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EFFECTS OF METEOROLOGICAL PARAMETERS ON ADEQUATE EVALUATION OF THE THERMAL ENVIRONMENT

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Abstract—1. Field measurements of the thermal environment were made during an outdoor study of eight subjects conducted at Fort Bliss, TX, U.S.A.

2. Meteorological parameters measured were temperatures, solar radiation, wind speed and humidity.

3. On two consecutive days, the rise in rectal temperatures for subjects wearing comparable chemical protective garments and carrying 22 kg loads averaged $0.5°C\,h^{-1}$ vs $0.2°C\,h^{-1}$.

4. The difference may be attributable to differences of 2.7°C in dewpoint temperature and $1.2\,m\,s^{-1}$ in wind speed, indicating that a small difference in meterological parameters can have an impact on individuals' thermal responses.

Key Word Index: Clothing; meteorology; heat transfer; human physiology; WBGT; heat strain

INTRODUCTION

A majority of environmental physiology studies, including biophysical evaluations of clothing, are conducted in environmental chambers. Sponsors of applied clothing tests often advocate more pragmatic evaluations obtained by outdoor tests. That preference towards field testing exists, in part, because the results from field studies often encourage a simplistic perception of the thermal environment. Proponents of outdoor tests believe that environmental variability will be adequately controlled by testing at the same site over several consecutive days with similar weather patterns. However, their implication that outdoor testing is a more optimal environment for biophysical clothing evaluation indicates a lack of awareness of the objectives of comparative biophysical testing and a failure to appreciate the complex variability of natural environments.

The meteorological or environmental data presented often consist of limited summary descriptions derived from local weather reports, typically recorded at local airfields, climatic summaries or periodic measurements with simple instruments, such as a WBGT instrument set (Yaglou and Minard, 1957). There is little indication that adequate anthropometrically-scaled meteorological data are being collected during current field studies even though an overview of meteorological instrumentation has been adequately presented in the literature oriented towards environmental physiology (ISO, 1985; ASHRAE, 1985). The value of directly measuring solar and thermal (IR) radiation to characterize the thermal environment is emphasized for the study of non-human species (O'Connor and Spotila, 1992; Walsberg, 1992), but many human environmental physiologists remain satisfied with the basic Vernon black globe thermometer (Wenzel and Forsthoff, 1989).

The complexity of the thermal environment is often ignored. For a heat stress study, such as the previous example, where test volunteers in chemical protective clothing were exposed to a transitory, stressful environment that impacted the thermal state of the test volunteers within a relatively short time period, frequent records in close proximity to the study site are necessary.

In addition, the data must be collected on an anthropometric scale. Direct measurements at the center of mass or head level are optimal for human studies. For standardization, it is convenient to round off the height to the nearest 0.5 m. Clauser *et al.* (1969) indicates that the body center of mass for males is 41.2% of the body length from the proximate end of the body. Hodgdon (1992) cites five studies of U.S. male military populations with a range in height of 175.0 to 177.6 cm. For six U.S. female military populations, the height of the female population ranged from 162.5 to 164.5 cm. The maximum standard deviation for all eleven studies was ± 7 cm.

For the male population, the body center of mass rounds off to 1.0 m.

Another convenient measurement height is 2.0 m, but that value exceeds the mean male height by more than a standard deviation. WBGT measurements are made at 1.2 m (4 ft). A compromise would be 1.5 m, approx. upper chest or lower head level for male subjects. Wind and air temperature measurements reported in this study were made at both 1.5 and 2 m, but if a single height had been selected, 1.5 m would be the preferred height.

The meteorological data must quantify the four basic parameters of the thermal environment (temperature(s), radiation, wind speed and humidity) that impact the potential for heat transfer by non-evaporative and insensible heat exchange pathways. Those four parameters define the potential for thermal stress which may be experienced during a study period. To ensure that the application of the data is not limited to the constraints of a particular model or index, standard meteorological instruments should be used to measure well defined environmental parameters. Rather than being limited by the crude nature of the existing data sets, the primary basis for model development should be scientific principles. The heat balance equation that forms the fundamental basis for rational heat exchange modeling has separate components for convection, conductance, radiation and evaporative heat transfer. An environmental data set which cannot support compartmental model development is not an adequate data set. O'Connor and Spotila (1992) present a discussion of the difficulties of attempting to model heat exchange in a natural outdoor environment even when the basic meteorological data are available.

One purpose of this paper is to describe the rationale for an "adequate" meteorological data collection system for a field study. A second purpose is to provide a demonstration of the practical limitations imposed by the natural variability of an uncontrolled environment on the use of field evaluations. This paper describes a meteorological data set that is minimally adequate for human study. Results from a recent study are described to demonstrate the importance of an adequate quantitative description of meteorological conditions. The database derived from the study has been used for partial model validation and will be used for future development of environmental heat exchange models.

METHODS

Subject activity and data collection

Nine subjects participated in the field testing after giving their free and informed voluntary consent. The purpose of the described study was to obtain thermal response data from eight subjects exposed to a hot–dry environment wearing clothing ensembles which provided various levels of thermal insulation and chemical protection while carrying a 22 kg "fighting load". The load consisted of the clothing worn and equipment carried including a helmet, a non-firing training rifle, and other items in a framed backpack. The test site was an oval 402 m paved track located at Fort Bliss, TX, U.S.A.

The objective of the protocol was to develop a database for hot–dry conditions which will be used to partially validate thermal heat strain models. Subject rectal temperature, three skin temperatures and heart rates were recorded every 30 s on an individual datalogger (Grant SQ32-2YS/8YS/1C/HR, Grant Instruments, Cambridge, U.K.) carried by each volunteer. Volunteers walked four laps in 24 min, rested for 6 min, then repeated the cycle for a maximum of 6 h in both "day" and "night" tests. Mission Oriented Protective Posture (MOPP) refers to the general level of chemical protection worn by a U.S. soldier. Subjects wore either MOPP-0 or MOPP-1 during two night test and two daylight test sessions. Half the subjects wore each level of chemical protection during each test. MOPP-0 level protection consists of wearing the regular uniform (lightweight U.S. Army Battledress Uniform or BDU) and carrying all chemical protective (CP) clothing. For MOPP-1, subjects wore the U.S. Army Battledress Overgarment (BDO), a water-vapor permeable two-piece CP suit, over the regular BDUs. For this study the BDO fastening was closed. On a third daylight test session, all subjects wore MOPP-4 level protection, including masks with filters. In MOPP-4, the BDO is sealed against chemical agents, and is worn with CP gloves, overboots and mask. For this study, the BDU was not worn under the BDO in MOPP-4. In MOPP-0 and MOPP-1, subjects participated in simulated marksmanship performance tests during "rest" periods. Those results are reported elsewhere (Tharion *et al.*, 1992).

