Exposure to Slowly Drifting Warm Thermal Environments Inside Greenhouses

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Abstract

An adaptation of the PHS method to slowly drifting thermal environments has been developed. The generalized PHS code has been used to predict the daily evolution of physiological responses and the maximum allowable exposure, given the detailed daily indoor evolution of temperature and humidity. Results indicate a strong dependence on outdoor meteorological conditions. Despite allowing an early morning start (7 am), the core temperature increase is usually quite fast, and exposures longer than 2.5 hours should be ruled out under most of the investigated circumstances. Exposure duration is always limited by the excessive core temperature, whereas water loss is largely inconsequential.

Results obtained using our generalized PHS model differ significantly from those of the standard (static) PHS model (i.e. using daily averages for air/radiant temperatures and humidity). A constant monitoring of the greenhouse thermo-hygrometric quantities, with time resolution not exceeding a few minutes, is a mandatory pre-requisite for reliable thermal risk assessment.

Keywords: thermal drifts, heat stress, PHS

Introduction

Occupational exposure to stressing thermal environments has a significant impact on human health and is potentially lethal. Because of the seriousness of the issue, several descriptors have been developed since the 1920's (Yaglou 1927). Assessment and evaluation of exposure to hot environments is currently performed through the PHS method, originally developed in the framework of a EU-sponsored multi-national research project (Malchaire et al. 2001) and later codified in EN ISO 7933.

Greenhouses are thermally peculiar environments, showing a daily thermal evolution intermediate between outdoors and masonry indoors: thermal drifts are large enough to rule out the use of constant input values (e.g. the arithmetic mean), but small enough to be tackled by a sequence of quasi-static responses by the human body. Thermal stress due to occupational exposure inside greenhouses has been only occasionally addressed in recent years (Okushima et al. 2000, Monarca et al. 2004, Gusman et al. 2008), with some additional studies (e.g. McNeill and Parsons 1999) focusing on outdoor environments with some climatic similarities. A detailed study of the human response to the daily fluctuations of thermal conditions inside a greenhouse is still missing.

In this paper we first present a generalization of the PHS method to slowly drifting warm thermal environments; the method is then applied to the assessment of human exposure to thermal stress inside greenhouses.

Method

The original PHS code included in EN ISO 7933 was developed to predict the human response to thermally stable environments. A modified version has been developed in this work to accomodate slowly drifting thermo-hygrometric data. In practice, environmental input values (t_a: air temperature, RH: relative humidity, t_g: globe temperature, v_a: air velocity) which are originally fed to the code by the user as constants, are now carried into the code from a table based on the information collected by a meteorological data logger. The native 1 minute time resolution of the code has not been changed.

Because the monitoring of meteorological conditions is usually extended over several months, the typical field acquisition rate is slower than 1 minute (10 minutes in our data). Accordingly, a 4th degree polynomial interpolation of temperature and humidity raw data has been applied. All tests have been run to track the time evolution of the rectal temperature (t_{re}) and of the cumulated water loss, in order to calculate maximum allowable exposure time both for heat storage D_{lim_tre} and for water loss D_{lim_loss} (EN ISO 7933).

Experimental data

All data presented and discussed in this paper have been collected inside the same greenhouse, part of a research centre located in north-western Italy, along the coast (43° 30' N). Continuous data acquisition has proceeded over one full year (Jan 1 – Dec 31, 2009), with a 10 minute resolution. The greenhouse is characterized by an iron and plastic case (height 3.2 m, width 8.5 m, length 36 m.) and displaying openings only on side walls, with a 10% total fractional opening surface. Measurements of indoor and outdoor air temperature and relative humidity have been carried out using probes connected to one µAGRICOMP data logger located in the central cross section of the greenhouse, at a height of 150 cm above the ground. The mean radiant temperature $\bar{t}_r$, which we have not measured, has been approximated using a two-step procedure: first the globe temperature t_g has been calculated using the empirical relation $t_g = 12 + 2 \times (t_a - 12)$ based on globe and air temperature data measured inside similar greenhouses (Monarca et al. 2004); then the forced convection equation (EN ISO 7726, equation 9) has been used to calculate $\bar{t}_r$, given t_a and t_g. The air velocity (v_a) has been set to zero. A constant clothing thermal resistance ($I_{cl} = 0.6$) has been estimated after visually inspecting several workers, using tables included in EN ISO 9920. Although work inside greenhouses is undoubtedly characterized by a short scale time variability (minutes), such fluctuations are inconsequential when it comes to predicting the long term (hours) evolution of the rectal temperature. Accordingly, metabolic activity (M) has been set constant at 1.4 met, based on the analysis of metabolic values listed in EN ISO 8996 for a variety of tasks.

