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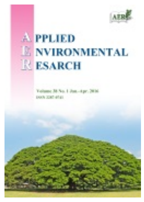

Empirically Derived Equation from Simple Heat Index for Calculating Wet Bulb Globe Temperature: A Case Study of Thailand

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Abstract

The Wet Bulb Globe Temperature (WBGT) index is a standard for assessing environmental heat stress, but the requirement of expensive instrument with specialized maintenance is limited its use. This study aims to develop the empirical equation to estimate the WBGT from Heat Index (HI) calculated from portable temperature and humidity recorder (THR), based on the data collected at seven sites covering all regions of Thailand. Comparative analysis shows that the HI values calculated from THR (HI_{THR}) are consistent well with those measured from the thermal environmental monitor (HI_{QT36}) as evidenced by a highly positive correlation between them (r=0.97; p<0.01; n=4,303). These results suggest high reliability of the portable THR and its acceptance to be used instead of the standard QT36 device. Based on a simple linear regression developed to estimate WBGT from the HI_{THR}, it was found that the model accounts for at least 90% of the variance of the observed WBGT (dependent variable). In addition, validation of the model with the statistical methods shows relatively small errors of the estimated WBGT values in comparison to the observed values. With this evidence, the developed empirical regression equation can be used to estimate WBGT with high accuracy and confidence. Simple and easier to use for the practitioners who are involved in public health works at community level, a heat monitoring tool kit consisting of a THR, WBGT chart and recommended actions were further developed based on the results obtained. This tool kit is a low-cost and simple device which can be used by various community-level stakeholders to prevent and reduce heat injuries and deaths of risk groups, especially the elderly. This tool is necessary in light of anthropogenic-induced warming and Thailand's aging society.

Keywords: Wet bulb globe temperature; Heat index; Empirical regression equation; Simple heat monitoring tool kit

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Introduction

Scientific evidence shows that continued human-induced global warming will result in more frequent, persistent and intense heat waves [1]. Prolonged exposure of extremely hot weather and exceptionally high temperature during heat waves can cause increased heat-related illnesses which leads to excess mortality. The 2003 European heat wave caused more than 70,000 deaths is the well-known example [2]. Heat stress is an individual experience which is dependent on the amount of heat internally generating from the physical activity and the characteristics of the environment governing the heat transfer between the atmosphere and human body [3–4]. Heat stress assessment is generally determined through meteorological parameters that enable to estimate the influence of several environmental factors on thermal comfort and physiological ability.

A variety of climate-based metrics has been employed to measure heat exposure for environmental health research [5]. Most of them are thermal indices which are a combination of at least two climate variables in order to well describe the complex condition of heat exchange between the human body and its environment. One of the most popular indices for environmental health research is Steadman's apparent temperature [6]. It, often also called Heat Index (HI), relies only on temperature and moisture by combining them to determine an apparent temperature - how hot it actually feels. Its drawbacks are, however, that it neglects wind and solar radiation and does not take into account other factors such as amount of clothing and acclimatization that may affect the way one feels temperature [7]. Moreover, the requisite data used for calculation of HI usually come from first-order weather stations not explicitly established for weather and health purposes. As a result, HI cannot be used to accurately represent heat stress in active people and can only be considered as an estimate of the actual heat load particularly in the case of indoor and shade environments [8].

Another well-known index is the Wet Bulb Globe Temperature (WBGT) which is a widely used and validated index for assessing the environmental heat stress [9]. It is able to capture the combined effects of air temperature, humidity, wind and radiative forcing on heat transfer between the environment and the human body [10]. The WBGT has been adopted as the standard criterion for environmental stress assessment defined by the National Institute for Occupational Safety and Health [11] and the International Organization for Standardization [12], and the threshold limit values (TLVs) defined by the American Conference of Governmental Industrial Hygienists [13]. Nevertheless, the WBGT is needed to use as a specialized instrument for heat stress measurement. It is relatively expensive and overhead with its sensor systems, including recalibration of electronic monitors and the need to regularly replenish the natural wet-bulb thermometer's H_2O reservoir. The WBGT index would be more accessible, and easier to use, if it could be calculated using temperature and relative humidity data from logger measures without the need for data from specialized instruments.

Given the important impacts of heat and extremely hot weather under ongoing human-forced warmer climate, this paper aims to develop the empirical equation to estimate the WBGT from HI calculated from temperature and humidity automatic recorder. This statistically derived equation is then used to further develop a simple tool for monitoring and warning heat exposure and stress at community level.

