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Evaluation of the Environmental Stress Index (ESI) for Hot/Dry and Hot/Wet Climates

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Abstract: Recently, a novel environmental stress index (ESI) which is composed from commonly used meteorological variables: ambient temperature (T_a), relative humidity (RH), and solar radiation (SR) was suggested as follows: $ESI=0.63T_a–0.03RH+0.002SR+0.0054(T_a·RH)–0.073(0.1+SR)^{-1}$; (°C) The purpose of the present study was to evaluate and validate the ESI for hot dry and hot wet climatic conditions. The ESI was applied to large meteorological databases from 2 different locations resembling hot/wet and hot/dry climates. Data analysis revealed high correlation between ESI and the wet bulb globe temperature (WBGT) index for each of the two databases: $P<0.05$, $R^2=0.985$ and 0.982, for the hot/dry and hot/wet conditions, respectively. Therefore, it is concluded that ESI, which is constructed from fast response and commonly used weather variables (T_a, RH, SR), and also found in a microsensor format is validated for hot/dry and hot/wet zones and as a potential index to serve as an alternative to the WBGT for heat category assessment.

Key words: Heat-stress, WBGT, Index, Ambient temperature, Humidity

Introduction

Hot climate conditions are prevalent over a large area of the world, and the ability to work or exercise in a hot climate is directly related to the prevailing heat stress level. The higher the heat stress the greater the risk of heat illnesses[1]. Thus, the safety of individuals performing in a hostile environment depends on following strict rules and limitations concerning exposures time and work intensity. The need for an adequate index to describe environmental heat stress which provides a reliable and consistent correlation with the induced physiological strain was already acknowledged by Haldane 101 yr ago[2].

In 1957, during an extensive period of development of heat stress indices, Yaglou and Minard introduced the wet bulb globe temperature (WBGT) index[3]. This index is obtained from three parameters: black globe temperature (T_g), which considers the solar radiation; wet bulb temperature (T_w); and dry bulb temperature (T_a), and is calculated as follows: $WBGT=0.7T_w + 0.2T_g + 0.1T_a$. The WBGT index gained popularity mainly due to its simplicity and convenience of use and soon was considered the most common heat stress index for describing environmental heat stress. It is in use in the field by the U.S. Army and it is the index on which sports associations base training safety guidelines to prevent heat injury[1, 4–7].

The World Health Organization (WHO) has also adopted it. In 1972, the National Institute for Occupational Safety and Health (NIOSH) established the WBGT as the criterion for determining occupational exposure to a hot environment[8].

Yet, inherent limitations of the WBGT have been reported[1, 9, 10], in terms of applicability across a broad range of potential scenarios and environments because of the inconvenience of measuring T_g. Usually the T_g is measured by a thermometer surrounded by a 6” blackened sphere and purportedly integrates the global radiation component of the thermal load. However, measuring T_g is cumbersome in many circumstances for two main reasons. First, T_g measurement requires about 30 min for the instrument to reach initial equilibrium. Second, the blackened sphere is often too large for specialized spaces. Therefore, measuring T_g becomes

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impractical, especially in transient situations. Recently, a 2” globe that responds faster has been introduced to replace the 6” globe.

In fact, there is no known laboratory—controlled study where the WBGT was evaluated. In 2001, Moran *et al.*[11] introduced a novel environmental stress index (ESI), which is based on measurements of T_a, relative humidity (RH), and solar radiation (SR). These three variables are more commonly used, simple to measure, and fast responders. The ESI was highly correlated with the WBGT index[11]. As a stress index, the ESI incorporates for the first time direct measurements of SR and RH[11, 12]. Additionally, all the three meteorological variables that make up the ESI are characterized by fast reading sensors easily obtained commercially. Recently, ESI was further evaluated for the physiological strain index (PSI) and for different physiological variables that reflect physiological strain including core temperature, heart rate, and sweat rate[13].

The purpose of the present study was to evaluate and validate the ESI for hot/dry and hot/wet climate conditions.