Weather data collection

A portable weather station was located at the northeast corner of the test track and three WBGT monitors were placed along the track (north, south and west). The weather station consisted of two battery powered data loggers (Campbell CR-7 and 21X, Campbell Scientific, Logan, UT), a tripod to support shielded air temperature thermometers (Type T) at 2, 1.5, 1 and 0.5 m, black globe thermometer at 1.2 m, a barometer (7105-A, Weathermeasure, Sacramento, CA) and two pole mounted cup anemometers (12102D, R. M. Young, Traverse City, MI) at 1.5 and 2 m, two net radiometers (Radiation Energy Balance Systems, Seattle, WA) and two humidity sensors (HMP 36, Vaisala, Helsinki, Finland). Two pyranometers (PSP, Eppley Laboratory, Newport, RI) were placed near the dataloggers. One was mounted on a shade ring to measure diffuse solar radiation. Two thermocouples and one thermistor ground probe (107, Campbell Scientific, Logan, UT) were used to measure ground or surface temperatures. Methods for deriving direct and diffuse solar radiation, thermal radiation and estimating reflected solar radiation are described elsewhere (Santee and Gonzalez, 1988). The WBGT monitors (Metrosonic hs-371, Rochester, NY) measured and recorded dry bulb, 15 cm (6 inch) black globe and naturally aspirated wet bulb temperatures and calculated the WBGT index. All data were recorded as 1 min averages.

RESULTS

Meteorological measurements

Meteorological data consisting of 24 separate data points, including duplicate back-up instrumentation, were logged by the primary meteorological station every minute. Each WBGT station logged an additional three points plus the WBGT index every minute. In this report, we present limited meteorological data for the two daylight test sessions on 16 and 17 August. Overall results are summarized in a technical report (Santee *et al.*, 1992a) and both meteorological and physiological data have been entered into a Physiological and Psychological Effects of NBC and Sustained Operations in Combat (P^2NBC^2) Soldier Performance Database. The results have also been used to evaluate the performance of a Heat Strain Decision Aid under development by USARIEM for the P^2NBC^2 program (Matthew and Santee, 1994).

Figure 1 presents the air temperature (T_a) at 1.5 m above ground for the 2 days. For the first 3 h of testing (0730–1030 MDT), $\bar{T}_a = 26.2$°C on 16 August and $\bar{T}_a = 26.9$°C on 17 August 1991. The average air temperature was 0.7°C cooler on 16 August.

Figure 2 presents air temperature at 2 m above ground, black globe temperature, ground temperature and track temperature on 16 August 1991. It presents considerably more quantitative information than just air temperature. For example, it is implicitly assumed that an asphalt surface exposed to direct sunlight will be warmer than air temperature, but "common sense" alone cannot quantify that difference.

Some investigators attempt to simulate soar radiation in environmental chambers by adjusting chamber infrared lamps to yield a specific elevation of black globe temperature (T_{bg}) over T_a while wind speed is held constant. Data from our study suggest that the intensity of the simulated radiation is not realistic. At Fort Bliss on 16 August, the average difference between T_a and T_{bg} from 0730 to 1030 h local time (MDT), was 12.9°C. On 17 August, for the same time period, the average difference was 8.1°C. T_{bg} is difficult to interpret over time, as demonstrated in the following section on radiation, due to the time factor between sun rise and solar noon, the wind factor and the effect of air temperature, which are not independent of solar or thermal radiation. In the specific case for 16 vs 17 August, 1992 at Fort Bliss, a relatively small difference in wind speed had a significant direct impact on T_{bg}. Based on equations relating the Reynolds and Nusselt numbers, forced convection is directly proportional to the 0.60 power of the wind velocity ($v^{0.60}$) for a sphere (Mitchell, 1976). An apparently insignificant mean difference of 1.2 m s^{-1} in wind speed would increase convective heat loss from the globe by a factor of 48%. The difference in wind speed during the two consecutive days probably accounts for most of the observed difference in mean T_{bg}.

Figure 3 presents the global radiation measured on the two days. For the first 3 h of testing, the average global radiation values were 429 W m^{-2} on 16 August and 406 W m^{-2} on 17 August 1991. In a natural, dynamic environment, the range of observed values is normally large as the sun rises towards its zenith. Results are similar when averages for direct, diffuse and reflected radiation are calculated separately. Based on the preceding values and Fig. 3, solar radiation would appear to be nearly equivalent, although the average global radiation was 23 W m^{-2} higher on 16 August.

Figure 4 presents the wind speed measured on the two days. Average wind speeds at 1.5 m above ground for the first 3 h were 1.3 m s^{-1} on 16 August and 2.5 m s^{-1} on 17 August. Wind speed was 1.2 m s^{-1} lower on 16 August; an indication that if work activities are constant then the potential for convective heat transfer was also lower on that day. As noted above, at low wind speeds, a relatively small difference in wind speed may have a significant impact on convective heat transfer. This is particularly important when comparing chamber to field results because numerous chamber studies (Bittel *et al.*, 1992; Santee *et al.*, 1992b; Antuñano and Nunneley, 1992) are conducted at low wind speeds.

Figure 5 presents the dewpoint temperature (T_{dp}) measured on both days. Average T_{dp} was 14.4°C on 16 August and 11.7°C on 17 August. Dewpoint

