Approach to the evaluation of the thermal work environment in the greenhouse-construction industry of SE Spain

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ABSTRACT

The aim of the present work was to evaluate the thermal environment of workers in the greenhouse-construction industry in SE Spain. For this, the heat stress of these workers was evaluated by the WBGT index, on developing quadratic equations of the maximum and minimum of this index according to the time of day. High correlation coefficients and good distributions of residuals were found. This evaluation revealed a high or very high risk of heat stress during the months of June to September over a large part of the work day, especially from 9:00 to 18:00 h (GTM). For this, work-rest regimes are proposed in order to control this risk. Finally, the application of the ESI index has been validated for determining the heat stress in greenhouse-construction workers in SE Spain.

1. Introduction

Spain has one of the highest accident rates in the European Union (EU), where the construction industry represents 27.3% of the labour accidents; of these 34.6% are serious, while 33.9% are mortal [1–3]. Some 74% of construction involves buildings, where 35.2% of the mortal accidents occur and 43% of all accidents [4].

In Spain, accidents from heat stress cause deaths in the construction sector due to the bad organization and prevention on the job. For the period 1990–2000, the greatest number of accidents in the construction industry were from overexertion (20.9%), followed by blows from materials and tools (20.5%), and falls from one level to another (10.7%), while exposure to high temperatures accounted for 0.1% [3]. However, if only the fatal accidents are analysed, falls from heights are the most significant (33.8%), followed by blows or being run over by a vehicle (15.9%), while exposure to high temperature reaches 0.2%. However, not only do such deaths occur in this sector, but also, as indicated by Armendáriz [5], heat stress occurs in jobs that require or generate a great quantity of heat, such as in the iron and steel industry, glass, and ovens in general, and in activities requiring strenuous physical exertion, as in agriculture and construction. Critical states of heat stress can provoke irritability, increased aggressiveness, distraction, errors, discomfort from sweating and trembling, accelerated or slowed pulse rate, etc., with negative repercussions on health and, in extreme situations, death [6–9].

In agreement with Chad and Brown [10], environmental heat considerably influences cardiovascular and thermoregulatory systems of workers undertaking heavy as well as light tasks. Therefore, Maiti [11], evaluating the work load in the construction industry of India, recorded values both of physical load as well as heat stress that exceeded the limit values recommended by health guidelines. In these circumstances, the construction workers felt that their effectiveness in their job was determined not only by the physical load of the work, but also by the impact of the physical environment, so that a greater environmental load diminished work efficiency while augmenting the potential for accidents. Kähkönen et al. [12] found similar results on determining the heat stress for several production sections, including construction in Tanzania. In this sense, Fundación MAPFRE [13] reported that in work environments with high temperatures, the attention and state of awareness of the workers diminished, altering job effectiveness and worker safety. Kroemer and Grandjean [14] found a correlation between work performance and higher environ-mental temperatures at work, while Miller and Bates [9] showed the deleterious effects of high air temperature on workers in the open air who did not receive adequate water. Thus, all workers active during the warm months should undergo a regime of work and rest in order for the body to maintain adequate temperature balance and hydration [9,15,16]. In addition, Zhao et al. [17] mentioned that workers in warm and humid environments tended to store heat in the body and to suffer an electrolyte imbalances, for which they could suffer a heat stroke from the loss of heat by evaporation, although the air temperature might not be very high. Furthermore, these authors indicated that the depressed excitability of the nerves and muscles, faulty concentration, and poor precision in tasks could result in lower productivity as well as higher accident rates. Many studies have identified the factors affecting worker productivity in the construction industry throughout the world [8,18–27], examining climate effects in general, and particularly the work environment, in relation to productivity [8,17,23,28–36]. The work of Hancher and Abd-Elkhalek [8] stands out with respect to the effect of the thermal environment on construction-worker productivity, based on the WBGT (Wet Bulb Globe Tempera-ture) heat stress index, which is determined from the air temperature, wet-bulb temperature, globe temperature, air humidity, sun exposure, type of clothes worn by the worker, and the worker exertion according to the task performed, which is the heat stress index adopted by the ISO 7243 [37] standard to determine heat stress. Srinavin and Mohamed [23] proposed a model to evaluate productivity as a func-tion of the thermal environment based on the PMV index [38], which considers the air temperature, relative humidity, radiant temperature, wind velocity, nature of the construction work, and the worker's clothes. Finally, Zhao et al. [17] proposed a model where they deter-mined the productivity of construction workers in a warm, humid environment in China, according to the WBGT heat stress index and to time of heat tolerance of the workers under these conditions, in turn formulating another model to calculate this tolerance time according to the WBGT heat stress index. Each model presented a different regression equation as a function of the intensity of the labour per-formed: heavy, moderate, light.

As shown, to evaluate heat stress in the workplace, specific indices have been developed, which can be classified into three groups according to their nature [39–41]: indices calculated using heat-balance equations ("rational indices"); indices based on objective and subjective tensions ("empirical indices"); and indices based on the direct measurement of environmental variables ("direct indices"). Clearly, the indices of the first two groups are more difficult to implement in the workplace, since they involve too many variables and some involve invasive measures. However, the third group of indices proves simpler and more applicable, since only environmental variables are involved. Thus, with respect to the direct indices, as far back as the beginning of the 20th century, Haldane [42] proposed an index based on wet-bulb temperature and, since then, a multitude of indices have been developed, for example: the DI (Discomfort Index)[43], the modified DI [44], MDI (Modified Discomfort Index) [45], SI (Simple Index) [46], and ESI (Environment Stress Index) [46,47]. There are reviews describing the indices developed as well as their advan-tages and disadvantages e.g. Goldman [48], Epstein and Moran [41]. The index most widely used internationally to evaluate heat stress is the WBGT proposed by Yaglou and Minar [49], which was later complemented with criteria of ACGIH, OSHA, and NIOSH, standard ISO 7243 [37] and adopted as the reference index to determine the heat stress in the workplace, although this index, like all others, has limited use, as shown by several authors [41,46,47,50–52].