Identification of representative days

Indoor thermo-hygrometric conditions show an obvious day to day variability due to variable outdoor climatic conditions. Our data indicate that outdoor daily high temperatures in excess of 30°C show up with a probability of about 3.5% (Figure 1), while daily high temperatures above 32°C have frequencies below 1% (2 days in all of 2009).

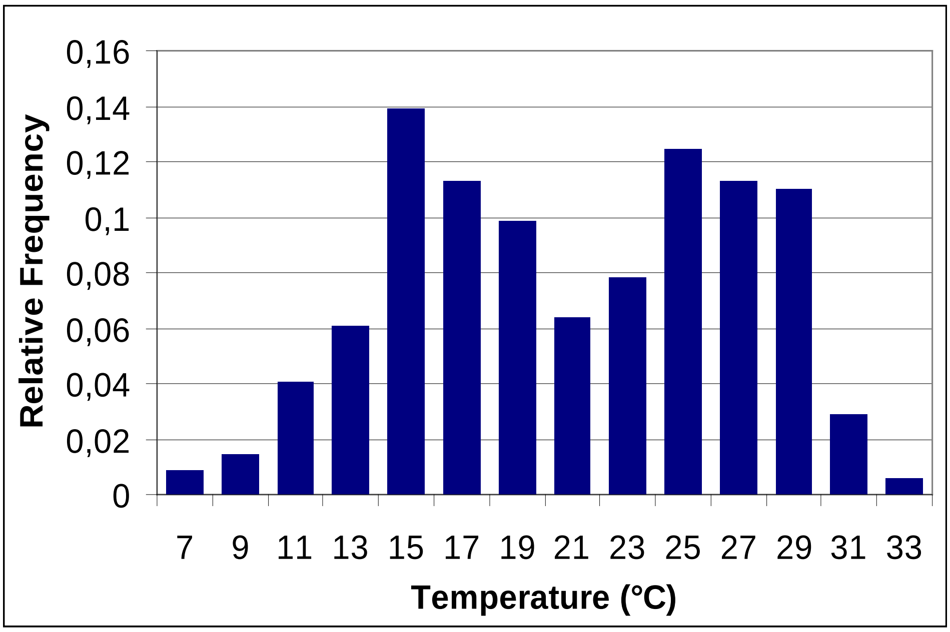

Figure 1. Histogram of 2009 daily outdoor high temperatures

Based on such data, three days with outdoor high temperatures of 28°C, 31°C and 34°C have been selected for this study. Such days, hereafter indicated with D1 D2 and D3, have been identified as a typical warm, hot and exceptionally hot summer day respectively, and the daily evolution of indoor temperature during each of those days is presented in Figure 2.