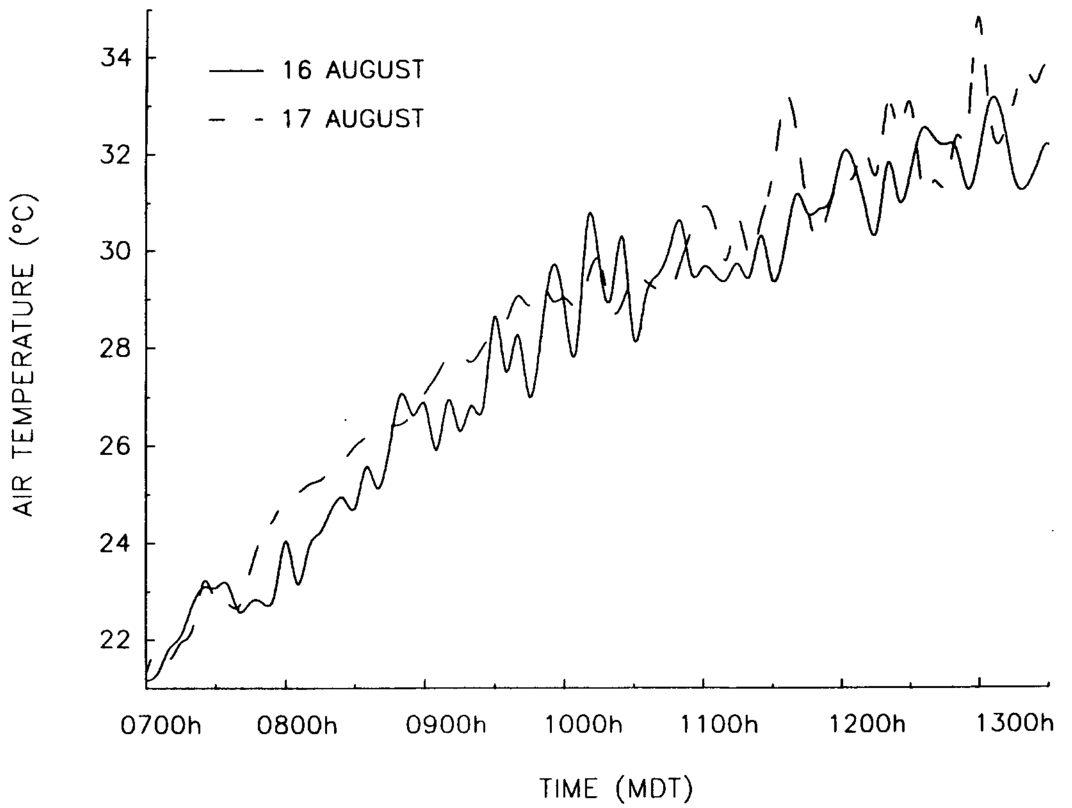

Fig. 1. A comparison of air temperatures (T_a) measured at 1.5 m at Fort Bliss, Texas on 16 and 17 August, 1991.

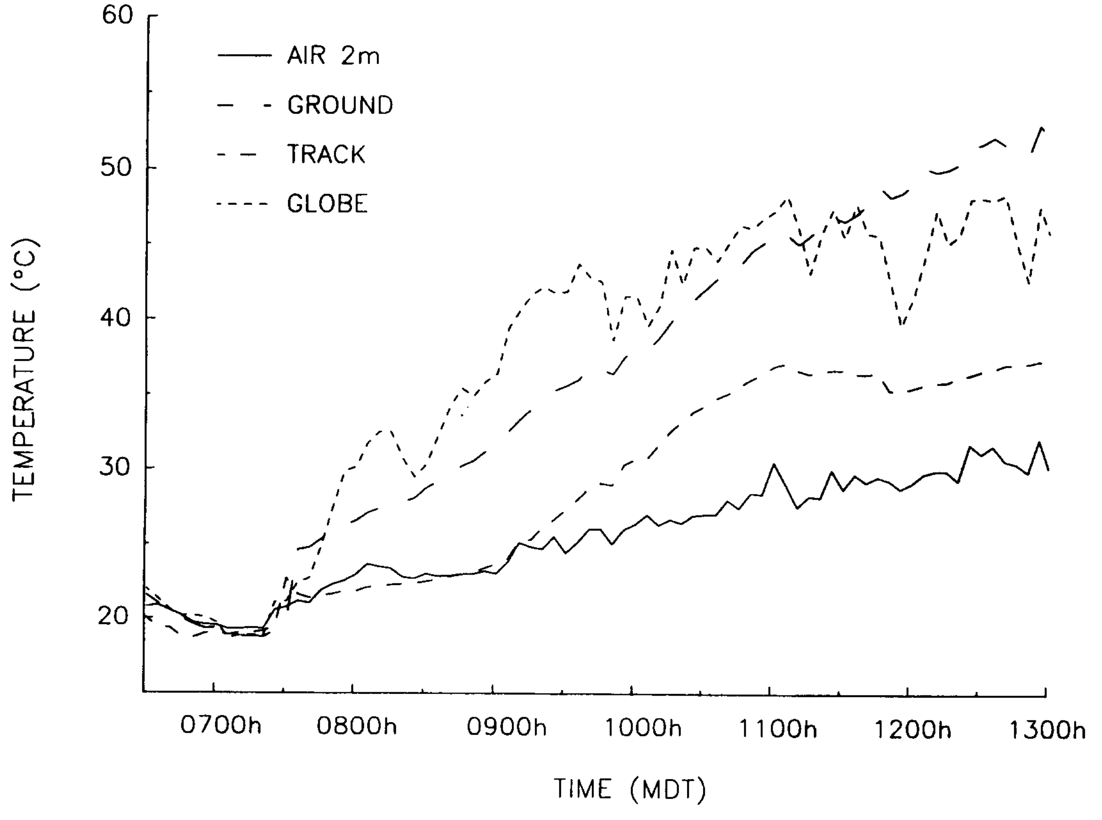

Fig. 2. A comparison of air (2 m), ground, asphalt track surface and black globe temperatures at Fort Bliss, Texas on 16 August, 1991.