In this context, Spain has among the largest surface areas of plastic-covered greenhouses worldwide, reaching some 45000 ha [53,54], with extremely dense concentrations in SE Spain, particularly in the province of Almería, with 26500 ha [55,56]. Here, intensified agriculture specializes in greenhouse-grown vegetables, with high input and yield, which generates the greenhouse-construction industry. Greenhouses are agricultural buildings with light, low-cost structures that provide the microclimatic conditions needed for year-round crops [57]. The traditional greenhouse model used in south-eastern Spain is called "*parral*", although in recent decades, this has been replaced by improved models called "*raspa y amagado*" and the multi-gabled model, which allow better climate control as well as automation [58].

New greenhouse construction as well as the maintenance and rehabilitation of the pre-existing ones occur mainly from June to September [59], raising high demand for labourers and making it common to hire workers without training or experience. Several authors [59–62] relate this to labour accidents in the construction industry. In addition, the greenhouse-construction companies are small, with limited resources and few workers [59], leading to a greater probability of accidents due to poor preventive measures [63,64]. The low-technology construction systems used in general implement few accident-prevention techniques for work safety [59,65,66].

Research on safety in this field is rather scanty in Europe, with the exception of notable studies in Sweden [67,68] that relate the common causes of accidents with associated injuries, categorizing the tasks of maintenance and repairs of greenhouse structures as one with the greatest risks. In Spain, Callejón-Ferre et al. [69] recently analysed the working conditions of agricultural workers in greenhouses of SE Spain in general, although without consid-ering those of the greenhouse-construction workers. Later, several direct indices of heat stress determined the stress suffered by workers inside the greenhouses performing cultivation tasks [70].

In addition, Pérez-Alonso et al. [66] recently evaluated the labour risks of different greenhouse-construction phases of SE Spain, pointing out the risk of heat stress as the cause of accidents and furthermore as the initial cause of many other accidents. Finally, Pérez-Alonso et al. [59] characterized the preventive activity of the greenhouse-construction industry of SE Spain, concluding that the management of labour risk is very poor, with no internationally recognized work-risk prevention programmes being adopted, and correlating the size of the company with its preventive activity (larger companies having more preventive activity).

2. Objectives

In light of the incidence of labour accidents due to heat stress, which also triggers other accidents, as well as the fact that heat stress strongly influences worker efficiency in the construction industry, as noted in the Introduction, it becomes necessary to identify which period of the work day of each warm month exceeds the limits established by the standards, in order to control heat stress among workers of greenhouse-construction companies active in SE Spain.

The specific objectives of the paper are:

- To determine the heat stress to which greenhouse-construction workers are subjected in SE Spain, using the WBGT index [37], during the warm period, which coincides with the highest activity of this construction sector. Also, the fluctuation of the work period over the day is characterized by mean and maximum values of the WBGT index for each month of activity with high temperatures.
- To determine the correlation of the ESI index with the WBGT index for the working conditions of the greenhouse-constructions employees in south-eastern Spain.

3. Material and methods

3.1. Study location

The experimental phase of the present study, in which the climatic data were recorded in order to determine the heat stress indices, was conducted in a plot (36°49′47.9994″N – 2°23′24″W) some 2 km from the University of Almería, since the location of the work environment is representative of the greenhouse-construction industry of SE Spain, with Almería being its chief exponent, with 26,500 has of greenhouses, representing 58.9% of the surface area of all the greenhouses in Spain [55].

In addition, to correlate the ESI index with the WBGT index, climatic data have also been used from the weather station of the Almería airport (36°50′38″ − 2°22′12″W).

3.2. Calculations

The thermal environment of the work was determined by applying the standard ISO 7243 [37], which prescribes the use of the WBGT index, which was calculated from the combination of two or three environmental parameters: wet-bulb temperature (Twn), globe temperature (Tg), outside environment with solar radiation, and the dry air temperature (Ta).

The WBGT was calculated from the following equations according to the standard ISO 7243 [37]:

- In the interior of buildings or on the exterior without solar radiation:

$$\mathrm{WBGT} = 0.7 \cdot \mathrm{Twn} + 0.3 \cdot \mathrm{Tg} \tag{1}$$

- On exteriors with solar radiation:

$$\mathrm{WBGT} = 0.7 \cdot \mathrm{Twn} + 0.2 \cdot \mathrm{Tg} + 0.1 \cdot \mathrm{Ta} \tag{2}$$

When the temperature is not constant around the workplace, in such a way that there may be notable differences between the measurements made at different heights, the WBGT should be calculated from three measurements: at the level of the heals, abdomen, and head. This means taking measurements at 0.1 m, 1.1 m, and 1.7 m from the ground if the working position is standing, and at 0.1 m, 0.6 m, and 1.1 m, if seated. If the environ-ment is homogeneous, it suffices to take measurements at abdomen height (1.1 m), as in the case of construction workers in general and in greenhouse construction in particular.

Thus calculated, the WBGT expresses the characteristics of the environment and should not exceed a certain value limit that depends on the metabolic heat (M) that the individual generates while working, i.e. the quantity of heat produced by the organism per unit of time, which is a necessary variable to evaluate heat stress. For this estimate, the data of metabolic consumption can be used, this being the total energy generated by the organism per unit of time (power), as a consequence of the task being performed by the individual, disregarding in this case the useful power (given that output is very low) and considering that all the energy consumed is transformed into caloric energy. Metabolic heat can be measured through oxygen consumption by the individual, or estimated through tables [41]. In addition, the insulation of work clothing must be considered in order to determine the level of heat stress. In this case the insulation is considered to be 0.6 clo, since the workers dress in trousers and tee-shirts typical of months of high temperatures; in fact, workers in SE Spain often do not even wear a tee-shirt during the heat of the day [66]. Several types of tables offer information on energy consumption during work. For the present research, the tables proposed by the standard ISO 7243 [37] were adopted to determine both the metabolic consumption as well as the limit reference values of the WBGT index (Table 1), which amount to five, one for each type of different metabolism. Construction workers, due to the construction tasks performed, present a type-2 and -3 metabolism [11,52]. In this sense, it is necessary to describe the different types of activities performed by the greenhouse-construction workers in south-eastern Spain, on undertaking the different stages of the construction process. In a simplified way, the stages of the construction process of a greenhouse of the Almería type are described in Fig. 1. In agreement with Pérez-Alonso et al. (2008), these activities can be classified as follows:

a) Direction and coordination of the work. This is the technician that assumes control of the execution of the work, as well as the work of coordinating health and safety, in addition to overseeing the layout and measurement of the parcel.

b) Boss or person in charge of the work. This is the worker responsible for supervising the work of all the phases of the building of the greenhouse, ordering materials and machinery for each phase of the work and assuming daily control of these activities. At times, this person drives the truck or van that transports the materials, equipment, and tools. Another specific job that is often carried out is the supervision of the alignment of the pillars when installed, as well as the correct forming until the concrete has set.

c) Masonry and framers. These are the workers in charge of all the building tasks, such as the building of perimeter walls and laying of foundations. In addition, they construct all the rigid structural elements.

d) Cable stretchers. These workers stretch and connect the cable structure of the greenhouse. The range of tools and equipment that they use is very broad, including winches to stretch the cables and all the tools used in bending, cutting and stretching wire, such as wire cutters, pliers, and wrenches.

e) Welders. These workers weld and solder metal elements during the greenhouse construction. The work usually involves an electric welder so that there is no need for electricity at the building site, or, if utilities are available, a generator can be used.

f) Plastic workers. These apply the plastic sheeting to the greenhouse, both on the roof as well as the walls of the structure. The work of placing the plastic on the roof is performed more than 2 m from the ground and tools to cut and seal plastic are used, as well as ladders and sometimes scaffolding (not usual) to climb onto the roof.

Table 1
Reference limit values of the WBGT index (°C) corresponding to different situations according to the standard ISO 7243 (1989).

Type of metabolism	Metabolism range		WBGT reference limit values	
	Referring to surface area unit of skin (W m^{-2})	Total for a surface area of 1.8 m^{-2} (W)	Heat-acclimated persons	Non-heat-acclimated persons
0 (Rest)	$M < 65$	$M < 117$	33	32
1	$65 < M < 130$	$117 < M < 234$	30	29
2	$130 < M < 200$	$234 < M < 360$	28	26
3	$200 < M < 260$	$360 < M < 468$	25[a]–26[b]	22[a]–23[b]
4	$M > 260$	$M > 468$	23[a]–25[b]	18[a]–20[b]

[a] still air.
[b] moving air.

Fig. 1. Stages of the greenhouse-construction process: (A) Weed clearing, land levelling, and soil preparation, (B) replanting, (C) digging and perforation of holes for the foundations and anchors, (D) foundations and anchors, (E) building of the structure, (F) placement of the plastic and (G) installation of windows and doors.

g) Drivers of vehicles with mechanical traction. The work of driving, handling, and maintenance of the machinery is in charge of two operators with official certification. The machinery or vehicles used are usually trucks, vans, tractors, excavators, augurs, concrete mixers, dumpers, etc.

h) Personal assistant. These are helpers for the specialized workers in the different jobs mentioned above. The tasks performed include soil preparation in the greenhouse, mixing the manure and sand, as this is prepared during the construction of the greenhouse.

Finally, calculations were made for the heat stress index ESI (Environmental Stress Index) proposed by Moran et al. [46] and validated by Moran et al. [47], to be correlated with the WBGT index, and to be validated in SE Spain. The following equation resulted:

$$\begin{aligned} \mathrm{ESI} = {} & 0.63\mathrm{Ta} - 0.03\mathrm{RH} + 0.002\mathrm{SR} + 0.0054(\mathrm{Ta}\cdot\mathrm{RH}) \\ & - 0.073(0.1 + SR)^{-1} \end{aligned} \tag{3}$$

where Ta (°C) is dry air temperature, RH (%) air humidity, and SR (W m^{-2}) solar radiation.

3.3. Experimental data

To determine the variation of the WBGT heat stress index over the work day for the warmest period in the thermal work environment as well as the ESI index, environmental variables were recorded: Twn (°C), wet-bulb temperature; Tg (°C), globe temperature; Ta (°C), dry air temperature, Ua ($\mathrm{m\ s^{-1}}$), wind velocity; RH (%), relative humidity; and SR ($\mathrm{W\ m^{-2}}$), solar radiation. These data were taken every 5 min each hour daily from 06:00 h to 19:00 h (GTM), from June to September 2009, the period of highest temperatures of the year in the study area. This is also the period in which new greenhouses are built and existing ones are maintained and therefore is the period when the workers in this sector most suffer heat stress [59,66]. To measure these parameters, an instrument to control the microclimate (HD32.1- Thermal Micro-climate de Delta Ohm Srl) was used with probes described in Table 2.

In addition, to compare the ESI index, the hourly data of the same daily and monthly period were analysed for the WBGT index: Ta (°C), dry air temperature, Ua ($\mathrm{m\ s^{-1}}$), wind velocity; RH (%), relative humidity; and SR ($\mathrm{W\ m^{-2}}$), solar radiation of the weather station at the Almería airport (Spain), provided by the Spanish Weather Agency (Agencia Española de Meteorología; AEMET), but in this case, the data corresponded only to a single hourly record (each hour on the hour) of the period in question.