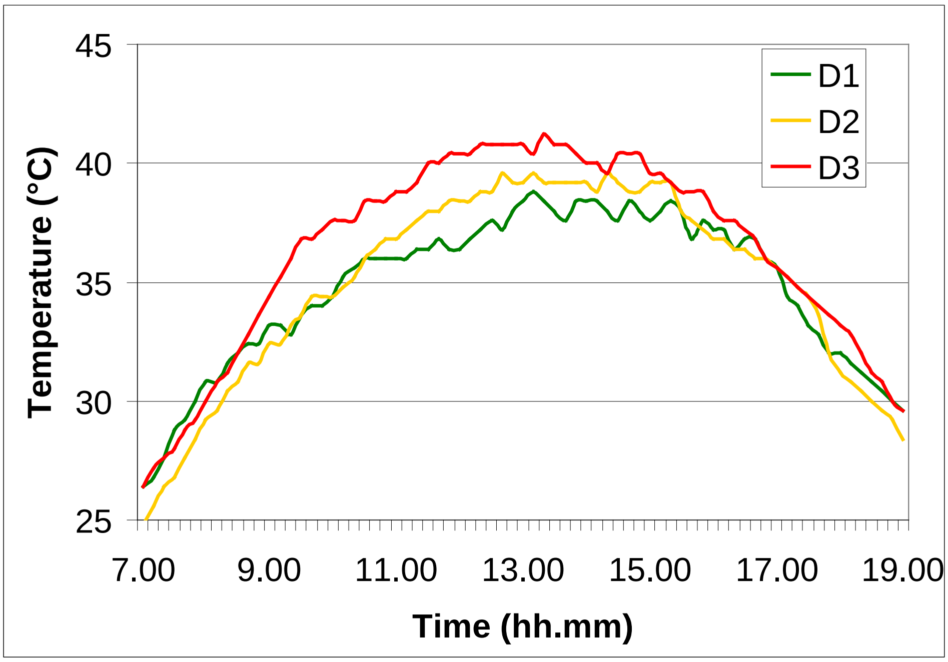

Figure 2. Indoor thermal evolution during D1 D2 and D3

It is also important to point out that what is an exception in this work (D3), may be the rule at more southern latitudes (e.g. south-east Sicily, 37° N), where greenhouses are also widespread and temperatures up to and occasionally in excess of 40°C should be expected.

Results

The effect of outdoor conditions

Figure 3 shows the rectal temperature evolution during D1 D2 and D3, where work has been assumed to start (Time = 0) at 7 am. The horizontal dashed line represents the maximum tolerable rectal temperature $(t_{re})_{lim}$, set at 38°C following EN ISO 9886. All three curves display the same three-stage profile where a short initial rise quickly gives way to a plateau where t_{re} flattens out, thanks to the evaporative cooling which is able to fend off the growing heat inflow. This second phase has a variable duration, inversely proportional to the heat load.

