Summer July 1, 2020

# Temperature and Relative Humidity Spatial Variability: An Assessment of The Environmental Conditions Inside Greenhouses

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# TEMPERATURE AND RELATIVE HUMIDITY SPATIAL VARIABILITY: AN ASSESSMENT OF THE ENVIRONMENTAL CONDITIONS INSIDE GREENHOUSES

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## ABSTRACT

Environmental conditions are among the most important factors that affect plant growth, yield, and quality in greenhouse production. Heating and ventilation requirements can affect the uniform distribution of climatic factors within a greenhouse, such as the temperature and relative humidity, which can prevent plants from growing evenly. Furthermore, in addition to affecting plant growth, the temperature and humidity spatial variability play an important role in the development of various diseases. Modern technology has provided tools for determining the spatial differences in greenhouse climate and investigating their cause(s).

This study was designed to investigate greenhouse climatic heterogeneity and its effect on plant growth. To this end, research was conducted from December to April in two different greenhouses—one covered with Polyethylene (PE), and the other with a double layer PE. Data loggers were located at six different points to measure the temperature and relative humidity values. The measurement data were classified as night, day, heating with, and heating without a thermal screen and were subsequently statistically compared. The measurements-based analysis demonstrated that the thermal uniformity was superior in a double layer covered greenhouse when compared to a single layer covered greenhouse and provided good insulation. In addition, the use of a thermal screen significantly contributed to climatic uniformity.

**KEYWORDS:**
Greenhouses, Greenhouse climate, Thermal uniformity, Thermal environment, Greenhouse heating

## INTRODUCTION

The goal of all greenhouse production is to generate high quantity and quality yield. Numerous factors affect the quantity yield and quality of greenhouse products, including the location of the greenhouse, the type of greenhouse, external climatic conditions, and the duration of exposure to sunlight. The greenhouse climate is one of the primary factors that affects product yield and quality [1]. Therefore, the greenhouse climate should be controlled based on the plant requirements. However, producers face problems in accessing technical information, particularly in relation to tomato growing [2]. The plants are adapted to temperatures between 17°C and 27°C during the growing period. Optimal temperatures range between 15–20°C at night and 22–28°C during the day [3]; inadequate or extreme temperatures in greenhouses are known to adversely affect plant growth. Relative humidity is also an important greenhouse climatic variable. High relative humidity can cause condensation on plant surfaces and increase the germination of certain pathogenic fungi (e.g., *Botrytis cinereal*, which damages fruit and plant flowers and is one of the most common greenhouse fungi). When the high relative humidity in the greenhouse decreases, the probability of infection caused by the pathogen also decreases [4, 5]. In contrast, low temperature and high relative humidity cause a lack of physical, chemical, and aromatic quality that necessitates the intensive use of pesticides and hormones [6]. Engindeniz, et al. [7] reported drug use of ~ 2850 grams per decare in their study of greenhouses in Turkey. This quantity is considerably higher than average values, and it is known that the excessive use of pesticides adversely affects human health and the environment. On the other hand, the waste generated by greenhouse enterprises contributes to environmental problems [8].

While an appropriate overall temperature value is crucial for optimal growing conditions, the temperature distribution throughout the greenhouse is an important factor in controlling the uniformity of plant growth [9]. A number of previous studies have evaluated the greenhouse climate uniformly, without distinguishing between the volume occupied by the crop and the area above the plants [10]. However, the myriad of variables that affect greenhouse environmental conditions complicate climate control and present challenges in terms of achieving uniformity [11]. In addition, spatial heterogeneity, which is specific to the biological and physical aspects of related processes and systems, makes optimizing greenhouse conditions more challenging. In modern greenhouses, measuring points are required at the plant level to create an objective and detailed view of the climate within the entire greenhouse area. Undesirable climatic gradients can cause significant differences in productivity, as well as in the plants' quantitative and qualitative characteristics [12]. They can also facilitate the formation of various diseases. Eliminating these temperature differences requires a precise and accurate distributed monitoring system [13], where carefully planned spatial positioning of the sensors is necessary to ensure homogenous plant growth and identify problem areas. In addition, applications such as heating, irrigation, fertilization, ventilation, and construction planning, which require high technology and, therefore, high installation costs, should be automated and controlled by computers and existing programs [14].

