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# AN ENVIRONMENTAL STRESS INDEX (ESI) AS A SUBSTITUTE FOR THE WET BULB GLOBE TEMPERATURE (WBGT)

Daniel S. Moran
Kent B. Pandolf
William T. Matthew
Richard R. Gonzalez

Biophysics and Biomedical Modeling Division

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U.S. Army Research Institute Of Environmental Medicine
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Daniel S. Moran, Kent B. Pandolf, William T. Matthew, and Richard R. Gonzalez

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13. ABSTRACT *(Maximum 200 words)*
This report summarizes the development of a new environmental stress index (ESI) to assess heat stress. Two independent studies containing four different databases were analyzed in order to evaluate ESI and a small light sensor that measures global radiation. The purpose of the first study was to develop a new environmental stress index (ESI). Meteorological measurements were taken in three climatic zones (hot/wet, hot/dry, and extremely hot/dry) for 60 days, and a new stress index with the following algorithm was developed: ESI=0.63Ta-0.03RH+0.002SR+0.0054 (TaRH)-0.073(0.1+SR)-1
Where Ta = ambient temperature, RH = relative humidity, and SR = solar radiation. The correlation coefficients between ESI and WBGT were very high (R2>0.981). Therefore, we concluded that ESI, based on fast response and accurate climatic microsensors (Ta, RH, SR) which can be combined in a portable device, has the potential to be a practical alternative to the WBGT.
A second study evaluated a small (5mm) light (L) sensor in order to measure global radiation (GR) for use in heat stress assessment and in the ESI. Data were collected from three instruments: L, pyranometer (P) and black globe. The data allowed the determination of a new model which converted the L data measured in mv to P values measured in W×m-2 as follows: P=-13.81+0.619L-0.0001278L2 .

The correlation coefficient between P and L was very high (R2=0.933, P<0.001). We conclude that the L sensor has the potential to measure global radiation for use in heat stress assessment and in ESI.

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## LIST OF ABBREVIATIONS

CumDI – cumulative discomfort index

CumET – cumulative effective temperature

DI – discomfort index

DU – discomfort units

ESI – environmental stress index

GR – global radiation

MDI – modified discomfort index

RH – relative humidity

SL – solar load

SR – solar radiation

$T_a$ – dry bulb temperature

$T_g$ – black globe temperature

$T_w$ – wet bulb temperature

WBGT – wet bulb globe temperature index

P – pyranometer

L – infra-red light sensor

PGR – predicts global radiation

## EXECUTIVE SUMMARY

This report summarizes the development of a new environmental stress index the ESI for heat stress assessment. Two independent studies containing four different databases were analyzed in order to evaluate the ESI and a small light sensor which measures global radiation and is in use in the ESI.

The purpose of the first study was to develop the ESI analytically and experimentally. Meteorological measurements were taken in three climatic zones (hot/wet, hot/dry, and extremely hot/dry) for 60 days, and the new stress index based on these databases was developed as follows:

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

Where, $T_a$ = ambient temperature, RH = relative humidity, and SR = solar radiation. The correlation coefficients between the ESI and WBGT were very high ($R^2>0.981$). Therefore, we concluded that the ESI has the potential to be a practical alternative to the WBGT based on fast response and accurate climatic microsensors ($T_a$, RH, SR) that can be combined in the future into a portable device.

The purpose of the second study was to evaluate a new and relatively small (5mm) light (L) sensor in order to measure global radiation (GR) for use in heat stress assessment and in the ESI. Data were collected continuously for twenty-five days between 09:00h until 17:00h in September through October using three instruments: L, pyranometer (P) and black globe. Analysis of the data led to the construction of a new algorithm which converted the L data measured in mv to P values measured in $W\cdot m^{-2}$ as follows:

$$P = -13.81+0.619L-0.0001278L^2$$

The analyzed data contained 771 measurements, and the correlation coefficient between P and L was high ($R^2=0.933$, $P<0.001$). Therefore, we concluded that the L sensor has the potential to measure GR for use in heat stress assessment and in the ESI.

## INTRODUCTION

Heat stress evaluation is generally determined through meteorological parameters that enable the estimation of the influence of several environmental factors on thermal comfort and physiological ability. The variables included in heat stress indices and their relative weights have changed over the years. Haldane (1905) developed an index for heat load and claimed that changes in the Wet Bulb Thermometer alone were enough to reflect the heat load. Over the years, other environmental indices have been suggested which include measurement of airflow and thermal radiation. Hill et al. [9] introduced the "Kata" thermometer, which enabled measurement of heat dissipation as a function of wind speed and other parameters. In 1932, Vernon [21] was the first to integrate radiant heat into an environmental stress index by using the globe thermometer.

