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On air temperature distribution and ISO 7726-defined heterogeneity inside a typical greenhouse in Almería

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A B S T R A C T

Studies about the air temperature inside greenhouses are usually focused on the crop growth. However, the thermal environment inside greenhouses can affect the safety of the workers and also their productivity. This work focuses on the study of air temperature conditions with respect to workers following the requirements and methods gathered in ISO 7726, which indicates that measurements should be taken at different points in both, horizontal and vertical directions in order to study heterogeneous thermal environments. For the present work, data were gathered by the Wireless Sensor Network (WSN) designed in our previous work, hereby extended by an experimental campaign carried out during a complete year in a typical greenhouse in Almeriía. The aim is performing a long-term study of air temperature inside a greenhouse as well as the assessment of air temperature heterogeneity. The results, which allow characterizing air temperature inside the greenhouse, prove the existence of patterns of heterogeneity as a function of the incidence of sunlight and time of day. During the analysed period, air temperature heterogeneity is mainly present in the central hours of the day and it is higher in the horizontal dimension rather than vertically. In addition, it has been observed that the vast majority of homogeneous days correlate with cloudy days. Finally, based on the results obtained some recommendations are presented for assessing the thermal environment of greenhouses.

1. Introduction

Areas of the South of Europe and specially Mediterranean coastal areas meet the optimum environmental conditions for growing vegetables in plastic-covered greenhouses (Hernández et al., 2017). Specifically, in Almeriía (Spain) they cover approximately 30,000 ha, the largest extension of greenhouses worldwide. Consequently, around 55,000 workers are employed each year in Almeriía (Cabrera et al., 2016). Greenhouses are agricultural buildings that consist of light metal structures covered with transparent plastic, with ventilation through the walls and ceiling, and diffuse solar radiation. These buildings maintain an adequate temperature and humidity allowing to extend the crops for almost the complete year (from the end of July to the be-ginning of June of the following year). However, these conditions are not the better for the wellbeing of the greenhouse workers, whose working period lasts practically the complete year, since maintenance work is also carried in non-crop periods (Pérez-Alonso et al., 2011; Callejón-Ferre et al., 2009; Callejón-Ferre et al., 2011b).

Despite greenhouses soften the outdoor climate environment, large variations in air temperature and humidity do still occur throughout the day. Humidity and specially air temperature are the main parameters that affect workers and crops inside of greenhouses (Vox et al., 2010; Zhao et al., 2001). In greenhouses of Almeriía, air temperature vary from around 50 °C in the middle of the day in summer to near 0 °C at night in winter.

Several authors (Callejón-Ferre et al., 2011a; Riemer and Bechar, 2016; Cecchini et al., 2010; Marucci et al., 2012; Diano et al., 2016; Okushima et al., 2001) have reported heat stress risk fundamentally during the warmer months (spring and summer). Environments with high temperatures and humidity can affect the safety of the workers, causing severe problems to the cardiovascular system and the thermoregulatory system of workers (Chad and Brown, 1995; Zhao et al., 2009). Moreover, these environments also have a negative impact in the productivity of workers. Additionally, Risk of cold in winter have been also pointed out (Callejón-Ferre et al., 2011a).

To assess the thermal environment and its influence to the workers,

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we need to follow several rules (Parsons, 2013). According to the International Standard Organization (ISO), the environment is classified in moderate or extreme. Depending on the category, a different index and ISO Standard must be used. To calculate these indexes, in any case, the measurement of several climatic parameters are required and in some cases also the metabolic rate of the activity carried out by the workers, based in ISO 8996 (ISO 8996:2004,), and the clothing in-sulation and sweat rate, ISO 9920 (ISO 9920:2007, 2007). Moreover, the ISO 7726 Standard (ISO 7726:1998, 1998) defines the specifications and methods that must to be fulfilled to asses the thermal environment. The specifications address the expected parameters of measuring instruments such as measurement range, accuracy, and response time. Regarding the methods, physical magnitudes may vary with the space as much horizontally as vertically and the environment can be con-sidered homogeneous or heterogeneous. An environment will be con-sidered as homogeneous if the physical magnitude under consideration is practically uniform in the analysed area. On the other hand, an environment will be heterogeneous if there are significant variations in the physical magnitude. The limits for each climatic parameters that define the environment as heterogeneous or not, with respect that parameter, are established in the ISO 7726. In case of heterogeneous environments, the rule states that the physical magnitudes need to be measured at different points both horizontally and vertically. In the latter, ISO 7726 specifically establishes three heights where the mea-surements must to be carried out: ankle, abdomen, and head.

Related to the thermal assessment inside a greenhouse and the heat stress in workers, only the work presented by Marucci et al. (2012) comply with the requirements for the measuring instruments described in the ISO 7726. However, these work only perform measurements in one position inside the greenhouse and in one height. Recent work carried out by López-Martínez et al. (2018), fulfilling with ISO 7726, reveals heterogeneity conditions of the greenhouse analysed. In this work, twelve measuring stations were distributed along the greenhouse, each one measuring climatic parameters at the three heights specified by the rule. According to that results obtained, it is pointed out that greenhouses are environment where the heterogeneity conditions can be achieved.

Others works, focused in the crop growth conditions, have shown large air temperature differences in vertical and also in horizontal direction inside greenhouses. Zhao et al. (2001), Soni et al. (2005) and Zorzeto and Leal (2017) measured vertical differences of around 7 °C, 10 °C and 14 °C, respectively. López et al. (2013) and Kittas et al. (2003) obtained horizontal differences of around 6 °C and 8 °C, respectively. Granados et al. (2016) measured the average temperature during January to March in a greenhouse, observing temperature differences of up to 4.4 °C at 6 a.m. and up to 9.1 °C at 2 p.m. between 0.2 and 2.6 m in height. In three different greenhouses in Almeriía studied by López et al. (2012b), it was recorded maximum air temperature differences between 10 and 12 °C for different tests performed between 11:30 a.m. and 2:30 p.m.. In simulations with computational fluids dynamics (CFD), large variations of temperature inside the greenhouse have been also observed: Boulard et al. (2017) obtained vertical differences of up to 12 °C, Molina-Aiz et al. (2004) obtained variations of temperature of around 9 °C in a similar greenhouse and in a location very close to the greenhouse studied in this work, and Tong et al. (2009) obtained variations of temperature as large as 12 °C. All these results also suggest that greenhouses may be heterogeneous environments when are evaluated according the ISO 7726.

To carry out the measurements inside of a greenhouse at different points at the same time, a sensor network is required. In recent years, Wireless Sensor Networks (WSNs) have been used to carry out measurements in different points. This type of networks are composed of battery-powered nodes provided with sensors that supply the corresponding information in real time and transmit it to a central base-station (BS) where it will be stored and from where nodes can be monitored and controlled (Ferentinos et al., 2017). The main advantages of WSN are the capability of measuring multiple points avoiding the use of wires, which are usually damaged and wore out when exposed to aggressive environment (high variations of air temperature and humidity) and could hinder the cultivation practices. Furthermore, thanks to the advances in electronics and wireless communications, it is possible to develop WSNs with a low cost and low energy consumption.

In the present work we have used a WSN to overcome the scarcity of real measured air temperature data inside a greenhouse during a complete year, also allowing us to assess whether air temperature is heterogeneous or not (according to ISO 7726) inside a typical greenhouse. This work is a continuation of our previous one (López-Martínez et al., 2018), in which the WSN and twelve measurement stations where designed and put into operation in a greenhouse. The present work carries out a measurement campaign during a complete year with the objective of evaluating the heterogeneous conditions of a greenhouse with respect to the air temperature.

To sum up, the aim of the present work is twofold:

- Monitoring, using a WSN, the air temperature distribution inside a typical greenhouse during a complete year, at three different heights and multiple points equally distributed horizontally. These data will allow to characterize the air temperature distribution of the greenhouse and its variations along the four seasons of the year.
- To study the air temperature heterogeneity inside a typical greenhouse according to ISO 7726 and providing some recommendations for the assessing of the thermal environment of a greenhouse.