There have been numerous studies on greenhouse climate homogeneity. For example, Bucklin, et al. [15] reported that greenhouse temperature changes at the plant level were highly problematic, but that correctly estimating such changes was difficult due to the high number of variables involved. Balendonck, et al. [16] examined the greenhouse environment's horizontal climate heterogeneity and noted significant differences in the measurements depending on the location, time, and season. Bartzanas, et al. [17] reported that knowledge of climate heterogeneity in greenhouse conditions can help in the design and optimization of ventilation openings. Kittas and Bartzanas [10] investigated the effect of ventilation opening configurations on the air velocity, temperature, and relative humidity distribution in greenhouses. The indoor temperature of greenhouses has been shown to be influenced by air exchange, outdoor air temperature, solar radiation, heating, ventilation, and wind [18].

Ventilation is an effective method for homogenizing the greenhouse climate. However, insect nets used in greenhouse ventilation openings cause spatial differences in greenhouse climate parameters [19]. Bucklin, et al. [15] reported a 0.5°C temperature difference every 0.25 m in a vertical direction. The value of the temperature difference was higher in greenhouses that heated rapidly on hot summer days when the air flow was low. Teitel, et al. [20] reported that the temperature gradient occurred at noon, corresponding to the peak of solar radiation in a greenhouse. Bojacá, et al. [21] modeled the effect of greenhouse temperature distribution on plant growth using geo-statistical methods. Other studies have employed the computational fluid dynamics (CFD) method to determine the temperature distribution in greenhouses [22-24]. The problem of homogeneity occurs in fan-pad systems used for cooling [25]. Further in-depth research is needed to investigate the spatial and temporal distribution of greenhouse climate parameters for integration into climate control systems and to measure the potential for energy conservation [16]. However, some studies have been conducted on modeling greenhouse environmental parameters [18, 26-28].

This study was conducted in two different greenhouses. Temperature and relative humidity were measured with data loggers at six different points. The measured data from the plant level were statistically compared, and the thermal uniformity was investigated.

## MATERIALS AND METHODS

The study was carried out in two greenhouses in the Kahramanmaras Province of Turkey. These greenhouses were 20 m long x 7.5 m wide (150 $m^2$ floor area), with a side wall height and ridge height of 3 m and 5 m, respectively. The greenhouses utilized natural ventilation from the roof, and 0.3 mm Polyethylene (PE) cover(s). The side walls of Greenhouse-1 (GH-1) were covered with a single layer of PE, and those of Greenhouse-2 (GH-2) were covered with a double layer of PE. There was 5 cm of air space between the two covers. The study was conducted between December and April. The temperature and relative humidity were measured at six different points 1 m from the ground. The wind speed was measured 6 m from the ground in 15 minute intervals from the south-east of the greenhouses. The measurements were taken using an anemometer and recorded with a data logger. The measurement device layout is shown in Figure 1.