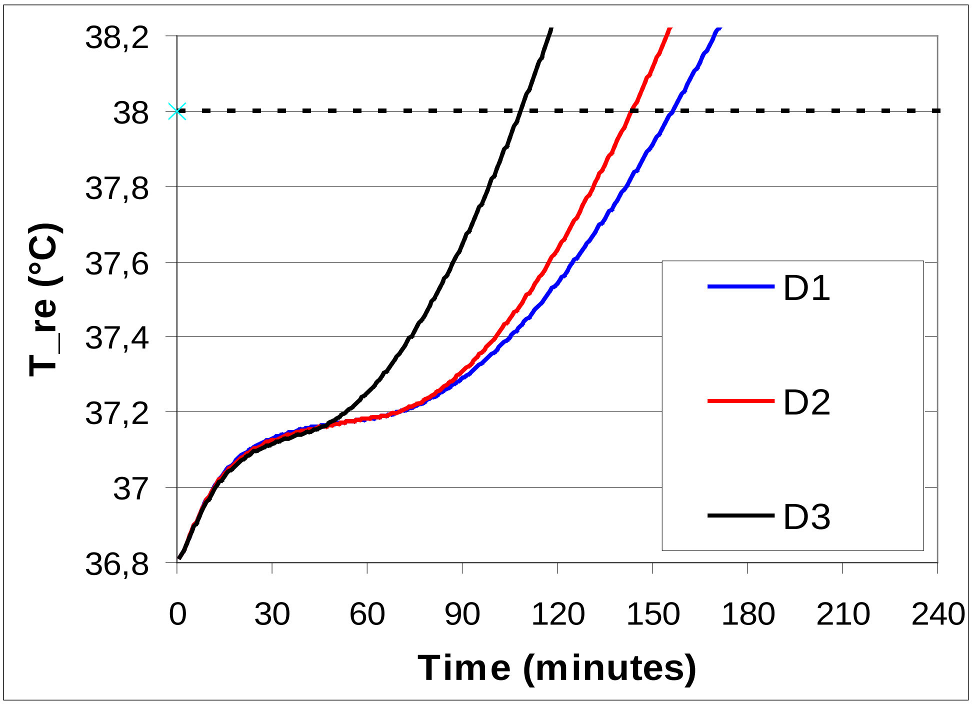

Figure 3. Rectal temperature evolution during days D1 D2 and D3

As air and radiant temperatures grow higher during the day, the maximum evaporative capacity of the body is eventually reached. Beyond this point, if the heat load keeps on increasing cooling can no longer effectively counteract the heat influx. Humidity inside a greenhouse is always large enough that loss of fluids via evaporation is severely curtailed, which explains the runaway growth of the rectal temperature in the third stage. The large humidity also implies that loss of fluids is never a factor: D_{lim_loss} is always more than twice as large as D_{lim_tre}, so that exposure duration is always set by the fast-rising rectal temperature, not by dehydration, and heat stroke is a more realistic threat that dehydration-related pathologies. The threshold $(t_{re})_{lim}$ = 38°C is crossed after 157, 144 and 109 minutes during D1, D2 and D3 respectively (that is between 8.50 and 9.40 am assuming the work starts at 7 am). The indoor air temperature at those times is between 32 and 36°C (see Figure 2). A rough extrapolation suggests that a daily high outdoor temperature around 25°C can be estimated as the critical level above which exposure becomes duration limited, that is t_{re} exceeds $(t_{re})_{lim}$ within the first four hours of morning work.

A “standard” 1.75m, 75 kg subject has been assumed. The effect associated to different physical complexion is minimal: the maximum allowable exposure of a slender, smaller subject (1.70m, 60 kg) is just 5% smaller. The size of the effect associated to heavier subjects is even smaller.

Constant vs. evolving meteorological input data

Figure 4 compares the predicted rectal temperature evolution in D1, D2 and D3, resulting from two different approaches: lines with squares for predictions resulting from our time-dependent input parameters; lines with no symbols for predictions resulting from an idealised thermally stable environment, with t_a $\bar{t}_r$ and RH set at their respective diurnal (7 am – 7 pm) averages. Because t_g data are estimates, not measurements, absolute values of D_{lim} found above have limited accuracy. However, since the variable input and the constant input models share the same approximation, their comparison is unbiased.

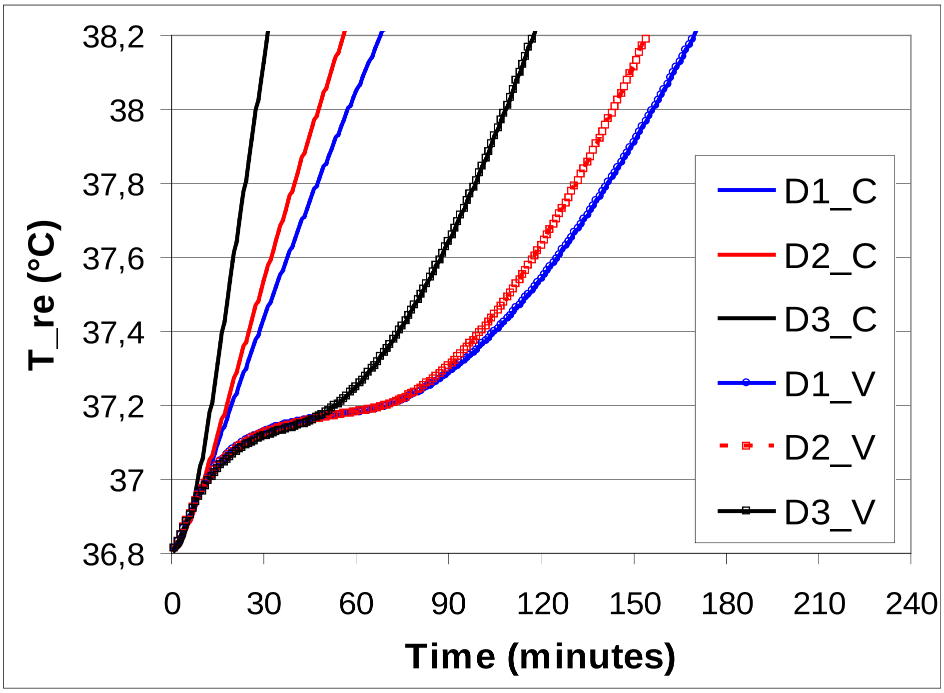

Figure 4. Rectal temperature evolution in idealized stable (constant, _C) and drifting (variable, _V) thermal environments

The constant input model systematically underestimates allowable exposure times, due to the gross overestimate of the early morning temperatures associated to the use of the average diurnal value. The accuracy of the static model can be improved by narrowing the time range over which the average is performed (e.g. 7 am – 12 am). However, it is unclear how to determine the appropriate time range, as it should depend on the (unknown) maximum allowable duration, implying an iterative procedure which is probably an unnecessary headache. Moreover, the shapes of the rectal temperature evolutions in the two models would not be reconciliated anyway, displaying a much steeper slope in constant input models. The reliability of thermally-induced stress assessments based on constant thermo-hygrometric inputs is strongly debatable.

PHS vs. WBGT

There are a few studies advocating the use of WBGT (EN 27243) as a descriptor of heat stress. In some cases the time evolution of WBGT is used to derive estimates of heat stress and acceptability of exposure. However, because WBGT is an empirical synthetic index developed to predict the mid to long term response of the human body, it is ill suited to track the short scale time evolution of thermo-hygrometric parameters typical of the system under investigation. Indeed, EN 27243 clearly mandates that assessment is to be performed using time-averaged values of relevant temperatures over a 1h range whose onset coincides with the working day start. Based on this 1h range concept, a sequence of WBGT values has been calculated here from averages of t_g and t_{nw}, (the latter approximated using the relation $t_{nw} = t_a - [14 - 0{,}14 \times RH]$, del Gaudio and Lenzuni 2002) taken over consecutive 1h periods (7-8 am, 8-9 am, 9-10 am ……….).

Table 1. Thermal stress assessment evolution using modified PHS and WBGT

Case	**D_{lim}**	**WBGT 7 – 8 am**	**WBGT 8 – 9 am**	**WBGT 9 – 10 am**	**Max Time Table A.1**	**Max Time Figure B.1**
	(minutes)	**(°C)**	**(°C)**	**(°C)**	**(minutes)**	**(minutes)**
D1	157	27.5	30.4	32.7	≈ 90	180
D2	144	26.8	30.4	33.3	≈ 90	160
D3	109	28.2	32.5	35.8	≈ 60	120