Materials and Methods

The database was obtained from a study conducted in Israel during June–August and contained 17,123 measurements. Weather measurements were collected every 10 min, during 24 h a day, for 60 d, at 2 different locations: Eilat, which is located by the Red Sea (latitude 29°55’N longitude 34°95’E), characterized as an extremely hot/dry zone with low relative humidity. The second site was in Bet-Dagan, which is located near the Mediterranean Sea (latitude 32°00’N longitude 34°49’E), and is a hot and very humid area. The collected meteorological measurements were used to calculate the ESI and the WBGT, which serves as the gold standard for environmental stress evaluation.

Measurements

The National Israeli Meteorological Service collected weather measurements from the two locations (Eilat and Bet-Dagan). T_a and T_w were measured with Campbell thermometers (model HMP45C), and relative humidity was measured with a Rotronic instrument (model, MP 100A). These three instruments were placed under a shelter (Stevenson screen) at 1.5 m height from the ground in an open space and a few hundreds m away from buildings. Under open sky, T_g was measured using the 6" Vernon black globe thermometer, solar radiation (SR) was measured using the EPLAB radiometer (sensitivity of 285–2800 nm), and wind velocity (V_a) was measured by the Young Instrument (model 05103).

Calculations

Heat stress indices were calculated as follows: WBGT was calculated according to Yaglou and Minard’s standard formula[3]; $WBGT=0.7T_w +0.2T_g +0.1T_a$

The ESI was calculated according to Moran *et al.* as follows[11]:

$ESI=0.63T_a–0.03RH+0.002SR+0.0054(T_a \cdot RH)–0.073(0.1+SR)^{-1}$; (°C)

Statistical analysis

For the validation of the ESI vs. the WBGT at the two sites, Pearson’s analysis was used for testing correlations between these indices. We computed the coefficient of determination (R-Square of the model) and plotted a series of residual plots versus predicted values for all data and for the two meteorological stations separately. All statistical contrasts were accepted at the $P<0.05$ level of significance. Data are presented in this study as means ± SE. For all computations and statistical analysis, we used SAS 8.0 Software, Procedures CORR and GLM.

Results

These data were collected every 10 min over 24 h for 60 d from two meteorological stations. Therefore, a wide range of weather measurements, over 17,123 data points for each variable was covered (Table 1). The WBGT and ESI were applied and analyzed for correlation for each of the two different stations.

The analysis between ESI and WBGT values, obtained from the hot/dry (Eilat) and the hot/wet (Bet Dagan) sites, are presented in Figs. 1 and 2 for correlations (bottom panel) and residual scattergram (top panel). At both sites, high correlations (R^2=0.985 and 0.982 for Eilat and Bet Dagan, respectively) between ESI and WBGT were found. However, in order to further test the correlation between the ESI and the WBGT we analyzed the residuals distribution around the line of identity during 24 h, and evaluated all the residuals in the two locations during different hours of the day (Fig. 3). The analysis revealed an average deviation of ± 0.35°C and ± 0.51°C for the hot/wet and the hot/dry zones, respectively, which were not statistically different from zero ($P>0.05$). The larger residuals were found around 08:00 and 16:00 for the hot/dry zone and around 06:30 for the hot/wet zone.

Table 1. Mean (± SD) and range of environmental measurements used to calculate ESI and WBGT in the two climatic zones hot/dry (Eilat) and hot/wet (Bet Dagan)

	T_a (°C)	T_w (°C)	RH (%)	T_g (°C)	SR ($W \cdot m^{-2}$)	V_a ($m \cdot s^{-1}$)	WBGT (°C)
Eilat	33.64 ± 4.48	21.22 ± 2.01	30.4 ± 13.4	39.92 ± 9.1	289 ± 353	3.7 ± 1.5	28.91 ± 2.92
	23.41–44.87	15.52–26.20	5.1–83.1	23.60–59.82	0–968	0–7.8	18.01–33.82
Bet Dagan	27.02 ± 3.32	22.75 ± 1.87	68.7 ± 13.8	33.34 ± 8.04	292 ± 337	2.9 ± 1.4	25.23 ± 2.8
	17.03–34.93	12.94–26.62	26.3–97.3	16.45–47.83	0–1022	0–10.8	15.7–31.17

Data were collected every 10 min over 24 h for 60 d.