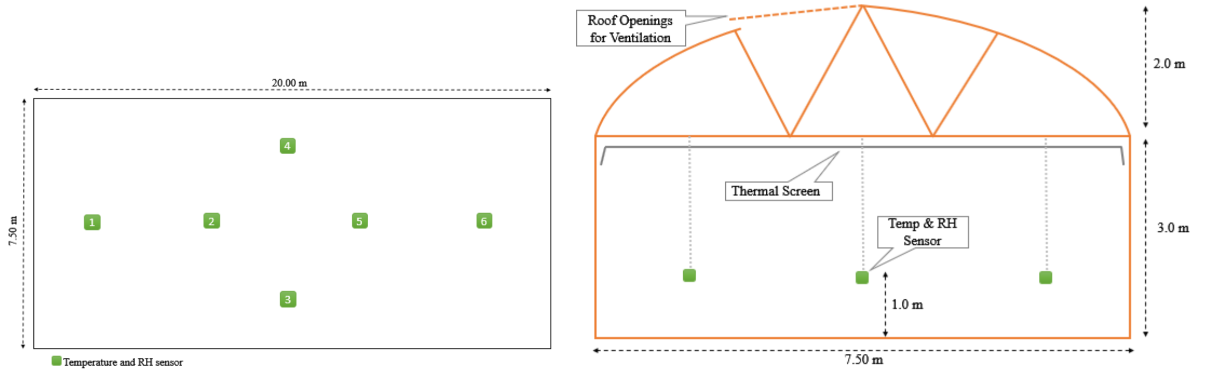

**FIGURE 1**
**Measurement plan layout schematic view**

HOBO U12 model data loggers were employed to measure the temperature and humidity. The instrument measured temperatures in the range of –20 °C to +70 °C with an accuracy of ±0.35°C; and the humidity measurements ranged from 5% to 95% with a sensitivity of 2.5%. Measurements were taken every 15 minutes. A 24 kW electric heater warmed the greenhouses by blowing in hot air; it was placed 60 cm from the ground at the short side of the greenhouse. The greenhouse heating was based on external climate conditions. Therefore, the heater was only used as necessary and was not employed every day. Similarly, on certain days, the greenhouse was heated without a thermal screen. The collected data were classified based on four specific conditions: (a) No Heating-Day (DNH), (b) No Heating-Night (NNH), (c) Heating-Without Thermal Screen (HNTS), and (d) Heating-With Thermal Screen (HWTS).

The aim of this study was to investigate the temperature and relative humidity uniformity by examining the difference between measurements made at multiple points in the greenhouses. To this end, the data were analyzed to determine whether there was a statistical difference between the temperature and relative humidity measurements, as well as the degree to which these variables were affected by wind speed. The spatial variability of each environmental variable was calculated based on the sensor measurements.

Three sets of assessments were performed: (a) the maximum difference between the measured values was determined and averaged over the relevant periods, (b) the standard deviation of these means was calculated, and (c) the mean relative deviation (MRD) was calculated, as shown below. While the first two assessments showed the average measurement size variability, Ferentinos, et al. [13] previously reported that MRD, when calculated using the following equation, is a uniformity criterion and that lower MRD values indicate a better uniformity.

$$MRD = \sum\left(|V_i - V_m| \,/\, (N \cdot V_m)\right), i = 1N$$

where $N$ is a specific variable's number of measurements, $V_i$ is the measurement i, and $V_m$ is the average value of all $N$ measurements.

In addition, the measurements' root mean square errors (RMSEs) were correlated with wind speed data to determine the degree to which the temperature and relative humidity in the greenhouse was affected by the wind speed.

## RESULTS

The statistical calculation results of the temperature measurement data for GH-1 (with a single layer of PE) are depicted in Table 1.

As shown in Table 1, the highest temperature difference between the sensors occurred during HWTS conditions (0.87°C) and the lowest temperature difference occurred during HNTS conditions (0.35°C). When using the MRD as a uniformity criterion, the temperature showed more uniform distribution when the heating system was running (i.e., in the HWTS and HNTS conditions). The heater may have aided the uniform temperature distribution in the greenhouse by generating a convective airflow from blowing hot air. In addition, the NNH conditions in which there was no heating or air movement demonstrated a higher MRD, which further supports this conclusion. With respect to the DNH conditions, although the measurements in the ventilation period were included in the MRD calculation, the MRD result was close to that of NNH. According to the ANOVA test for the sensor measurements, the difference between the measurements in the NNH, HNTS, and HWTS conditions was significant ($P < 0.05$). The statistical calculation results of the temperature measurement data for GH-2 (double layer of PE) are depicted in Table 2.

**TABLE 1**
**Average temperature and standard deviation (°C) with the maximum average difference (Single Layer)**

| | No Heating | | | | Heating | | | |
|---|---|---|---|---|---|---|---|---|
| | DNH Day (05.00-20.00) | | NNH Night (20.00-05.00) | | HNTS Without Thermal Screen (20.00-05.00) | | HWTS With Thermal Screen (20.00-05.00) | |
| Data Logger Sensor | Avg | Std | Avg | Std | Avg | Std | Avg | Std |
| 1 | 17.56 | 10.45 | 4.98 | 3.51 | 12.18 | 2.88 | 10.83 | 2.99 |
| 2 | 16.94 | 9.74 | 5.31 | 3.51 | 12.53 | 2.81 | 10.45 | 2.47 |
| 3 | 17.40 | 10.20 | 5.27 | 3.54 | 12.39 | 2.83 | 10.49 | 2.43 |
| 4 | 17.04 | 9.77 | 5.02 | 3.55 | 12.49 | 2.52 | 10.27 | 2.57 |
| 5 | 17.25 | 9.96 | 5.01 | 3.54 | 12.22 | 2.79 | 10.20 | 2.56 |
| 6 | 16.84 | 9.77 | 4.83 | 3.60 | 12.23 | 2.95 | 9.96 | 2.46 |
| Max diff. | 0.73 | | 0.48 | | 0.35 | | 0.87 | |
| Avg std. | 0.281 | | 0.185 | | 0.150 | | 0.298 | |
| Avg MRD | 0.5085 | | 0.5944 | | 0.1764 | | 0.2068 | |

**TABLE 2**
**Average temperature and standard deviation (° C) with the maximum average difference (Double Layer)**

| | No Heating | | | | Heating | | | |
|---|---|---|---|---|---|---|---|---|
| | DNH<br>Day<br>(05.00-20.00) | | NNH<br>Night<br>(20.00-05.00) | | HNTS<br>Without Thermal Screen<br>(20.00-05.00) | | HWTS<br>With Thermal Screen<br>(20.00-05.00) | |
| Data Logger Sensor | Avg. | Std | Avg. | Std | Avg. | Std | Avg. | Std |
| 1 | 17.33 | 10.16 | 5.42 | 3.43 | 12,78 | 2,11 | 14,64 | 3,13 |
| 2 | 17.47 | 10.22 | 5.59 | 3.36 | 12,65 | 2,06 | 14,53 | 3,43 |
| 3 | 17.49 | 10.00 | 5.63 | 3.39 | 12,81 | 2,12 | 14,61 | 3,43 |
| 4 | 17.20 | 9.84 | 5.66 | 3.45 | 12,71 | 2,06 | 14,48 | 3,32 |
| 5 | 17.08 | 9.73 | 5.50 | 3.39 | 12,59 | 2,08 | 14,36 | 3,43 |
| 6 | 17.19 | 9.94 | 5.47 | 3.48 | 12,77 | 2,10 | 14,17 | 3,53 |
| Max diff. | 0.41 | | 0.25 | | 0.22 | | 0.47 | |
| Avg std. | 0.164 | | 0.097 | | 0.085 | | 0.174 | |
| Avg MRD | 0.5016 | | 0.5198 | | 0.1301 | | 0.1922 | |

As shown in Table 2, there was a maximum temperature difference of 0.47°C during the HWTS conditions, while the minimum temperature difference of 0.22°C occurred during HNTS conditions. These results parallel those of GH-1, with the exception that the temperature differences in GH-2 were lower. According to the ANOVA test for GH-2, the difference between the DNH, NNH, HNTS, and HWTS values was not significant (P>0.05).

The statistical calculation results of the relative humidity measurement data for GH-1 (single layer of PE) are depicted in Table 3.

The results shown in Table 3 indicate that the maximum relative humidity difference in GH-1 was 3.28%, during DNH conditions, and the minimum difference was 1.05% during HNTS conditions. The highest MRD was noted during DHN, but the MRD values were low in all cases. According to the ANOVA test, the difference between the measured values of DNH, NNH, HNTS, and HWTS was not significant (P>0.05).

