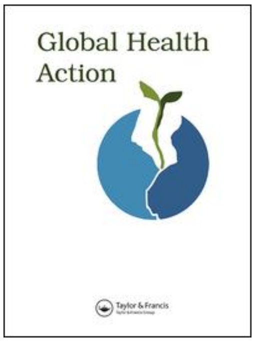

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Climate change and occupational heat stress: methods for assessment

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Background: Presumed effects of global warming on occupational heat stress aggravate conditions in many parts of the world, in particular in developing countries. In order to assess and evaluate conditions, heat stress must be described correctly and measured correctly.
Objective: Assessment of heat stress using internationally recognized methods.
Design: Two such methods are wet bulb globe temperature (WBGT; ISO 7243) and predicted heat strain (PHS; ISO 7933). Both methods measure relevant climatic factors and provide recommendations for limit values in terms of time when heat stress becomes imminent. The WBGT as a heat stress index is empirical and widely recognized. It requires, however, special sensors for the climatic factors that can introduce significant measurement errors if prescriptions in ISO 7243 are not followed. The PHS (ISO 7933) is based on climatic factors that can easily be measured with traditional instruments. It evaluates the conditions for heat balance in a more rational way and it applies equally to all combinations of climates.
Results: Analyzing similar climatic conditions with WBGT and PHS indicate that WBGT provides a more conservative assessment philosophy that allows much shorter working time than predicted with PHS.
Conclusions: Both methods should be used and validated worldwide in order to give reliable and accurate information about the actual heat stress.

Keywords: *global warming*; *heat stress indices*; *physiological strain*; *productivity*

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Different scenarios have been reported forecasting the gradual warming of the planet. During the next century we might expect anything between 1.8 and 4.0°C (average 3.0°C) increase in global temperature (1). Although criticism has been raised against some of the predictions by IPCC, a majority of researchers agree on the warming effect. Accordingly, increasing attention has been paid to the environmental effects of global warming, but health effects have got great attention also (2, 3). Less attention, however, has been paid to the effects on occupational health. Conditions for manual work in many types of industry and in agriculture get worse with anticipated effects of global warming, in particular in developing countries. In particular, heat stress in work places will increase and affect strain and performance of workers and their productivity (4–6). Fifty years ago Wyndham noticed that productivity in the gold mining industry dropped quickly when it became hot in the mines (7). His data was further analyzed by Axelson, who applied his findings to hot work places in general (8). In order to cope with internationally recognized limit values (for example, an increase in core temperature to 38.0°C as suggested in ISO 7243 and ISO 7933), measures must be taken to reduce heat exposure. Most such measures will immediately compromise work output and productivity, affecting the individual economy as well as the local and national economy.

Wet-bulb globe temperature – WBGT (ISO 7243)

Many heat stress indices have been developed and most of them can be used to identify conditions when workers cannot cope with them and preventive measures are required (9–11). The WBGT is probably the most well known and used worldwide (11) and also adopted as an international standard (12, 13). The WBGT is based on relatively simple measurements of climatic factors and provides reference values for work-rest regimes when it becomes too hot (Fig. 1). Extensive research since the 1950s has provided good evidence that the severity of physiological strain can be related to values for WBGT (ISO 7243 and Fig. 1). The formula for calculation of WBGT depends on whether solar radiation is present or not.

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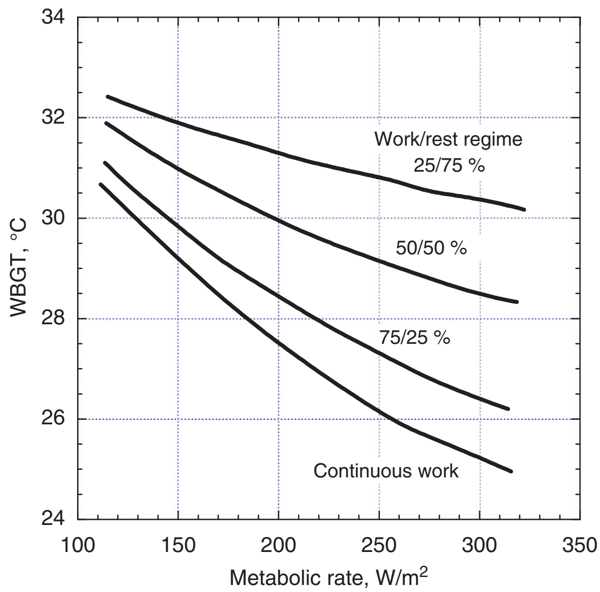