Materials and methods

1) Data collection

In this study, the QUESTemp36 thermal environment monitor (QT36) and the RC-4HC temperature and humidity automatic recorder (THR) are used to measure natural wet-bulb temperature (T_{nwb}), dry-bulb temperature (T_{db}) and black-globe temperature (T_{bg}). Both devices are placed in an open-space indoor environment at about 80-100 cm above the ground on tripod following standard specification of the device as specified in the instruction manual, and its convenience for maintenance (Figure 1). We select to place these devices in the shade condition within building and houses because this environment represents real situation of heat stress which directly affects the human health, leisure activities and welfare of residents [14]. Previous studies have shown that most of daily lives of people, especially higher-risk groups such as the elderly and children take place in shade environment within buildings and houses rather than outdoors [15–16]. The QT36 is one of the most popular devices for environmental health research [17–19]. It combines three sensors including natural wet-bulb sensor with water reservoir and wetted wick, a shielded dry-bulb thermometer and a 5 cm black globe [20]. The natural wet-bulb sensor utilizes a wick and has a reservoir for distilled or deionized water. A daily refill of the water reservoir is therefore required to ensure there is enough water in the reservoir, and a weekly change of the wick is necessary to maintain the purity of the wick [21].

The THR as a simple device is used to measure temperature and humidity for calculating HI. Its measurement range (accuracy) of temperature and humidity is -40ºC to 85ºC (±0.5ºC) and 0%~100% (±3%), respectively [22]. It can record 16,000 data continuously. Many researches have used it to measure temperature and humidity for environmental health studies [14, 22–23]. Moreover, the THR is expedient to measure heat environment and suitably use for preventing dangers from heat stress, as its currently available version is inexpensive and easy to maintain.

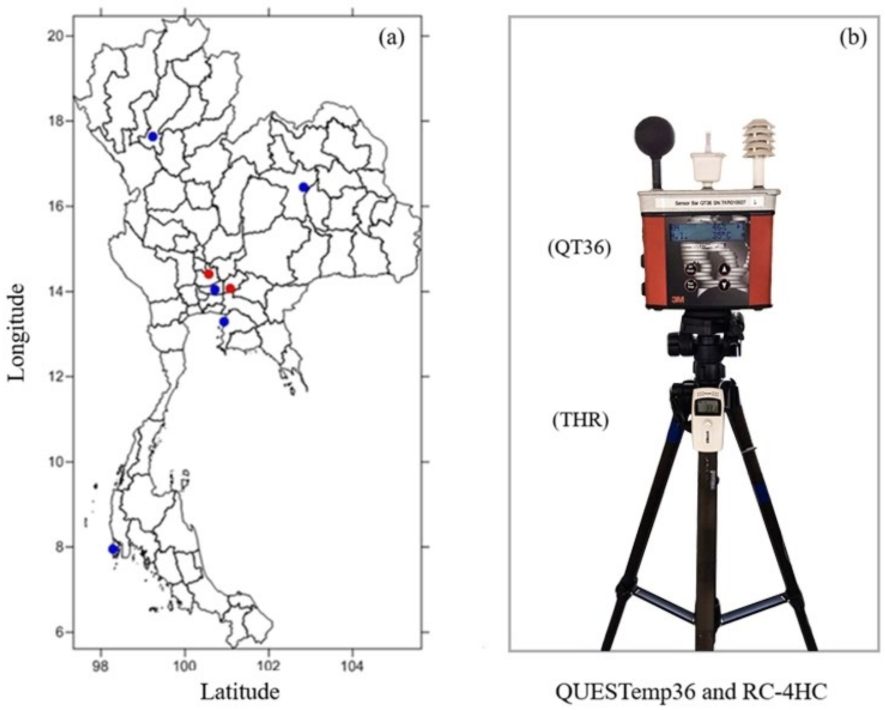

Figure 1 Pictures showing (a) locations of stations measuring natural wet-bulb temperature (T_{nwb}), dry-bulb temperature (T_{db}) and black-globe temperature (T_{bg}) by (b) QT36 and THR devices. The blue dots represent the stations where the data collected for developing the equation while red dots denote the stations where the data collected for validating the developed equation. Pictures of QT36 and THR devices.

The above-mentioned data for developing the empirical equation to estimate WBGT from THR-based HI are collected in five provinces covering all regions of Thailand during October–April 2018 (Figure 1). The study areas are composed of Pathum Thani, Lampang, Khon Kaen, Chonburi, and Phuket. This selection criteria of the measurement stations take into account of regional differences in terms of topographical patterns and meteorological conditions, and the cooperation of local agencies to maintain the devices. In addition, the data collected in Phra Nakorn Si Ayutthaya and Nakorn Nayok during February–March 2019 are used for validating the developed equation (Figure 1). The time interval records are set as 30 min and the data are exported to a computer for initial quality check and recorded in an electronic form at the end of the weekly measurement period.