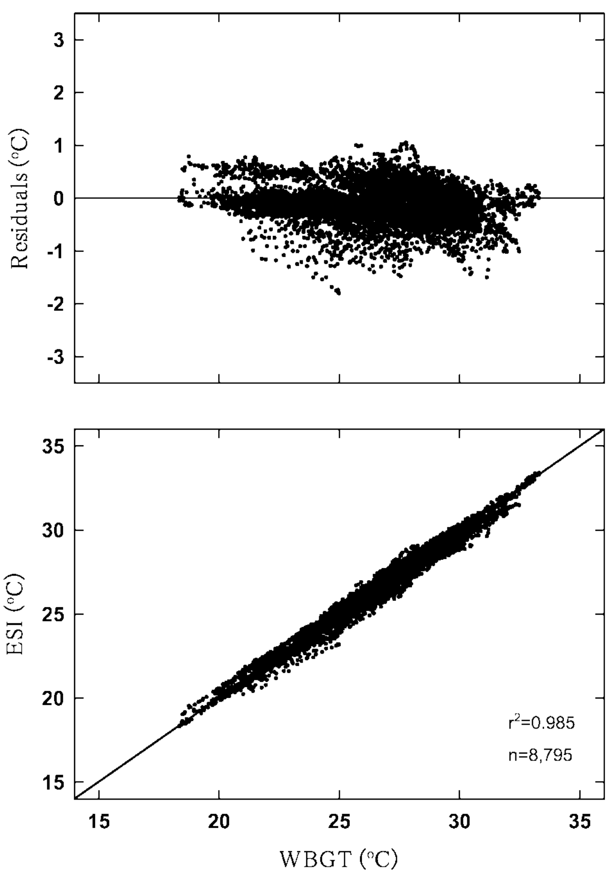

Fig. 1. Comparison of the ESI with the WBGT index obtained from hot/dry zone (Eilat) showing correlation (bottom) and residuals (top).

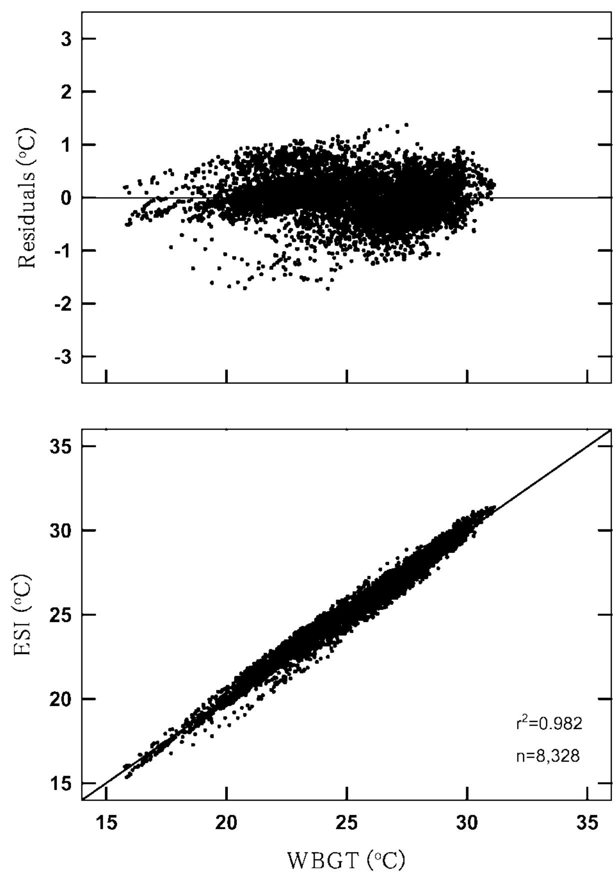

Fig. 2. Comparison of the ESI with the WBGT index obtained from hot/wet zone (Bet Dagan) showing correlation (bottom) and residuals (top).

Discussion

In this study, the recently developed ESI for the evaluation of environmental heat stress reliably matches values calculated by using the commonly in use WBGT. The ESI, which is based on simple understandable variables: T_a, RH, and SR, was applied for areas with hot/dry and hot/wet climatic conditions.