This paper is organized as follows: initially, the material and methods are explained in Section 2. The experimental results and their discussion are detailed in Section 3. Finally, we outline some conclusions in Section 4.

2. Material and Methods

2.1. Experimental setup

The experiment was carried out in a greenhouse located at 15 km east of Almeriía (36°52′*N* - 2°17′255 *W* and 98 m above sea level), in the southeastern Spain. The experimental campaign was performed during a complete year, since December 2016 to November 2017 and the time between measurements was 30 s. The greenhouse is raspa y amagado type, the most common in this region. Its surface area is 1024 m^2 (32 × 32 m) and the heights of the gutter and ridge are 3.4 m and 4.1 m, respectively. The drawing of the greenhouse is defined in Fig. 1. The structure is made of steel, with the resistant elements of wire mesh type and is covered by three polyethylene layers of 200 μm, with 81%visible light transmittance and 29% diffuse light transmittance. Inside the greenhouse, the soil is covered of gravel and sand, and tomato plants are cultivated. Ventilation is natural through lateral windows and roof vents. There are windows on all four sides of the greenhouse and 4 roof vents. The area of each window is specified in Fig. 2. Each window is opened and closed by means of an electric engine with a power of 0.5 hp, being all of them controlled by a central control sta-tion. The central control station closes the windows either air velocity is greater than 35 km/h or air temperature is lower than around 8 °C, since this temperature value is also related with relative air humidity. These values are selected in order to achieve the optimal physiologic and production conditions for the plants cultivated, in this case tomato plants.

The implemented WSN comprises 12 measurement stations distributed inside the greenhouse (Fig. 1). Each station consists of a structure with three heights where the sensors are installed. Air temperature (*ta*), globe temperature (*tg*), relative air humidity (*RH*) and air velocity (v_a) have been measured at the three heights, while UVI ultraviolet radiation (UVI) is measured only at the higher height of each

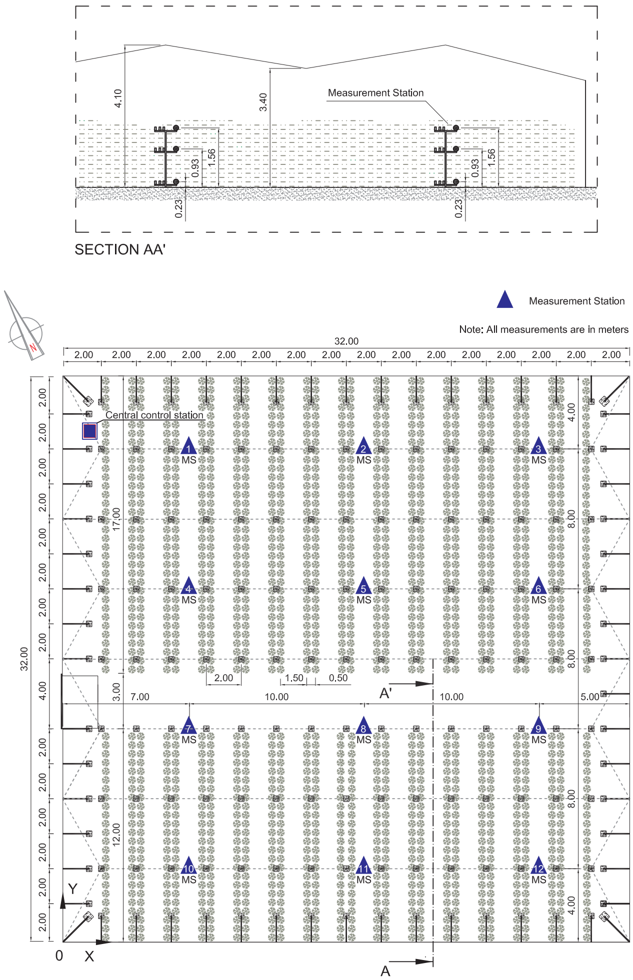


Fig. 1. Drawing of the greenhouse, where also are defined the locations of the measurement stations.

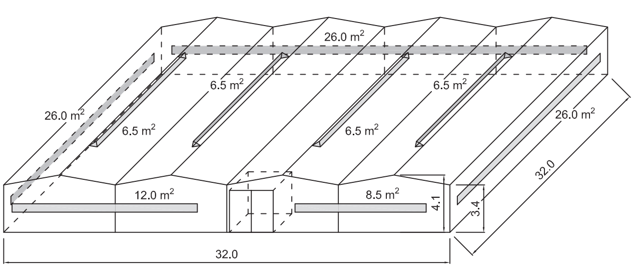


Fig. 2. 3D model of the greenhouse, where the dimensions of the windows are specified.

station. Therefore, the measurement stations are composed by four probes for each height (to measure air temperature, globe temperature, relative air humidity, and air velocity) and a UVI probe located at the top height, as it can be seen in Fig. 3. The heights were selected at 0.23 m, 0.93 m and 1.56 m according to the 50th percentile of Spanish population (Carmona-Benjumea, 2001). The characteristics of the measuring instruments fulfil with the specifications defined in ISO 7726 (except for UVI measurement that is not considered in the standard) and are presented in Table 1.

These climatic parameters have been measured using a WSN that employs IEEE 802.15.4 and ZigBee as communication protocol, and a smartphone to transmit the data by 4G to a server installed in the Data Processing Centre of the University of Almeriía (CPD-UAL) enabling access to these data by a web interface (HTTP) or by safe Secure Shell

Fig. 3. One of the 12 measurement stations located inside the greenhouse.

(SSH) links. Mesh topology is used (where nodes are connected directly to each other for peer-to-peer communication) at the communication low level, but it is modified by firmware and software so that communication follows a logical tree, generating routing tables which can be changed at any time via the Internet. Network architecture is ex-plained in detail in López-Martínez et al. (2018).

Table 2 summarizes some related works regarding the use of WSNs (Pérez-Alonso et al., 2011; Marucci et al., 2012; Zorzeto and Leal, 2017; Molina-Aiz et al., 2004; Ferentinos et al., 2017; Balendonck et al., 2014; Vox et al., 2014; López et al., 2012a; Srbinovska et al., 2015; Bojacá et al., 2009; Kittas et al., 2008). The communication protocol used for most of them, and also in our present work, is IEEE 802.15.4 plus ZigBee. Regarding the network topology, some works (Ferentinos et al., 2017; Balendonck et al., 2014; Srbinovska et al., 2015) use a star topology (comprising a central node connected to all the sensing nodes) while others (Vox et al., 2014) use a tree topology (comprising a central node connected to the sensing nodes without loops).

2.2. ISO 7726 complying and heterogeneity assessment

The Standard ISO 7726 defines the basic physical magnitudes associated to the study of the thermal environment: air temperature (*ta*), mean radiant temperature ($\overline{tr}$), absolute air humidity (*AH*, expressed by the partial vapour pressure) and air velocity (v_a). An approximate value of mean radiant temperature can be obtained by measuring globe temperature (*tg*) and other basic parameters such as air temperature and air velocity. Globe temperature combines the effects of radiation, air temperature and air velocity and is measured by means of a black sphere with a temperature sensor at its centre. Thus, considering this method for calculating mean radiant temperature, the climate para-meters that must be measured to assess the thermal environment are: air temperature (*ta*), globe temperature (*tg*), absolute air humidity (*AH*), and air velocity (v_a). By means of these parameters, other para-meters required to obtain different thermal stress indices can be cal-culated, as operative temperature (t_o) for PMV index (ISO 7730:2005,)

Table 1
Characteristics of the measuring instruments used.

Climatic parameter	Measurement range	Accuracy	Model and manufacturer
Air temperature (*ta*)	−15 °C to 250 °C	±0.06 °C at 0 °C	Pt-100 515–725 (TC Direct)
Globe temperature (*tg*)	−15 °C to 250 °C	±0.06 °C at 0 °C	Pt-100 515–725 (TC Direct)
Relative air humidity (*RH*)	0 to 100% *HR*	±3% *HR*	Si7021-A20 (Silicon Labs)
Air velocity (v_a)	0.05 to 20 m s^{-1}	±10%	Rev. C (Modern Device)
UVI	0 to 15	±1	Si1145/46/47 (Silicon Labs)

and natural wet-bulb temperature (t_{nw}) for WTGB index (ISO 7243:2017,).