The statistical calculation results of the relative humidity measurement data for GH-2 (double layer of PE) are depicted in Table 4.

As shown in Table 4, the maximum relative humidity difference in GH-2 was 3.35% during the HNTS conditions, and the minimum difference was 1.90% during the NNH conditions. Although the MRD values in both greenhouses were higher in DNH than in other cases, the relative humidity showed a uniform distribution. In the DNH conditions, a non-uniform relative humidity distribution

**TABLE 3**
**Average relative humidity and standard deviation (%) with the maximum average difference (Single Layer)**

| | No Heating | | | | Heating | | | |
|---|---|---|---|---|---|---|---|---|
| | DNH<br>Day<br>(05.00-20.00) | | NNH<br>Night<br>(20.00-05.00) | | HNTS<br>Without Thermal Screen<br>(20.00-05.00) | | HWTS<br>With Thermal Screen<br>(20.00-05.00) | |
| Data Logger Sensor | Avg. | Std | Avg. | Std | Avg. | Std | Avg. | Std |
| 1 | 70.57 | 16.43 | 87.87 | 3.01 | 84,61 | 4,22 | 85,14 | 3,03 |
| 2 | 73.61 | 14.15 | 88.46 | 2.93 | 84,61 | 4,17 | 85,15 | 2,40 |
| 3 | 72.63 | 16.22 | 89.72 | 2.67 | 85,66 | 3,96 | 85,04 | 2,49 |
| 4 | 73.69 | 15.54 | 90.29 | 2.27 | 84,92 | 5,32 | 84,95 | 3,83 |
| 5 | 72.61 | 15.69 | 89.36 | 2.25 | 85,04 | 4,28 | 85,05 | 3,97 |
| 6 | 73.85 | 15.28 | 89.97 | 2.27 | 84,75 | 4,81 | 86,28 | 2,08 |
| Max diff. | 3.28 | | 2.42 | | 1.05 | | 1.33 | |
| Avg std. | 1.231 | | 0.936 | | 0.395 | | 0.502 | |
| Avg MRD | 0.1927 | | 0.0234 | | 0.0427 | | 0.0264 | |

**TABLE 4**
**Average relative humidity and standard deviation (%) with the maximum average difference (Double Layer)**

| | No Heating | | | | Heating | | | |
|---|---|---|---|---|---|---|---|---|
| | DNH Day (05.00-20.00) | | NNH Night (20.00-05.00) | | HNTS Without Thermal Screen (20.00-05.00) | | HWTS With Thermal Screen (20.00-05.00) | |
| Data Logger Sensor | Avg. | Std | Avg. | Std | Avg. | Std | Avg. | Std |
| 1 | 71.41 | 17.18 | 89.20 | 3.40 | 85,04 | 4,68 | 85,39 | 5,51 |
| 2 | 71.36 | 17.05 | 88.92 | 2.87 | 86,43 | 3,04 | 86,71 | 2,99 |
| 3 | 70.17 | 16.03 | 87.57 | 2.70 | 84,19 | 3,84 | 84,68 | 2,95 |
| 4 | 72.34 | 14.81 | 87.30 | 2.66 | 84,61 | 3,09 | 85,20 | 3,06 |
| 5 | 72.05 | 15.73 | 88.79 | 2.68 | 85,90 | 3,15 | 85,65 | 3,36 |
| 6 | 71.13 | 15.65 | 87.56 | 3.21 | 83,08 | 5,64 | 85,79 | 3,18 |
| Max diff. | 2.17 | | 1.90 | | 3.35 | | 2.03 | |
| Avg std. | 0.761 | | 0.833 | | 1.203 | | 0.681 | |
| Avg MRD | 0.2022 | | 0.0245 | | 0.0382 | | 0.0340 | |

could be caused by ventilation, as the relative humidity could change rapidly in the time between opening and closing the natural ventilation openings. According to the ANOVA test, the difference between the DNH, NNH, HNTS, and HWTS values was not significant (P>0.05).