The strength of any prediction index is its ability to predict with reproducibility actual environmental heat load under wide, varied, and extreme climatic conditions. Previously, the ESI was evaluated for 10 and 9 databases, which were pooled into 2 groups and revealed a very high correlation between ESI and WBGT (R_2=0.980 and 0.964, respectively)[14]. However, pooled data analysis can mask part of the data obtained from extreme climatic zones during specific hours. Therefore, in this study we validated the ESI in 2 zones, which are considered in Israel as the extreme

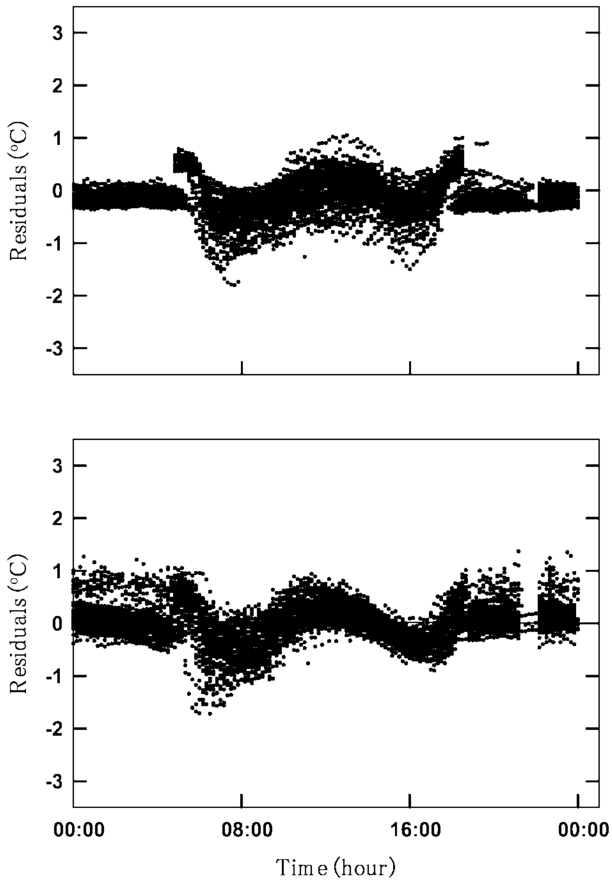

Fig. 3. The residuals scattergram obtained from comparisons between the ESI with the WBGT during 24 h. Data obtained from hot/dry zone (Eilat; top) and hot/wet zone (Bet Dagan; bottom).

zones for hot/dry and hot/wet climate conditions during 24 h. Thus, although this analysis revealed with larger residuals distribution during specific hours, the deviations of most of the prediction residuals were within an acceptable range.

ESI differs from other indices that have been suggested in the past in two aspects. First, this stress index uses for the first time direct measurements of SR and RH. The measurements of these variables are not as cumbersome as measuring T_g and T_w which are used in the calculation of the WBGT. Second, the three meteorological variables used in ESI are characterized by fast-reading responses that take only a few seconds to reach equilibrium.

This study which is based on a large independent database confirms the results of previous studies[11, 14]. In the present study, ESI was evaluated for extreme climatic conditions: hot/dry and hot/wet covering a T_a range of 12.9–44.9°C and an RH range of 5.1–97.3%. Previously the ESI was validated only in comparison to other stress indices [WBGT, the discomfort index (DI), and the modified DI (MDI)], but in a recent study ESI was evaluated under different combinations of metabolic rates, clothing and solar radiation in parallel to the physiological strain index (PSI) and to 3 independent physiological variables (rectal temperature, heart rate, and sweat rate)[13]. The high correlations (R≥0.838) found between the three indices (WBGT, DI, and MDI) and between ESI and the physiological variables after 120 min exercise-heat stress exposure, and the high correlations found in this study between ESI and WBGT under extreme climatic conditions provide the final support for its validity as a heat load index.

In conclusion, ESI has the potential to serve as a substitute to the WBGT index and to be used in postulating safety limits during athletic training and military activity conducted in the heat and in prescribing work rest cycles and fluid replacement regulations under such activities.

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