In 1957, Yaglou and Minard [22] introduced the empirical index Wet Bulb Globe Temperature (WBGT), which gained popularity mainly due to its simplicity and convenience of use. It is considered to be the most common heat stress index for describing environmental heat stress. This index is obtained mainly from three parameters: black globe temperature ($T_g$) , which reflects the solar radiation; wet bulb temperature ($T_w$); and dry bulb temperature ($T_a$). This index is calculated as follows: $WBGT=0.7T_w + 0.2T_g + 0.1T_a$. As noted before, the index has gained immense popularity over the years. The WBGT is in use in the field by the U.S. Army and is the index on which sports associations base training safety orders as guidance to prevent heat injury [1,2,11,12,13]. It has also been adapted by the World Health Organization (WHO). In 1972, the National Institute for Occupational Safety and Health (NIOSH) established the WBGT index as the criterion for determining occupational exposure to a hot environment [14]. In 1982, WBGT was approved by the ISO organization as an international standard for heat load assessment, and the index is commonly used as a safety index for workers in various occupations [3,4,7,16]. Later on, work-rest regime regulations were made based on this index. However, WBGT is limited in evaluating heat stress due to the inconvenience of measuring $T_g$. The $T_g$ is usually 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 equilibrium. Second, the blackened sphere is often too large for specialized spaces like helicopter cockpits or armored vehicles. Therefore, measuring $T_g$ becomes impractical, especially in transient situations. It is important to note that the statistical correlation of this index to physiological responses has been only partially tested and is based mainly on the correlation between the number of heatstroke cases during Army training and the heat load as calculated by the WBGT [22].

In 1959, Thom [20] of the US Weather Bureau developed an index based only on two parameters as presented in the following calculation:

$$DI = 8.3 + 0.4T_a + 0.4T_w$$

where DI stands for Discomfort Index expressed in Discomfort Units (DU). Sohar et al. [18], adapted the DI and changed it to a simple algebraic average between the dry and wet bulb temperatures:

$$DI = 0.5T_w + 0.5T_a$$

This new adaptation was based on experiments in which a cumulative amount of sweat was measured over 24 hours and compared with the cumulative discomfort index (CumDI). A high correlation was found between these two parameters (R=0.89). Likewise, a strong correlation was also found between CumDI and Cumulative Effective Temperature (CumET)– another index for assessing heat load [19].

The DI index is in use at many research stations and institutes, both the Israeli Weather Bureau for assessing heat stress and the Israeli Army (IDF) for defining different degrees of heat load and their integration into training restrictions and limitations. The measurement of heat load prior to a military activity in the IDF is done by use of a psychrometer. This instrument consists of two mercury thermometers. One measures the $T_a$ and the other the $T_w$. The arithmetic average between these temperatures is the DI. The psychrometer has its limitations. To get a reliable measurement, one must keep the tip of the Wet Bulb Thermometer wet by using distilled water. In addition, the psychrometer must be rotated for 90 sec at a certain speed. To not follow these instructions might result in a false calculation of the DI.

Over the last few years, major progress has been made in the field of portable heat load instrument technology. New instruments are able to measure and present a variety of meteorological parameters (e.g., $T_a$, relative humidity [RH], and wind speed) and display the calculated heat load on a screen. Moreover, no special training is needed to operate these instruments. It is worth mentioning that the microsensors in these instruments have a fast response time, and displaying the results is a matter of waiting just a few seconds. The simplicity of operation makes these instruments accessible to laymen who couldn't use them previously.

There were two purposes in this study. The first was to develop a new thermal load index constructed from microsensors for $T_a$, RH, and solar radiation (SR), and thereby assess and determine whether this newly developed index can serve as a reliable and valid alternative to WBGT for measuring environmental stress. The second purpose was to evaluate a new relatively small (5 mm) light sensor to measure global radiation for use in heat stress assessment.

## MILITARY RELEVANCE

It is important for military commanders to have a real time knowledge regarding environmental stress in a number of situations (e.g., during training, combat and deployments to hot/cold environments). Current techniques of evaluating environmental stress are not simple to carry out. They are cumbersome, labor intensive, time consuming, and do not use the latest technology and sensors for weather measurements. Current technology is limited in providing real time environmental stress which require the integration of reliable microsensors with a microprocessor into a portable, ultra lightweight, user friendly device.

The existing U.S. military heat stress monitoring systems are based largely on the WBGT [12], whereas the IDF system is based on the DI [18]. The inherent limitations of the WBGT and the DI have been reported have been reported [6,10,13] in terms of applicability across a broad range of potential military scenarios and environments. These limitations can be attributed, in part, to early constraints on sensor and computational complexity.

Mathematical models of human heat strain allow full consideration of the complex interactions of environment, clothing, acclimatization status, and metabolic heat production that ultimately determine soldier performance limits in a given scenario.

# METHODS

## STUDY I

The database was obtained from a study conducted in Israel and contained 25,549 measurements. Weather measurements were collected every 10 min, during 24 hours a day for 60 days at 3 locations: Eilat and Farahan, which are located in a desert zone and are characterized as low relative humidity; and Tel Aviv, which is located near the Mediterranean Sea and characterized as a higher humidity zone. Another database that was applied to test the validity of the newly developed index was obtained in June 2000. This database includes 409 measurements, which were collected from 16 different locations all around Israel over 16 days. $T_a$ was measured using a mercury-in-glass thermometer, and $T_w$ was measured using a naturally aspirated wet bulb. $T_g$ was measured using the Vernon black globe thermometer, and SR was measured using the EPLAB radiometer. RH was measured using the Testoterm 452 measuring kit.

### Calculations

Heat stress indices were calculated according to the following publications: WBGT was calculated according to Yaglou and Minard standard formula WBGT= $0.7T_w + 0.2T_g + 0.1T_a$, [22], DI was calculated as suggested by Sohar et al. [17] as

$DI=0.5T_a+0.5T_w$, and MDI as suggested by Moran and Pandolf [13] as $MDI=0.75T_w+0.30T_a$. The newly developed environmental stress index (ESI) was constructed as follows:

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

## Statistical analysis

For the development of ESI, we constructed a series of algorithms for WBGT as dependent variables, and Ta, RH, SR, and their interactions using variable transformations (inverse, and Quadratic) as independent variables. Pearson's analysis was used for testing bivariate correlations between the independent and the dependent variables. All equations employed were linear models using a least squares algorithm. For all models, we computed the coefficient of determination (R-Square of the model) and plotted a series of residuals plots versus predicted values for all data and for every meteorological station 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.