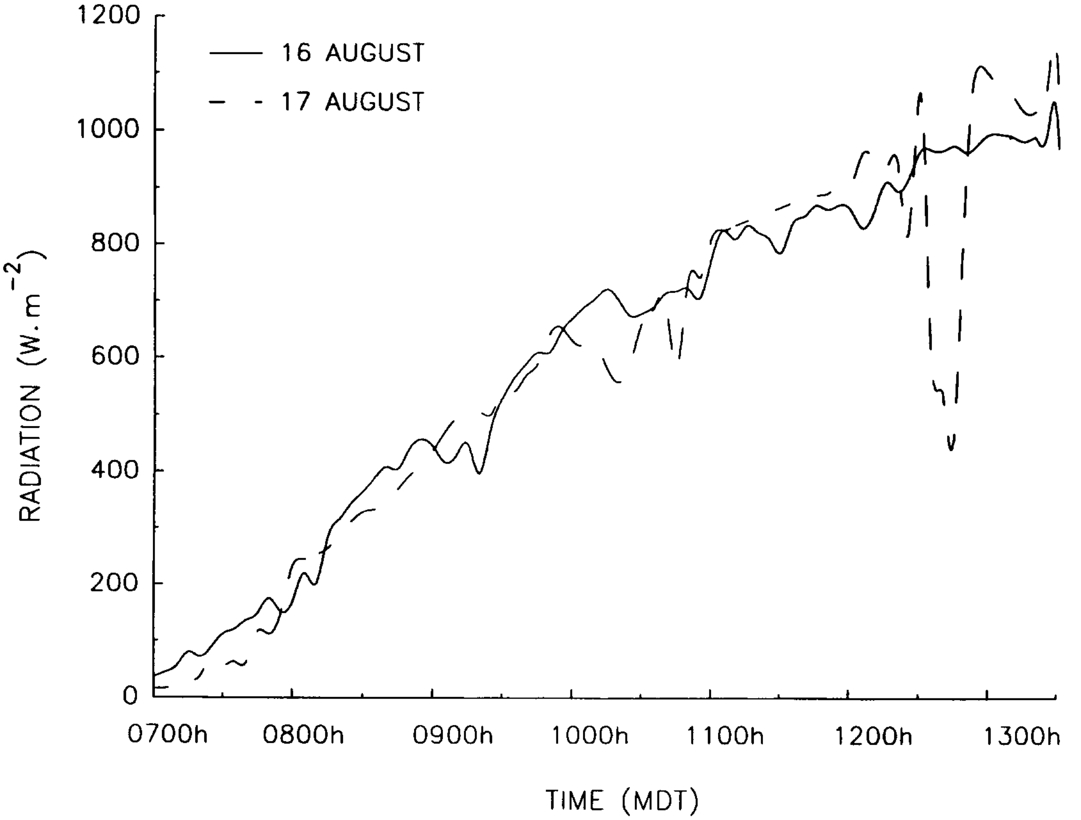

Fig. 3. A comparison of global solar radiation at Fort Bliss, Texas on 16 and 17 August, 1991.

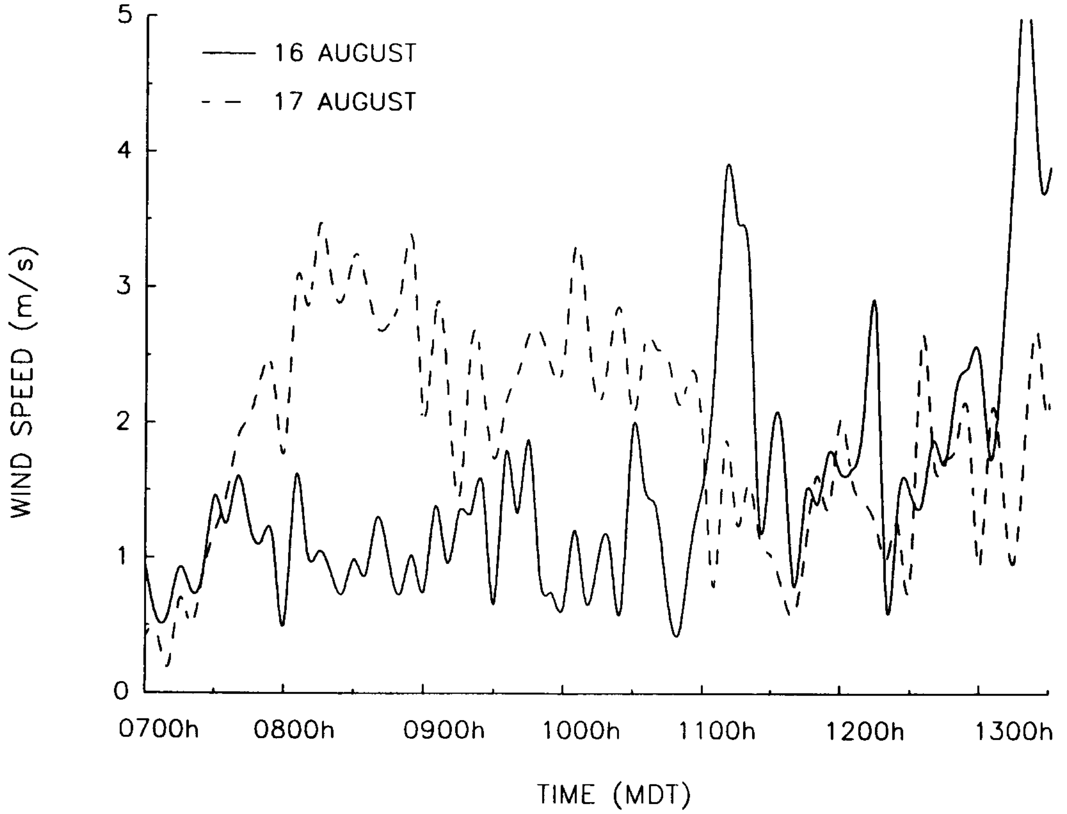

Fig. 4. A comparison of wind speeds measured at 1.5 m at Fort Bliss, Texas on 16 and 17 August, 1991.