Fig. 1. Recommended work–rest regimes for combinations of metabolic rate (x-axis) and values for the WBGT-index (Y-axis). At a work rate of 210 W/m^2 and a WBGT of 30°C a 1-hour shift should be split into 30 minutes of work and 30 minutes of rest. Modified from ISO 7243.

$$\mathrm{WBGT} = 0.7 \times T_{\mathrm{nwh}} + 0.3 \times T_{\mathrm{g}} \quad \text{no solar radiation}$$

$$\mathrm{WBGT} = 0.7 \times T_{\mathrm{nwh}} + 0.2 \times T_{\mathrm{g}} + 0.1 \times T_{\mathrm{a}} \quad \text{solar radiation present}$$

The T_{nwb} is the natural wet bulb temperature, measured with a wetted sensor exposed to wind and radiation. The T_{g} is the globe temperature measured by a sensor placed inside a hollow, black-painted metal globe and T_{a} is the air temperature shielded from radiation. Details of the sensor design and accuracy are provided in ISO 7243. It must be kept in mind that neither T_{nwb} nor T_{g} are fundamental meteorological parameters and must not be confused with psychometric wet bulb temperature and mean radiant temperature. Significant errors arise if that is the case.

If compliance with ISO 7243 is requested (and it is in many national regulations), it allows a calculation of work capacity (or productivity) per hour on the basis of the measured WBGT values (4). Fig. 1 shows the recommended work–rest regimes at different metabolic rates and WBGT values, with the aim of keeping the core body temperature of an average worker below 38.0°C. It is readily seen that at a certain workplace temperature and work rate, work time must be reduced for the worker to maintain this body temperature. Hence, work output and productivity decrease for an average worker but there are, of course, substantial individual variations.

Except for air temperature none of the climatic factors in WBGT are basic thermal factors. The basic climatic factors that determine heat balance and heat stress on the exposed human are air temperature, humidity, air movement, and heat radiation (Table 1). During the years, modification of sensors and replacement of sensors have been proposed and introduced (14). However, the validity of measuring the true WBGT according to ISO 7243 has not always been tested. Several types of integrating instruments are on the market. Although sensors in some of these instruments do not meet the requirements in ISO 7243, it seems that measured factors are corrected in the software and the displayed WBGT is close to the value measured with an instrument with correct sensors (Salman et al. 2010, unpublished observations). If a correction is not made, however, the determination of WBGT on the basis of (e.g. dew point temperature) relative humidity and globe temperature with a small globe (e.g. 4–5 cm diameter) may produce an error of more than 5°C. Such a deviation may put a person at danger if WBGT is underestimated and require unnecessary preventive measures if overestimated. Similar observations were reported by Budd (14).

Table 1. Determination of PHS requires values for the following factors

Climate factor	Individual factor
Air temperature	Thermal insulation of clothing
Mean radiant temperature	Water vapor resistance of clothing
Water vapor pressure in air	Metabolic rate
Air velocity	

Wet-bulb globe temperature (WBGT) and meteorological data

The WBGT and other similar indices are typically intended for use in local places where people actually are exposed to the climatic conditions – for example, workplaces or sporting events. From a global warming perspective, the use of meteorological data for prediction of regional or even local heat stress becomes of interest. Several studies have reported formulas for prediction of WBGT from meteorological data (15, 16). The problem as mentioned before, however, is that WBGT is based on climatic measurements with specially designed sensors and its relation to the basic weather data is complex (16). Nevertheless, it seems that reasonable accuracy can be achieved (Lemke and Kjellstrom, unpublished observations).

In conclusion so far, it seems that WBGT can be a valid estimator of heat stress when it is measured with accurate instruments or predicted from meteorological data. A remaining problem with the last option is that data refers to weather stations (and larger geographical regions) rather than local places where people are exposed. This requires further corrections and further work to investigate. It

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should also be pointed out that the ISO 7243 criteria for rest–work periods has been based on interpretation from limited datasets, and further quantitative research on the relationship between WBGT exposure levels and core body temperature or health and productivity risks is needed.

Predicted heat strain – PHS (ISO 7933)

In order to avoid the complex transfer of meteorological data into WBGT and the problem of using inaccurate instruments, a more modern and rational heat stress index can be used. Such an index is PHS [Predicted Heat Strain, ISO 7933 (17)]. The PHS is based on an analysis of body heat balance and the required sweat rate for the maintenance of a stable core temperature. If balance cannot be achieved, the increase in core temperature and sweat loss is calculated. The time for these physiological variables to reach defined limit values is calculated and reported as recommended exposure time.