3.4. Data analysis

First, a descriptive analysis was made of the climatic parameters recorded in the data-gathering phase, as well as those provided by AEMET at the Almería airport (Spain). Afterwards, the WBGT index was calculated for each of the 12 records every 5 min of each hour of the day from 06:00 h to 19:00 h (GTM) for the four study months, thereby determining the mean values, standard deviation, and range of this index for each of the 13 hourly intervals of the experimental days, as well as for the maximum WBGT, its maximum value, stan-dard deviation, and range of each hourly interval each day. Next, a univariate analysis of variance (ANOVA) was used to determine the mean and maximum WBGT with respect to the variables hourly period of the day and month.

Table 2
Characteristics of the probes of the instrument HD32.1- Thermal Microclimate.

Parameters	Probe characteristics
Tg (°C)	Globe temperature probe, thin-film sensor Pt100, flat-black globe Φ 150 mm surface area, measurement field −10 °C ÷ 100 °C, uncertainty measured: Class 1/3 DIN
Tnw (°C)	Double wet-bulb probe with natural ventilation and dry-bulb temperature probe, temperature sensor Pt100, measurement field 4 °C ÷ 80 °C, measurement uncertainty: Class A
Ta (°C); RH(%)	Combined temperature and relative-humidity probe, RH capacitive sensor, thin-film Pt100 temperature sensor, measurement field −10 °C ÷ 80 °C, and for RH 5% ÷ 98%, measurement uncertainty: 1/3 DIN for temperature and ÷2.5% for RH
Ua ($\mathrm{m\ s^{-1}}$)	Omnidirectional hot-wire probe, measurement field: air velocity 0 ÷ 5 $\mathrm{m\ s^{-1}}$, measurement uncertainty ÷0.1 $\mathrm{m\ s^{-1}}$, work temperature 0–80 °C. Ventilator probe Φ 16 mm, measurement field: velocity 5 ÷ 50 $\mathrm{m\ s^{-1}}$, resolution 0.01 $\mathrm{m\ s^{-1}}$, working temperature − 25 ÷ 80 °C
SR ($\mathrm{W\ m^{-2}}$)	Pyranometer, measurement field 0 ÷ 2000 $\mathrm{W\ m^{-2}}$, resolution 0.1 $\mathrm{W\ m^{-2}}$, sensitivity 285–2800 nm

Afterwards, for the two series calculated from the mean and maximum WBGT, the variables (by hourly period) and WBGT index were represented in a two-dimensional graph for easy visualization of the hourly distributions as well as the cut-off points with the limit values prescribed by the standard ISO 7243 [37]. In addition, quadratic regression curves were drawn for each of the four months studied, both for mean and maximum WBGT, providing the coefficient of determination of the model (R^2) and the scattergrams of the series of residuals against the predicted values, adopting a significance level of $p < 0.01$ for all the comparisons. With these regression curves, by intersection with the straight lines of null slope that represent the limit values of mean and maximum WBGT set by the standard ISO 7243 [37], values were found for the hours of the day that limit the interval where the heat stress occurs. Finally, to correlate the ESI and WBGT indices in south-eastern Spain, the ESI index was calculated for the data recorded in the experimental parcel as well as those from the Almería airport, and Pearson's correlation coefficients were determined between the two indices. For all the statistical analysis made, the program SPSS Statistics 17.0 was used.

4. Results

From the data recorded in the experimental plot, and those provided by the AEMET for June and September, Table 3 presents the results of the descriptive analysis made using the climatic variables recorded.

Table 4 presents the mean hourly values for each month for the WBGT index, in addition to its mean, standard deviation, and range each month. Similarly, Table 5 lists the hourly maximum values of the WBGT each month as well as the mean, standard deviation, and range each month.

Also, from the ANOVA for the mean and maximum WBGT, with respect to the variables hourly period of the day and month, Tables 6 and 7 indicate the hourly and monthly periods that showed statistically significant differences in the value of the mean and maximum WBGT, respectively.

The values of the mean and maximum WBGT index by hourly periods of each month can be seen in Fig. 2 together with the limit values prescribed by the standard ISO 7243 [37] for metabolism types 2 and 3 for persons acclimated or not to heat, and according to whether there was appreciable air movement or not.

After the quadratic regression curves were drawn for each of the four study months both for the maximum and mean WBGT, the expressions of which are shown in Table 8 together with their coefficients of determination (R^2), the hours of each work day per month (shown in Table 9) in which problems due to heat stress could arise were identified, in agreement with the values admitted by the standard ISO 7243 [37].

Finally, Table 10 shows the Pearson's correlation coefficients determined between ESI and WBGT indices.

5. Discussion

5.1. Study limitations

The thermal environment of greenhouse-construction workers in Spain was evaluated in Almería, as it is the province with the

Table 3
Mean (±SD) and range of experimental climatic variables for each data series.

	Twn (°C)	Tg (°C)	Ta (°C)	Ua (m s^{-1})	RH (%)	SR (W m^{-2})
Experimental plot	23.57 ± 2.38	36.34 ± 4.89	30.24 ± 2.58	4.06 ± 3.49	48.63 ± 9.51	488.60 ± 245.56
	14.50–28.70	20.10–47.10	20.90–38.40	0.00–21.08	14.20–82.30	0.00–979.00
Almería airport			28.59 ± 3.04	5.11 ± 2.96	54.05 ± 14.64	548.01 ± 271.60
			19.50–37.30	0.00–16.11	16.00–84.00	5.56–969.44

greatest surface area of greenhouses in Spain, although other zones of SE Spain may have different thermal environments, depending on local environmental parameters.

5.2. Descriptive analysis of the environmental parameters

The field data for environmental variables presented in Table 3, recorded in the experimental plot, indicate that the wet-bulb temperature ranged between 14.50 and 28.70 °C, with a mean value of 36.34 ± 4.89 °C; the dry-bulb temperature fluctuated between 20.90 and 38.40 °C, with a mean value of 30.24 ± 2.56 °C; wind velocity was between 0.00 and 21.08 m s^{-1}, with a mean value of 4.06 ± 3.49 m s^{-1}; relative humidity varied between 14.20 and 82.30%, with a mean value of 48.63 ± 9.51%; and solar radiation ranged 0.00e979.00 W m^{-2}, with a mean of 488.60 ± 245.56 W m^{-2}. Similarly, for the data recorded at the Almería airport, the dry-bulb temperature fluctuated between 19.50 and 37.30 °C, with a mean value of 28.59 ± 3.04 °C; wind velocity ranged 0.00e16.11 m s^{-1}, with a mean value of 5.11 ± 2.96 m s^{-1}; relative humidity varied from 16.00 to 84.00%, with a mean of 54.05 ± 14.64%; and solar radiation ranged 5.56e969.44 W m^{-2}, with a mean of 548.01 ± 271.60 W m^{-2}. The minor variations between the different environmental parameters for the experimental plot and the Almería airport were due fundamen-tally to the different position and the number of hourly measure-ments on the plot (12) vs. only one record per hour at the airport. A comparison of these data with those of studies in other countries and different periods would be biased and therefore was not undertaken, except with respect to the study by Gaspar and Quintela [52], per- formed at the University of de Coimbra (Portugal), for its proximity to SE Spain. For a period of data records of only 9 days in August 2006 for 4 h per day with 15 measurements per hour, the wet-bulb tempera-ture fluctuated between 19.10 and 22.50 °C, with a mean value of 20.90 ± 0.90 °C; the globe temperature varied between 40.10 and 51.70 °C, with a mean value of 45.30 ± 3.50 °C; dry-bulb temperature fluctuated between 27.80 and 39.20 °C, with a mean value of 33.60 ± 3.00 °C; wind velocity ranged 0.70e2.9 m s^{-1}, with a mean value of 1.70 ± 0.60 m s^{-1}; and solar radiation varied between 644.00 and 923.00 W m^{-2}, with a mean value of 812.60 ± 85.00 W m^{-2}.

5.3. The thermal environment of greenhouse-construction workers in SE Spain

From the field data recorded for the environmental parameters on the experimental plot, the values of the WBGT index were calculated for each hourly period of the day. Table 4 presents the mean values of the WBGT index, while Table 5 lists the maximum values. As can be seen in Table 4 and Fig. 2, for June, the range of the mean WBGT index varied between 20.70 and 26.71 °C, with a mean value of 24.82 ± 2.00 °C, with a maximum (26.71 °C) between 13:00 and 14:00 h; for July the mean WBGT index range was between 24.89 and 29.76 °C, with a mean value of 28.15 ± 1.61 °C and a maximum (29.76 °C) between 14:00 and 15:00 h; for August the mean WBGT index ranged from 23.73 to 29.14 °C, with a mean value of 27.59 ± 1.75 °C and a maximum (29.14 °C) between 12:00 and 13:00 h; and for September the mean WBGT index ranged between 19.55 and 25.45 °C with a mean value of 23.53 ± 1.93 °C and a maximum value (25.45 °C) between 12:00 and 13:00 h. Similarly, Table 5 and Fig. 2 reflect that in June the range of the maximum WBGT index varied between 26.15 and 30.72 °C, with a mean value of 29.35 ± 1.59 °C and a maximum (30.72 °C) between 12:00 and 13:00 h; for July, the range of the maximum WBGT index varied between 27.10 and 35.20 °C, with a mean value of 32.04 ± 2.70 °C, and a maximum value (35.20 °C) between 13:00 and 15:00 h; for August, the range of the maximum WBGT fluctuated between 27.10 and 32.00 °C, with a mean value of 30.28 ± 1.71 °C and a maximum (32.00 °C) between 11:00 and 12:00 h; and for September the range of maximum WBGT varied between 25.10 and 29.80 °C, with a mean of 28.38 ± 1.70 °C, and a maximum (29.80 °C) between 11:00 and 12:00 h and between 13:00 and 14:00 h.

Based on these results for the mean and maximum WBGT, and the risk limits of heat stress prescribed according to the WBGT by the American Conference of Governmental Industrial Hygienists

Table 4
WBGT index mean for hourly periods of the day and month, and their statistics.

Hour (h)	WBGT index mean (°C)			
	June	July	August	September
06–07	20.70	24.89	23.73	19.55
07–08	22.76	26.00	25.61	21.47
08–09	24.85	27.64	27.42	23.45
09–10	25.85	28.60	28.30	24.37
10–11	26.41	28.92	28.72	24.99
11–12	26.48	29.30	28.99	25.17
12–13	26.63	29.43	29.14	25.45
13–14	26.71	29.63	29.03	25.37
14–15	26.34	29.76	28.96	25.04
15–16	25.64	29.34	28.75	24.44
16–17	24.91	28.88	28.05	23.61
17–18	23.42	27.65	26.75	22.22
18–19	21.90	25.91	25.19	20.81
Mean ± SD	24.82 ± 2.00	28.15 ± 1.61	27.59 ± 1.75	23.53 ± 1.93
Range	20.70–26.71	24.89–29.76	23.73–29.14	19.55–25.45

Table 5
WBGT index maximum by hourly periods of the day and month, and their statistics.

Hour (h)	WBGT index maximun (°C)			
	June	July	August	September
06–07	26.15	27.10	27.10	25.30
07–08	27.71	28.60	28.60	26.90
08–09	29.45	30.90	30.90	28.60
09–10	30.47	31.20	31.20	29.60
10–11	30.49	31.60	31.20	29.70
11–12	30.60	33.50	32.00	29.80
12–13	30.72	34.90	31.60	29.60
13–14	30.68	35.20	31.80	29.80
14–15	30.35	35.20	31.40	29.40
15–16	30.30	34.10	31.20	29.40
16–17	29.53	33.90	30.30	28.50
17–18	28.42	31.60	29.10	27.20
18–19	26.73	28.70	27.20	25.10
Mean ± SD	29.35 ± 1.59	32.04 ± 2.70	30.28 ± 1.71	28.38 ± 1.70
Range	26.15–30.72	27.10–35.20	27.10–32.00	25.10–29.80

Table 6
Results of the univariate analysis of variance (ANOVA) for the WBGT mean and maximum for the hourly periods of the day.