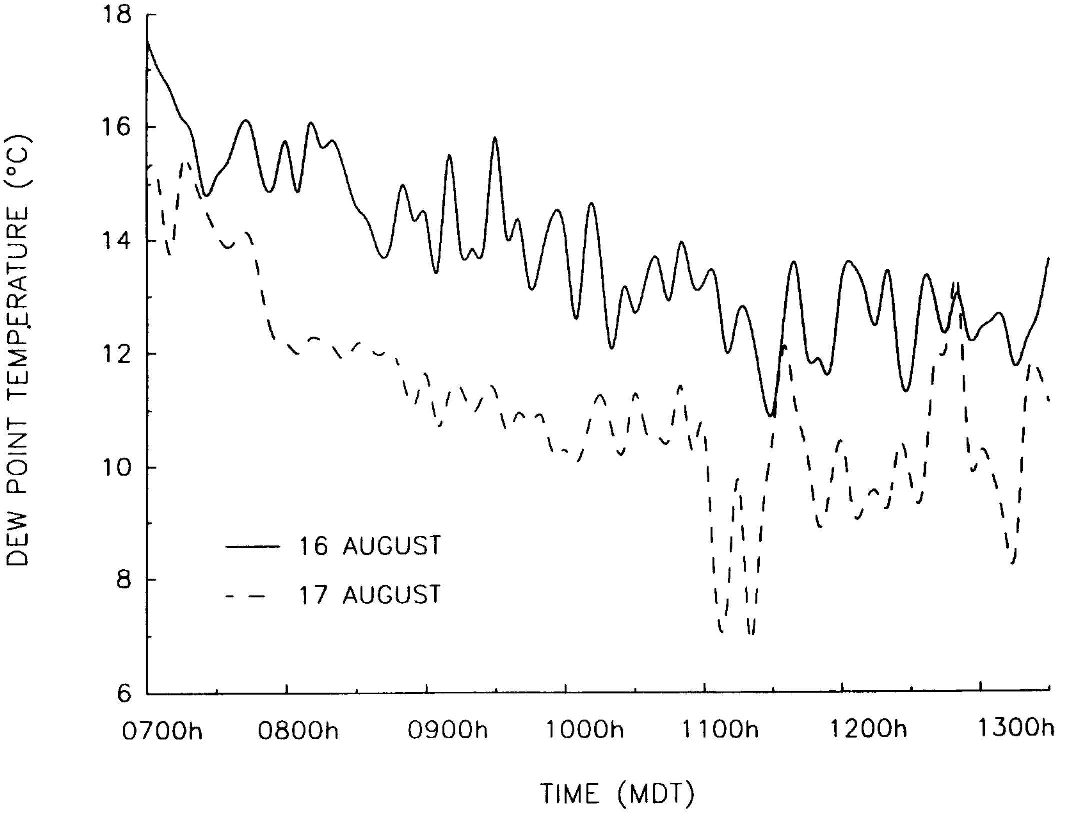

Fig. 5. A comparison of dewpoint temperatures (T_{dp}) at Fort Bliss, Texas on 16 and 17 August, 1991.

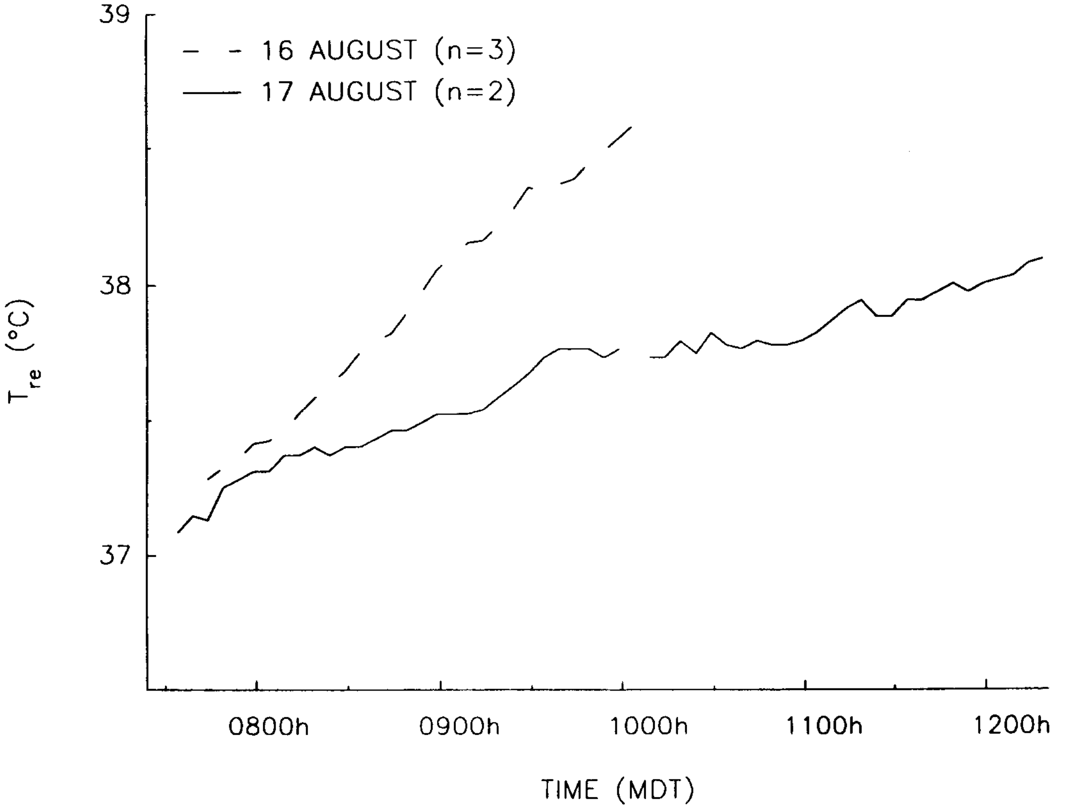

Fig. 6. A comparison of average subject rectal temperatures (T_{re}) in chemical protective clothing (MOPP-1) at Fort Bliss, Texas on 16 and 17 August, 1991.

temperature was 2.7°C higher on 16 August; an indication that the potential for evaporative heat transfer was lower on that day due to the effects of an equivalent evaporative heat transfer coefficient and the gradient between skin and ambient water vapor pressure. The ambient water vapor (P_w) was 0.4 kPa higher on 17 August.

Subject thermal responses

Figure 6 shows that the average rise in rectal temperature as a function of time on 16 August for load-bearing soldiers wearing chemical protective clothing over regular uniforms (MOPP-1) was 0.5°C h^{-1} ($n = 3$) vs 0.2°C h^{-1} ($n = 2$) on 17 August. Due to missing skin surface temperature measurements, mean skin temperatures could be calculated for only three subjects, but chest skin surface temperatures were available for all five subjects. For the available data, the mean chest temperature for the 3 h period was 35.7°C on 16 August and 35.6°C on 17 August. However, Fig. 7(a) and (b) shows that individual chest surface temperatures demonstrate considerable variability.

Overall thermal environment

The rectal temperatures for subjects wearing MOPP-1 on 16 August had a more rapid rate of increase relative to the thermal response observed from the subjects on 17 August. During the first 3 h, average air temperature was 0.7°C cooler on 16 August, an indication that the potential for heat strain experienced by subjects on 16 August would be slightly less than the thermal strain experienced on 17 August. Solar radiation levels were essentially equal on the two days. However, the higher relative humidity and lower wind speed on 16 August would both increase the potential environmental heat stress relative to the following day. The reduced potential for evaporative and convective cooling offsets the slight advantage of a lower air temperature on 16 August and contributes to a higher rate of heat storage on that day, as indicated by the greater rate of rise in rectal temperature.

As Figs 1–5 demonstrate, average values for dynamic environmental conditions are not ideal descriptive statistics. The 3 h average values essentially represent mid-points in a progression rather than the means of normal distributions. However, the average values can be used to illustrate how relatively small differences in environmental parameters can impact heat transfer potential. In calculating convective heat loss, the advantage of a cooler air temperature is evident from the difference between the two average air temperatures (0.7°C) if subject surface temperatures are equal. If the average body surface temperature (T_{sk}) is a neutral 33.5°C. and other physiological and environmental variables are constant, the difference between the average air temperatures would cause an 11% greater heat loss by convection on 16 August relative to the convective loss on 17 August. In actuality, the situation is more complex because the actual temperature difference is determined by the combination of the external environmental condition (T_a) and the physiologically influenced skin surface temperature. If 35.6°C is used as the surface skin temperature (T_{sk}) for both days, the importance of the difference in T_a becomes less. Using the higher surface skin temperature, the convective heat transfer on 16 August will only be 8% greater relative to the loss on 17 August. The actual heat loss is further reduced when well-insulated clothing, such as chemical protective clothing, is worn (Gonzalez *et al.*, 1974). Also, the convective heat transfer, as a function of wind speed, is not constant.