2) Heat index and wet bulb globe temperature

2.1) Heat index (HI)

The HI, commonly referred to as the apparent temperature, has been originally developed by Steadman as an assessment for sultriness [24]. This index is based on the human energy balance and is determined as the result of various extensive biometeorological studies [25–26]. The HI is the combination of air temperature and relative humidity and is an attempt to estimate what humans feel as an apparent temperature. When the relative humidity is high, the evaporation rate of water is reduced. This means that heat is removed from the body at a lower rate, causing it to retain more heat than it would in dry air. The HI is widely used by public service advisories and is effective when the temperature is greater than 26ºC (80ºF) and relative humidity is at least 40% [27]. In this study, we used the Steadman's apparent equation derived from a multiple regression analysis [26] which the formula is as follows (Eq. 1 and Eq. 2):

$$\begin{aligned} \mathrm{HI} = & -42.379 + 2.04901523\mathrm{T} + 10.14333127\mathrm{R} - 0.22475541\mathrm{TR} \\ & -6.83783 \times 10^{-3}\mathrm{T}^2\ 5.481717 \times 10^{-2}\mathrm{R}^2 + 1.22874 \\ & \times 10^{-3}\mathrm{T}^2\mathrm{R}\ 8.5282 \times 10^{-4}\mathrm{TR}^2 \end{aligned} \quad \text{(Eq. 1)}$$

$$°\mathrm{C} = (°\mathrm{F} - 32) \times 5/9 \quad \text{(Eq. 2)}$$

Where T represents the air temperature (°C) and RH denotes the relative humidity (%). HI values calculated from this formula have an error of ±0.08°C [28–29], and can be classified into four categories as shown in Table 1 based on the health risk criteria.

Table 1 The categories of HI values based on health risk criteria adapted from NOAA [30]

Heat Index (°C)	Description
27–32 (Caution)	Fatigue possible with prolonged exposure and/or physical activity.
32–41 (Extreme caution)	Heat stroke, heat cramps, or heat exhaustion possible with prolonged exposure and/or physical activity.
41–54 (Danger)	Heat cramps or heat exhaustion likely, and heat stroke possible with prolonged exposure and/or physical activity.
> 54 (Extreme danger)	Heat stroke highly likely.

2.2) Wet bulb globe temperature (WBGT)

The WBGT was formulated in 1957 by the United States Army and Marine Corps/Navy as a way to measure the heat stress on the body [31]. The formula has not changed since it was created. In 1982, the formula was certified by the International Standards Organization (ISO 7243, ISO/DIS 7933) [32–33] and has been used by several organizations such as the American College of Sports Medicine (ACSM), International Olympic Committee (IOC), and the Occupational Safety and Health Administration (OSHA). Public health authorities of developed countries such as in the USA have used the WBGT for heat stroke investigation [34]. In Thailand, it has been used to measure heat stress for industrial environments [35–36].

The basic idea of the WBGT is simple. T_{bg} responds to the environmental heat load, while T_{nwb} responds to the ease or otherwise of evaporation. Specifically, radiant heat warms T_{bg} to some level above T_{db} while wind cools it towards T_{db}. Consequently, T_{bg} measures the combined effect of radiant heat, air temperature and wind speed. Similarly, evaporation cools T_{nwb}, the amount of cooling being increased by low humidity and by wind, while radiant heat warms it. Thus, the WBGT responds to all four elements of the thermal environment but not necessarily in the same way as the human body, because of differences in size and shape [31, 37]. Different equations have been used to calculate the WBGT, depending on the presence of solar radiation. Eq. 3 is used to evaluate the heat stress in the outdoors where solar radiation is present, while Eq. 4 is used to evaluate the heat stress in the indoors or outdoors without solar radiation [31].

$$WBGT\ (°C) = 0.7T_{nwb} + 0.1T_{db} + 0.2T_{bg} \quad \text{(Eq. 3)}$$

$$WBGT\ (°C) = 0.7T_{nwb} + 0.3T_{bg} \quad \text{(Eq. 4)}$$

Where T_{nwb} is natural wet-bulb temperature (°C), T_{db} is dry-bulb temperature (°C), and T_{bg} is black-globe temperature (°C).

As shown in Table 2, the U.S. Army work/ rest guidelines include five WBGT-measured heat categories. Each heat category spans a range of 1.1–1.7°C (2–3°F). The work/rest in the OSHA guidelines spans similar ranges. Therefore, to identify the correct heat category, a WBGT model must be accurate to better than 1°C.

Table 2 The U.S. Army work/rest guidelines [38]

Heat category	WBGT index (°C)	Easy work	Moderate work	Hard work
1	25.6 – 27.7	NL	NL	40/20 min
2	27.8 – 29.3	NL	50/10 min	30/30 min
3	29.4 – 31.0	NL	40/20 min	30/30 min
4	31.1 – 32.2	NL	30/30 min	20/40 min
5	> 32.2	50/10 min	20/40 min	10/50 min

Note: - Easy work including walking on hard surface 2.5 mph < 30 lb. load, weapon maintenance, marksmanship training.
- Moderate work including patrolling, walking in sand 2.5 mph no load, calisthenics.
- Hard work including walking in sand 2.5 mph with load, field assaults.
- NL means no limit.

3) Data quality control and analysis methods

At first, the measured data are subjected to quality control checks. The commonly used objective methods which include outliers, data consistency and missing data are applied to address the data quality [39]. Outliers identified are then re-evaluated by comparing their values to adjacent days and to the same day at the nearby stations of Thai Meteorological Department before being edited or removed. Based on the quality control checks, no missing data are found.