Independent Variables/ANOVA F; significance; degress of freedom	Factors		Count	Means	Homogeneous groups
	Periods	Periods nomenclature			
WBGT mean $F = 2.659$; $p = 0.010$; df = 12	06–07	1	4	22.22	1- 3/4/5/6/7/8/9/10/11*
	07–08	2	4	23.96	2- 5/6/7/8/9*
	08–09	3	4	25.84	3- 1*
	09–10	4	4	26.78	4- 1/13*
	10–11	5	4	27.26	5- 1/2/13*
	11–12	6	4	27.49	6- 1/2/13*
	12–13	7	4	27.66	7- 1/2/13*
	13–14	8	4	27.69	8- 1/2/13*
	14–15	9	4	27.53	9- 1/2/13*
	15–16	10	4	27.04	10- 1/13*
	16–17	11	4	26.36	11- 1*
	17–18	12	4	25.01	
	18–19	13	4	23.45	13-4/5/6/7/8/9/10*
WBGT maximum $F = 4.557$; $p = 0.000$; df = 12	06–07	1	4	26.41	1- 3/4/5/6/7/8/9/10/11/12*
	07–08	2	4	27.95	2- 4/5/6/7/8/9/10/11*
	08–09	3	4	29.96	3- 1/13*
	09–10	4	4	30.62	4- 1/2/13*
	10–11	5	4	30.75	5- 1/2/13*
	11–12	6	4	31.48	6- 1/2/13*
	12–13	7	4	31.71	7- 1/2/12/13*
	13–14	8	4	31.87	8- 1/2/12/13*
	14–15	9	4	31.59	9- 1/2/12/13*
	15–16	10	4	31.25	10- 1/2/13*
	16–17	11	4	30.56	11- 1/2/13*
	17–18	12	4	29.08	12- 1/7/8/9*
	18–19	13	4	26.93	13- 3/4/5/6/7/8/9/10/11*

Significance level for the differences in means with the DMS *post hoc* test: $*p < 0.05$.

[15], for the mean values of the maximum WBGT each month, the risk level of heat stress was very high for July and high for the other three months. In addition, when the risk level was analysed for the hourly periods of the work day each month, the risk level was found to be very high for July and August from 7:00 to 18:00 h, and for June and September from 8:00 to 18:00 and 17:00 h respectively. The level proved high for the rest of the period of the work day for the four months. For the mean values of the mean WBGT, the risk level of heat stress for July and August was very high from 9:00 to 17:00 h and high for the rest of the work day, while for June and September the risk level was high from 8:00 to 18:00 and 17:00 h respectively, but moderate for the rest of the work day. In general, the risk level was high or very high, as reported in other studies for the construction sector in other countries: Tanzania [12], Israel [46,47], Australia [9], and Portugal [52].

As shown in Table 6, mean and maximum WBGT presented significantly differed from the means in the ANOVA, although, as would be expected, there was a higher number of significant differences between more hourly periods of the day in the WBGT index maximum than in the medium. For both cases, the hourly periods that presented the greatest significant differences were the first (06–07 h) and last (18–19 h). It was also notable that for the mean WBGT the period of 17–18 h did not significantly differ from any of the others, and the periods 08–09 h and 16–17 h differed only with regard to the first (06–07 h). These results, excepting geographical differences, agreed with those reported by Maiti [11] in Rambag, Mumbai (India), in a study where the work load in construction activities was determined for a measurement period of 1.5 h from 9:00 to 17:00 h from April to mid-June, as the ANOVA gave significant differences of the WBGT mean for each of the 6 hourly periods analysed, with a maximum value of 33.35 °C, a minimum of 26.25 °C, and a mean of de 30.26 ± 1.52 °C, with the highest mean being found in the hourly period of 12:30 h, with a value of 31.4 °C. These results also agree with those of Gaspar and Quintela [52] in Coimbra (Portugal), for the same period of months as analysed in the present study and between 08 and 09 h and 18–19 h, given that differences were found between hourly periods and different months, although these authors did not perform an ANOVA to detect such differences in a significant way. Thus, the maximum value of the WBGT that they found was 32 °C in July and for the periods13–14 h and 14–15 h, coinciding with the same period of maximum value of the present research in Spain, but in

Table 7
Results of the univariate analysis of variance (ANOVA) for the WBGT mean and maximum for the months.

Independent Variables/ANOVA F; Significance; Degress of freedom	Factors		Count	Means	Homogeneous groups
	Months	Months nomenclature			
WBGT mean $F = 18.892$; $p = 0.000$; df = 3	June	6	4	24.82	6–7/8*
	July	7	4	28.15	7–6/9*
	August	8	4	27.59	8–6/9*
	September	9	4	23.53	9–7/8*
WBGT maximum $F = 8.064$; $p = 0.000$; df = 3	June	6	4	29.35	6–7*
	July	7	4	32.04	7–6/8/9*
	August	8	4	30.28	8–7/9*
	September	9	4	28.38	9–7/8*

Significance level for the differences in means with the DMS *post hoc* test: $*p < 0.05$.