## STUDY II

This database was obtained from a study conducted near Tel Aviv, Israel, during the autumn season, September through October, for 25 days. Global radiation measurements were collected daily, every 15 min between 09:00h and 17:00h. These data were collected using three instruments placed under the open sky at 1 m height: black globe ($T_g$) using the Vernon-black globe thermometer, EPLAB pyranometer (P), and infra-red light (L) sensor.

## Statistical analysis

The new model to predict P values from L data was constructed as a linear model that was fitted by the least square method using SAS 8.0 software. Optimization of the constants was executed by the DUD (does not use derivative) method (Ralston and Jennrich, 1978). Correlation coefficients between P and L were computed using Pearson correlation analysis. All statistical contrasts were accepted at the $P<0.01$ level of significance.

## RESULTS

### STUDY I

These data were collected every 15 min over 24 hr for 60 days. Therefore, a wide range of weather measurements was covered as depicted in Table 1.

Table 1. Mean (±SD) and range of environmental measurements of the ESI validation vs. the WBGT (n=25549)

| | $T_a$ (°C) | RH (%) | $T_w$ (°C) | $T_g$ (°C) | SR (W·m$^2$) | WBGT (°C) |
|---|---|---|---|---|---|---|
| Mean±SD | 30.5±5.2 | 47.3±21.8 | 21.5±2.1 | 37.0±9.3 | 301.4±350.7 | 25.5±3.08 |
| Range | 17.1-44.6 | 5.2-97.2 | 12.9-26.7 | 16.4-59.4 | 0-1041 | 15.3-33.6 |

At first we calculated and applied the DI and the MDI vs. the WBGT. In spite of the high correlation between DI and MDI with WBGT, ($R^2$=0.840 P<0.01 and $R^2$=0.882 P<0.01, respectively), the DI observations over-estimated WBGT (Figure 1), whereas the MDI observations under-estimated WBGT (Figure 2). In both comparisons, the residuals were distributed non-symmetrically with a trend from the zero line as shown in Figsures 1 and 2.

Next, we constructed a new simple index (SI) for stress evaluation based on $T_a$, RH, and SR as follows: $SI = 0.66T_a + 0.09RH + 0.0035SR$. Each one of these three variables was significant as a component in the index (P<0.01). However, when SI was compared with WBGT, in spite of the high correlation ($R^2$=0.932, P<0.01), the residuals were distributed non-symmetrically with a trend from the zero line (Figure 3).

In order to improve the correlation with WBGT and to provide better distribution around the line of identity, we introduce here the new ESI. The ESI is based on the same three variables ($T_a$, RH, and SR), but also includes parameters of interaction ($T_a \cdot RH$), and transformation $[(SR+0.1)^{-1}]$ from these three variables. These two terms were found to be highly statistically significant in their contribution to ESI, with a high F-Value and greatly eliminating the time effect from the residuals plots. The ESI was applied to the same database as the DI, MDI, and SI, and a highly significant correlation coefficient ($R^2=0.981$, $P<0.001$) was obtained with residuals distributed symmetrically without a trend around the zero line.

A separate database was applied to test the validity of this new index. This database was complied from 16 different meteorological stations at different climatic zones in Israel. The ESI observation was also highly correlated (R2 = 0.92, P< 0.01) with WBGT, and the residuals were distributed symmetrically around the zero line.