All 30-min records of T_{nwb}, T_{db} and T_{bg} which have passed the quality control tests are averaged as hourly data. Hourly HI values are then calculated from THR data. Pearson's correlation analysis is used to evaluate association between the HI values calculated from THR data and those measured from QT36. The Pearson's correlation coefficient is a simple statistic determining the degree of linear dependence between two variables. To develop the empirical equation to estimate the WBGT from HI calculated from THR data, a simple linear regression analysis is used. It involves fitting a linear function to a response variable and an independent variable. In our analysis, HI calculated from THR and WBGT are independent and response variables, respectively. Coefficient of determination (R^2) derived from the regression equation is then used to evaluate the developed equation performance. To validate the developed empirical equation, bias, root mean square error (RMSE) and mean absolute error (MAE) are then used [40–41]. These statistics are calculated based on the data at two provinces in the central and eastern parts of Thailand.

Results and discussion

1) Characteristics and variations of the calculated HI and the measured WBGT

We evaluated the consistency and reliability of the HI values calculated from THR (HI_{THR}) by comparing with those (HI_{QT36}) measured from QT36. Our analysis shows that the HI_{THR} values, taking all five stations together, are consistent well with the HI_{QT36} values as evidenced by highly positive correlation between them ($r=0.97$; $p<0.01$; $n=4,303$). From temporal variation perspective, the HI_{THR} and HI_{QT36} values, for an example, at Chonburi station (Figure 2) show a clear coherent pattern. That is, on diurnal cycle, both HI values correspondingly reach peak at the afternoon and exhibit minima at night. These results indicate the high consistency and acceptable reliability of the portable THR with respect to the standard QT36 device.

Table 3 shows the HI_{THR} and the HI_{QT36} and WBGT measured by QT36 at five stations. Overall, the averaged values of both calculated and measured HI at all stations are in range of 29.9 to 38.2°C. By comparison, however, the HITHR values are lower than the HI_{QT36} values. The minimum values of averaged HI are recorded at Lampang station (Table 3). This may be due to complex geographical setting of the station characterized by mountainous and hilly with narrow valleys and occasional intermountain depressions forming a highly complex [42]. As a result of this, large diurnal variations of temperature normally occur with high temperature appearing in the daytime while temperature dropping dramatically after midnight. Our analysis shows that the maximum values of averaged HI are found at Phuket station (Table 3). This is probably because Phuket has a tropical monsoonal climate with warm and humid all year round. Notably from April to May, temperature and relative humidity are elevated, leading to the HI values are correspondingly high. Moreover, Phuket Island has the highest rate of urbanization compared with all provinces in Thailand and shows the fastest growth in the tourism industry [43]. These combined phenomena may result in higher maximum HI values than other stations.

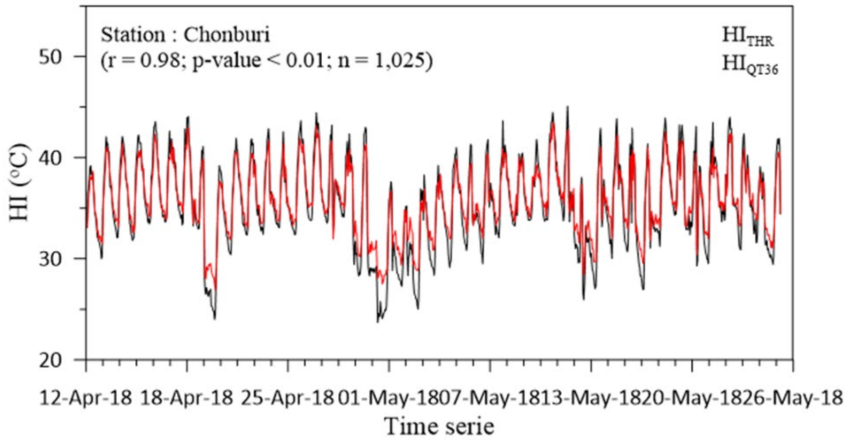

Figure 2 Temporal variation patterns of the HI values calculated from THR and those measured from QT36 at Chonburi station.

Table 3 Averaged HI and WBGT values measured by THR and QT36 at five stations

Stations	HI_{THR} (°C)	HI_{QT36} (°C)	$WBGT_{QT36}$ (°C)
Pathum Thani	31.7 (±4.2)	31.5 (±3.5)	25.7 (±1.8)
Lampang	29.9 (±5.8)	30.6 (±5.6)	24.5 (±2.9)
Khon Kaen	32.1 (±6.0)	32.7 (±4.1)	26.7 (±2.3)
Chonburi	35.4 (±4.4)	35.8 (±3.3)	27.8 (±1.3)
Phuket	38.2 (±2.3)	37.0 (±2.0)	28.3 (±0.9)
All Stations	29.6 (±5.6)	31.7 (±4.3)	26.3 (±2.5)

Regarding the WBGT, the lowest and highest values (24.5°C and 28.3°C) are found at the same stations of the HI values (Lampang and Phuket stations). In general, the HI_{THR} values conform to HI_{QT36} values and WBGT value in all stations. All HI values are higher than WBGT, due to the fact that WBGT incorporates four environmental factors (air temperature, relative humidity, solar radiation and wind speed) that contribute to heat stress while HI combines only temperature and relative humidity [44]. When further considering the differences between WBGT and HI values with respect to health impact levels, the HI values are higher than WBGT values about 3.8, 8.9 and 12.7°C, respectively. Our results are consistent with the study of Bernard and Iheanacho [45] who found that the HI was higher than the WBGT about 2°C at the lowest health impact level and the difference became larger at the danger level. The values measured in this study also agree well with the study of Courtney et al. [46] who simulated weather data such as temperature, relative humidity, wind speed and other parameters to evaluate WBGT. Their results showed that HI values were generally higher than WBGT values. The range of WBGT values in this study is classified as level one and two of heat category based on the work/rest guidelines (Table 2). However, it should be noted that the guidelines are originally designed for the U.S. Army as a measure to prevent heat-related injuries during training.

Our results also show that the measurements of HI_{THR} and HI_{QT36} from five stations are highly correlated. The complete correlations are found at all stations of Pathum Thani ($r=0.98$, $p<0.01$, $n=849$), Lampang ($r=0.98$, $p<0.01$, $n=1,110$), Chonburi ($r=0.98$, $p<0.01$, $n=1,025$), Khon Kaen ($r=0.97$, $p<0.01$, $n=724$) and Phuket ($r=0.96$, $p<0.01$, $n=595$).

2) Development of empirical regression equation for estimating WBGT

A simple linear regression is used to develop the empirical equation for estimating WBGT. The HI_{THR} calculated from temperature and relative humidity data measured in five provinces covering all regions of Thailand that has correlated well with the observed WBGT as described in the previous section is chosen as the independent variable. When the HI_{THR} is regressed against WBGT even individual station or all stations combined, coefficients of determination (R^2) are significant at the 1% level. It is found that the regression models account the variance of the observed WBGT (dependent variable) for at least 90% (Figure 3). By comparison, the determination of variability in the WBGT based on this study is obviously higher than the study of Patel et al. [20] who analyzed Liljegren and Matthew model for estimated WBGT in Georgia and Arizona with R^2 of 0.71, 0.85, 0.63 and 0.68, respectively. The empirical regression equation results shown in Figure 3(d) suggest that the highest R^2 value is recorded at Chonburi station (R^2=0.96, n=1,025). Conversely, the lowest R^2 is found at Phuket station (R^2=0.90, n=595). Figure 3 graphically displays calculated HI_{THR} compared to observed $WBGT_{QT36}$. What stands out from Figure 3 is that the best fit lines for both indices have very similar slopes. Thus, it can be concluded that the empirical regression equation developed can be used to estimate WBGT with high accuracy and confidence.