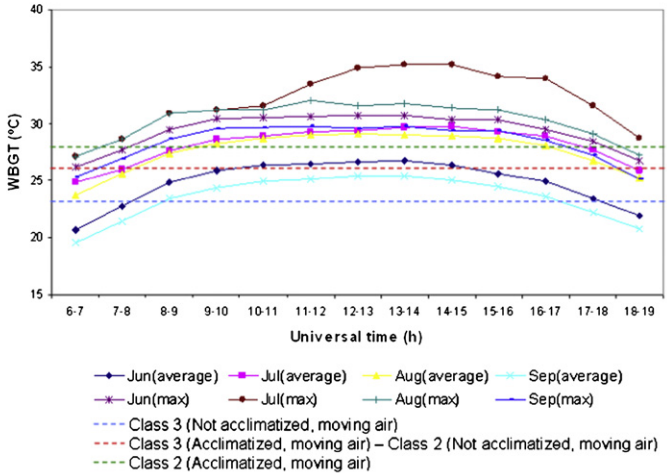

Fig. 2. Maximum and mean WBGT index for hourly periods for each month.

this case the value was higher in both periods, with the same value of 35.2 °C. Similarly, Gaspar and Quintela [52] reported differences in the values of the mean and maximum WBGT index for the different months, concluding that the months studied could be classified in descending order of intensity of heat stress to which workers are subjected in Coimbra (Portugal) in the following way: July, August, September, and June, which coincided partially with the results found in the present work with SE Spain, since, as reflected in Fig. 2 and in Tables 4, 5, and 7, such a classification would be July, August, June, and September, with the order of the months June and September not coinciding.

In addition, Table 7 shows significant statistical differences in the means of the mean and maximum WBGT indices. Thus, for the mean, June presented differences with respect to July and August but not September, while July and August differed from June and September. In terms of the maximum WBGT index, June presented differences with respect to July only, and July differed from the other three months; August differed from July and September, and finally September from July and August.

In addition, as can be seen in Table 8, quadratic regression curves for each of the four study months both for the maximum and mean WBGT, which would be those that fit the eight curves of Fig. 2, in all cases presented high values of their coefficients of determination (R^2), above 0.94. The only exception was the July curve for the maximum WBGT, with a value of 0.89. This was not a coincidence, but rather can be seen in Fig. 2, the curve of the maximum WBGT for July, and to a lesser degree the July curve, which presented an irregular increase in the WBGT against a quadratic distribution during the hours of the day of greatest heat stress, a phenomenon that did not occur in the other two months. This phenomenon was also noted by Gaspar and Quin-tela [52] in Coimbra (Portugal) but for the maximum WBGT curves of June and to a lesser degree for July and August.By the intersection of these quadratic curves with straight lines of null slope that represent the limits of the WBGT prescribed by the standard ISO 7243 [37], for the types-2 and -3 metabolism, presented by construction workers, depending on the activity undertaken [11,12,52], the type of heat acclimation, and the type of air movement, the hourly intervals of each work day of each month in which heat-stress occurred were identified, as shown in Table 9. It bears highlighting that only for the mean WBGT values of the months of June and September no problems of heat stress were found for a person with a type-2 metabolism and acclimated to the heat regardless of the type of air movement, as well as for the month of September in two cases: for a person with a type-2 metabolism and not heat acclimated, and for a type-3 metabolism of a non-acclimated person and moving air. For all the other combina-tions of months with a type-2 or-3 metabolism of a person acclimated to heat or not, and air with or without movement, there was a problem of heat stress in some hourly period of the day. It bears emphasising that for the maximum WBGT index, and especially in some case for the mean WBGT, the problems of heat stress started at the onset of the work day (6:00 h) and lasted to the end of the day (19:00 h). In the months of June and July, for a type-3 metabolism and persons not acclimated, and both with and without air move-ment, there was a risk of heat stress throughout the work day (6:00–19:00 h). Therefore, the new workers who begin in the construction sector during these two months should undergo a heat acclimation period of at least 8–10 days, and should be assigned tasks demanding less exertion, appropriate to a type-2 or lower metabo-lism, if there is no appreciable air movement. Also, all workers who are active during the critical months should follow a work-rest regime to maintain an adequate body-temperature balance and proper hydration [9,15,16], according to personal needs. In this sense, OSHA (Occupational Safety and Health Administration, US Department of Labour) recommends the threshold limits of heat exposure estimated by the ACGIH [15].

The work-rest relationship is advised to be 25% of the work and 75% rest for each hour of work when the WBGT is 32-2 °C for light jobs, 31.1 °C for moderately heavy work, and 30.0 °C for heavy work. The recommendation is 50% of work and 50% rest for each hour of work when the WBGT is 31.4 °C for light labour, 29.4 °C for moderate, and 27.9 °C for heavy. These threshold values are based on the assumption that the workers should be acclimated, completely dressed, and with sufficient water and salt restoration. Also, the WBGT of the rest area should be the same or very similar to that of the worksite. For all this, given that most greenhouse-construction tasks can be considered heavy or moderately heavy for all the months analysed, WBGT values exceed 30.0 and 31.1 °C, especially in July and August, and therefore a work-rest regime should be administered at 25% work and 75% rest for each hour of work, as proposed by Maiti [11] in India for workers in the construction industry, and it would even be advisable to impose a period of no work from 9:00 h to 15:00 h, especially in July and August, as practised for decades in agriculture in Spain. In addition,

Table 8
Equations of the regression curves for each month of the WBGT mean and maximum according to the hour of the day.

Month	Regression equation	Adjusted R^2	Std. Error of the Estimate
June (mean)	$WBGT = 4.365 + 3.707 \cdot t - 0.152 \cdot t^2$	0.975	0.315
July (mean)	$WBGT = 11.41 + 2.933 \cdot t - 0.177 \cdot t^2$	0.965	0.301
August (mean)	$WBGT = 9.4 + 3.232 \cdot t - 0.130 \cdot t^2$	0.969	0.308
September (mean)	$WBGT = 3.551 + 3.606 \cdot t - 0.147 \cdot t^2$	0.985	0.241
June (maximun)	$WBGT = 13.317 + 2.916 \cdot t - 0.120 \cdot t^2$	0.949	0.361
July (maximun)	$WBGT = 5.296 + 4.575 \cdot t - 0.178 \cdot t^2$	0.890	0.897
August (maximun)	$WBGT = 13.458 + 3.099 \cdot t - 0.129 \cdot t^2$	0.941	0.415
September (maximun)	$WBGT = 11.768 + 3.075 \cdot t - 0.128 \cdot t^2$	0.941	0.412

Significance level for all the regression equations and all the coefficients $p < 0.01$ t: Hour of the day.