In this section, the relationship between wind speed, temperature, and relative humidity measurement RMSEs were investigated, as wind speed is one of several external factors that can affect the indoor thermal uniformity. Regression analyses were performed for wind speed and sensor measurements, and the results are depicted in the graphs below.

The results of the wind speed data plotted against the temperature measurement RMSEs from both greenhouses are depicted in Figure 2 for each of the four conditions tested.

The results shown in Figure 2 found no significant correlation between RMSE and wind speed, although RMSE was higher in DNH. The maximum RMSE value under NNH conditions was 0.5°C in GH-1; while the RMSE value in GH-2 was lower. In addition, the wind speed and the RMSE correlation under NHN conditions showed a slight decrease due to the wind speed (Figure 2b, f). Under HNTS conditions, the RMSE increased to a maximum of 1°C. This higher value may have been due to air circulation in the greenhouse. There was also a slight decrease in RMSE as a function of the increasing wind speed. Since the thermal screen was absent, air leaking from the roof area created convective air movement in the greenhouse and reduced spatial temperature differences. RMSE values under HWTS conditions showed differences between the two greenhouses, depending on wind speed. In GH-1, the RMSE value, particularly at low wind speeds, reached a maximum at 1.61°C; whereas GH-2 depicted an RMSE at 0.5°C. This may have been caused by poor sealing of a single layer PE greenhouse. The indoor temperature was more affected by the external environment depending on the PE tightness. In addition, due to the low wind speed, the indoor temperature showed higher spatial variability. Achieving thermal uniformity was more successful in the double layer PE greenhouse with a thermal screen.

High relative humidity is a major problem in many greenhouses [29, 30], and the spatial variability of the relative humidity is also an issue that must be addressed when considering the optimal conditions for plant growth and preventing diseases. Here, the wind speed was plotted against the RMSE of the relative humidity values measured at different points in the greenhouse, and the results are shown in Figure 3.

As shown in Figure 3, in general, RMSEs in the DNH conditions were higher than in other cases. In addition, there was a slight correlation between wind speed and RMSE in the decreasing direction. The sensor measurements taken during the NHN conditions showed that the RMSEs reached a maximum at ~ 2%, but were slightly higher in GH-1. Furthermore, as the wind speed increased, the RMSE values decreased. The relative humidity showed a more uniform distribution in GH-2 heating were not operational. In GH-1, the increase in wind speed generated air movement in the internal environment by allowing air to leak through the single, poorly sealed PE, and the difference between the measurement points decreased. Therefore, relative humidity was more uniform in the well-insulated