ISO 7726 also defines the specifications relatives to the spatial variation of physical magnitudes, which are different depending on the type of environment considered (comfort-class C or heat stress-class S). In this work heat stress is possible, so class S environment is selected. One of the specifications is three heights where physical magnitudes must to be measured in the case that environment is heterogeneous, corresponding to ankle, abdomen and head. To consider a thermal environment as heterogeneous, any parameter considered as basic for the ISO 7726 (air temperature, mean radiant temperature, air velocity or partial vapour pressure) must be out of a limit with respect to its mean value. The limits that define a heterogeneous environment are summarized in Table 3. To calculate the mean value of each basic parameter weighting factors must be applied to each measurement height, being 1 for ankle and head, and 2 for abdomen.

Despite there are four basic parameters and any of them show variations along the greenhouse, previous results of López-Martínez et al. (2018) suggest that the air temperature is the climatic parameter that may show larger variations. In fact, no mean radiant temperature heterogeneity was found in the period studied. In addition, air temperature may be the parameter with more influence over workers in the greenhouse. According to this, the present work has been focused in the air temperature variations. Additionally, the relationship between air temperature and globe temperature along the year has been obtained in order to show the influence of diffuse solar radiation inside the greenhouse. Ultraviolet Radiation Index (*UVI*) also has been measured to determine the presence of clouds. In total, more than two million of measurements have been studied in the year analysed from the 36 points of measurement (12 stations by 3 heights).

As described before, to consider an environment as heterogeneous, some measurement must be out of the range specified respect to the weighted mean value of all the measurements (of all the measurement stations). In this case for air temperature, the range defined in ISO 7726 is ± 2 °C. The time when no value is out of this range, the environment is considered as homogeneous. To assess heterogeneity, first, mean value and heterogeneity limits are calculated. For horizontal hetero-geneity, the weighted mean of the 3 heights per each measurement station is calculated, resulting 12 values for each instant of time. These values are compared with the heterogeneity limits and if one of them exceeds the limits, horizontal heterogeneity exists. On the other hand, for vertical heterogeneity, the mean of the 12 measurement stations per each height is calculated, resulting 3 values for each instant of time, which are compared with respect the mean value in the same way that horizontal heterogeneity. The heterogeneity conditions of the green-house has been evaluated along a complete year, comparing the dif-ferences between the four seasons of the year.

2.3. Considerations and study limitations

An aspect to take into account for the results interpretation is that data have been analysed using time in UTC (Coordinated Universal Time). Local time in Almeríía is CET (Central European Time) with daylight saving time in summer.

Greenhouses environment is peculiar since it cannot be classified as indoors due to the existence of diffuse solar radiation, low wind speed, and high humidity. In addition, plastic covers are not fully waterproof and dusk and calcium carbonate (coming from paint the covers with whitewash) are present in the environment. Measurement stations have been exposed to these difficult operation conditions, making necessary weekly visits to clean and maintenances tasks. This facts have caused the loss of measurements of some station during short periods of time, specially during holiday periods.

3. Results and discussion

First, the results of the air temperature measurement campaign inside the greenhouse are presented and distribution of air temperature is analysed. Next, air temperature heterogeneity in the greenhouse, according to ISO 7726, is assessed during a complete year both horizontally and vertically. Finally, from the results obtained, some recommendations are exposed for assessing air temperature heterogeneity of the thermal environment in a greenhouse.

3.1. Variation of air temperature

Next we summarize the measurements of air temperature carried out during the experimental campaign. In Table 4, minimum and maximum values of air temperature for each month are gathered. As it is logical, its minimum values are measured at dawn and maximum values at midday. The maximum value for air temperature took place in August and is 55 °C, whereas the minimum value were measured in January is around 1 °C. It is striking that the vast majority of the maximum and minimum values were measured at the height 3 or top height of the measurement stations. This trend could be observed in Fig. 4, where the weighted mean of the measurements of each height for two different sunny days is represented (for January, 30th and July, 30th 2017). Temperature in height 3 is higher than the rest of heights during the day, but at night height 1 is the highest, whereas height 3 is the lowest. This is because the thermal gradient is reversed, as the floor works as thermal accumulator and at night it transfers heat to the en-vironment.

It has been calculated the mean air temperature per seasons in each instant using the weighting factors for heights defined in ISO 7726, obtaining a average day per season. This is shown in Fig. 5, together with the standard deviation. As expected, in summer and winter air temperature inside the greenhouse is the highest and lowest, respectively. In spring it can be observed that the temperature is higher than autumn in the middle of the day whereas at night the temperature is a bit lower. Standard deviation is higher in the middle of the day than at night for all the seasons. In addition, standard deviation also seems to increase with air temperature as it is higher in warmer seasons. The presence of clouds has influence in air temperature inside the greenhouse. The percentage of cloudy days per season was 39%, 39%, 56% and 28% for autumn, winter, spring and summer, respectively.

Videos with a 3D representation of data showing how air temperature varies during the day have been included in this work.[1] In

[1] See: https://www.youtube.com/playlist?list=PLguxjVND_tkzeqU0prXUZXZzix9ZNIsyu.

Table 2
Summary of related works regarding the use of WSNs.

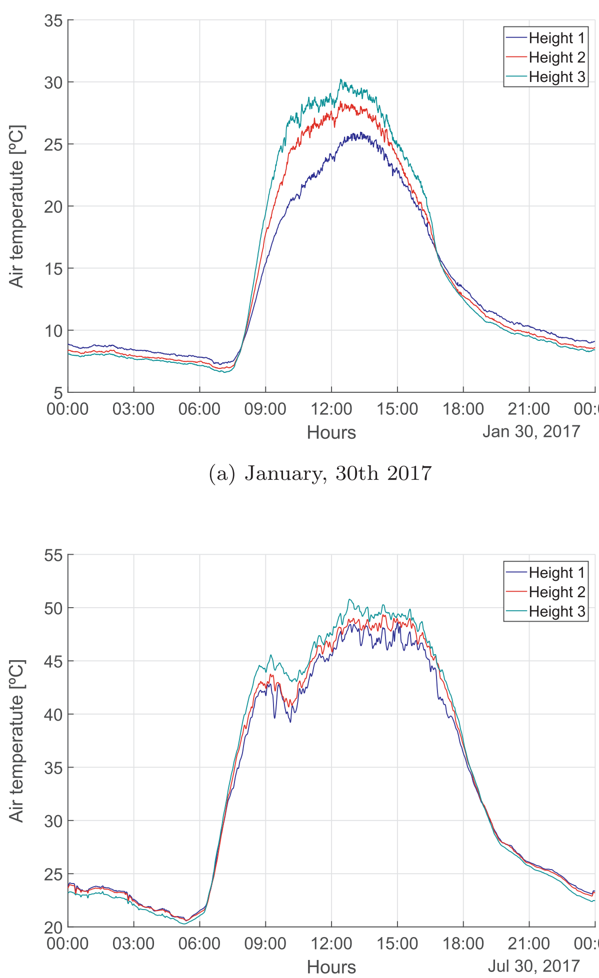
Work	Application	Stations			ISO 7726 application	Measurement campaign	Time between measurements	Accuracy/range of measurement instruments			
		Configuration (horizontal × vertical)	Heights (m)	Total measurements				Air temperature	Globe temperature	Relative humidity	Others
Balendonck et al. (2014)	Horizontal climatic heterogeneity and crop growth	100 × 1	Different at each trial	100	No	60 days (10 for each trial)	1 min.	SHT71 (±0.4 °C)		SHT71 ±5% RH	–
Bojacá et al. (2009)	Effect of temperature distribution on the crop growth	25x1	1.5	25	No	28 days	6 min	±0.01 °C			Solar radiation
Ferentinos et al. (2017)	Climatic heterogeneity and crop growth	5 × 1	1.8	1	No	4 months (3 different trials)	30 s.	SHT75 (±0.3 °C)		SHT75 ±2% RH	Solar radiation
Kittas et al. (2008)	Impact of insect screens and ventilation openings on the greenhouse climate	24 × 2 + 12 × 1 + 12 × 1	1.1–2 + 1.1 - + 2.85	72	No	2 months (during 10–17 h)	5 min	±0.1 °C		±2%.	Air velocity, solar radiation, vapor pressure
López et al. (2012a,b)	Characterize airflow and temperature distribution of greenhouses	12 × 2	1–2	24	No	–	–	±0.18 °C		±2.5%	Air velocity
Marucci et al. (2012)	Thermal stress by workers employed in vegetable grafting	1 × 1	1.5	1	Yes	10 months	–	Pt-100 1/3 DIN (±0.13 °C)	Pt-100 1/3 DIN (±0.13 °C)	±2%	Air velocity, damp bulb temperature, partial vapor pressure
Molina-Aiz et al. (2004)	Influence of wind speed on the ventilation performance	4 × 3 + 1 × 6 + 6ground- + 10top + 4windows	0.5–1.5–2.5 + 0.5-1–1.5-2–2.5–3 + gro-und + top + -windows	38	No	4 days (during different periods of time)	30 s.	NTC (±0.4 °C)		±3% RH	Air velocity, solar radiation
Pérez-Alonso et al. (2011)	Thermal stress in the greenhouse construction	12 × 1	-	12	No	4 months	5 min.	Pt-100 Class A (±0.25 °C)	Pt-100 1/3 DIN (±0.13 °C)	±2.5%	Dry air temperature, air velocity, solar radiation
Srbinovska et al. (2015)	Crop growth	5 × 1	–	5	No	7 days	30 min.	SHT11 (±0.5 °C)		SHT11 ±3% RH	
Vox et al. (2014)	Crop growth	2×1	–	2	No	20 days	60 s.	SHT75 (±0.4 °C)		SHT75 ±2% RH	Air pressure, solar radiation
Zorzeto and Leal (2017)	Vertical and horizontal climatic heterogeneity with evaporative cooling	21 × 2 + 3 × 1	1.2–2.4 + 4.5	45	No	30 days (3 different trials)	30 s	SHT75 (±0.4 °C)		SHT75 ±2% RH	Air velocity
López-Martínez et al. (2018) and this work	Thermal stress and climatic heterogeneity	13 × 3	0.23–0.93–1.5-6	39	Yes	1 year (01/12/16–31/11/17)	30 s	Pt-100 1/10 DIN (±0.07 °C)	Pt-100 1/3 DIN (±0.07 °C)	±3% RH	Air velocity, UVI

Table 3
Thresholds from which the environment is considered heterogeneous.

Basic parameters	Range (respect to mean value)
Air temperature (ta)	±2 °C (0–50 °C)
Mean radiant temperature ($\overline{tr}$)	±10 °C (0–50 °C)
Air velocity (v_a)	±(0.3 + 0.15·v_a) m s^{-1}
Partial vapour pressure (P_a)	±0.45 kPa

Table 4
Minimum and maximum values of air temperature measured at any point of the greenhouse for each month.

	Air temperature (°C)	
	Min.	Max.
December 2016	3.9	34.0
January 2017	1.1	36.2
February 2017	2.3	37.5
March 2017	3.9	41.7
April 2017	6.5	41.7
May 2017	8.9	44.1
June 2017	14.0	53.6
July 2017	12.4	54.5
August 2017	18.8	55.0
September 2017	13.2	44.8
October 2017	10.6	41.9
November 2017	4.4	36.3



(a) January, 30th 2017

(b) July, 30th 2017

Fig. 4. Mean air temperature for each height for two different dates.

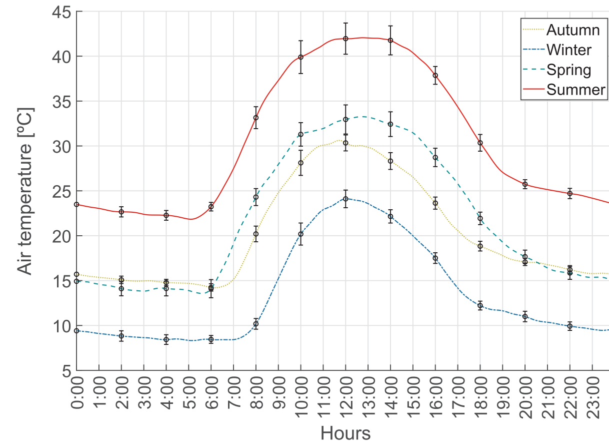


Fig. 5. Average day and confident intervals (± 1σ) of mean air temperature per season.

Fig. 6, a capture of a determined instant of the video is shown for air temperature. All the measurements recorded by the measurement stations are represented in the videos, that is 36 measurements (12 stations by 3 heights). The four images of Fig. 6 are different views of the same time. Each measurement is represented by a blue[2] marker and for each station, a label of the weighted mean value of this station is shown at the top of these markers. In a scale of colours, the weighted mean air temperature of each station also is visualized at the bottom of the z-axis. Markov Random Fields (MRF) has been used to interpolate the rest of points of the scale colour inside the greenhouse. It should be noted that the two images on the left have a scale of colours indicated in the bottom-left image and it is different to the two images on the right which have a scale of colours specified in the bottom-right image. At the bottom right, another valuable information is provided by the vi-deos: the overall minimum and maximum values, and the maximum temperature difference among all the sensors installed. In addition, it is provided the partial minimum values, maximum values and maximum temperature differences for each of the three heights measured (that correspond to ankle, abdomen and head).

Finally, from the 3D videos, air temperature distribution inside the greenhouse is studied horizontally in different periods of the day. In Fig. 7, a top view of the greenhouse for four different moments of a day (January, 8th 2017) has been represented. At night (5:00 UTC), there is few difference of temperature (around 2.5 °C) and the west side of the greenhouse is a bit warmer. In the morning (10:40 UTC), the southeast side of the greenhouse is heated by the sun and consequently is warmer than the rest. Temperature variations are high reaching near 11 °C. In the early afternoon (15:40 UTC), temperature distribution changes due to the position of the sun and temperature differences decrease. The southeast side of the greenhouse gets cold at the same time that the west side gets hot. At 20:40 UTC, sun has gone down and variations of temperature are low as at 5:00 and as is usual at night. Results show that the patterns are similar in the rest of days of the year. When sun rays strike in the walls and lateral windows (where there is not plastic cover), it heats this side of the greenhouse producing higher tempera-ture differences respect other areas in the greenhouse. Therefore, distribution of temperature inside the greenhouse is influenced by the position of the sun. Variations of temperature are high at midday and decrease as approach to night. In a nearby location and the same type of greenhouse, CFD simulations of Molina-Aiz et al. (2004) obtained variations of temperature close to these: 15 °C at 14:30 (July, 16th 2003), 5.3 °C at 19:30 (April, 18th 2003) and 4.8 °C at 20:15 (July, 13th 2003). It should be noted that this greenhouse has a larger area than the

[2] For interpretation of color in Fig. 6, the reader is referred to the web version of this article.