The convective heat transfer coefficient for a standing man is proportional to $v^{0.53}$, where v is the average wind speed (Mitchell, 1976). Without correcting for small differences in air viscosity, the average convective heat loss would be 41% greater on 17 August than it was on 16 August because of the difference in wind speed. Of even greater importance is the product of the evaporative heat transfer coefficient and difference in evaporative potential. Evaporative potential is directly proportional to the difference between saturated and ambient water vapor pressure. Using the Antoine equation (Harrison, 1965) to approximate saturated water vapor pressure, the difference in water vapor pressures was 1.79 kPa on 16 August and 2.19 kPa on 17 August. Based on the ratio between the differences for the two days, the average evaporative cooling potential was about 22% greater on 17 August.

The average WBGT values (three stations) for the two days were 25.4°C (16 August) and 23.4°C (17 August). WBGT is an empirical index that does not integrate the effects of different clothing or work rate. To compensate for CP clothing, 4° (NIOSH, 1986) or 5.6°C (FM21-10, 1988) should be added to WBGT. The WBGT correction values are based on unquantified assumptions. A new index proposed by Antuñano and Nunneley (1992) specifically for heavy protective clothing, the Heat–Humidity Index (HHI), averages the natural wet bulb and dry bulb temperatures. The 3 h HHI values were 24.0°C and 23.4°C respectively for 16 and 17 August. Although the initial WBGT values indicate no significant environmental stress, the modified WBGT values indicate a significant difference in the potential for thermal strain. Using the more conservative guidance in

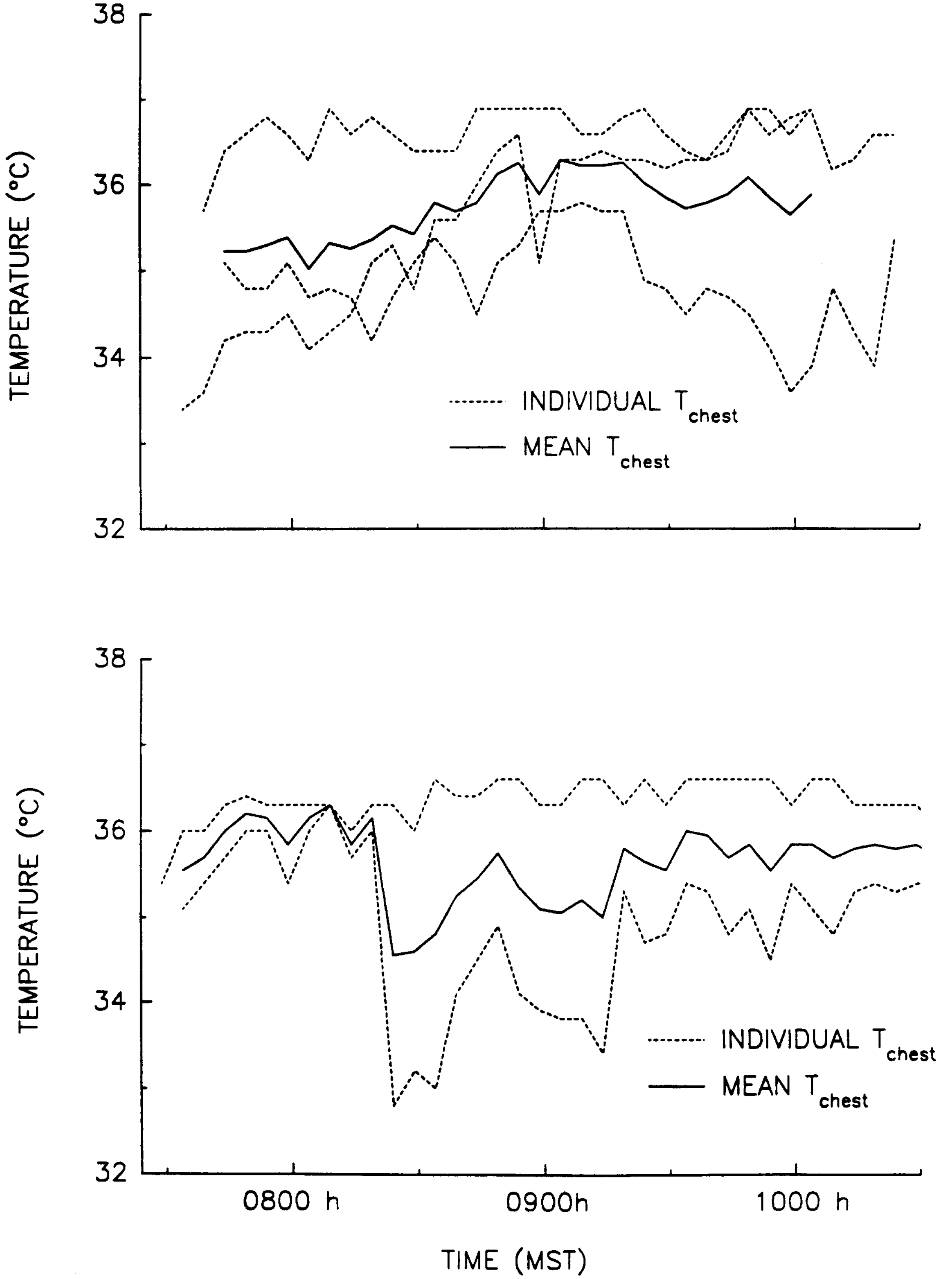

Fig. 7. (top) Individual and group average chest surface skin temperatures for subjects wearing chemical protective clothing (MOPP-1) at Fort Bliss, Texas on 16 August, 1991. (bottom) Individual and group average chest surface skin temperatures for subjects wearing chemical protective clothing (MOPP-1) at Fort Bliss, Texas on 17 August, 1991.