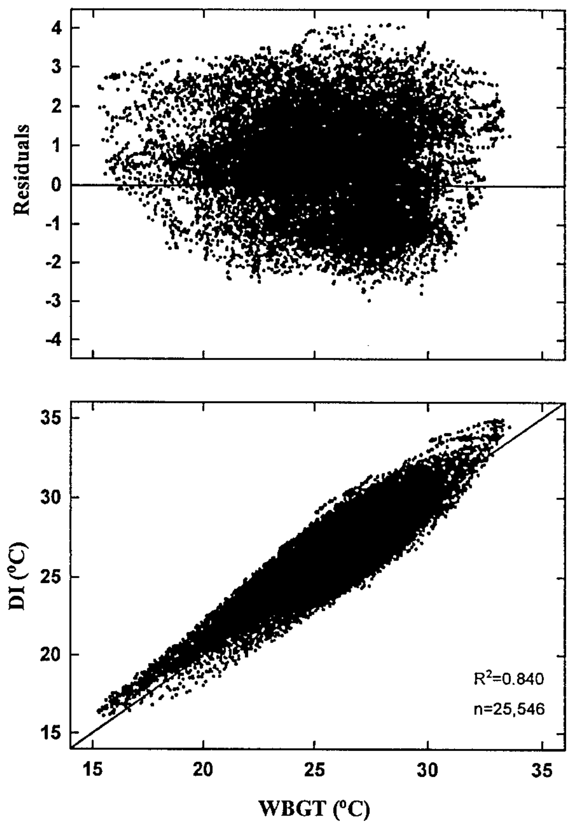



**Figure 1. Comparison of DI [18] with the WBGT index showing correlation (bottom) and residuals scattergram (top).**

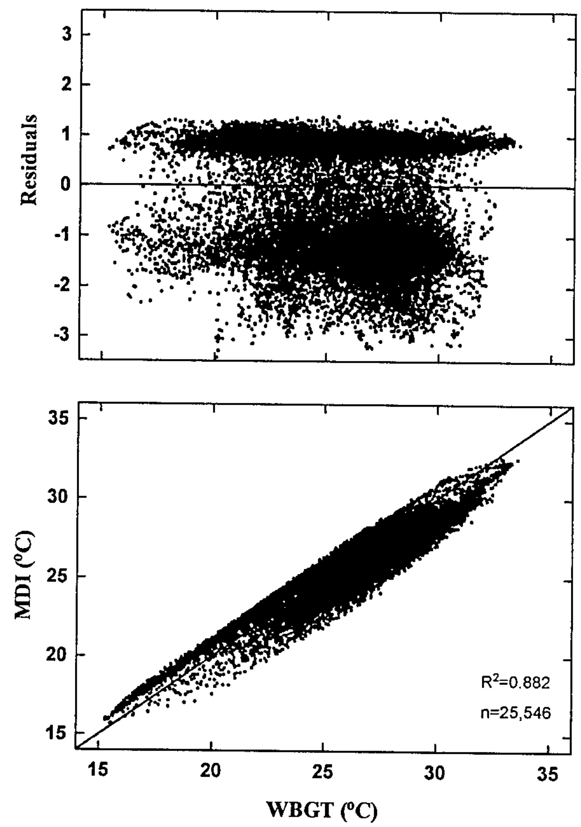



**Figure 2. Comparison of MDI [13] with the WBGT index showing correlation (bottom) and residuals scattergram (top).**

Figure 3. Comparison of suggested SI with the WBGT index showing correlation (bottom) and residuals scattergram (top).

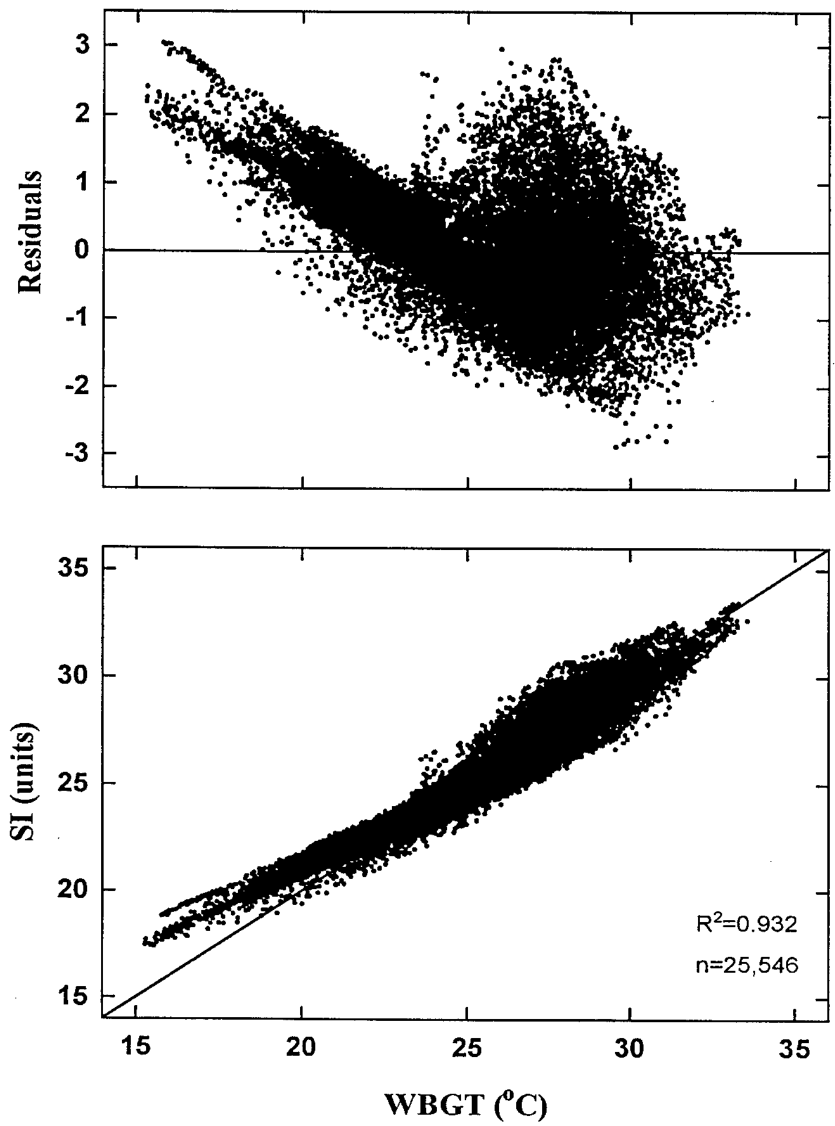


Figure 4. Comparison of suggested ESI with the WBGT index showing correlation (bottom) and residuals scattergram (top).

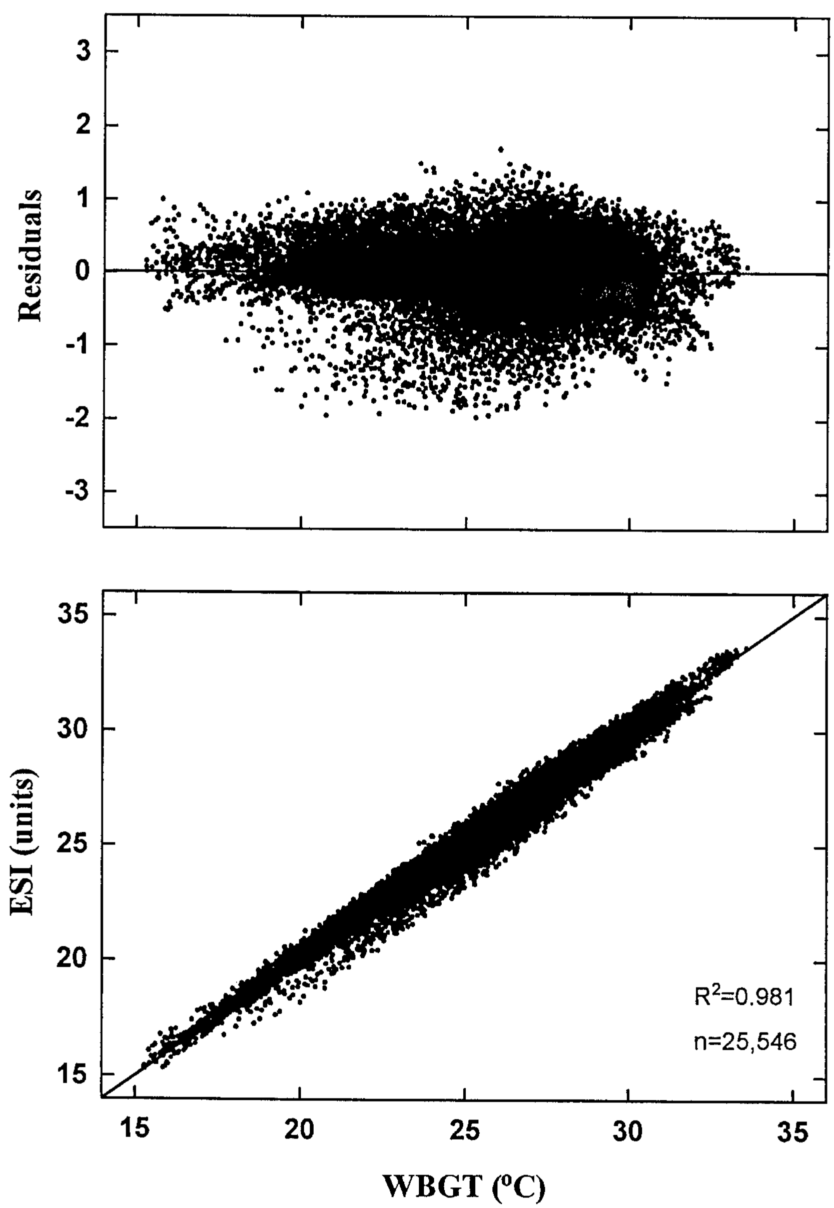
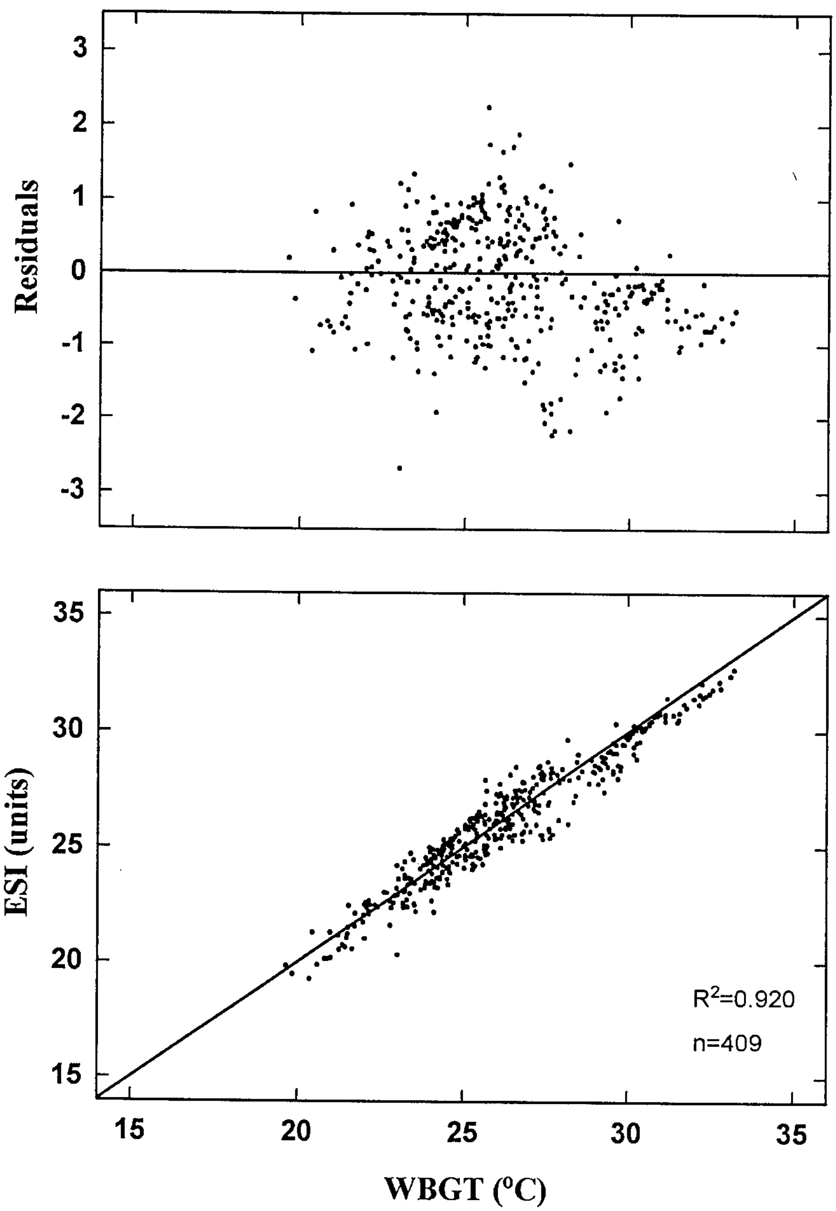


Figure 5. Comparison of suggested ESI with the WBGT index showing correlation (bottom) and residuals scattergram (top). Database for this figure was collected from 16 different locations.



**STUDY II**

The data in this study were collected a wide range of weather measurements, as depicted in Table 2.

Table 2. Mean (±SD) and range of environmental measurements for the predicted global radiation (PGR) model validation vs. global radiation measurements obtained from pyranometer.

| | $T_g$ (°C) | Global radiation ($W{\cdot}m^{-2}$) | Infra-red light sensor (mv) |
|---|---|---|---|
| Mean ± SD | 34.54±3.75 | 347±255 | 770±581 |
| Range | 23.42-42.44 | 0-798 | 10-1921 |

Analysis of the daily collected data from these three instruments revealed that in spite of the different units, the same pattern for P and L occurred during each day, where $T_g$ was slower in its response and lagged behind P and L in its values (Figure 6). Furthermore, in some days during the morning, $T_g$ did not reflect solar radiation (Figure 6, top panel), whereas in other days, $T_g$ accounted for the change from clear skies to overcast only a few hours after the change (Figure 6, bottom panel). In order to focus on $T_g$'s global radiation response and to eliminate $T_a$'s contribution, we analyzed the data as $T_g$-$T_a$.

Therefore, we constructed a new model, which predicts global radiation (PGR) from L data measured in mv for P values measured in $W{\cdot}m^{-2}$, as follows:

$$PGR=-13.81+0.619L-0.00012278L^2; \quad W{\cdot}m^{-2}$$

The analyzed data contained 771 measurements, and the correlation coefficient between PGR and L was high ($R^2$=0.933, P<0.001). In general, the residuals were distributed symmetrically without a trend around the zero line as shown in Figure 7. Analysis of this new model by the hour of the day, for data taken every 15 min between 09:00h to 17:00h, revealed the residuals scattergram around the zero line with no significant trend at any specific hour (Figure 8).