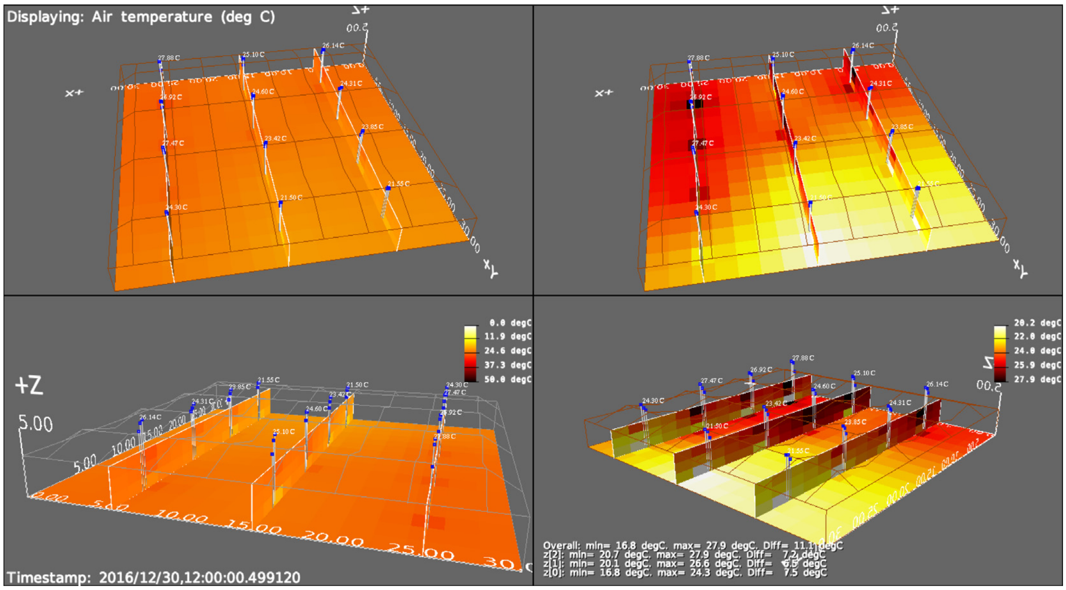


Fig. 6. Air temperature distribution inside the greenhouse (four different views). Image capture of the 3D video at 12:00 UTC, 30th Dec 2016.

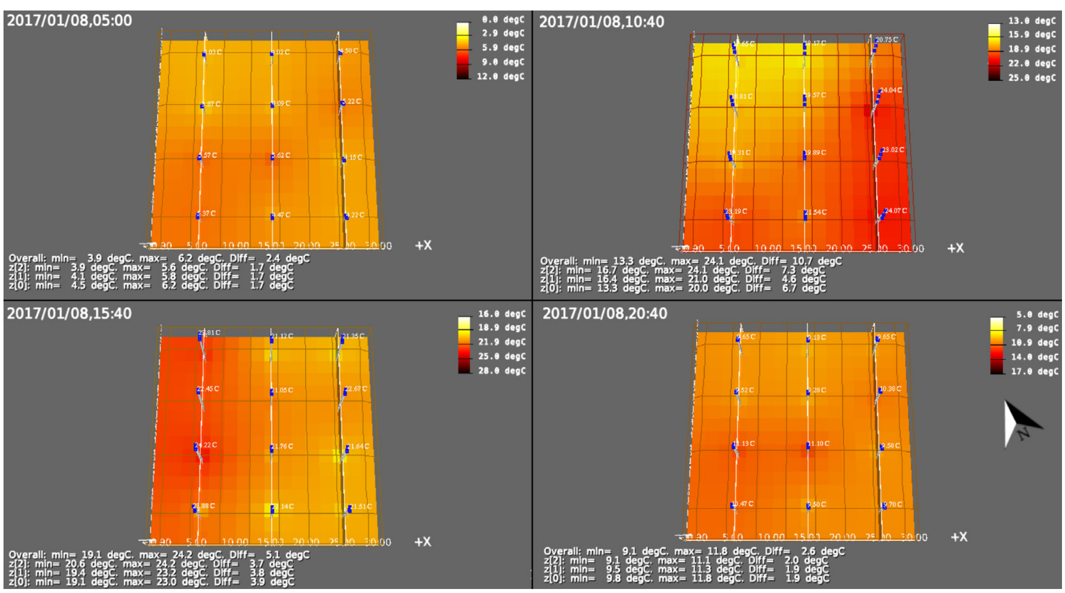


Fig. 7. Air temperature distribution inside the greenhouse at four different moments along a day (January, 8th 2017): 5:00 UTC, 10:40 UTC, 15:40 UTC and 20:40 UTC.

greenhouse studied in this work and temperature variations could be a bit higher for that reason.

3.2. Assess of air temperature heterogeneity

First, it has been studied the quantity of heterogeneous days per month and also per season (Figs. 8–11). So that, each day has been classified in one of the three categories: heterogeneous for more than 3 h, heterogeneous from 30 min to 3 h and homogeneous, where days with very shorts period of heterogeneity (less than 30 min of hetero-geneity) have also been included in the group of homogeneous days. The intervals of categories have been defined in this way to avoid considering a day heterogeneous with very few time or some ”peaks” of heterogeneity and to difference between days with low or high heterogeneity.

Figs. 8 and 9 represent the percentage of heterogeneous and homogeneous days per each month. Fig. 8 shows horizontal heterogeneity, where the heterogeneity (in some of the two categories of heterogeneity) is greater than 60% in all the months. In all the year, more than 80% of days are heterogeneous.

Similarly, Fig. 9 shows the vertical heterogeneity per months. It must be highlighted that the greenhouse is much more heterogeneous horizontally than vertically as it can be seen from the figures. In addition, when the environment is heterogeneous vertically, it is for less time than horizontally. Around 49% of the days are heterogeneous vertically in the complete year.

Figs. 10 and 11 shows the percentage of heterogeneous and homogeneous days, but in this case per season. In Fig. 10 the percentage of horizontal heterogeneous and homogeneous days per season is plotted. In winter and summer there is a higher percentage of homogeneous days than in autumn and spring.

In the same way, the percentage of vertical heterogeneous and homogeneous days is shown in Fig. 11. In this case, it seems that heterogeneity is concentrated in cold seasons (winter and autumn)

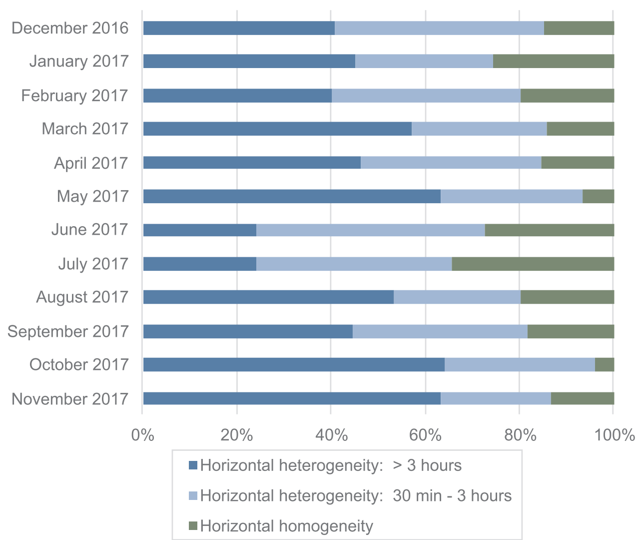


Fig. 8. Percentage of horizontal heterogeneous days per months.

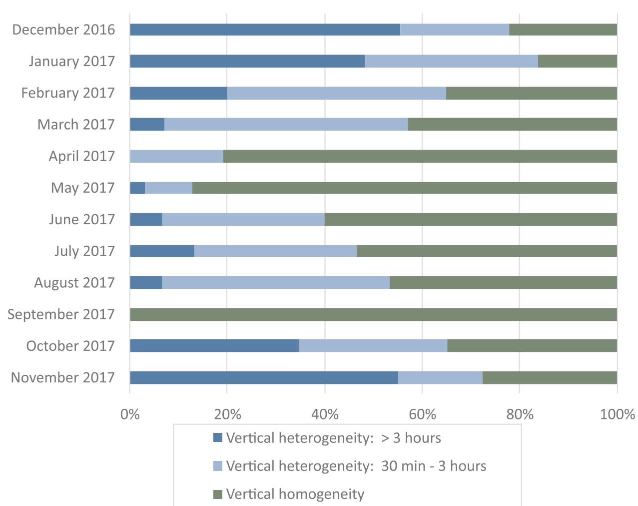


Fig. 9. Percentage of vertical heterogeneous days per months.

whereas in spring and summer there is a big quantity of homogeneous days.