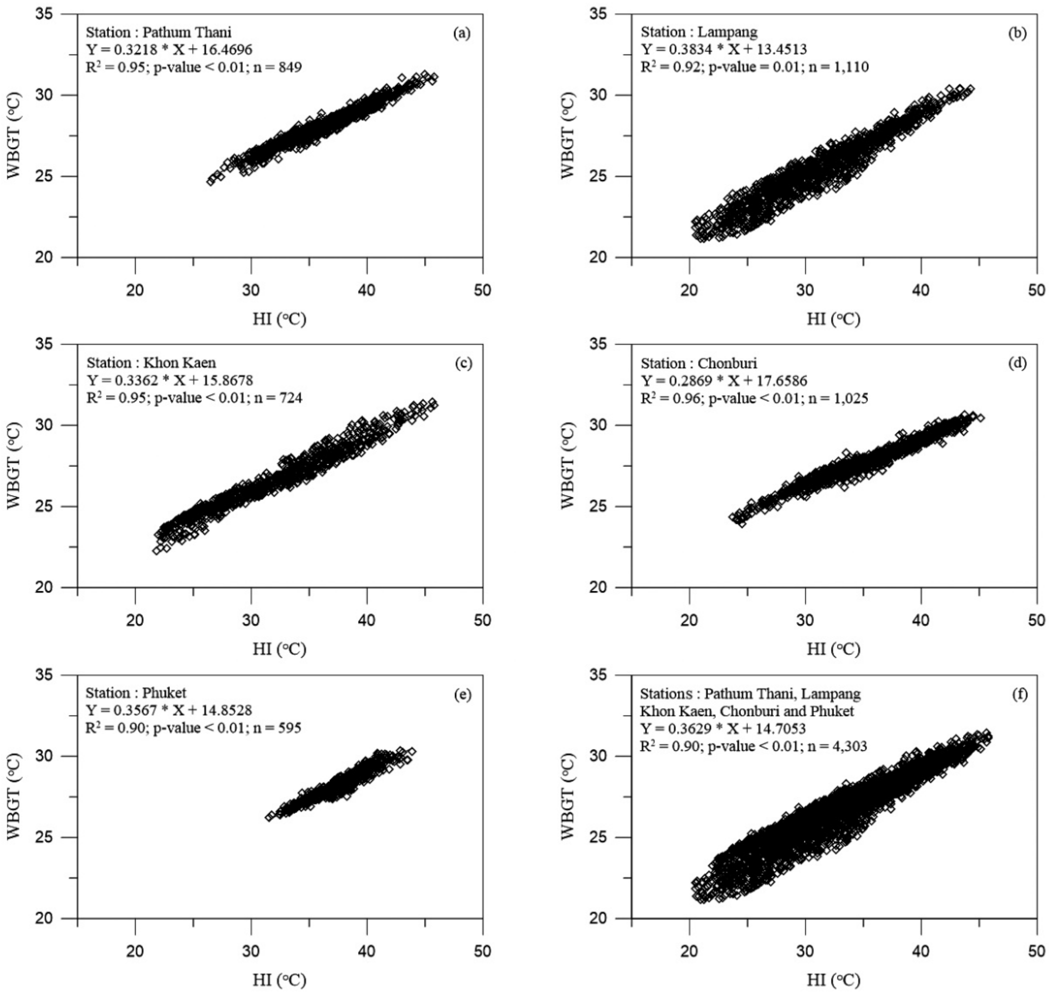

Figure 3 Regression plots with their statistics between the calculated HI_{THR} values as the independent variable against the measured WBGT as the dependent variable at individual station and all stations combined.

To validate the skills of the developed equations, the temperature, relative humidity, HI and WBGT data collected at two stations in the central and eastern parts of Thailand during February-March 2019 are used. Analysis of bias, RMSE and MAE as a statistical technique to evaluate the model skills shows that the averages of bias (-0.34), RMSE (0.49) and MAE (0.4) have relatively small errors of the estimated WBGT values in comparison to the observed values. When compared with the study of Cooper et al. [47] which evaluated WBGT portable monitor accuracy, it was found that the bias, RMSE and MAE of THR approximate to smallest error WBGT portable (bias=-0.64, RMSE=0.44 and MAE=0.24). Figure 4 presents WBGT values of both instruments. From the above analysis, it can be seen that the equations have a good estimation with accepted accuracy. Therefore, it is reasonable to say that the estimated WBGT values from HI_{THR} are close to the measured WBGT values from QT36. The validated results with the statistical methods provide additional confidence that the portable THR and developed equations can be used to estimate WBGT.

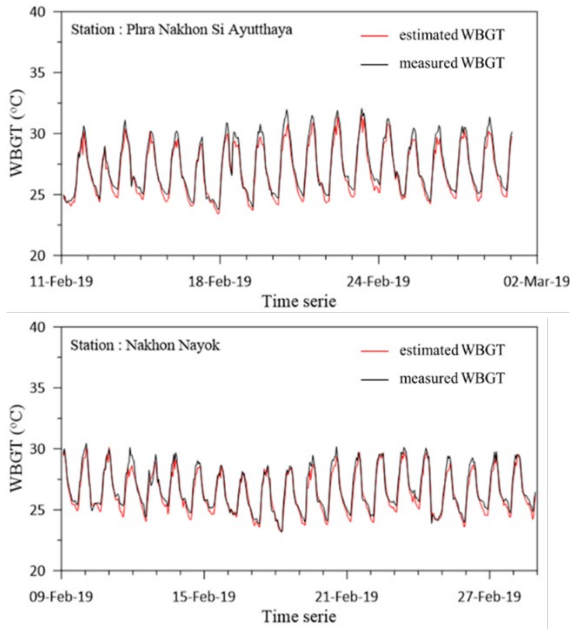

Figure 4 The WBGT values measured by QT36 and the estimated WBGT values from HI_{THR} based on the linear regression equations.

3) A simple heat monitoring and warning tool

The results above are used to further develop a simple and easy-to-use heat monitoring tool kit for public health officers to determine some decisions of warning and protecting risk groups in hot weather situations especially elderly and children. This tool kit consists of three components which are THR, WBGT chart and recommended actions.

The WBGT chart as a popular methodology widely applied in extreme hot weather warning to public (e.g. Heat Index chart by National Oceanic and Atmospheric Administration; Humidex chart by Canadian Centre for Occupational Health and Safety) was created based on the regression equation (Y=0.3629X +14.7053). With the WBGT chart, temperature and relative humidity data from THR can be directly converted to the WBGT values without any calculation. That is to say, the values in the chart provide the WBGT values derived from the developed equation with respect to diffident temperature and relative humidity values. For example, if the air temperature is in range of 33-33.9°C and the relative humidity is in range of 55-59%, the WBGT is then 28.4°C (Figure 5).

The recommendation actions modified from U.S. Army work/rest guidelines of WBGT and heat-related illness of HI [30, 38] are shown in Table 4. Both indices are the long-accepted index to represent the environmental contri-butions to heat stress and commonly reported to public in many countries [8]. Important information is a combination of the risk of heat-related illness into the WBGT guideline. For this study, the recommended actions are made into five band colors associated with the WBGT level, health impact, activity level/rest time and drinking water. The band colors let officers know the WBGT status, and can be used to help determining the risk of heat-related illness for risk groups, actions needed to protect themselves, and when those actions should be triggered. For example, when WBGT is in range of 27.8–29.3°C (Level 2), exercising or working in hot weather will stress an individual's body after 50 min. To prevent heat-related illnesses, Therefore, planning 10 min of breaks for each hour and taking at least 0.5 L of water should be done.

There are three steps to use the simple heat monitoring tool kit as follows: 1) measuring the air temperature and relative humidity with the THR, 2) comparing the value with the WBGT chart (Figure 5) to get the WBGT value, and 3) comparing the WBGT with recommended actions (Table 4). Therefore, this tool will be useful for monitoring and warning extremely heat weather situation in form of WBGT which is an appropriate index as it is calculated from multiple climate variables, representing the heat stress and effects of hot weather better than the HI. Such a simple heat monitoring tool kit will be an important mechanism to increase preparedness and prevention of heat-related illnesses at community level.

Relative Humidity	Temperature																
	27°C	28°C	29°C	30°C	31°C	32°C	33°C	34°C	35°C	36°C	37°C	38°C	39°C	40°C	41°C	42°C	43°C
40%	24.5	24.7	25.1	25.5	25.9	26.4	27.0	27.6	28.2	28.9	29.7	30.5	31.3	32.2	33.2	34.2	35.2
45%	24.5	24.9	25.3	25.7	26.2	26.8	27.4	28.1	28.8	29.6	30.4	31.3	32.3	33.3	34.4	35.6	36.8
50%	24.7	25.0	25.5	26.0	26.5	27.2	27.9	28.6	29.5	30.4	31.3	32.3	33.4	34.6	35.8	37.1	38.4
55%	24.8	25.2	25.7	26.3	26.9	27.6	28.4	29.3	30.2	31.2	32.3	33.4	34.7	35.9	37.3	38.7	40.2
60%	24.9	25.4	26.0	26.6	27.4	28.2	29.0	30.0	31.1	32.2	33.4	34.7	36.0	37.4	38.9	40.5	42.2
65%	25.0	25.6	26.3	27.0	27.8	28.7	29.7	30.8	32.0	33.2	34.6	36.0	37.5	39.1	40.7	42.5	44.3
70%	25.2	25.8	26.6	27.4	28.3	29.4	30.5	31.7	33.0	34.4	35.8	37.4	39.0	40.8	42.6	44.6	46.6
75%	25.3	26.1	26.9	27.9	28.9	30.1	31.3	32.6	34.1	35.6	37.2	38.9	40.7	42.7	44.7	46.8	49.0
80%	25.5	26.4	27.3	28.4	29.5	30.8	32.2	33.7	35.2	36.9	38.7	40.6	42.6	44.6	46.8	49.1	51.5
85%	25.7	26.6	27.7	28.9	30.2	31.6	33.1	34.7	36.5	38.3	40.3	42.3	44.5	46.8	49.1	51.6	54.2
90%	25.9	27.0	28.2	29.5	30.9	32.5	34.1	35.9	38.8	39.8	41.9	44.2	46.5	49.0	51.6	54.3	57.1
95%	26.1	27.3	28.6	30.1	31.7	33.4	35.2	37.2	39.2	41.4	43.7	46.1	48.7	51.4	54.2	57.1	60.1
100%	26.3	27.6	29.1	30.7	32.5	34.4	36.4	38.5	40.7	43.1	45.6	48.2	51.0	53.9	56.9	60.0	63.2

Normal (WBGT ≤ 27.7℃)
Caution (WBGT 27.8 - 29.3˚C)
Extreme Caution (WBGT 29.4 - 31.0℃)
Danger (WBGT 31.1 - 32.2℃)
Extreme Danger (WBGT > 32.2°C)

Figure 5 The WBGT chart derived from the developed equation with different air temperature and relative humidity values.

Table 4 Modified recommended actions for prevention heat illness

Level	Band	WBGT (°C)	Risk of Heat Illness	Activities	Water l/h
Normal	White	25.6–27.7	-	NL	0.4
Caution	Green	27.8–29.3	Fatigue is possible with prolonged expose and activity	50/10 min	0.5
Extreme	Yellow	29.4–31.0	Heat stroke, heat cramps, or heat exhaustion possible with prolonged exposure and/or physical activity	40/20 min	1
Danger	Red	31.1–32.2	Heat cramps or heat exhaustion likely, and heat stroke possible with prolonged exposure and/or physical activity	30/30 min	1
Extreme Danger	Black	> 32.2	Heat stroke imminent	20/40 min	1

