ORIGINAL ARTICLE

Development of a hot weather warning tool for heat index monitoring in Thailand

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ABSTRACT

This study aims to develop and test an extremely hot weather warning tool. The tool consists of a Node MCU ESP8266 microcontroller, air temperature and relative humidity sensor (DHT22), real time clock module (DS3231), micro-SD-card adapter (HW-125), display screen (2004A), and breadboard-shield. It is connected and controlled by Arduino IDE program. Its measurement ranges for temperature, humidity, and heat index are <10 to >50°C, 0 to 100%, and <27 to >50°C, respectively. This device also presents real-time health impacts by displaying one of five warning levels, namely 1) normal level (HI < 27°C), 2) caution level (HI 27°C to <32°C), 3) extreme caution level (HI 32°C to <41°C), 4) danger level (HI 41°C to <54°C), and 5) extreme danger level (HI ≥ 54°C). The data can be directly transferred to a computer by a card adapter. Based on validation with the occupational health and safety standards instrument, no outliers or missing data were found. HI_{EHT} had a highly positive correlation with HI_{QT36} ($r=0.99$; $p<0.01$; $n=4,182$). Heat Index data measured by this tool was found to have acceptable values with a bias of 0.54 and RMSE of 0.99. For the pilot areas tested, it was found that the extremely hot weather warning tool can fully measure and record, as well as continuously display the results according to the tested date and time. These results show that the developed tool is a simple, easy-to-use, inexpensive, tiny, and portable instrument that can be used to monitor and measure heat to widely communicate extremely hot weather warning information to vulnerable groups and the general public in the community.

Key words:
climate change adaptation; extremely hot weather; simple device; health impact

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INTRODUCTION

Scientific evidence shows that current human-caused global warming is affecting nature and people's lives worldwide. More severe and frequent climate extreme events, particularly heatwaves, have caused widespread and pervasive effects on cities, ecosystems, infrastructure, and people and limit the chances of a livable future for all.[1-3] The changing climate has already produced considerable shifts in the underlying social and environmental determinants of human health at local-to-global scales. Heat-related deaths in people over 65 have increased by 53.7% over the past 20 years, reaching 296,000 deaths in 2018.[4] The worst affected groups are children under the age of five, the chronically ill, the socially isolated, and those working outdoors or in non-cooled environments.[5, 6] New knowledge indicates that human-induced climate change has either caused these destructive effects or increased their likelihood. The anticipated increase in global temperature and heatwave, together with other environmental factors will significantly increase heat health risks for the most vulnerable people, particularly those who reside in low-income countries, where coping or adaptation measures are limited.[6]

Accumulated evidence has shown that Thailand is recognized as a country that is highly vulnerable to climate change including extremely hot weather.[7-8] The Heat Index in Thailand as a whole has increased significantly by 0.53°C per decade (2.3° C for 43 years).[9] It was at the caution level (27 to <32°C) but will gradually rise to the extreme caution level (HI 32 to <41°C) in the future. Under a high emission scenario (Representative Concentration Pathway 8.5; RCP8.5) with little effort to reduce greenhouse gases emissions, heat-related deaths among the elderly are projected to increase from 3 deaths to about 58 deaths per 100,000 by 2080.[10] Exposure to extremely hot weather results in a range of negative health impacts, from mortality and morbidity due to heat stress and heatstroke to respiratory disease and exacerbations of cardiovascular conditions. In 2016, 2,473 cases of heat illness were reported among outdoor workers (4.12 per 100,000 workers) in Thailand, most commonly among agricultural and construction workers aged 15-60 years.[11] These findings suggest that extremely hot weather contributes to elevated cases of heat-sensitive illness and poses health risks to the public and especially the elderly, whose numbers have quickly grown due to an ageing society.[9, 12-13]

Nowadays, major governmental agencies in Thailand primarily use daily measurements of maximum temperature obtained from the Thai Meteorological Department (TMD) to communicate and warn the public of extremely hot weather and heat.[14] Most provinces only have a single monitoring station which does not adequately capture the true extent of extremely hot weather and heat stress at a larger spatial scale.[15] Moreover, temperature alone has not been considered a moral indicator of the human thermal environment or heat.[16] Two-parameter thermal indices have been mostly developed to describe the complex conditions of heat exchange between the human body and its thermal environment.[17-18] A commonly used thermal index for environmental health research is Heat Index (HI) which combines air temperature and relative humidity to determine an apparent temperature representing how hot it actually feels.[19] HI must be measured with a specific instrument to record heat stress. It is relatively expensive and difficult to use. Thus, this study focuses on the development of a simple instrument that can measure air temperature, relative humidity, and HI for providing extremely hot weather warnings. Additionally, it is user-friendly for practitioners and volunteers involved with public health networks within the community.

