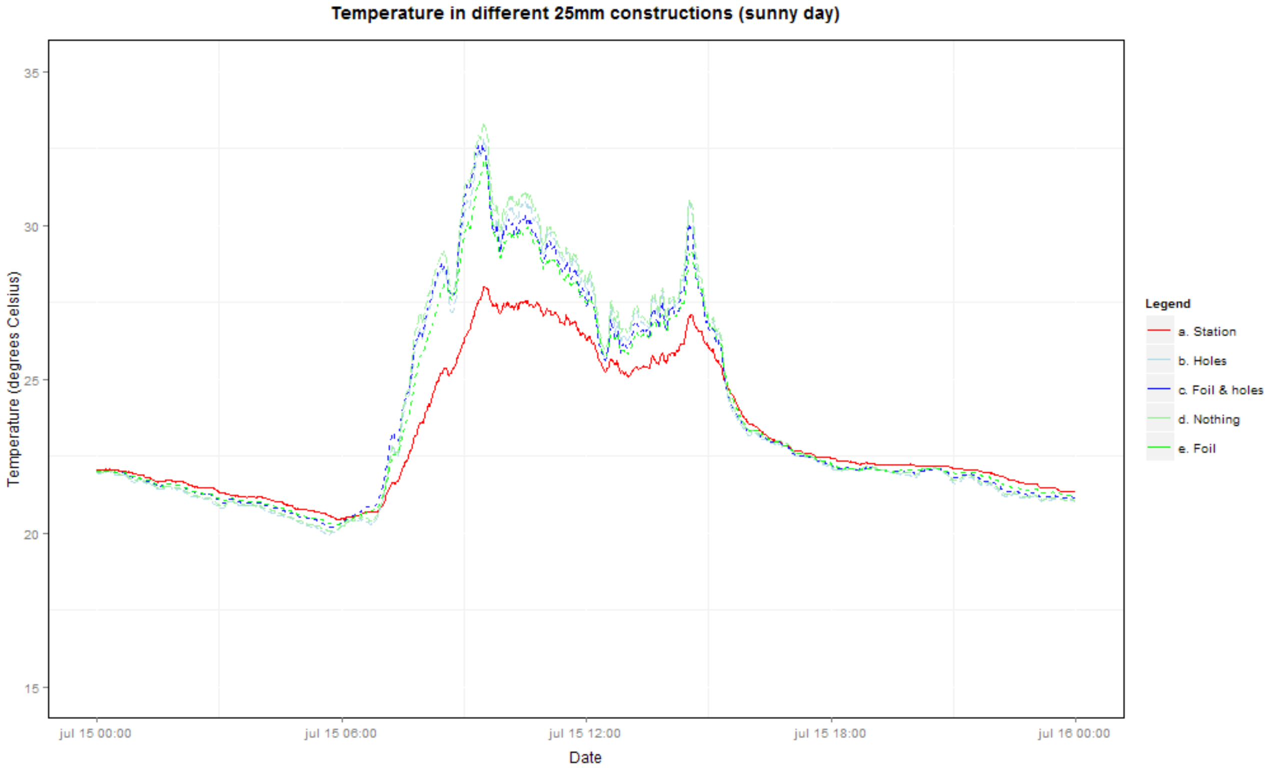
2. Percentage of observations in different temperature categories for different sensor & temporal resolutions

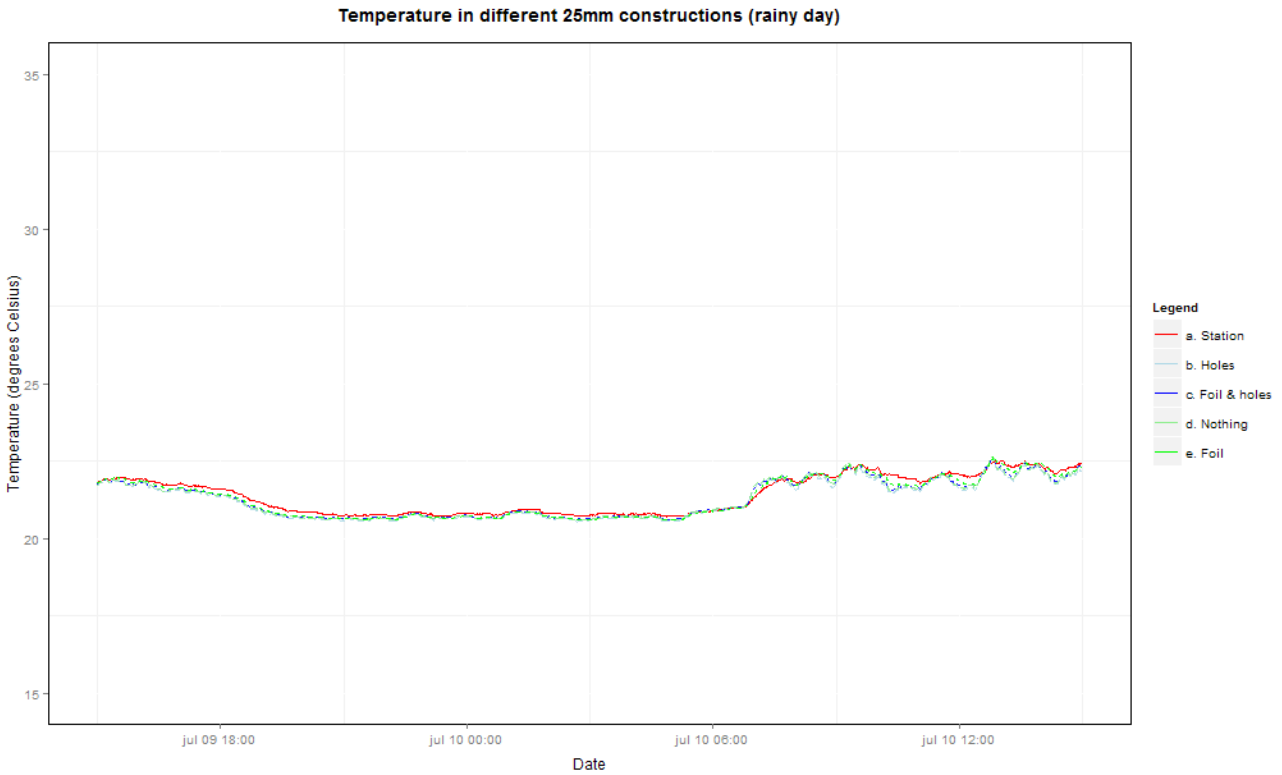
		< 20	*20-21*	*21-22*	*22-23*	*23-24*	*24-25*	*25-26*	*26-27*	*27-28*	*28-29*	*29-30*	*> 30*
Type 1													
Minute		11.8%	18.7%	24.4%	13.8%	5.8%	6.5%	6.0%	7.0%	3.6%	1.6%	0.8%	0.1%
Normal													
1-hour	*linear*	11.8%	19.1%	24.4%	12.7%	6.1%	6.9%	6.2%	6.3%	3.9%	2.0%	0.6%	0.1%
1-hour	*spline*	11.8%	19.2%	24.2%	12.8%	6.0%	7.0%	6.2%	6.2%	4.0%	1.9%	0.6%	0.1%
2-hour	*linear*	11.8%	19.0%	24.4%	12.9%	5.4%	5.9%	6.1%	7.5%	3.8%	3.0%	0.1%	-
2-hour	*spline*	11.8%	19.2%	24.3%	12.9%	5.4%	5.9%	6.2%	7.3%	4.0%	2.9%	0.2%	-
Random													
1-hour	*linear*	12.7%	18.5%	25.0%	12.3%	6.2%	6.9%	6.4%	6.3%	3.5%	1.5%	0.6%	-
1-hour	*spline*	12.7%	19.0%	25.0%	12.5%	6.7%	4.8%	6.6%	7.3%	2.8%	2.5%	0.2%	-
2-hour	*linear*	12.5%	17.9%	24.8%	13.4%	6.2%	5.9%	7.5%	7.2%	2.9%	1.9%	-	-
2-hour	*spline*	12.9%	19.1%	25.2%	12.1%	7.1%	4.4%	7.1%	6.6%	2.8%	2.7%	0.2%	-
Type 2													
Minute		13.2%	20.8%	24.6%	11.2%	5.5%	6.5%	6.1%	6.5%	3.5%	1.3%	0.9%	0.0%
Normal													
1-hour	*linear*	13.7%	20.0%	25.3%	11.0%	4.5%	7.2%	7.1%	5.3%	4.2%	1.2%	0.6%	-
1-hour	*spline*	13.6%	20.1%	25.2%	11.0%	4.5%	7.2%	7.1%	5.3%	4.2%	1.2%	0.6%	-
2-hour	*linear*	14.1%	20.7%	23.4%	11.9%	3.7%	6.0%	7.1%	7.0%	3.7%	2.4%	-	-
2-hour	*spline*	14.1%	20.8%	23.3%	11.9%	3.7%	6.0%	7.1%	7.0%	2.4%	3.7%	-	-
Random													
1-hour	*linear*	13.5%	19.3%	25.3%	10.8%	6.1%	7.6%	6.1%	5.7%	3.8%	1.2%	0.6%	-
1-hour	*spline*	13.9%	19.8%	24.3%	11.3%	6.3%	5.2%	7.2%	6.5%	2.5%	3.0%	-	-
2-hour	*linear*	13.5%	18.7%	24.2%	12.5%	7.1%	5.6%	7.5%	7.2%	2.2%	1.4%	-	-
2-hour	*spline*	14.0%	19.4%	24.5%	11.0%	7.2%	4.8%	7.1%	5.6%	3.2%	2.9%	0.1%	-