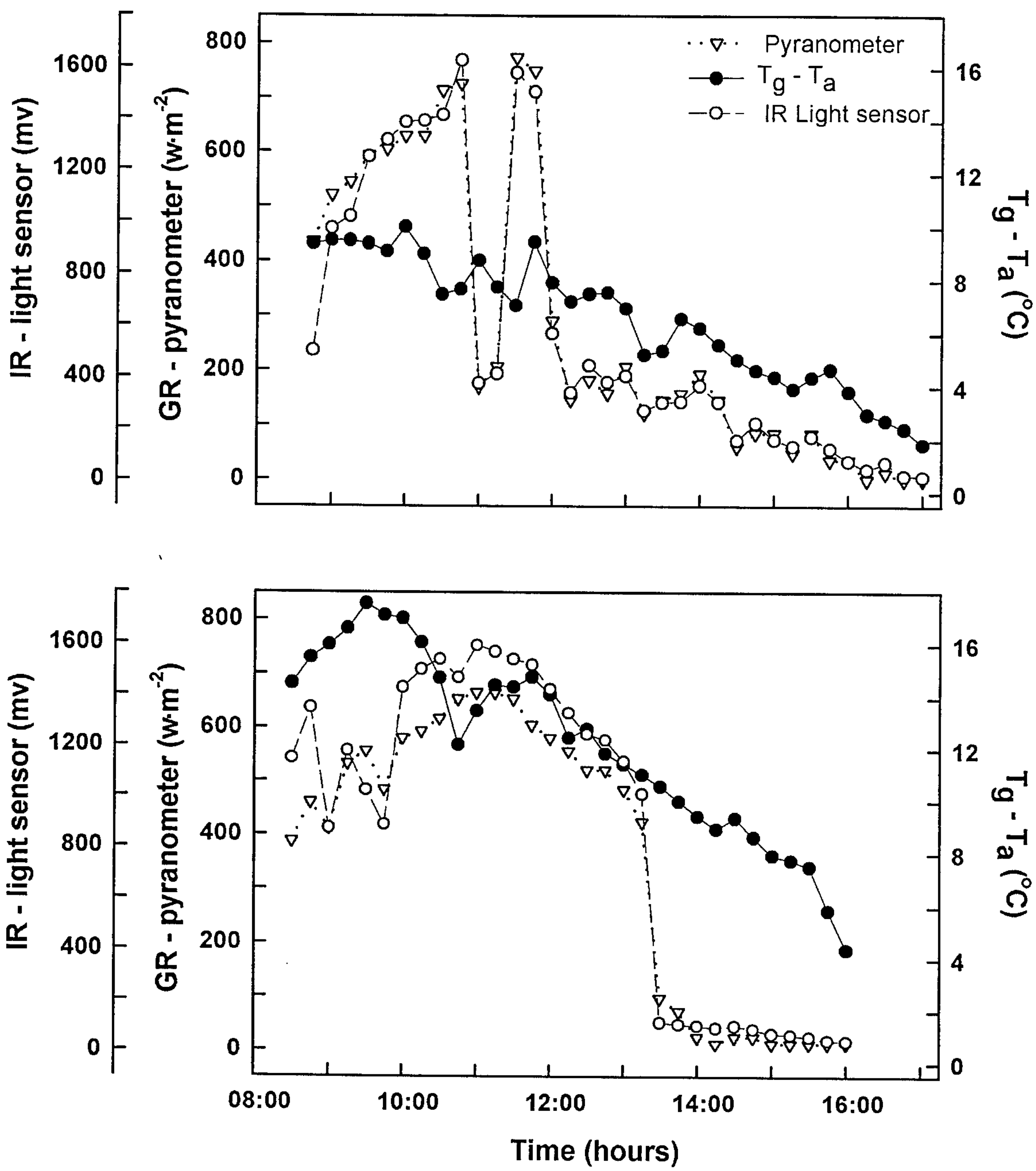



**Figure 6. Global radiation (GR) measured by pyranometer, black globe thermometer (Tg) and infra-red (IR) sensor during two partly cloudy days. Data showing the Tg did not reflect the GR in the morning (top) and lagged behind the change to overcast in the afternoon (bottom).**

Figure 7. Comparison of the suggested predicted global radiation (PGR) model with global radiation measured by pyranometetr. Data showing correlation (bottom) and residuals scattergram (top).

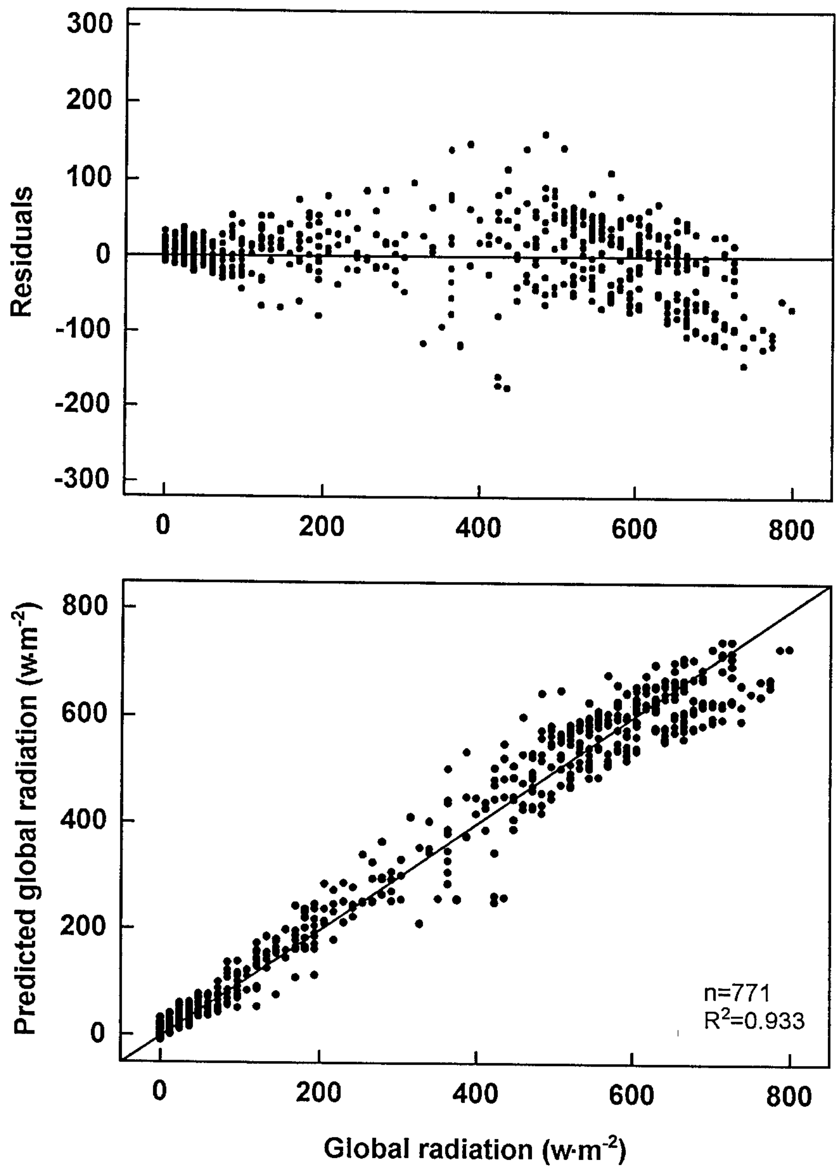
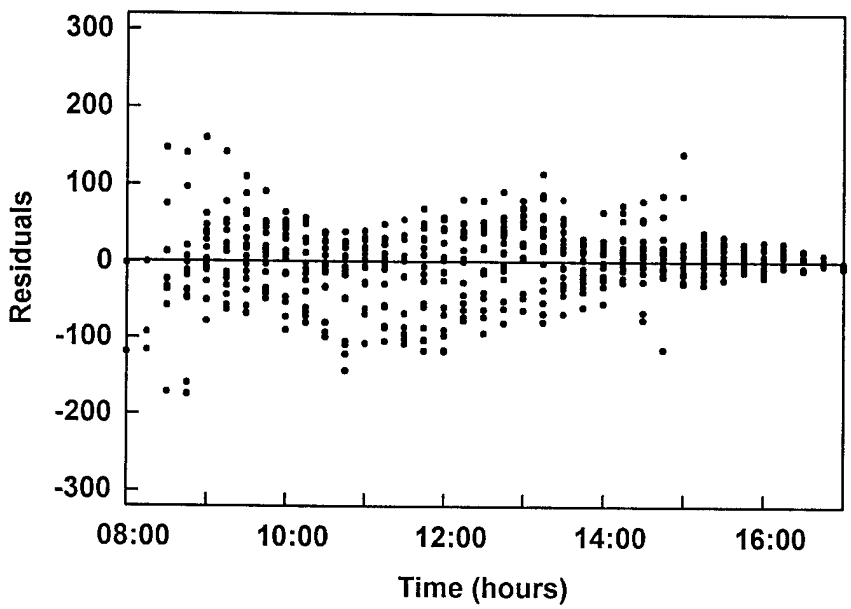