The tool kit can be implemented as a component of existing Community Heat-Health Surveillance and Warning System developed by the Department of Health [48], and operate with the public health local network (Figure 6). The network consists of the District Public Health Office (DPHO), the Health Promoting Hospital (HPH), the public health volunteer, the community leader, and the local municipality. The operation should be scheduled in summer (from mid-February to mid-May) [49]. First of all, the staff of the HPH will measure the temperature and relative humidity using an automatic recorder (THR) at 01.00 pm. and 03.00 pm. Then, interpret the measurements obtained through the use of the WBGT chart (Figure 5) and the recommended actions for heat illness (Table 4). When the WBGT values at normal to caution level, the HPH will inform the network to prepare for critical incidents. Once the WBGT values at extreme to danger level, the network has to urgently warn the community of the extreme heat weather situation and actions needed to protect themselves (Table 4) via the broad-casting tower and community radio twice a day [50]. In case of the WBGT values at extreme danger level, the volunteer will visit to the risk groups' houses, and coordinate with the HPH, the community leader, and the local muni-cipality for referring the patients and risk groups to the hospital or the community cooling center. Finally, the volunteer will not only report the number of patients to the HPH, but also to the DPHO in order to evaluate the situation. For the validation, it should be conducted by using the following criteria of the WMO-WHO: 1) the simplicity of the tool kit 2) the acceptability of the users, and 3) the period and the sensitivity of the warning [27]. Furthermore, the warning system and tool kit should be piloted in various community settings to test the reliability of the model under differing settings and conditions.

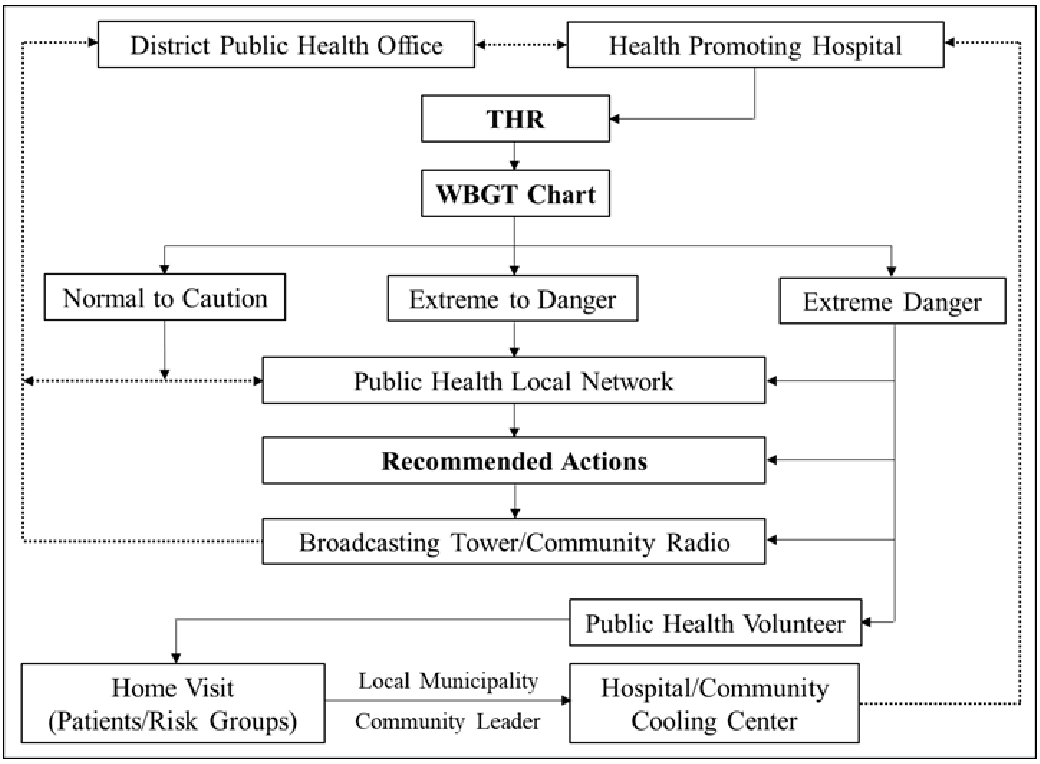

Figure 6 The implementation of simple heat monitoring tool kit at the community level adapted from the Department of Health.

Conclusions

This study, which developed an empirically derived equation from simple heat index for calculating wet bulb globe temperature in Thailand highlights the following key findings:

1) The portable THR can reliably calculate HI and the HI_{THR} values, which are consistent with the HI_{QT36} values as evidenced by the highly positive correlation between them. These results indicate the high consistency and accepted reliability of the portable THR with respect to the standard QT_{36} device.

2) The regression models developed account for the variance of the observed WBGT (dependent variable) for at least 90%. In addition, validation of the model with statistical methods shows relatively small errors of the estimated WBGT values in comparison to the observed values. Thus, the empirical regression equation developed can be used to estimate WBGT with high accuracy and confidence.

3) As a simple and easy to use tool for the practitioners and non-scientists who are involved in public health work at the community level, a heat monitoring tool kit consisting of THR, WBGT chart and recommended actions, was developed based on the results. This simple heat monitoring tool kit is an important low-cost device which can be used by various community-level stakeholders to prevent and reduce heat injuries and deaths for vulnerable people who are increasingly exposed the extremely hot weather conditions under on-going anthropogenic-induced warming and aging society. This tool can undoubtedly be an effective part of Thailand's climate change adaption plan relevant to health sector.

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