Annex 4: Temperature in different sensor shields

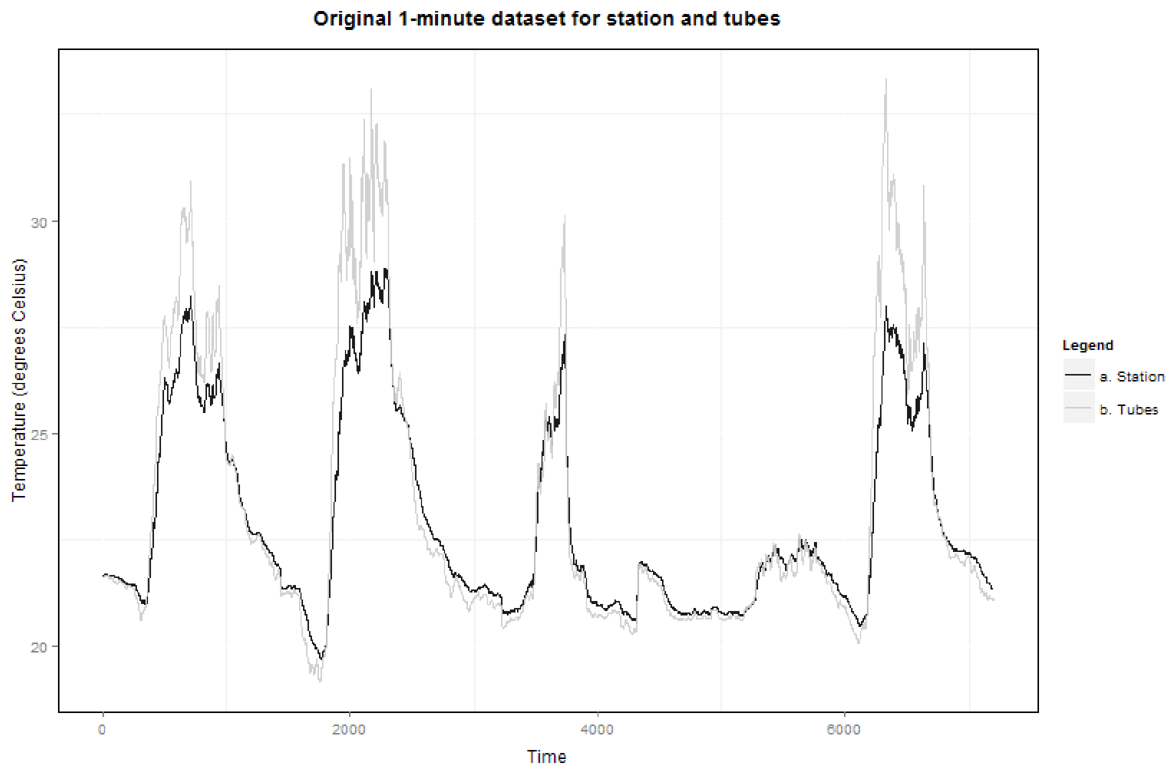


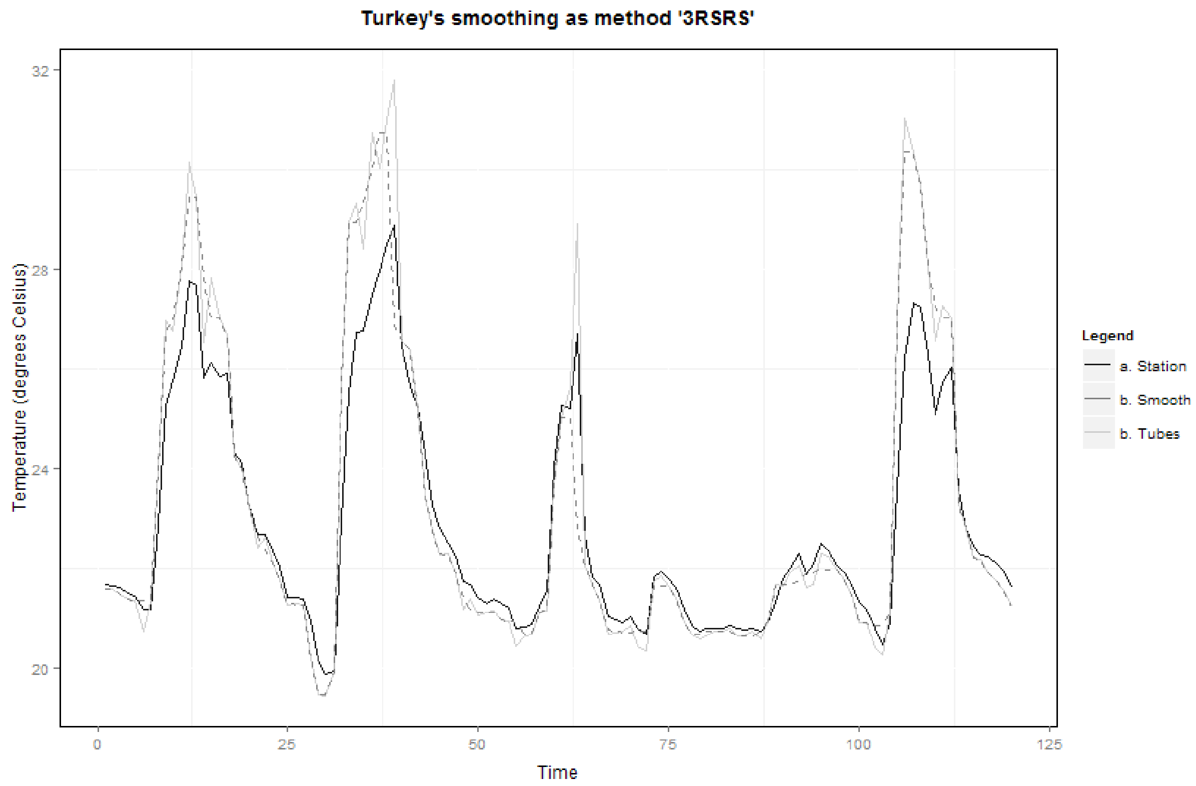



Temperature in different 25mm constructions (sunny day)
Temperature (degrees Celsius)
35
30
25
20
15
jul 15 00:00
jul 15 06:00
jul 15 12:00
jul 15 18:00
jul 16 00:00
Date
Legend
a. Station
b. Holes
c. Foil & holes
d. Nothing
e. Foil

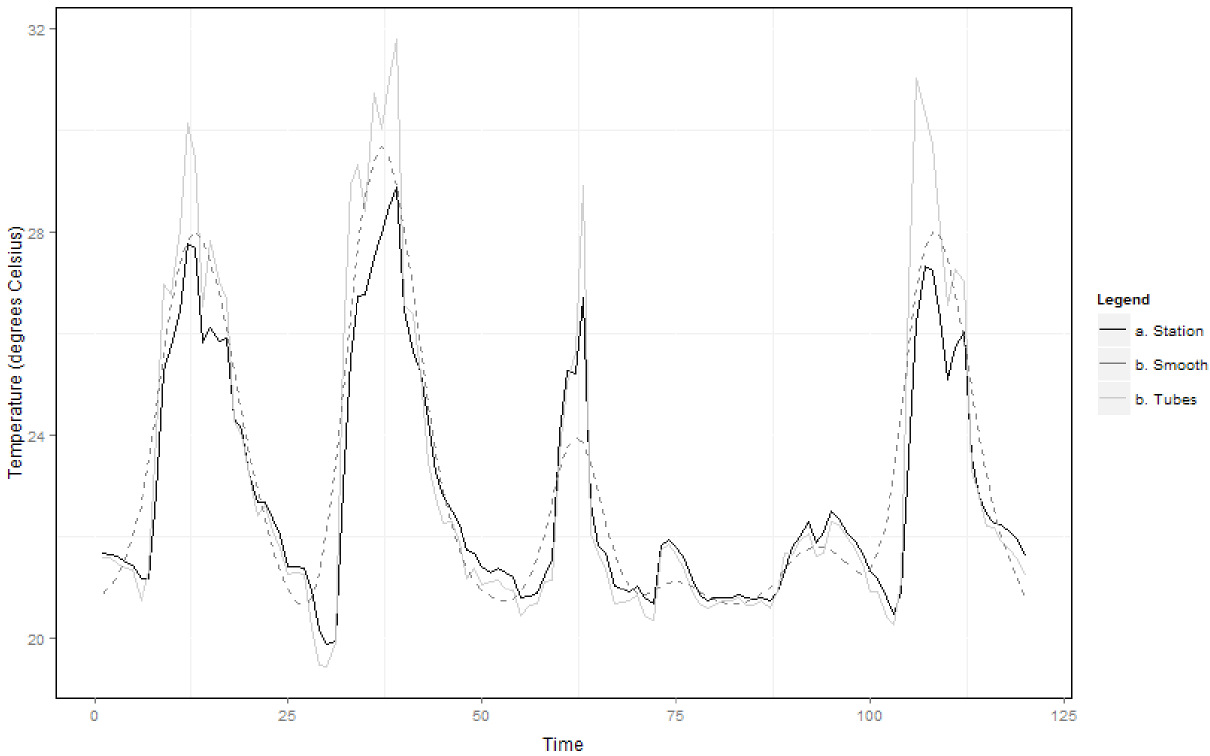

Temperature in different 25mm constructions (rainy day)
Temperature (degrees Celsius)
35
30
25
20
15
jul 09 18:00
jul 10 00:00
jul 10 06:00
jul 10 12:00
Date
Legend
a. Station
b. Holes
c. Foil & holes
d. Nothing
e. Foil

Annex 4: Impact of smoothing techniques on different types of days

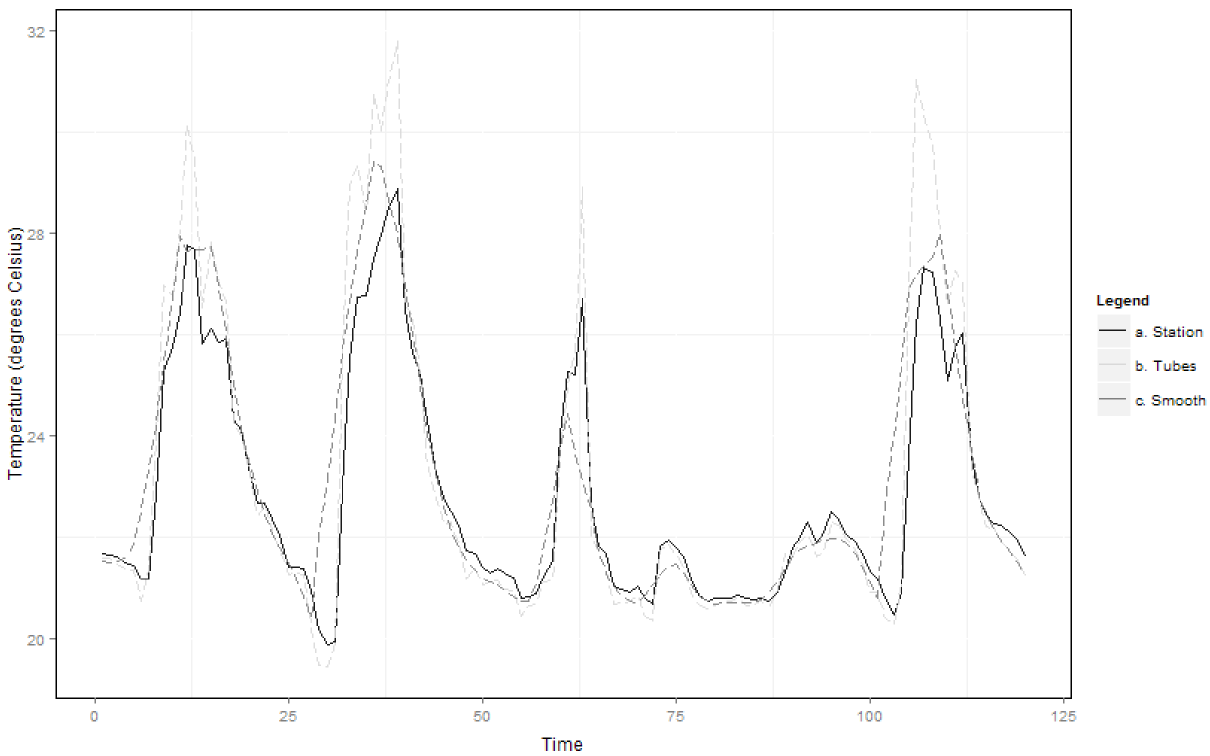




Smoothing spline with a 0.5 smoothing value



LOWESS smoothing, taking into account an 9 hour window



Notes

---

[i] http://datasheets.maximintegrated.com/en/ds/DS1923.pdf

[ii] This value is slightly lower than can be expected (2730 observations) with one 8 and one 16-bit observation.

[iii] Tarara, J.M., and G.-A. Hoheisel. 2007. *Low-cost Shielding to Minimize Radiation Errors of Temperature Sensors in the Field.* HortScience 42(6): 1372-1379.

[iv] Thomas, K.T., and A.R. Smoot. 2013. *An Effective, Economic, Aspirated Radiation Shield for Air Temperature Observations and Its Spatial Gradients.* J. Atmos. Oceanic Technol., 30, 526–537.

[v] Holden, Z.A., A.E. Klene, R.F. Keefe, and G.G. Moisen. 2013. *Design and evaluation of an inexpensive radiation shield for monitoring surface air temperatures*. Agricultural and Forest Meteorology 180 (2013) 281–286

[vi] http://www.wmo.int/pages/prog/gcos/documents/gruanmanuals/CIMO/CIMO_Guide-7th_Edition-2008.pdf

[vii] http://www.resenv.cn/Knowledge/ShowPDF?fileName=IX-ISO&docName=ISO%2017714-2007.pdf

[viii] http://cran.r-project.org/web/packages/zoo/index.html

[ix] http://www.sciencedirect.com/science/article/pii/S0377042707002890

[x] http://cran.r-project.org/web/packages/crs/

[xi] http://cran.r-project.org/web/packages/pastecs/index.html

[xii] http://cran.r-project.org/web/packages/quantreg/index.html

[xiii] Data derived from FAO's Ecocrop database: http://ecocrop.fao.org/ecocrop/srv/en/home