METHODS

Tool configuration

To develop a simple device for extremely hot weather warning (EHT), a temperature and humidity sensor (DHT22), real time clock (DS3231), liquid crystal display (LCD2004A), and SD-card adapter (HW-125) were used and assembled. This hardware was selected based on consideration of several factors such as low cost, accuracy and resolution levels, compact size, and ease of use.[20-21] All parts were connected to Node MCU ESP8266 microcontroller and controlled by Arduino IDE program.[22-23] The configuration of the EHT consisted of: 1) DHT22 measuring temperature and moisture, 2) DS3231 setting date and time, 3) Node MCU calculating HI, 4) HW-125 recording data, and 5) LCD2004A to show values (Figure 1).

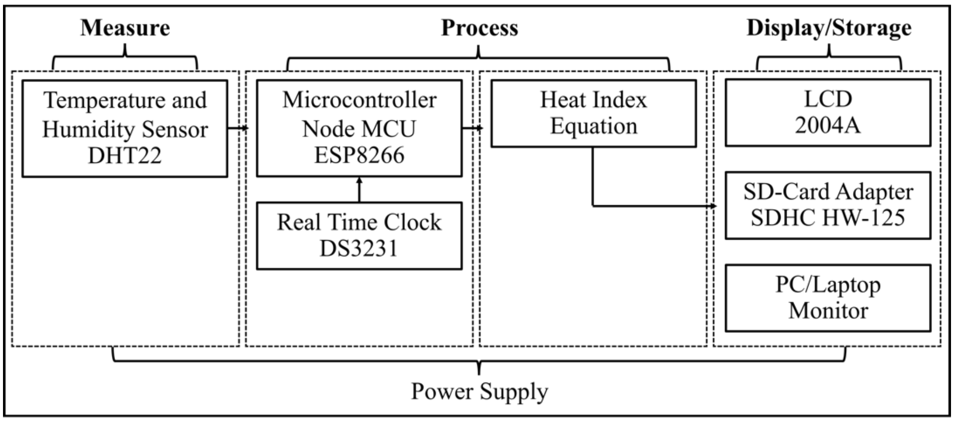

Figure 1. Architecture of the system developed for the EHT device

Data collection

After the system was assembled, the EHT was first tested at the Environmental Research and Training Center (ERTC) in Pathum Thani Province from January 2022 to June 2022. The selection criteria taken into account for the measurement area were the distance in terms of maintaining the devices, daily check conditions, and safety. Both the EHT and the QUESTemp36 (QT36) were used to measure temperature (T), relative humidity (RH), and HI. The EHT results were compared with measurements from the QT36 thermal environment monitor standard instrument.[24] The QT36 is the most popular device for occupational and environmental health research and it can automatically measure HI.[25] Both devices were located in an indoor environment at 1.1 m above the ground on a tripod following the instruction manual (Figure 2).[26] The time interval records were set at 30 minutes. Data was subsequently transferred to a computer for initial quality checking and recorded in an electronic format at the end of the weekly measurement period. Additionally, we selected pilot areas based on variability and trend of Heat Index in Thailand from 1975-2017.[9] The EHTs were used at the Lao Bua Ban Health Promoting Hospital in Maha Sarakham Province, Hua Ta Lae Subdistrict Administrative Organization in Chaiyaphum Province, and Ban Ao Nam Bor School in Phuket Province as the pilot areas to evaluate its performance. The data collected in the pilot areas from March 2022 to May 2022 were used to validate the EHTs (Figure 2).

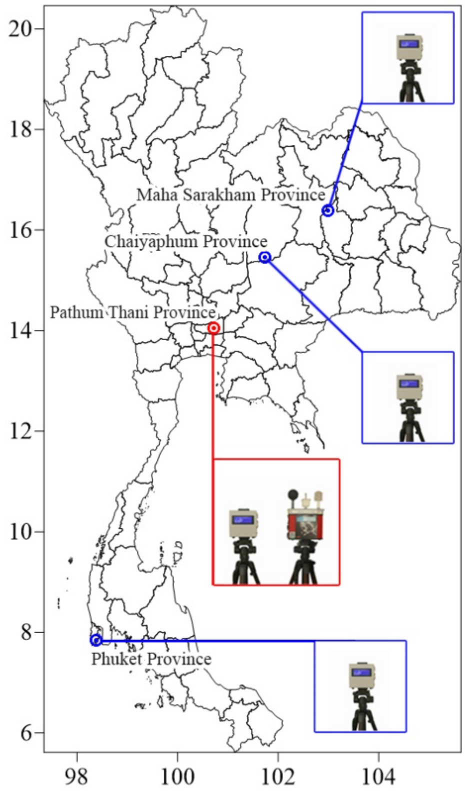

Figure 2. Station location measuring T, RH, and HI by the EHTs and QT36 devices (red dot) and the stations where data was collected to evaluate the EHT performance (blue dots).

Data quality control and analysis methods

The measured data was subjected to quality control checks. Commonly used objective methods including missing data, outliers, and data consistency were applied to address the data quality.[27] