Monitoring Spatial and Temporal Distribution of Temperature and Relative Humidity in Greenhouses based on Wireless Sensor Technology

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Abstract

A homogeneous greenhouse climate has economic advantages due to a more homogeneous crop, lesser diseases and possibilities to save energy. The horizontal distribution of temperature and humidity, obtained with a dense grid of low-cost wireless sensors, opens ways to control homogeneity, either by adapting the greenhouse infrastructure or by selectively operating greenhouse heating and ventilation. Trials were performed with 100 sensors in four commercial greenhouses, to evaluate their practical use, observe climate variability and determine amount of sensors needed for an accurate estimate of the spatial and temporal climate distribution. We observed long-term averaged spatial differences for temperature and humidity of respectively 1.0 – 3.4 ^oC and 10 – 40 %, and actual spatial differences are larger. The greenhouses investigated showed that at least 9 sensors per hectare (± 33 m apart) were necessary to detect long term cold or wet spots.

Keywords: Greenhouse, Climate, Sensor, Accuracy

1. Introduction

A homogeneous climate in the greenhouse leads to a uniform and good quality crop. A uniform crop can be harvested in one single operation, and sold at high price, especially when the quality is good due to the absence of fungal diseases that might show up at fixed cold or wet spots in the greenhouse. Less disease means less use of fungicides. Further, at smaller temperature gradients in the greenhouse, while preventing cold and wet spots, farmers may use smaller temperature margins for their climate controller setpoints and save energy. Under Dutch conditions, a general rule of thumb is that a 1 ^oC lower setpoint leads to a 10% lower energy input (Nijs, 1997). Details of the spatial distribution of temperature (T) and relative humidity (RH) in greenhouses, can therefore (considerably) contribute to the economic revenue of the farmer.

Apart from large daily and seasonal climatic variations, which arise from alternating set-points, smaller variations in T and RH can be observed as “wandering” wet or cold spots in the greenhouse (Campen & de Gelder, 2007). These effects arise from natural driven forces (climatic setpoints, solar radiation, wind etc.) and may trigger disease outbreaks. Growers accept it, but use wider setpoint margins for the climate controller to prevent negative affects upon crop quality. RH and T are closely related, and in (semi-) closed greenhouses with homogeneous absolute humidity, temperature is the main driving actor. Apart from unpredictable differences, there are also static differences in the horizontal climate distribution. Generaly, these lead to a lesser uniform crop. Vijverberg (1986) has shown that these differences arise from inhomogeneous infrastructures and differences or defects in heating, ventilation, screens, etc. Rather than the unpredictable differences, static differences can be amended by altering the infrastructures to obtain a more homogeneous climate.

To what extend horizontal temperature differences are acceptable is not so clear. Bloem (2000) advises a boundary of ± 2 ^oC. According to the Dutch environmental certifying organisation (Stichting Milieukeur, 2010) the aim is to stay within ± 0.75 ^oC. For RH there are no boundaries found, but farmers try to stay away from saturation by maintaining a reasonable vapour pressure deficit at a maximum RH in the range of 90 − 95%. Growers use T-RH monitoring boxes, developed for use in greenhouses, with ventilated air inlets and a housing that prevents heating by direct solar radiation. The accuracy used for RH is specified to be at least ± 3% in the range of 70 − 90% (Stichting Milieukeur, 2010). Growers position their monitoring boxes in such a way that they obtain a reasonable estimate of the average climate in a compartment. The use of boxes is normally limited to 1 per individually controlled compartment, but sometimes a few extra boxes are placed at the outer edges in the greenhouse. To obtain the full spatial distribution of the greenhouse climate, far more monitoring points are needed. However, this would lead to extensive cabling and very high costs. Recently miniature wireless sensors have become available that measure T and RH based upon solid-state sensing elements. These sensors are non-ventilated but cost 5 upto 10 times less than standard monitoring boxes.

With the aim to amend static inhomogenities, a large quantity of these sensors could be used to obtain the spatial climate distribution, for instance by employing a carry-in-service. Growers could detect energy leakages or tune a separate heating system along the side windows. On the other hand, sensors could be installed permanently, and based upon a spatial distribution obtained in real-time, the climate could be influenced actively. For instance, a row ventilation system, nowadays used in (semi-) closed greenhouses where outside cold and dry air – brought in via side ventilators – is mixed with inside warm and wet air to de-humidify the greenhouse as an alternative to opening the roof windows, could be controlled based upon the temperature gradient in the row.

In this study we try to identify whether wireless sensors can be used to obtain the spatial distribution of the greenhouse climate with good accuracy and indicate where cold or wet spots can be found in realtime (crop diseases) and for longer periods (crop inhomogeinity). With respect to costs, it is important to know how dense the monitoring grid should be. For this we need a norm for the maximum allowed spread of T and RH, the measurement accuracy as well as the variability of the climate. To this end monitoring experiments were performed with wireless sensors in some typical dutch greenhouses under a number of different seasonal circumstances, infrastructures and crops. It served a solid impression on their capabilities to show the spatial climate distribution in a greenhouse.

2. Materials and methods

During the winter season of 2008-2009, observational trials were conducted in commercial greenhouses for gerbera, matricaria, tomato and cucumber, in which climatic data were obtained during 10 consequetive days. All greenhouses were modern dutch climate controlled greenhouses fitted with standard facilities. The greenhouses for growing flowers were equipped with the Aicro-breeze ventilation system (Hoogendoorn Growth Management, NL). The trials with gerbera and matricaria were repeated once, later in the season. Data was obtained with 100 standard, commercially available, wireless T-RH sensors (WiSensys, Wireless Value, Emmen, NL) equipped with SHT71 solid-state temperature and humidity sensing elements (Sensirion, Switserland). The SHT71 sensing element is meant for a wide range of consumer and research applications, and the specified accuracy of this element is ± 0.4 °C at 25 °C, ± 1 °C from 0 °C to +50 °C, and ± 2°C from -20 °C to +80 °C for temperature and ± 3% from 20% to 80% or otherwise ±5 % for RH. Sensirion sells also a version with a higher specification (SHT75). Although nowadays, this sensing element is used by the manufacturer of the wireless sensors, it was not available at the time of our trials. To prevent heating by direct solar radiation, the sensor housing was additionally fitted with a small, credit card sized, white plastic plate that was placed just above the sensing element. Data communication was handled with a base station (Wireless Value) and a readily available inductrial PC, running data acquisition software (Sensorgraph, version R4C6 (Wireless Value). Between the base station and the PC we used a wireless link (Tranzeo Wireless Technologies Inc.). The setup was similar to the one used by Van Tuijl et al. (2008). For sensor mounting we used several principles. For matricaria, tomato and cucumber we used a clamp commonly used in greenhouses to attach crop stems to a vertical or horizontal crop wire (Clipr®, Pellikaan, Gemert, NL). For gerbera the sensors were attached to a PVC tube which was mounted on a frame part of the gutter system (Figure 1).

Figure 1. *Wireless T-RH sensors showing the solar screen just above the sensor and mounting principles with a Pellikaan hook for tomato (left) end with a PVC-tube for gerbera (right).*

The hundred sensors were placed on a regular rectangular grid in the horizontal plane near the growing tip of the vegetable crop or flower, corresponding with a height at which growers place their standard T-RH box. The grid was choosen to span the total width of the greenhouse from the left to right side windows. Not to disturb crop treatment, the grid was tailored to the local infrastructure. To obtain sufficient statistical information about the spatial variation, part of the sensors (6 × 6) were placed at a double grid density for the gerbera trials. Table 1 gives the used grid dimensions.

Table 1. *Sensor layout and dimensions for all trials in the period October 2008 to April 2009.*

	Gerbera 1	*Matricaria1*	*Gerbera 2*	*Tomato*	*Cucumber*	*Matricaria 2*
Days of the year	306 - 315	335 - 344	18 - 27	38 - 47	52 - 61	91 - 100
Grid (m^2)	11.8 × 9.7	13.5 × 9.6	11.8 × 9.7	15 × 12.8	9 × 9.6	13.5 × 9.6
Surface (m^2)	127.0 × 48.5	202.5 × 48	127.0 × 48.5	215 × 64	81× 86.4	202.5 × 48
Sensor grid	12 × 6	16 × 6	12 × 6	16 × 6	10 × 10	16 × 6
Sensor amount	99	96	99	96	100	96
Sensor density (ha^{-1})	88	79	88	58	128	79

Data were recorded every minute and averages over ten minutes were used for analyses. For each trial, the 10 days were splitted into two periods of each 5 days (D1, D2). Data was also splitted into day and night periods, alined with sunset and sunrise. Data about the inside and outside climate as well the settings for screens, ventilation and heating were taken from the climate computer as hourly averages.

3. Results and analyses

Mutual equality of sensors: offset calibration

Rather than using an absolute sensor calibration check and knowing that end-users will not have such a facility available, we performed a simple test to check sensor equality. Before each trial (except for the cucumber trial) all sensors were mutually compared to obtain a sensor offset value. In the laboratory, all sensors were placed in a cardboard box at room temperature (19 – 27 °C) and humidity (25 – 49 %) and 10-minute averages for T and RH were recorded during two hours. For each individual sensor the difference with the mean value over all sensors was computed. We compensated for internal heating and layout differences in the cardboard box. The mean difference was used as an offset correction for the specific sensor prior to further analyses of the T and RH data. It reveals small systematic differences and makes malfunction evident (e.g. low battery).

Figure 2 shows the result of the sensor comparison. For temperature, the offsets range from -0.41 to +0.39 °C (st.dev. = 0.16) and for RH from -1.12 to +1.58 % (st.dev. = 0.49). These values are within the sensor specification. However, residual error analyses of recorded data with and without offset correction showed a small but significant enhancement of the data when using the offset correction. Since small T and RH differences may have significant impact on energy use, we recommend to check the sensors in advance and to compensate for possible offsets.

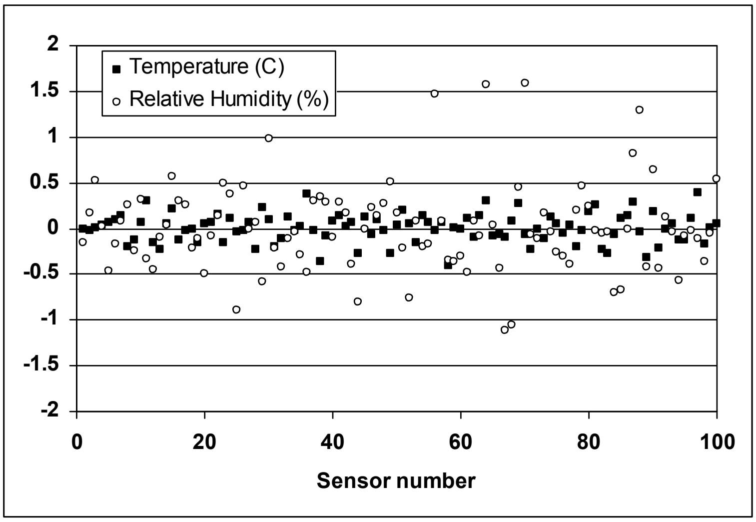

Figure 2. *Offset values for all 100 sensors for T (in °C) and RH (in %).*

Instanteneous/actual climatic variations

To gain insight in relative climatic differences, we obtained the actual minimum and maximum value of T and RH for all sensors for 10-minute intervals and computed the differences with the instantaneous/actual mean value of all data defined as ΔT_{min}, ΔT_{max}, ΔRH_{max}, ΔRH_{min}. Instantaneous/actual total differences can be computed from:

$$\Delta RH = \Delta RH_{\max} - \Delta RH_{\min} \text{ , and: } \Delta T = \Delta T_{\max} - \Delta T_{\min} . \quad (1)$$

Table 2. *For all trials, maximum and minimum T and RH differences as compared to the overall averages. Values shown are the extremes found during a 10 days period.*

	T(°C)		*RH (%)*	
	ΔT_{min}	ΔT_{max}	ΔRH_{min}	ΔRH_{max}
gerbera 1	-3.8	5.4	-16.8	12.4
gerbera 2	-3.1	4.2	-13.0	9.0
matricaria 1	-2.8	2.8	-16.4	8.5
matricaria 2	-4.2	4.8	-22.6	19.7
tomato	-2.8	2.8	-21.9	10.6
cucumber	-3.1	3.4	-11.4	0.4

Table 2 shows the overall minimum and maximum values over the whole 10 days period for all trials. Figure 3 shows the instanteaneous values for matricaria 2 only. ΔRH and ΔT can be relatively high (11.8 − 42.3 % and 5.6 − 9.2 °C, respectively) with an uneven distribution towards high temperatures and low humidities. These high total differences occur only during daytime and have extremes at high solar radiation. The variation during the nighttime is much smaller than during daytime.

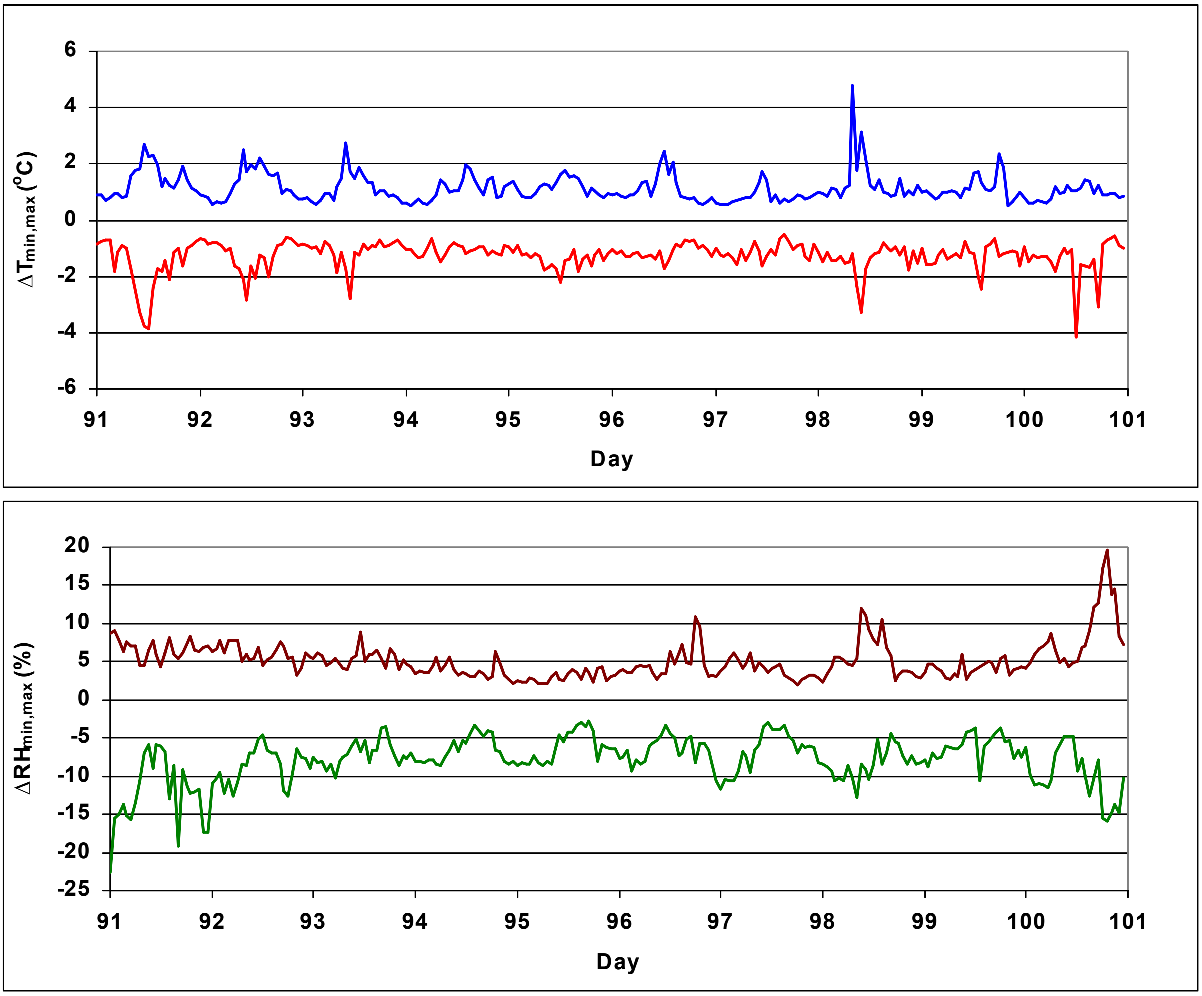

Figure 3. *Instantaneous differences for T (upper) and RH (lower) with reference to the overall mean of 100 sensors for the matricaria 2 trial.*

Direct radiation affects non-ventilated sensors, and Van Tuijl et al. (2008) advised to use a solar radiation shield to prevent heating of the sensor element. Even while we used this radiation shield, under practical circumstances, the sensors were still affected. Therefore, we compared sensor readings also with absolute data taken from the standard T-RH box. We used the first period (5 days) of the matricaria 1 trial as example, having 4 days with medium and 1 day with high solar radiation. On an hourly basis we obtained the ΔT_{min} and ΔT_{max} referred to the temperature taken from the T-RH box (T_{box}). Figure 4 gives these, as well as averaged values over 5 days (T_{mean}).

During the night (18.00h – 9.00h), T_{mean} deviates not more than 0.2 °C from T_{box}. The maximum deviation is about ± 2 °C ($\sigma_T \approx 0.7$ °C). Since this is far more than the accuracy of the sensors, a large portion of this deviation is therefore due to local differences. Nevertheless, the standard T-RH box gives a good estimate of T_{mean}. For a few sensors we observed erroneous readings for RH when these values approach 100%. Although this is outside the specified range for the sensors, in practice this is a situation that occurs easily during the night.

During the day (9.00h – 18.00h) the deviations are much bigger (-4 up to +6.5 °C). Now, T_{mean} has a positive deviation of about 1.0 °C around noon, and the standard deviation increases to 1.5 °C. Because we expect that local heating of the air due to radiation is also observed with the standard T-RH-box, and because the effect on temperature measured with the sensors is larger for the positive side, we conclude that the sensors indeed are influenced by direct solar radiation. Allthough the calculated mean effect is 1.0 °C, individual sensors may give higher values up to 7 °C. We advise manufacturers of non-ventilated T-RH sensors to enhance solar radiation shielding.

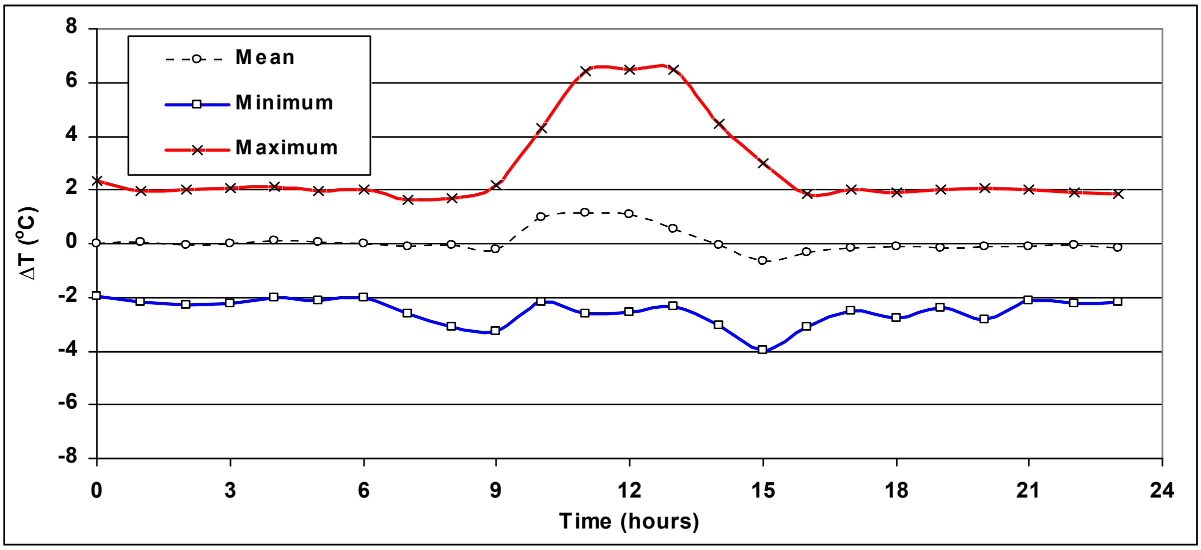

Figure 4. *Hourly maximum and minimum differences for temperature referred to the temperature measured with the standard T-RH-box, averaged over 5 days for the first period of the matricaria 1 trial.*

By using CFD simulations, Campen et al. (2007) showed that ΔT depends strongly on the difference between the greenhouse outside and inside temperature according to:

$$\Delta T_{diff} = T_{inside} - T_{outside} \text{ and } \Delta T = f \cdot \Delta T_{diff} \,, \quad (2)$$

in which the factor f = 0.20 – 0.25. We obtained f for all trials and periods, and plotted f as a function of ΔT_{diff} (Figure 5). The factor has a weak linear correlation with ΔT_{diff} (R^2 = 0.46), given as:

$$f = 0.4497 - 0.02037 \cdot \Delta T_{diff} \,, \quad (3)$$

for 5 < ΔT_{diff} < 20 °C, which is in accordance with the results from Campen et al. (2007) for values of ΔT_{diff} around 10 °C. For smaller ΔT_{diff}, f is larger (upto 0.35), and for larger ΔT_{diff}, it becomes smaller (downto 0.1).

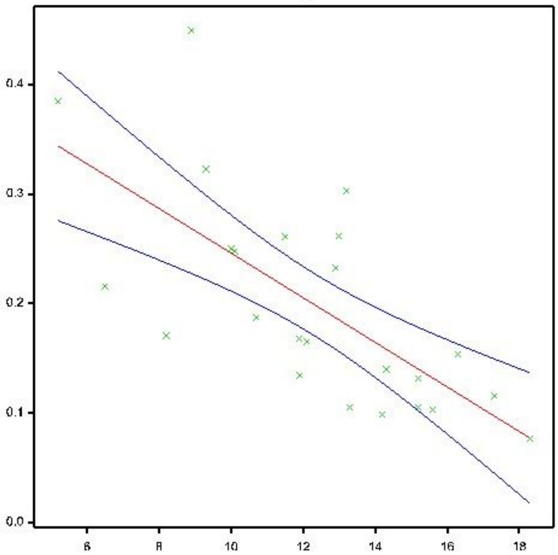

Figure 5. *Factor f plotted as a function of ΔTdiff (°C).*

Static climatic variations

For all 6 trials, for both periods (5 days) and for daytime and nightime, all horizontal long-term location/layout dependent variations have been computed using a geostatistical approach. Based on a variance model, dependent on the distances between sensors and the means calculated from these 24 conditions, Kriging was used to interpolate 2D-regular grid distribution plots to show long-term static horizontal variations. Figure 6 shows a plot for the matricaria 1 trial. Here we see a large temperature gradient (4 °C) during the night between the main pathway and the left and right side of the greenhouse, which was due to mis-fitted windows in the sides. After repair, this gradient disappeared in the repeated trial (matricaria 2).

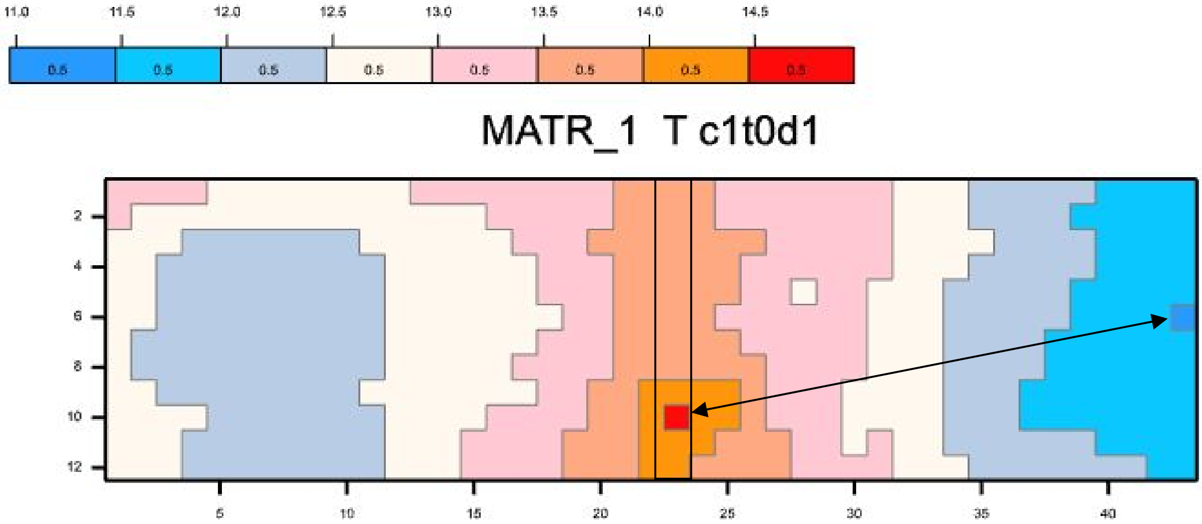

Figure 6. *Static temperature distribution for Matricaria1 (night, period D1). Colors represent equal sized temperature levels on the scale given. The plot shows a Kriged interpolated graph obtained using a grid size of 5 x 5 m^2. X-axis and y-axis are shown in number of grid points. The arrow shows the temperature gradient from main path (15°C) to side wall (11°C).*

Figure 7 shows the static RH distribution for the gerbera 1 trial. In the right wing a persisting wetter spot is observed (RH = +2.5 %). Although the static deviation is relatively small, the grower confirmed its existence, through local crop observations, and from experience with a lesser crop quality due to susceptibility for diseases in this area.

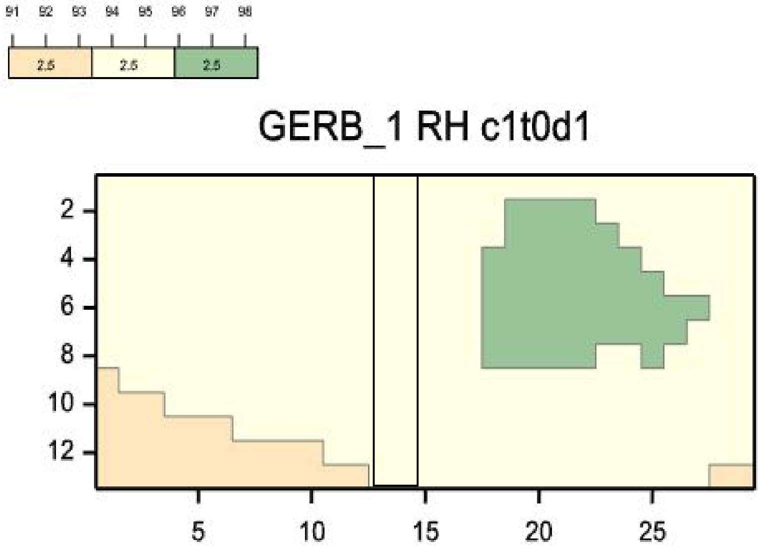

Figure 7. *Static distribution of relative humidity for gerbera 1 (night, period D1).*

Based on all 2D-distribution plots, an index for the uniformity ($U_{\mathrm{RH,T}}$) of the greenhouse climate was obtained. U gives the fraction of the greenhouse surface that has static differences staying within the boundaries: $\Delta T < 1.5$ °C and $\Delta RH < 7.5$ %. Table 3 shows that in most cases the greenhouses have a good long-term homogeneity ($U > 0.8$), especially for RH and for the vegetable crops. Apart from the earlier mentioned window problem with matricaria1, in some cases (matricaria 2-D1, gerbera1-D2) a low uniformity was observed for either T or RH during nighttime, indicating a more critical humidity and/or ventilation problem. Besides U, Table 3 also gives a prediction of ΔT and ΔRH based upon Kriging.

Table 3. *Uniformiy index ($U_{T,RH}$) for T and RH, as well as the prediction of ΔT and ΔRH (denoted with a *) given for all trials, periods and day/night times.*

	D1-night	D2-night	D1-day	D2-day	D1-night	D2-night	D1-day	D2-day
	U_{T}				U_{RH}			
gerbera 1	0.920	1.000	0.881	0.899	1.000	1.000	1.000	1.000
gerbera 2	0.844	0.546	0.992	0.942	1.000	1.000	1.000	1.000
matricaria 1	0.746	0.828	0.808	0.859	0.915	0.909	0.946	0.942
matricaria 2	1.000	1.000	1.000	0.999	0.560	0.806	0.992	1.000
tomato	1.000	0.999	0.988	1.000	1.000	1.000	1.000	1.000
cucumber	1.000	1.000	1.000	0.999	0.999	0.999	0.999	0.999
	ΔT^* (°C)				ΔRH^* (%)			
gerbera 1	2.22	1.26	2.40	1.91	22.25	40.15	13.45	8.85
gerbera 2	3.25	2.21	2.40	1.96	16.64	14.54	13.45	11.26
matricaria 1	2.53	3.37	1.35	2.26	20.28	18.16	13.28	12.92
matricaria 2	0.92	1.14	1.31	0.97	15.32	17.31	12.46	11.63
tomato	1.24	1.22	1.31	1.19	10.41	13.78	11.21	13.67
cucumber	1.06	1.14	1.10	1.12	26.45	26.29	11.16	11.25

This table shows that static variations may range from 1.0 – 3.4 °C and 9 – 40 % for temperature and relative humidity respectively.

Sensor density

To obtain the required density of the monitoring grid, that does not miss a cold or wet spot, it is important to know the actual accuracy of the monitoring system as well have a measure of the required accuracy. The accuracy of the sensors themselves is known, but this accuracy is for the specific spot at which the sensor is placed. In the overall accuracy, there is added uncertainty, due to the natural variability of temperature and relative humidity (greenhouse skeleton, vents, orientation, screening etc.). To get an impression of the measurement accuracy at any arbitrary point in the greenhouse, we used variograms. It shows the variances of the differences between the readings of any two sensors as a function of the distance between the sensors.

Figure 8, as an example, shows two of these variograms. For small distances (near zero) the variance globally resembles the measurement error of two sensors closely placed to each other. The bigger the distance, the more closely the curves follow the natural variances in the greenhouse. The shape of the curve depends strongly upon the greenhouse infrastructure and the climatic differences between the outside and inside of the greenhouse. For matricaria 1 (Figure 8, left) there is a maximum (*var.* = 1.05) at about 90 m. Thereafter the variances drop again. This means that there is a repetitive pattern of warm and cold regions, in this case probably dominated by the strong temperature gradient between side walls and middle parthway. For cucumber we do not see this pattern because the climate is much more homogeneous in this smaller greenhouse. Therefore variograms are characterized for distances (d in m) smaller than 50 m by fitting a linear function with an inter-section point on the y-axis and a slope. Statistical analyses showed no significant difference between night and day times, and the variance can be described as as:

$$Var(T,d) = 0.0344 + 0.0024 \cdot d \quad \text{and:} \quad Var(RH,d) = 1.097 + 0.0583 \cdot d\,. \tag{4}$$

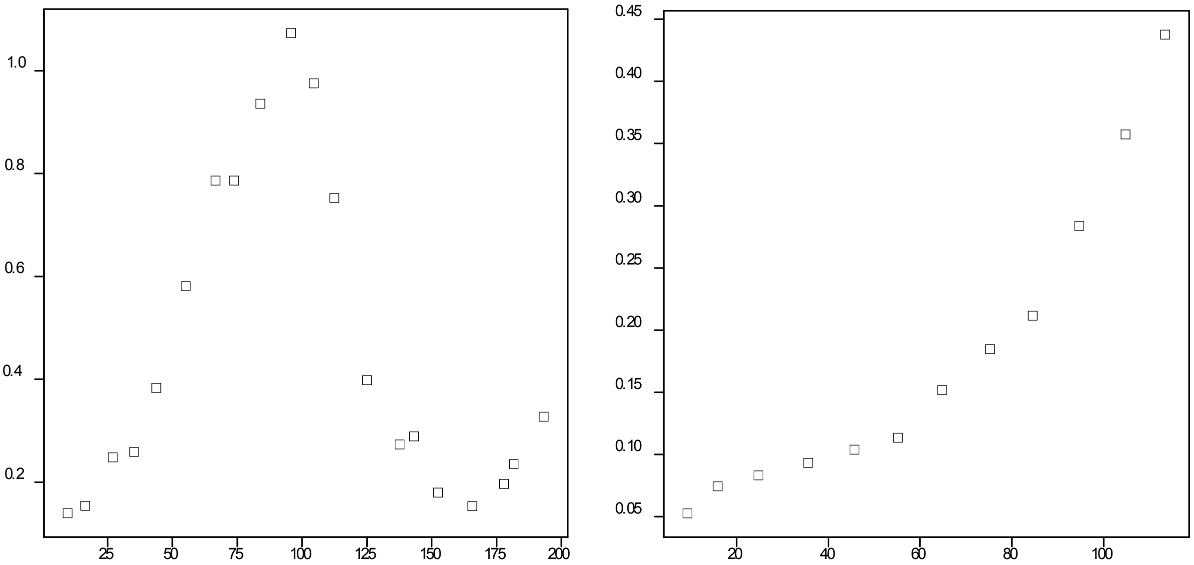

Figure 8. *Temperature variograms for matriacria1 (left) and cucumber (right) during the nights of period D1. The horizontal axis shows the distance between sensors, and the vertical axis shows the variance.*

We must consider the fact that this data was obtained during the winter period, and that in periods with smaller ΔT_{diff}, the slopes will be less. The above equations can give the variances for a specific grid density (g), when using:

$$d = \sqrt{\frac{10{,}000}{g}} \quad , \tag{5}$$

in which the g is given as the number of sensors per hectare. Figure 9 shows the results for T and RH. Densities below 4 per hectare (d = 50 m) the curves are not reliable, because the fitted variance beyond distances of 50 meter suffer from the specific infrastructure of the greenhouse (Fig. 8). But with 1 sensor per hectare, the variance comes near the maximum variance of a single T-RH monitoring box, placed at an arbitrary location.

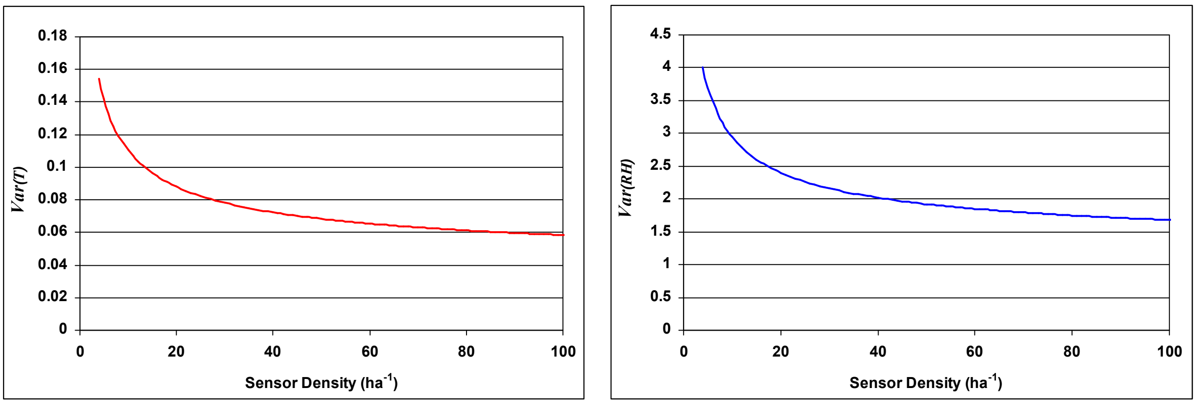

Figure 9. *Variance for T (left) and RH (right) as a function of sensor density.*

If we assume that the needed accuracy should be at least the one specified for homogeinity as $\Delta T < 1.5$ °C (Stichting Milieukeur, 2010), then for g above 9 ha^{-1}, we already can fulfill this need. Beyond 30 ha^{-1}, the increased sensor density does not pay off with an increased better local estimate, the curves become flat. The figures are indicative and based upon a limited set of experimental data obtained in specific periods and for specific greenhouses. For individual cases the graphs might be completely different, and we advice growers to obtain such curves for their typical situation. Manufacturers are adviced to use highly accurate sensing elements, to get a better performance at the same grid densities.

4. Conclusion

The wireless sensor network worked fine, and under standard conditions (15 – 25 °C and RH < 95%) the sensors have an accuracy of ± 0.4 °C and ± 3 % for respectively T and RH. During daytime, there is a large influence of direct solar radiation on the measurement of both temperature and RH. During the night, especially at humidities above 95%, the sensors become less reliable for RH. There is a small offset difference between the sensors and it is adviced that sensors are being checked and corrected by the manufacturer for this offset.

For the observed greenhouses with matricaria, gerbera, cucumber and tomato, the horizontal climatic variations ΔT and ΔRH consist out of static variations in the order of 1.0 – 3.4 °C and 9 – 40 %, and instantaneous variations in the order of 5.6 – 9.0 °C and 11.8 – 42.3 %. There are large differences between the several cropping systems, and we observed a more homogeneous climate in the high grown vegetable crops compared to the lower growing flower crops. ΔT is strongly correlated with difference between the inside and outside temperature in the greenhouse. The experiments agree with the rule of thumb that ΔT is a factor 4 – 5 lower than this difference, for differences around 10 °C.

ΔT and ΔRH can not be obtained accurately enough with a single or very few T-RH monitoring boxes per hectare, because the natural variations in greenhouses are high. For the observed greenhouses, and for the specific periods, we found that by applying a dense sensor grid of at least nine sensors per hectare (33 × 33 m^2), ΔT and ΔRH can be obtained while not missing a cold or wet spot. By applying more sensors, the accuracy becomes higher, however with more than 30 sensors per hectare do not lead to a better estimate. An estimate better than ± 0.5 °C and ± 2.6 % is not achievable, because of the sensor specification and local differences even if placed next to each other. A better accuracy can only be obtained by implementing more accurate sensing elements like for instance the SHT75 (Sensirion).

5. Acknowlegdment

This work was supported by the Dutch Horticultural Production Board (PT) and the Dutch Ministry of Agriculture, Nature and Food Quality (LNV).

6. References

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