Figure 8. Comparison of the PGR with global radiation measured by pyranometer. Data showing residuals scattergram by the time of the day.



# DISCUSSION

## STUDY I

The present index (ESI), introduced to evaluate environmental heat stress, reliably matches that described by WBGT. The ESI is based on $T_a$, RH, and SR, which depict the thermal load reflected by the climatic conditions. Arithmetically, the first developed version (SI) is simpler to calculate and is based on only three environmental terms. However, the SI has two shortcomings: a trend to lower residuals at lower predicted values, and a clear time effect as shown in the residual plots (Figure 3). The ESI corrects these two shortcomings and also has a much smaller error distribution.

The ESI differs from other indices that have been suggested in the past in two ways. First, ESI is based on SR and RH, apart from using $T_a$. In fact, there are indices based on indirect measurements of SR and RH. For example, the WBGT uses $T_g$ for evaluating SR, and $T_w$ is used for estimation of RH. However, the ESI as an environmental stress index, for the first time, uses direct measurements of SR and RH. Second, the three meteorological variables used in the ESI are characterized by fast reading responses that require only a few seconds to reach equilibrium. For an index to be valid and practical, it should allow for the comparison and evaluation of a combination of different meteorological parameters, as far as their influence on the individual is concerned. It also helps to find different combinations of these parameters that cause parallel subjective thermal sensations. Moreover, the index must enable one to assess the different contributions of each of the meteorological parameters on the individual (Givoni and Goldman, 1972).

Although $T_g$ gives an assessment of solar radiation, the calculation of WBGT involves measuring $T_g$ from a thermometer surrounded by a 6" blackened sphere, which is not practical to use under many circumstances (Moran and Pandolf, 1999). Furthermore, measuring $T_g$ by a black globe thermometer requires about 20-30 min for the instrument to reach equilibrium. The $T_w$ might be useful for relative humidity assessment. However, $T_w$ is not convenient to measure. First, the tip of the thermometer must be wet with distilled water, and second, the psychrometer in which $T_w$ is placed must be rotated for 90 sec. The direct measurements of RH and SR when used in ESI are not as cumbersome as measuring $T_g$ and $T_w$ for calculating the WBGT.

In conclusion, although there are many heat stress indices, this is the first time that SR and RH have been included in a comprehensive thermal stress assessment. This simple index is easier to interpret and use than other indices available to date and includes the more common meteorological variables (e.g., $T_a$, RH, SR). To implement the current guidelines and limitations for exercise in a hot climate, there is a great need for the development of an accurate, miniature and portable heat stress measurement device. This study suggests that the ESI is an ideal index to be used in such a device.

### STUDY II

The newly developed PGR model incorporating a light sensor (L) measurement adequately evaluated global radiation as shown by the high correlation coefficient between PGR and pyranometer measurement of 0.966. Although the database for this study was collected only at one location, the range of the measurements for each day was wide, as seen in Table 2. Furthermore, since the study was conducted during the autumn, we had many days where the sky was not clear, partly cloudy, or completely overcast. The present study suggests a simple, fast response method to measure and evaluate global radiation. This method should be easier to measure, interpret, and use as a potential substitute for $T_g$, which is incorporated in the WBGT. Therefore, we suggest that the L sensor has the potential to measure global radiation. However, more studies should be done for further validation.

## CONCLUSIONS

Although the WBGT is the most common heat stress index and has been adopted by many organizations, we found that there is a great need to combine the new micro-sensors that measure climatic conditions with programmable microchips in order to develop a new environmental stress index. The present study suggests a simple heat stress index to evaluate climatic conditions. This index is easy to measure and practical, since it is based on more commonly used sensors (e.g., RH, L) than the WBGT index. The ESI is capable of overcoming current technical difficulties evident in present measurements of classical WBGT (e.g., $T_g$, $T_w$), while providing an easy-to-operate index that utilizes fast response micro-sensors for heat stress assessment, since there are already existing micro-sensors for measuring $T_a$ and relative humidity (RH).

In summary, we suggest that the ESI has the potential to be widely accepted, used universally, and implemented in a relatively small, portable device. However, further investigation is required to evaluate the IR-light sensor and ESI for different global climates and barometric conditions from sea level to low and high terrestrial areas.

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