Regarding the climatic conditions that favour the presence of heterogeneity, it has been observed a great influence of the clouds in the air temperature distribution inside the greenhouse. Thus, respect to the total horizontal homogeneous days (which were around 55), 75% of them correspond to cloudy days. On the other hand, only 33% of the heterogeneous days are cloudy. In the case of vertical homogeneity, 64% of the total homogeneous days (around 153) were cloudy. The percentage of cloudy days in the total heterogeneous days is only 16%. An example of this behaviour can be observed in Fig. 12, where horizontal heterogeneity, vertical heterogeneity and UVI are represented for two consecutive days (January, 27th and 28th 2017). In the graph of horizontal heterogeneity, the weighted mean air temperature of each measurement station is plotted in colour lines. The mean value of the 12 measurement stations is plotted in continuous black line, while discontinuous lines are the heterogeneity limits. It can be observed that the cloudy day is totally homogeneous whereas in the sunny day some of the measurements station surpass the heterogeneity limits at midday when UVI is high. In the graph that shows the vertical heterogeneity, the mean value for each height are represented in colour lines, while the weighted mean value and the heterogeneity limits are plotted in continuous and discontinuous black lines respectively. As for the

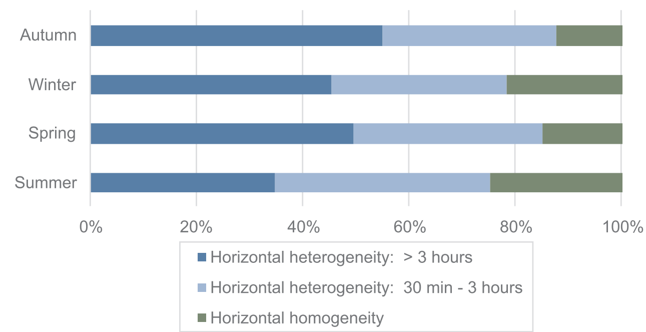


Fig. 10. Percentage of horizontal heterogeneous days per seasons.

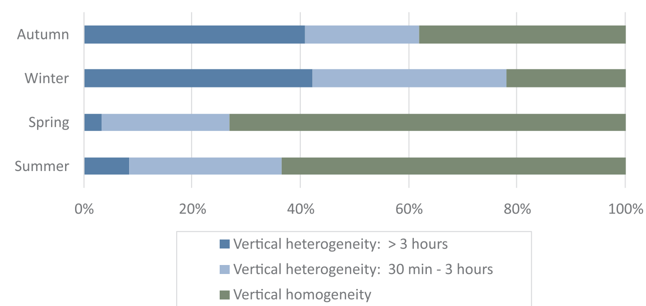


Fig. 11. Percentage of vertical heterogeneous days per seasons.

horizontal case, cloudy day remains homogeneous along the day, while the sunny day shows heterogeneity conditions.

Next, it has studied the periods of the day when heterogeneity is produced. In order to do it, it has been obtained the percentage of heterogeneous days (with respect to the total days of each season) but evaluated at every moment of time throughout the day. Heterogeneity, both vertical and horizontal, is produced in the central hours of the day and never at night. Fig. 13 shows the results for horizontal heterogeneity. Between 9 and 15 h are concentrated the greater percentages of heterogeneous days and it can also be observed that from 19 to 7 h the environment in the greenhouse is homogeneous. As in Fig. 10, spring and autumn are more heterogeneous horizontally than winter and summer.

In like manner, Fig. 14 shows the periods of the day when vertical heterogeneity occurs. In this case, the greenhouse is homogeneous approximately from 17 to 7 h. The period of heterogeneity is concentrated in less time and with lower percentages than horizontal heterogeneity. Winter and autumn (the coldest seasons) are more heterogeneous vertically than spring and summer as it can also be seen in Fig. 11. It must be highlighted that winter is the less horizontal heterogeneous season, but results to be the most heterogeneous vertically. Inversely occurs with spring, that is the most horizontal heterogeneous season and the less heterogeneous vertically.

For all the seasons except spring the shape of the curves are more or less similar both for horizontal heterogeneity and for vertical heterogeneity, increasing the percentage of heterogeneity until the maximum value was reached and from this point they decreased gradually until homogeneity is reached. However, in spring it can be observed that when the maximum value is reached, the percentage decreases but later increases again until finally decreases, producing a kind of valley in the shape of the curve around 13 h. In Figs. 13 and 14 also can be observed that heterogeneity lasts more time in seasons in which the day is longer as spring and summer. Therefore, it can be affirmed that heterogeneity depends on the sun hours during a day.

Finally, to evaluate quantitatively the heterogeneity, maximum air temperature differences respect to the mean value (in absolute value) and overall maximum air temperature differences inside the

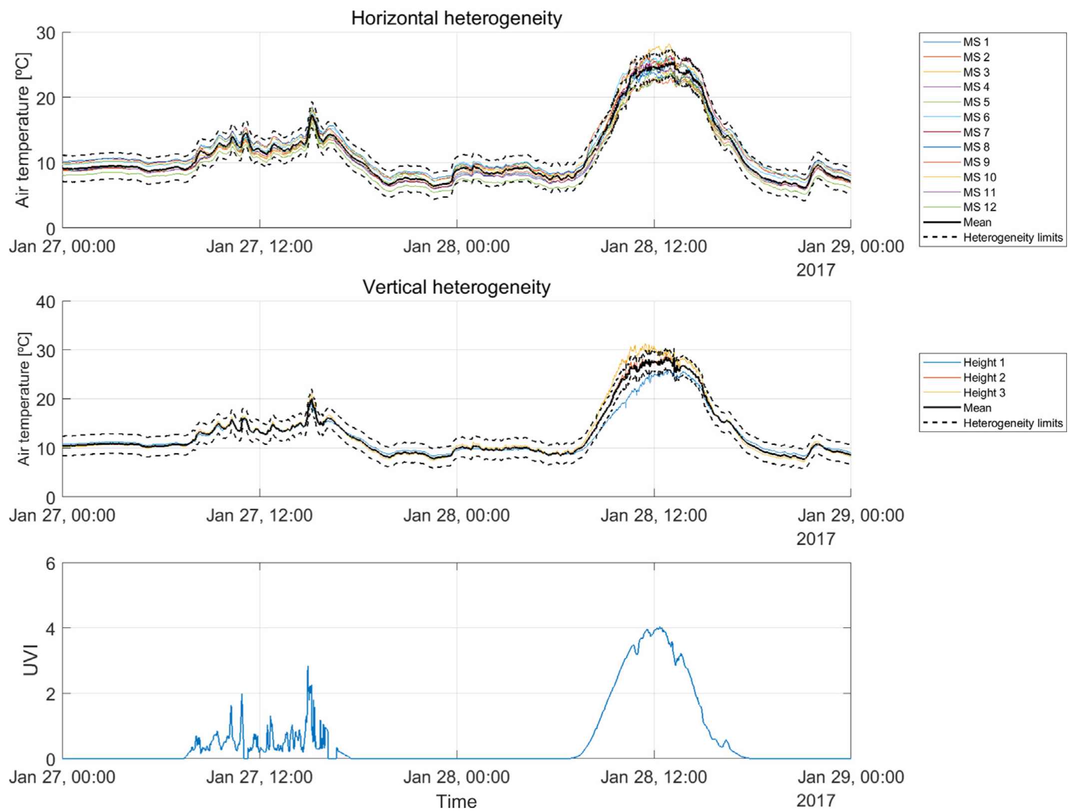


Fig. 12. Horizontal heterogeneity, vertical heterogeneity and UVI for two consecutive days (January, 27th and 28th 2017), the first one cloudy and the second one sunny.

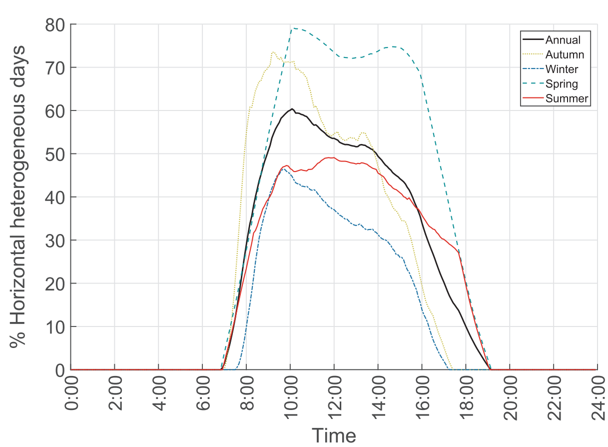


Fig. 13. Percentage of horizontal heterogeneous days at every moment of time throughout the day.