In practice, the climatic factors are measured or obtained from meteorological stations. Clothing properties and metabolic rates are estimated on the basis of tables (18, 19). The strain criteria for PHS are an increase in rectal temperature to 38.0°C and a water loss of 3% of body weight (higher if rehydration takes place) (17). When either of these criteria is met, the associated exposure time is calculated and suggested as recommended maximum work time.

Comparison of strain with WBGT and PHS

At a WBGT of 29°C, continuous work at 150 W/m^2 may be carried out for more than 1 hour (Fig. 1). Calculating PHS with basic climatic factors (Table 1) producing the same value for WBGT (29°C) provides a recommended exposure time of more than 4 h and a similar level of strain. Fig. 2 shows that rectal temperature, according to PHS, will not exceed the limit value of 38.0°C even after 4 h of exposure.

Increasing humidity from 33 to 60% for the actual climate (air temperature 30°C and globe temperature 44°C) gives a WBGT value of 32°C. According to the reference values in ISO 7243 (Fig. 1), work must now be interrupted by long rest pauses (45 min every 4 h) in order to comply with the strain criterion. The PHS calculation, however, shows that rectal temperature and water loss stay below the critical values also after 4 h of work.

Increasing air temperature to 35°C (60% relative humidity) with PHS gives an increase in rectal temperature beyond 38.0°C after about 59 min (recommended work time). The corresponding WBGT is 34.3°C and almost no work time per hour is recommended (Fig. 1 and Table 2).

Table 2 provides more details about the recommended (WBGT, Fig. 1) and calculated (PHS) work times with the two indices. In Fig. 2A the climatic conditions corresponds to a WBGT of 29°C and there is no

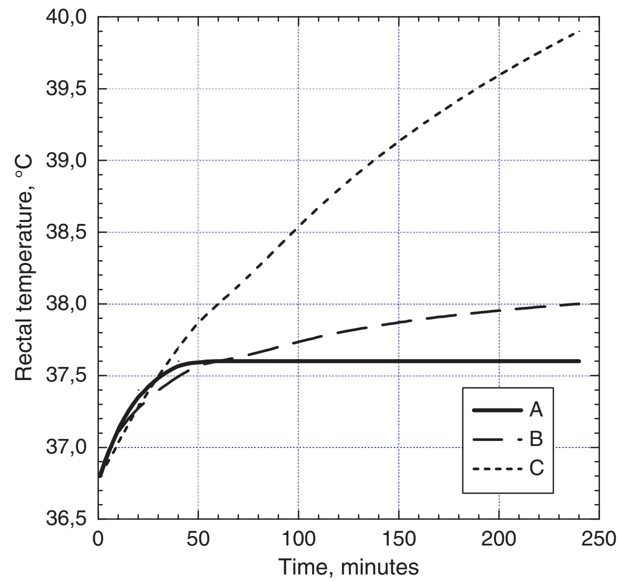

Fig. 2. Evolution of rectal temperature during moderate work (150 W/m^2) in light clothing. A represents an air temperature of 30°C, a globe temperature of 44°C, a relative humidity of 35%, and a WBGT of 29.0°C. B represents an air temperature of 30°C, a globe temperature of 44°C, a relative humidity of 60%, and a WBGT of 32.0°C. C represents an air temperature of 35°C, a globe temperature of 44°C, a relative humidity of 60%, and a WBGT of 34.3°C.

limitation to work. The PHS calculates a work time of 302 min and the limit criteria is dehydration. In Fig. 2B the WBGT is 32°C and only 15 min of work per hour is recommended. The PHS calculates a safe work time of 213 min and the limit criteria is a rectal temperature reaching 38.0°C. In Fig. 2C the WBGT is 34.3°C and no work is recommended. the PHS calculates that rectal temperature will rise to 38.0°C in 59 min, which becomes the recommended work time.

The information in Table 2 is further detailed in Fig. 3 where WBGT work times have been interpolated

Table 2. Calculated or recommended work time based on WBGT and PHS for the analyzed ambient conditions (see text and Fig. 1)

Ambient conditions (see also Fig. 2)	WBGT	PHS
Ta = 30°C, Tg = 44°C, r.h. 33% (A)	29.0°C; no limit per hour	302 min[a]
Ta = 30°C, Tg = 44°C, r.h. 60% (B)	32.0°C; <15 min per hour	213 min[b]
Ta = 35°C, Tg = 44°C, r.h. 60% (C)	34.3°C; no work at all	59 min[b]

[a]Dehydration limiting.
[b]Rectal temperature limiting.
r.h. = relative humidity.