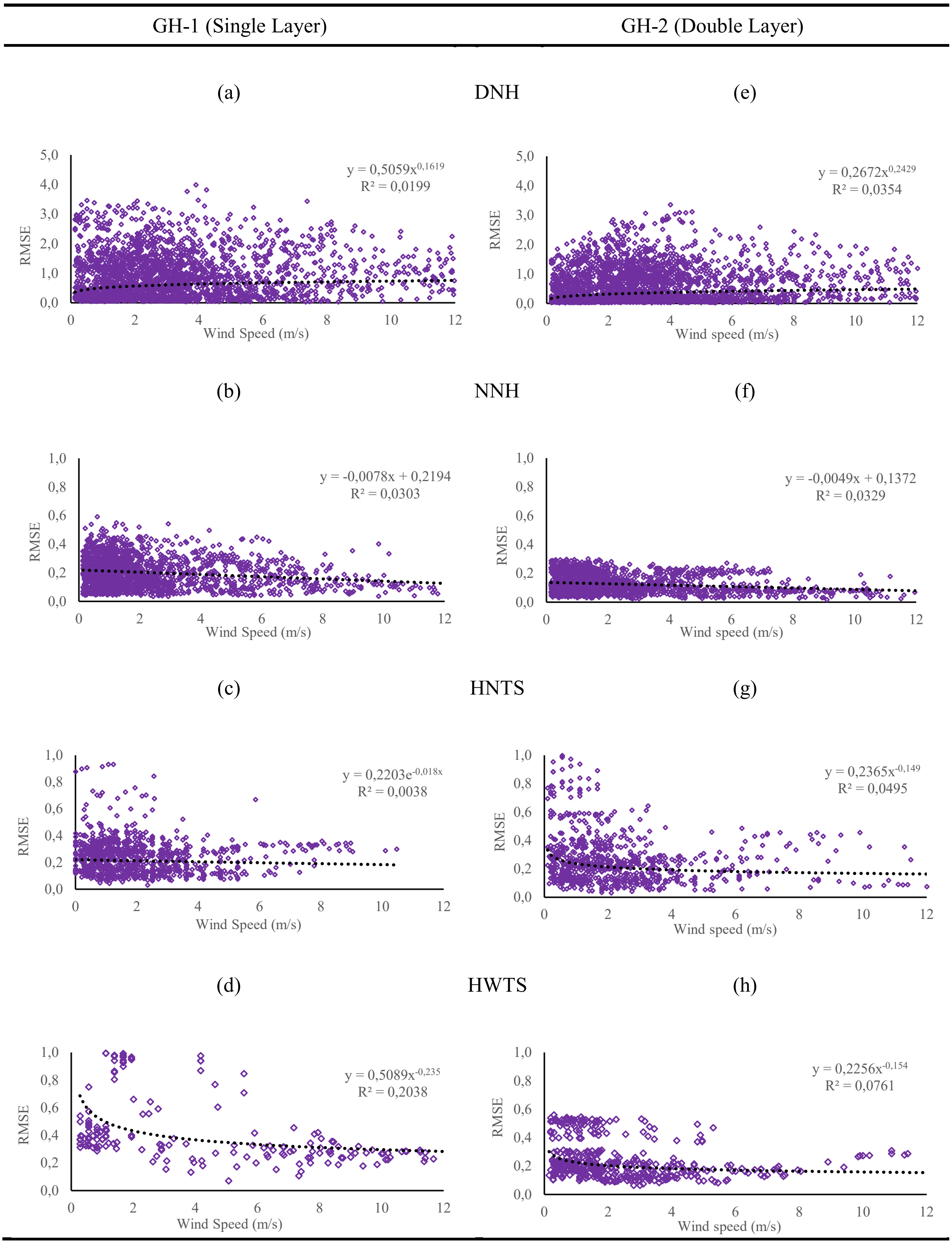

**FIGURE 2**
**RMSEs as a function of wind speed (Temperature)**

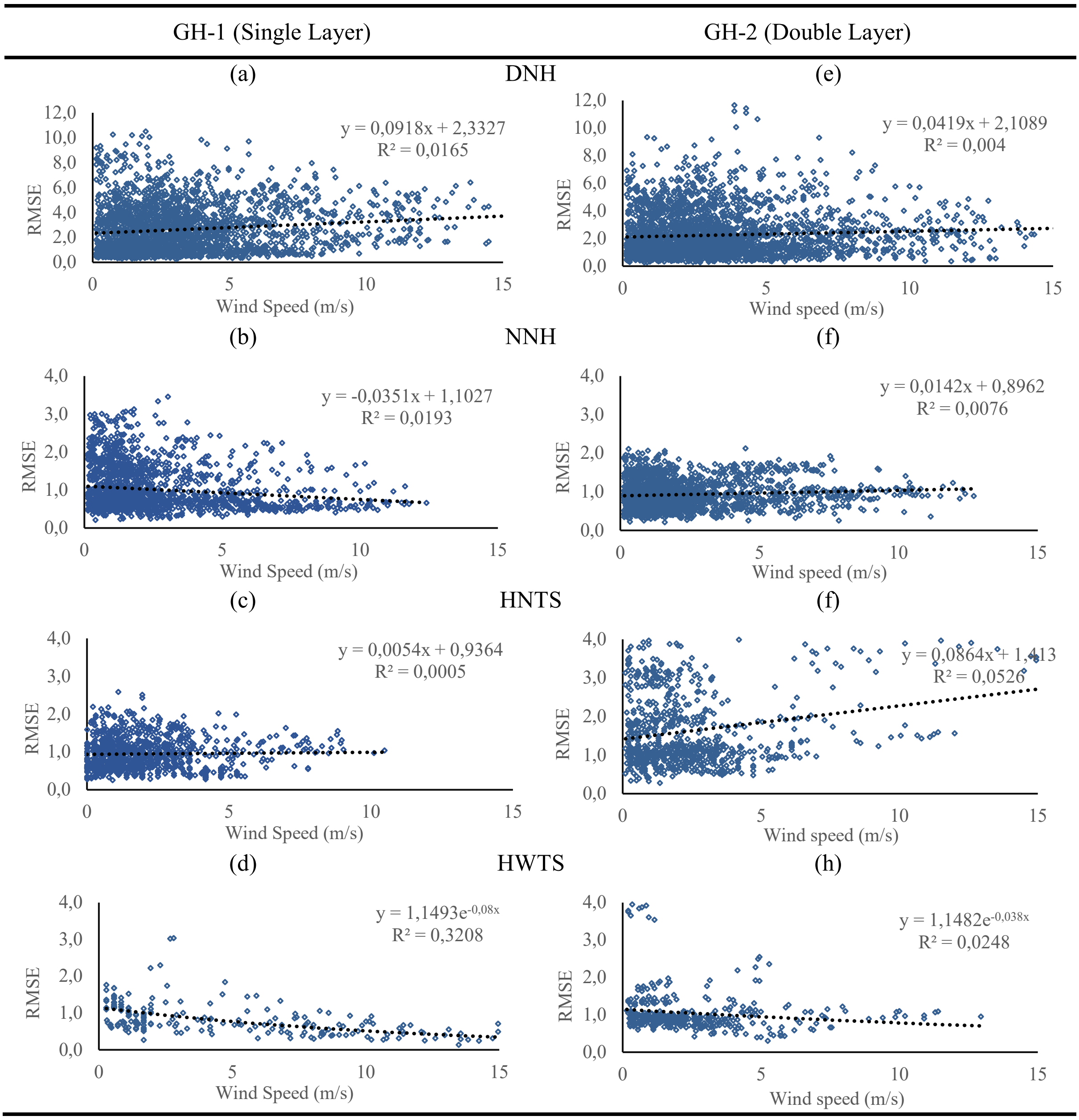

**FIGURE 3**
**RMSE as a function of wind speed (Relative Humidity)**

greenhouse, and the external wind speed positively contributed to the relative humidity uniformity in the less insulated greenhouse. The RMSE values under HNTS conditions were not affected by the wind speed in the external environment. In general, the relative humidity was higher due to the insulation in the double layer PE. Here, the convective air flow generated by the hot air blowing heater in the indoor environment resulted in a greater difference. Under HWTS conditions, the RMSE values were largely below 2%. Although some measured RMSE values were higher, they were limited to certain areas. There was also a slight correlation between the wind speed and the RMSE in a decreasing direction in GH-1. No significant correlation was observed in GH-2.

## CONCLUSION

Temperature and relative humidity measurements were taken at different points throughout two greenhouses to determine the spatial differences present in the greenhouse climate. An analysis of the data showed that there were significant differences between the measured values at non-heating periods. At night, when the heater was not operating, the stagnant indoor air caused spatial temperature differences. In addition, the increase in wind speed during periods when the heater was not running reduced the spatial temperature differences caused by greenhouse leakage and the use of thermal screens; therefore, the use of thermal screens positively contributed to thermal uniformity. In any evaluation, the sensors' accuracy and sensitivity should be considered, as well as the environmental and physical conditions. Recent advances in technology have facilitated the collection of data from multiple points and have enabled them to be analyzed instantly, which promotes the development of new greenhouse control strategies. Conducting further studies on control systems will increase greenhouse production quality and yields and promote the efficient use of resources.

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**Received:** **23.05.2019**
**Accepted:** **11.04.2020**

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