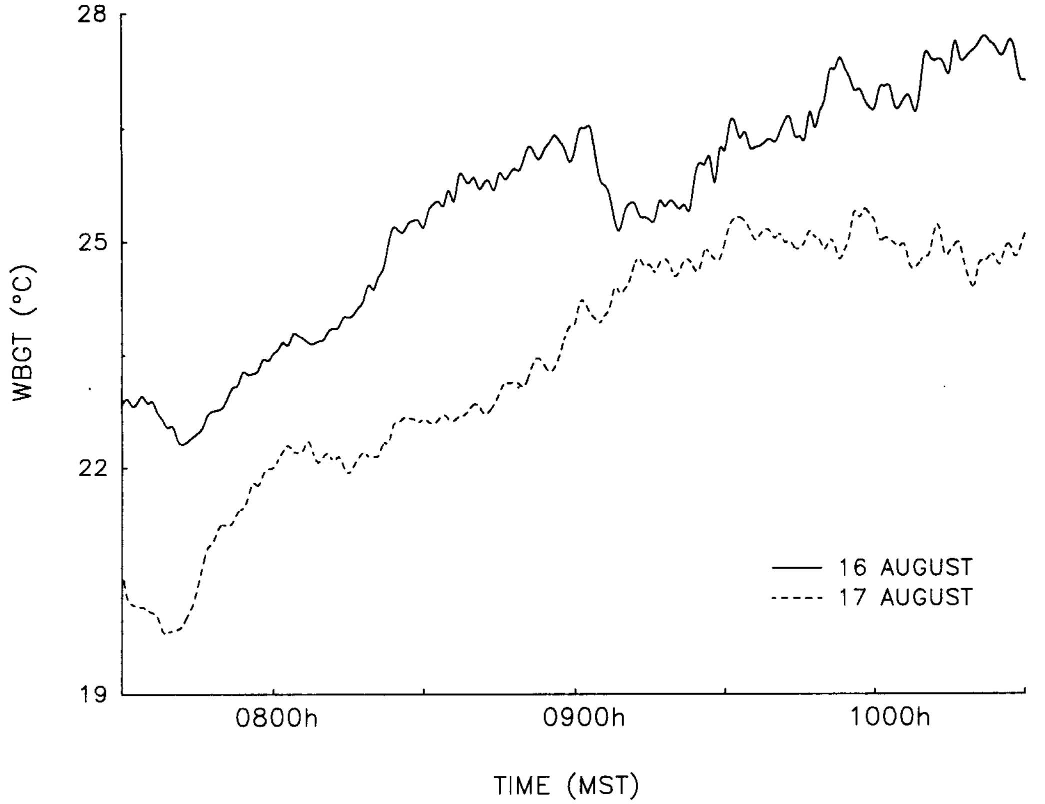

Fig. 8. A comparison of WBGT temperatures at Fort Bliss, Texas on 16 and 17 August, 1991.

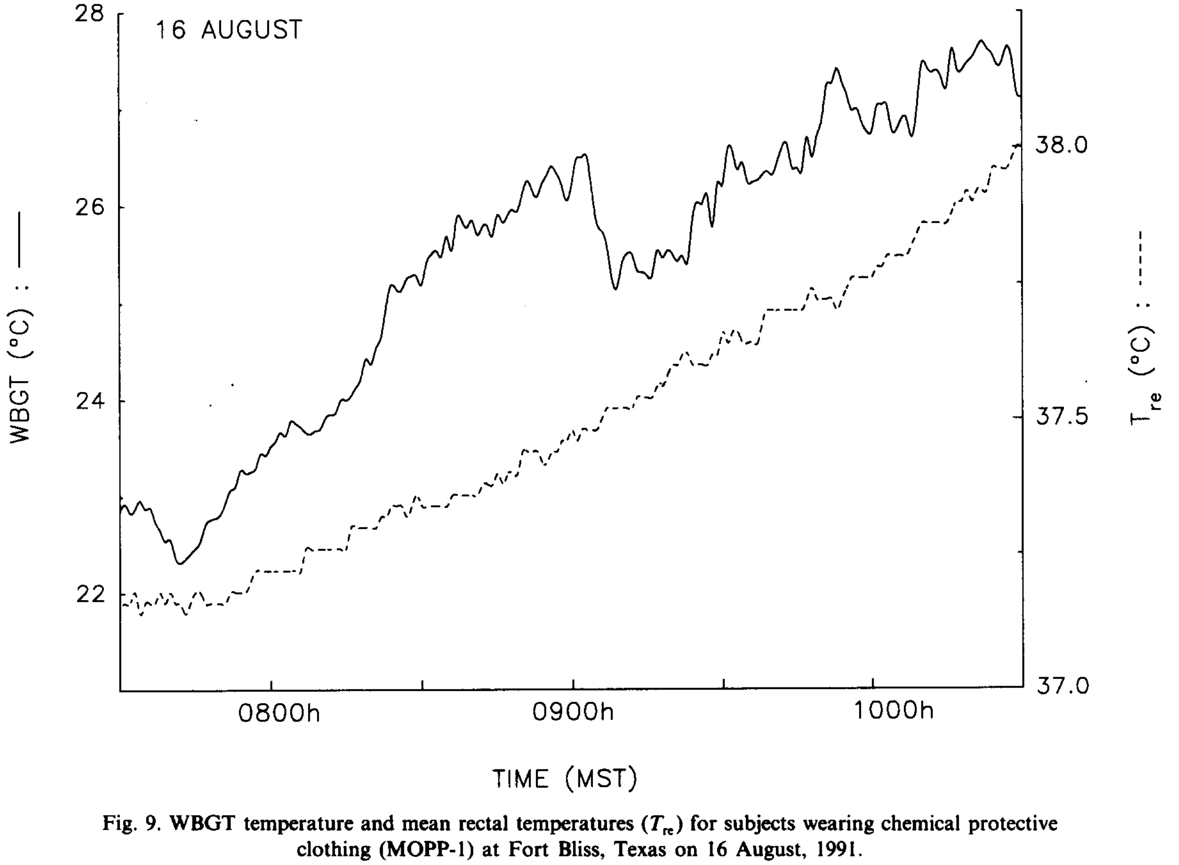

Fig. 9. WBGT temperature and mean rectal temperatures (T_{re}) for subjects wearing chemical protective clothing (MOPP-1) at Fort Bliss, Texas on 16 August, 1991.

FM 21-10, on 17 August, soldiers could potentially sustain a work–rest cycle of 50/10 min, whereas on 16 August, the sustainable work–rest cycle would be 45/15 min and their water requirement would also increase. If the NIOSH compensation level is applied, the recommended work–rest cycle for 16 August would remain the same, but continuous work should be possible on 17 August.