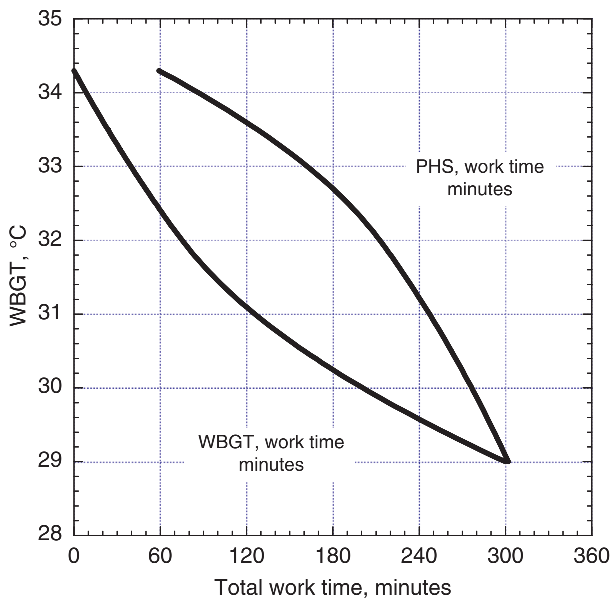

Fig. 3. Calculated total work time calculated with WBGT and PHS for three values of WBGT. See text for a further explanation.

from Fig. 1 for the three conditions. Total work time is calculated for a 5-h work period. It is readily seen that work time with WBGT is only 75 min (15 min every hour). Much longer work time is calculated for PHS at higher WBGT values.

Over longer work shifts (4 h or more) dehydration may become a critical factor for exposure. Analyzing the same climate as before (air temperature 30°C and globe temperature 44°C, relative humidity 33%, 150 W/m^2) with PHS shows that the limit value for water loss is exceeded after a little bit more than 5 h (302 min). Work time should be adjusted accordingly and a rehydration program applied during the shift. The WBGT is 29°C and continuous work is allowed; however, no quantitative information is available on rehydration needs.

Discussion

Apparently, WBGT overestimates the heat strain on people. This is in line with reports from several developing countries (China, India, Thailand, Dubai, and others) where work is performed under climatic conditions that would require considerable limitations if the WBGT recommendations were followed. A recent study by Zhao et al. (20) predicts work times for light work of more than an hour at a WBGT of 34°C. From a safety point of view, the conservative approach of WBGT may be valuable. However, unnecessary breaks and stops in a work shift affect performance, productivity, and the economic outcome for the worker. The adoption of a more precise and rational method for assessment of heat stress is recommended when health issues and economic aspects are evaluated. An attempt to summarize the pros and cons of WBGT and PHS is given in Table 3.

Table 3. Comparison of WBGT and PHS in terms of complexity, versatility, and validity

WBGT+	WBGT−
Internationally accepted heat stress index	Requires specific instruments (often expensive)
Worldwide recognized	Exposure limits based on a specific instrument
Good screening index	Limits not linear related to all climate
Simple interpretation of work time	Many cheap instruments do not comply with the standard and produce too high or too low WBGT values
Can be derived from weather data	Complex algorithms needed to calculate WBGT from weather data
PHS+	**PHS−**
Internationally accepted heat stress index	Direct reading instrument not yet available
Well recognized (in particular in Europe)	Computer program needed (freely available)
Can be measured with simple climatic instruments	
Easily calculated from meteorological data	
Applies to all climates, normal clothing, and low to high activity	
Limit values are based on *physiological strain*	
Increase in core temperature and water loss	
Strain level can be changed depending on purpose	
Work time calculated based on reaching limit criteria	
Subsequent exposures can be analyzed for accumulated effects	
Allows risk assessment	

In summary, the extensive and worldwide use of WBGT provides a basis for a first and rough estimation of the nature and significance of heat stress provided measurements are made correctly with accurate instruments. When it comes to a quantitative evaluation of heat stress in terms of actual strain on workers and consequences for productivity and economy, PHS is recommended. The

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PHS is also more convenient to calculate from weather data as it is based on the four basic climatic factors.

However, validation of the calculated core body temperatures and water losses in different populations and climate settings would be of great value. The advancement of research in this field may soon provide us with even more detailed mathematical models and climate indices based on them – for example, the Universal Thermal Climate Index – UTCI (2, 21).

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