Table 9
Limits of the hourly intervals per day (6:00 h to 19:00 h) for each month where heat stress could occur, as a function of the reference limit values of the WBGT index (°C) corresponding to the different metabolism situations, type of heat acclimation, and air movement, according to the standard ISO 7243 (1989).

	Hourly intervals between 6:00 h and 19:00 h in which heat stress occurs				
Type of metabolism/acclimatization/air movement	2/a[a]	2/n[a] 3/a[a]/m[b]	3/a[a]/s[b]	3/n[a]/m[b]	3/n[a]/s[b]
WBGT limit	28	26	25	23	22
June (mean)	No problem	9:40–14:43	8:36–15:47	7:05–17:18	6:29–17:55
July (mean)	8:37–16:27	6:51–18:14	6:08–18:56	6:00–19:00	6:00–19:00
August (mean)	9:03–15:49	7:15–17:37	6:33–18:18	6:00–19:00	6:00–19:00
September (mean)	No problem	No problem	10:08–14:24	8:00–16:31	7:16–17:15
June (maximun)	7:07–17:11	6:00–18:38	6:00–19:00	6:00–19:00	6:00–19:00
July (maximun) August	6:43–18:59	6:00–19:00	6:00–19:00	6:00–19:00	6:00–19:00
(maximun) September	6:24–17:38	6:00–18:52	6:00–19:00	6:00–19:00	6:00–19:00
(maximun)	7:50–16:11	6:15–17:46	6:00–18:24	6:00–19:00	6:00–19:00

[a] Type of heat acclimation: a. acclimatized person. n. person is not acclimatized. [b] Type of air movement: s. still air. m. moving air.

the workers should protect themselves by applying highly protective sun screen over the entire period of June to September. This period of no work has also been proposed by Gaspar and Quintela [52] for construction workers with type-2 or -3 metabolisms in Coimbra (Portugal), but these authors restrict it to hours between 12:00 and 16:00 h, a period less limiting, in line with the lower WBGT values found by these authors as opposed to those of the present work for SE Spain. Therefore, for SE Spain, heat stress of construction workers outdoors was found to occur in all the months analysed when considering the maximum values of the WBGT index, since they exceeded 26 °C, highlighting July and August as the critical period, from 06:00 h to 19:00 h.

However, if only the mean WBGT values are considered, in July and September, no heat stress was found among heat-acclimated persons. For persons not acclimated to the heat, even for the WBGT mean values, in June and September, heat stress appeared from 9:00 h to 17:00 h, exceeding the limits of 22 °C in still air and 23 °C in moving air, appropriate for a type-3 metabolism, persons not acclimated to heat. Given that standard ISO 7243 [37] specifies different limits of the WBGT for the type-2 and -3 metabolism, depending on appreciable air movement, but does not specify (nor does the literature) the degree air movement, and the cause for choosing a higher limit value in situations of appreciable air movement derive from the fact that, with air velocities of more than 1 m s^{-1}, there is a small variation in the WBGT for increasing velocities [6]. The mean value of the air velocity in the present study, 4.06 m s^{-1}, can be considered to characterize the experimental results, and therefore the results are discussed in terms of reference values, since the standard ISO 7243 [37] considers that the characteristic values corresponding to the maximum heat-stress situation should be adopted. Consequently, the maximum WBGT values were considered relevant, as they were in Gaspar and Quintela [52].

On the other hand, it should be indicated that because the results of the present study show conditions of thermal stress in the greenhouse-construction workers of south-eastern Spain during the high temperature period, the productivity of these workers is found to diminish, as indicated by numerous studies on the effect of thermal stress on worker performance [8,17,23,28–36].

Finally, the ESI index has been validated for determining the heat stress in greenhouse-construction workers in SE Spain. It should be highlighted that the correlation coefficient between WBGT and ESI was 0.960 ($p < 0.01$), a value greater than that reported by Morán et al. [46], on validating the ESI index by the environmental data of 3 meteorological stations in Israel, which was 0.920 ($p < 0.01$), though the correlation coefficient for each of the 3 meteorological stations separately surpassed 0.980 ($p < 0.01$). Similarly, Morán et al. [47], on validating ESI by physiological variables, determined a correlation coefficient between WBGT and ESI of 0.988 ($p < 0.05$). This confirmed a strong correlation between ESI and the physiological variables. In both works, Morán et al. [46,47] also confirmed that the WBGT index presented values somewhat higher than those of the ESI index, as found in the present work.

Table 10
Pearson's correlation coefficients for the WBGT and ESI indices.

	$ESI_{airport}$	ESI
WBGT	0.910**	0.960**
$ESI_{airport}$		0.956**

$ESI_{airport}$: ESI index calculated with data from Almería airport. **$p < 0.01$.

6. Conclusions

The present study, evaluating the thermal environment of the workplace for greenhouse-construction workers of SE Spain, demonstrates a high or very high risk level of heat stress from June to September for a large part of the work day, particularly from 9:00 to 18:00 h. To control this risk, work-rest regimes are recommended. Also, the risk should be corrected by enforcement of legislation on work health and safety and by preventive policies based on training and information of workers as well as employers. In addition, the workers should protect themselves by applying highly protective sun screen over the entire period of June to September. The hourly periods of the work day most limited in terms of heat-stress risk were determined by generating quadratic regressions of the maximum and mean WBGT index according to the hour of the day, with high correlation coefficients and good distributions of residuals. Also, the application of the ESI index has been validated to determine the heat stress of greenhouse-construction workers in SE Spain.

Finally, it became necessary to expand the present research to validate the evaluation of heat stress for these workers by physiological methods [38].

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