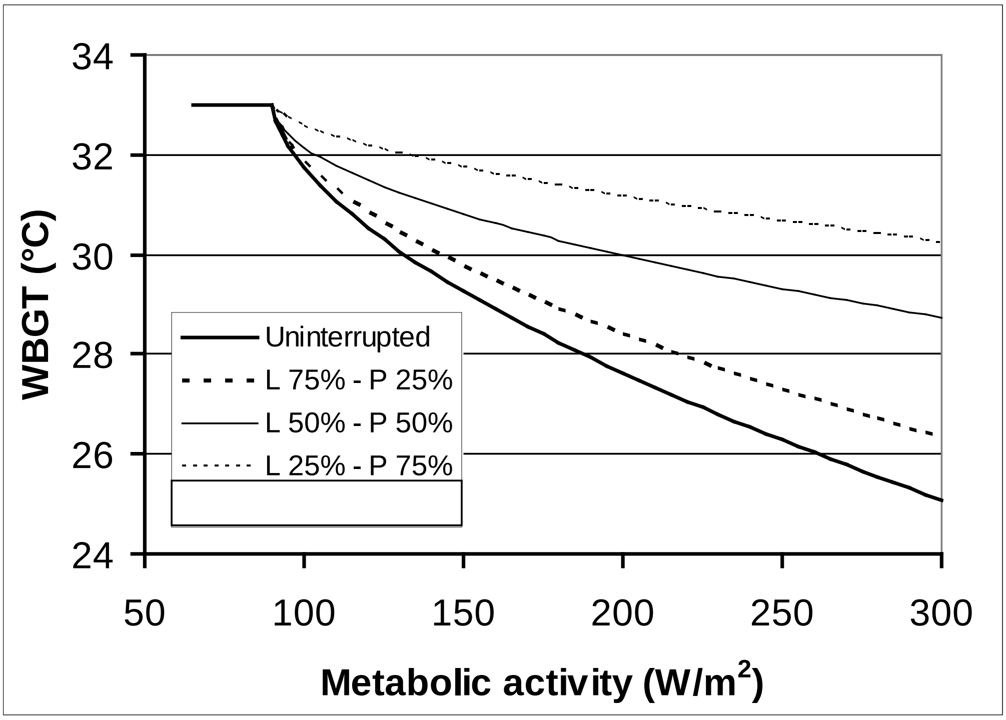

Figure 5. Low-M extrapolation of limit WBGT curves as a function of metabolism

Table 1 compares thermal stress assessments carried out using the method discussed in this paper (quantified by the maximum allowable duration of the exposure D_{lim}) and using WBGT as detailed above. Two procedures for WBGT-based assessment have been applied: in the first, a limit value $(WBGT)_{lim}$ = 30°C has been assumed, as indicated in EN 27243 Table A.1 for a metabolic class 1 (as implied by our estimate of M = 1.4 met) and an acclimated subject. WBGT values indicate that the limit is exceeded sometime in second hour of exposure (D1 and D2), and at the end of the first hour of exposure (D3). This assessment method strongly underestimates allowable exposure times, showing a behaviour similar to the constant input models discussed above. The second procedure has exploited the information displayed in EN 27243 Figure B.1. Since we have M = 1.4 met = 81 W/m^2, we need to extrapolate the four curves which appear in this Figure below their starting point at about 2 met, or 116 W/m^2. Such an extrapolation leads to predict a collapse into a single line at and below 93 W/m^2 (see Figure 5). In this "low-M limit", a sharp transition from continuous uninterrupted exposure to no exposure allowed, occurs at the threshold $(WBGT)_{lim}$ = 33°C. Estimated maximum allowable exposure times based on the crossing of this threshold, shown in Table 1, show a good agreement with the method outlined in this paper. It also picks up correctly the fact that t_{re} shows a runaway upward trend, so that no short scale work-rest cycle is helpful. This surprisingly good performance of WBGT is a direct consequence of the fact that WBGT is calculated here following its time evolution, although with a modest 1 hour resolution.

Conclusions

Results obtained using the generalized PHS model differ significantly from those of the standard (static) PHS model (i.e. using daily averages for air/radiant temperatures and humidity). The static model systematically underestimates allowable exposure times (by a factor of 2 or more), due to a gross overestimate of the early morning temperatures associated to the use of the average diurnal value.

The accuracy of the static model can be somewhat improved adapting the averaging range, but this also introduces an undesired fuzziness in the method.

The use of static WBGT should be ruled out. However, the use of WBGT can lead to reliable predictions of the maximum exposure time, and as such can be used to make decisions on the work schedule, provided it can track the daily evolution of meteorological quantities.

While PHS is recognized as a much more accurate assessment method than WBGT, the choice of the descriptor is not as vital as is the ability to track the evolution of meteorological data, itself associated to the availability of continuous monitoring.

The method outlined in this paper is particularly relevant in environments, such as greenhouses, where the thermal environment can be extremely stressing, and the temperature evolution is fast.

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