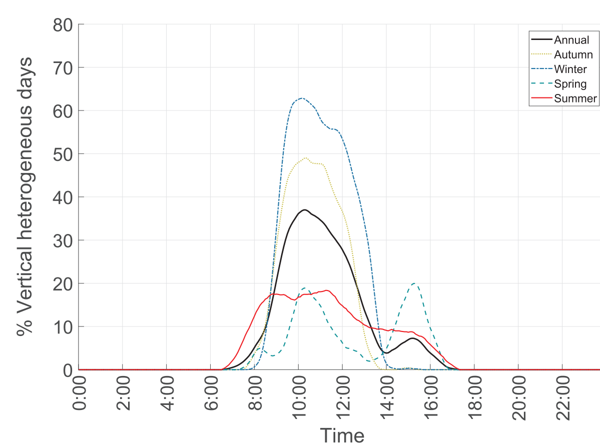


Fig. 14. Percentage of vertical heterogeneous days at every moment of time throughout the day.

greenhouse have been obtained for all the days in the complete year. For each instant of time, it have been calculated the mean, maximum and minimum values of these maximum air temperature differences for all the days of each season. This values have been plotted and compared in Figures from Figs. 15–19. Fig. 15 shows the maximum horizontal air temperature differences respect to mean value, in absolute value. The mean of these values exceed the heterogeneity limit for all the seasons, and the maximum value occurs in summer with a difference of 6.3 °C. In Fig. 16 the maximum vertical air temperature differences respect to mean value are shown, in absolute value. In this case, the mean of these values is lower than for horizontal heterogeneity and only exceed the heterogeneity limit for autumn and winter, justly in the seasons when there is more percentage of vertical heterogeneity. The maximum value takes place in winter (5.8 °C). It also can be observed that minimum values for vertical heterogeneity are close to 0 °C of difference and lower than for horizontal heterogeneity. It was seen before in Figs. 13 and 14 that heterogeneity occurs during the day and never at night, confirming in Figs. 15 and 16 that the maximum air temperature difference never exceeds the heterogeneity limit.

Figs. 17 and 18 represent the maximum horizontal and vertical air temperature differences, respectively. For horizontal differences, the mean values reach around 4 °C in all the seasons and the maximum value occurs in spring with a value of 8.4 °C. For vertical differences, it can be observed that the mean value is higher in autumn and winter, reaching values close to 4 °C while in spring and summer the mean value reaches around 2 °C. Something similar occurs for the maximum values, which are higher in autumn and spring, reaching up to 10.6 °C in winter. The minimum values for vertical dimension are lower than for horizontal one, in like manner that for the maximum air tempera-ture differences respect to mean value (Figs. 15 and 16).

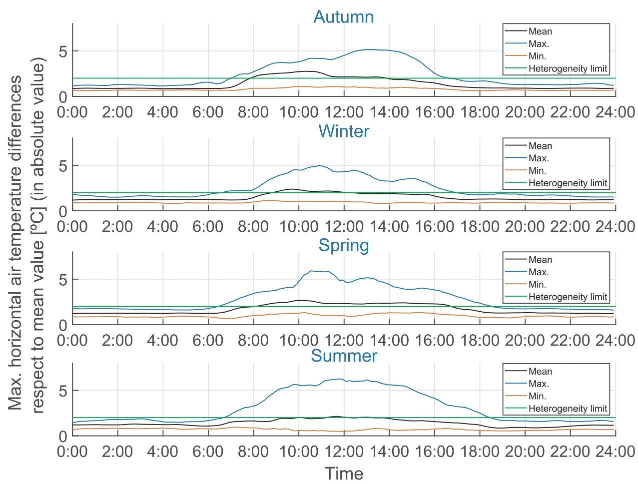


Fig. 15. Maximum horizontal air temperature differences respect to mean value, in absolute value.

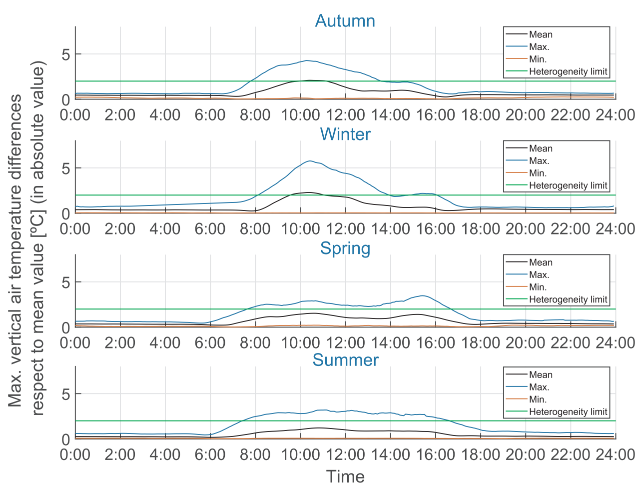


Fig. 16. Maximum vertical air temperature differences respect to mean value, in absolute value.

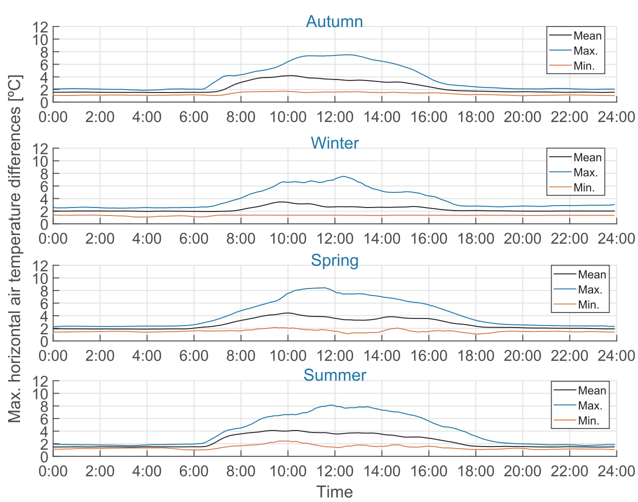


Fig. 17. Maximum horizontal air temperature differences.

Finally, Fig. 19 shows global maximum air temperature differences in the greenhouse. The maximum global air temperature difference is reached in spring and is 15.8 °C. It is observed that the mean value

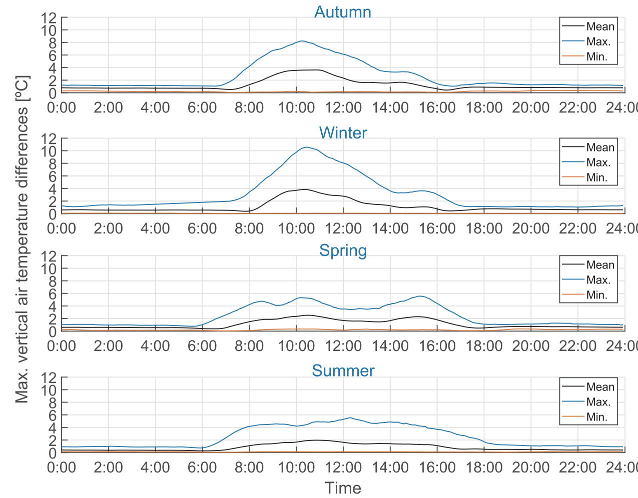


Fig. 18. Maximum vertical air temperature differences.