The basic premise behind thermal indices and equivalent temperatures is that a single parameter does not suffice to describe the environmental stress. The counter assumption is that a combined term that integrates the interactions of the individual environmental parameters will fit the data better. For this study, mean WBGT was calculated from the three WBGT monitors located at the test site. Figure 8 plots WBGT for the two days. On the basis of WBGT, a clear difference in physiological strain would be expected between the two days. Figure 9 plots WBGT and T_{re} for 16 August, using two different temperature scales. WBGT and T_{re} appear to track well until after 0900 h. Between 0900 and 0930, a decline in WBGT does not elicit a corresponding response in T_{re}. In that time interval on 16 August, direct solar radiation and T_{bg} also decline. It is not possible to determine whether the lack of linkage between WBGT and T_{re} is due to the use of T_{bg} as a variable or a failure of the WBGT model to correctly represent the relationship between solar radiation and physiology.

DISCUSSION

Relatively small environmental differences can have a significant impact on the thermal strain experienced by individuals exposed to that environment. A comparison of the meteorological data for 16 and 17 August supports the general observation that natural environments can not be wholly replicated because meteorological conditions will not be exactly the same even on consecutive days. On the basis of air temperature and solar radiation the two days described were very similar, but differences of 9.6% rh and 1.2 m s^{-1} wind speed had an important effect on the thermal strain experienced by the test participants. A problem arises when the assumption is made that conditions are "almost" equivalent and it is therefore thought to be statistically justifiable to pool data without regard to the "small" differences between days. Data from our field study may provide a basis for convincing advocates of outdoor testing that environmental chamber testing is a necessary prerequisite to achieve the degree of control needed for a legitimate comparison of military or civilian clothing based on the physiological responses of a volunteer population. We consider field studies to be an important "reality check" which cannot be totally neglected, but we would not recommend that the scientific evaluation of thermal properties of prototype clothing be based solely upon data collected during field studies.

Although there may be some appropriate concern regarding collection of excess data (Haslem, 1986), when data are collected to establish a database for thermal modeling, the limitations of that database set limits on the development or modification of future models. The three temperature WBGT input set, consisting of the air, natural wet bulb and black globe temperatures, is an example of a specialized data set which has limited utility for the expansion of modeling beyond the context of the specific index. Many of the other models require inputs which utilize more basic meteorological measurements (Gonzalez *et al.*, 1974), such as wind speed and humidity. By measuring only the WBGT set, often the data cannot be used with other models nor can the data be used to develop new models that are not based on the WBGT data set.

For example, a black globe temperature sensor, in conjunction with a measurement of wind speed is adequate if mean radiant temperature ($\bar{T}_r$) is the only desired product. A black globe does not, however, allow separation of incoming radiation into solar and thermal components nor integrate the effects of absolute humidity on the black globe. $\bar{T}_r$ is the present standard for standing figures (ISO, 1985), but a prone subject, such as a battlefield marksman or medical casualty on a stretcher, presents a different surface area to incoming radiation. If the different radiation values are known, the radiant heat load can be calculated directly from surface areas and clothing emissivity and absorptivity (Blażejczyk and Krawczyk, 1991).

Another consideration, in regard to concern over excessive data collection, is the simple question: if one does not collect it during the study, when will one have the opportunity to redo the experiment? It is relatively easy to collect additional ground and air temperatures. Figure 2 presents considerably more quantitative information than a single air temperature. For example, it is commonly understood that after exposure to strong, direct solar radiation, asphalt surface temperatures will be warmer than air temperature, but the data in Figure 2 directly quantify that information. For example, without a specific measurement, the only basis an investigator has for generating a hypothesis regarding the impact of high track temperatures on foot sweating and blistering is anecdotal evidence.

It is often difficult to interpret a field study with comprehensive physiological data, if there is only a minimal section of meteorological summary values for 6–12 h from a weather station in "proximity", or only limited WBGT or Botsball readings are made during the course of the experiment. A requisite assumption for "environmental" studies should be that the environment will be adequately quantified. The requisite knowledge to rigorously monitor the physical environment is available to investigators, but that knowledge needs to be put into practice. Field studies which take into account meteorological parameters are difficult to conduct. Often, the time available for a study is limited and such field studies often require the transport of staff, test volunteers and equipment to a distant locale. Consequently, investigators may deliberately choose not to expend the effort required to adequately monitor environmental conditions during field studies. Without a rigorous description of the physical environment to support the data analysis, it is unlikely that modeling efforts can progress beyond the observations collected in indoor environmental chambers.

Another consideration when meteorological data are collected in support of physiological research is that the nature of the available data may drive the selection and development of environmental models. To some degree, investigators attempting to conduct human environmental research are handicapped by the simplicity of the WBGT index. At the time of its development, the WBGT index was an important, but limited step, in applied physiology. The simplicity and ready acceptance of the underlying relationship between air temperature, humidity, wind and solar radiation were strong factors in the almost universal acceptance of the WBGT index. It has proved almost impossible to argue with success. For this study, the compensated WBGT values showed some discrimination between thermal stress occurring on the two test days. New empirical indices, that share in simple instrumentation and appealing mathematical simplicity of the WBGT index, continue to be proposed (Antuñano and Nunneley, 1992). The simple instrumentation and "pencil and paper" mathematics, which allowed the widespread application of the method by both military and civilian managers, have persisted even though laptop computers and digital electronic meteorological instrumentation have rendered reliance on pencil and paper technology obsolete. Rational indices that integrate heat balance over a wide range of activities and clothing are now a practical alternative (Gonzalez and Gagge, 1973; Gonzalez *et al.*, 1978; Stephenson *et al.*, 1988). Wenzel and Forsthoff (1989) criticized the limitation of the globe thermometer and noted that other meteorological data are measured with relatively sophisticated instruments. The important advantage of using standard meteorological measurements, over any WBGT instrument set, to project or anticipate the potential for heat injury casualties associated with the local thermal environment is that such available climatic summaries are fundamental meteorological observations of air temperature, wind speed and relative humidity.

SUMMARY

This paper documents a description of meteorological monitoring of the thermal environment during the collection of subject thermoregulatory responses while wearing different chemical protective clothing. The limited data indicate that even a small difference in meteorological conditions can have a noticeable impact on individuals' thermal responses. The WBGT index is inadequate because it does not integrate clothing and work intensity into the basic calculation and the WBGT instrument set is inadequate because no wind speed data are collected. The limitations of the available databases collected during field studies set limits on the development or modification of future or current models. Neither the WBGT index nor a single measurement of ambient dry bulb temperature can begin to describe the complexity of the actual environment.

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