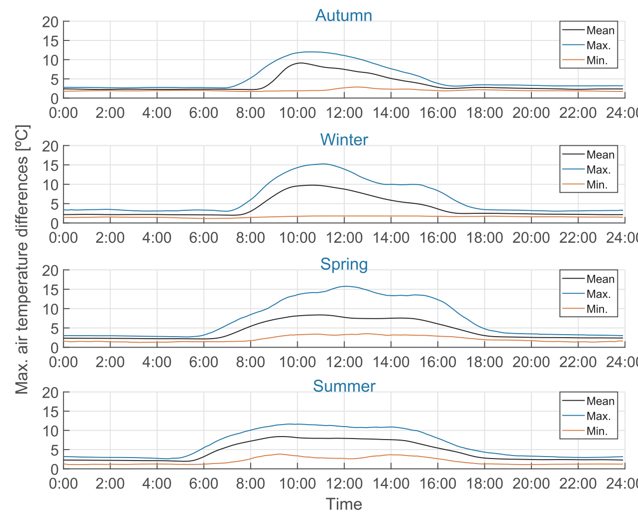


Fig. 19. Global maximum air temperature differences.

reaches more than 8 °C in all the seasons.

3.3. Relationship between air temperature and globe temperature inside the greenhouse

Greenhouse workers are exposed to diffuse solar radiation that goes through the plastic cover. This radiation is a factor to consider in the evaluation of the thermal conditions of the workers. Globe temperature is a qualitative measure of the incident radiation when compared with respect to the air temperature. Although to lesser extend tan direct solar radiation, diffuse solar radiation also causes an increment in globe temperature. Fig. 20 shows mean monthly air temperatures vs. mean monthly globe temperatures. Since including the 24 h of the day will do not give relevant information, especially at night, when air temperature and globe temperatures equals, the daily time interval included has been only from 10 to 15 h, when solar radiation is high (see Fig. 12). In Fig. 20, globe temperature vary from around 25 °C in December to more than 50 °C in July. The largest differences between globe temperature and air temperature occur in March and April (around 7–8 °C), while the shortest differences take place in November and December (around 4 ° C). It can be observed that the consecutive monthly values draw a closed curve without loops. This representative curve shows that the diffuse solar radiation produces larger variations between globe tem-perature and air temperature in winter and spring than in autumn and

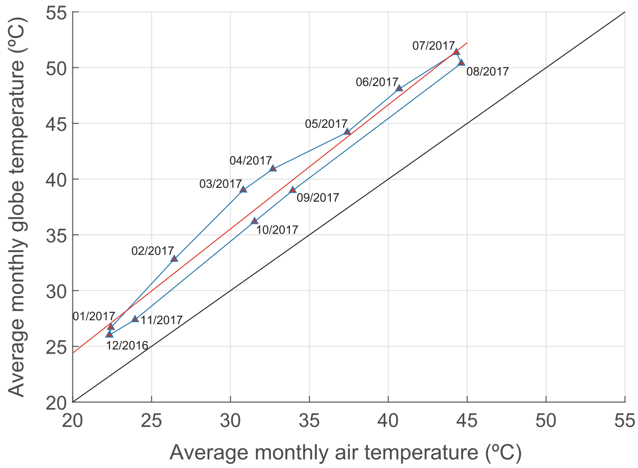


Fig. 20. Relationship between mean monthly air temperature and mean monthly globe temperature inside the greenhouse from 10:00 to 15:00 h.

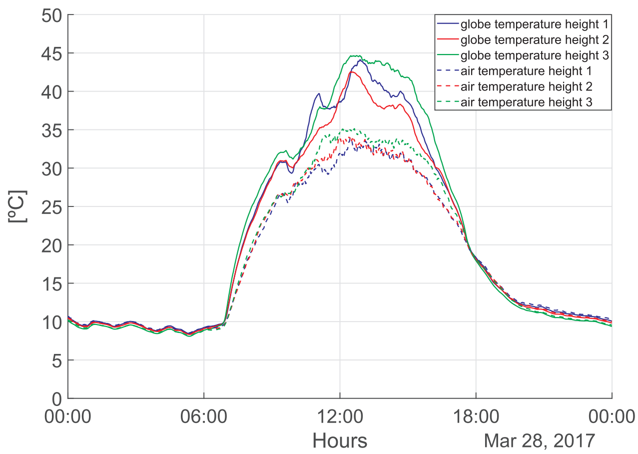


Fig. 21. Globe temperature and air temperature for the 3 heights measured during March, 28th 2017.

summer, respectively. In view of these results, although there is a trend to increase this difference when sun altitude is higher (summer solstice), this is not only related with the solar radiation, where in the months of June and July would achieve the maximum values.

In Fig. 21, globe temperature and air temperature for a day (March, 28th 2017) are plotted for the three heights measured. This day has been selected because is a day with high differences between globe temperature and air temperature, obtaining a maximum difference of 11.6 °C.

3.4. Recommendations for assessing the thermal environment inside greenhouses

Based on the results discussed above, the authors of this work propose the following recommendations for assessing the thermal environment inside a greenhouse:

- Any greenhouse will probably be a heterogeneous environment with respect to the air temperature according to the ISO 7726 Standard. Therefore, measurements must be taken at different locations, both horizontally and vertically, to asses the horizontal and vertical heterogeneity, respectively.
- Whether the environment must be considered heterogeneous or not is a condition that changes along the day. Larger air temperature differences usually take place at the central hours of the day, which also correspond with the highest values of air temperature. Therefore, it is recommended to include this period of time in the measuring schedule. Besides this, the work schedule of workers must be, obviously, also considered when designing the measurement schedule.
- The presence of clouds is a critical factor for the air temperature distribution inside the greenhouse. Cloudy days favour homogeneity, while also softening temperature values. Therefore, measurements should be scheduled preferably during sunny days.
- According to the ISO 7726, measurements must be taken at three heights (ankle, abdomen, and head) to evaluate the vertical heterogeneity. Regarding the horizontal heterogeneity, the Standard does not provide recommendations about the number of points or the places where measuring stations must be placed. The results obtained in the present work shows that the horizontal air distribution is conditioned by the azimuth and elevation of the sun. North–South and East–West air temperature differences have been observed along the greenhouse. Accordingly, at least four measurement points distributed with respect the Cardinal points are recommended.
- Greenhouse thermal conditions inside greenhouses are not controlled and show large variations along the year. For a complete evaluation of the heat stress or cold risk, the study should be extended along a complete year. Results provided in this work may be useful to select the most appropriate periods to evaluate the heat stress risk.
- Regarding the WSN used to gather the measurements, it is strongly recommended to place radio antennas at a height high enough to avoid the loss of line of sight between antenna pairs for each transmission link, taking into account the over-the-year growth of the crop. This becomes particularly important for radio bands in the GHz range, due to the strong absorption (attenuation) of radio waves by living (wet) plants.

4. Conclusions

This work has been focused on studying the air temperature distribution and its heterogeneity conditions in a “raspa y amagado” greenhouse through a complete year. The results provide experimental measurements for a typical greenhouse during a complete year, in an area where agriculture under plastic have a great influence in the economy and is an important source of employment. Until now, there is no deep study on the thermal conditions and risk of heat stress of the greenhouse workers that meets with ISO 7726 requirements. The measurements together with the measuring instruments used in the present work meet with the requirements and methods gathered in ISO 7726 to study the thermal environments. Therefore, the results obtained of air temperature distribution and heterogeneity conditions can be useful for further studies of the heat stress risk of workers.

Heterogeneity has been confirmed for large periods of time, in both vertical and horizontal directions. The study reveals that the environment is more heterogeneous horizontally than vertically. Besides, winter and summer are more homogeneous horizontally than autumn and spring whereas vertical heterogeneity is concentrated in cold seasons. Globally, Periods of time during the day of horizontal heterogeneity are greater than of vertical heterogeneity. It has been also observed a big influence of clouds in horizontal and vertical homogeneous days, with most cloudy days correlating with homogeneous days. Air temperature heterogeneity fundamentally depends on the sun, with heterogeneity happening in the central hours of the day and never at night. Also, the differences of temperature along the greenhouse has been observed in West-East and North–South direction according with the sun movement.

Plastic cover of greenhouses allows the incidence of diffuse solar radiation towards its interior. This is a factor to take into account for the evaluation of the thermal conditions of the workers, since it causes variations of up to around 12 °C between globe temperature and air temperature.

Finally, based on the results obtained some recommendations are presented for assessing the thermal environment of greenhouses.

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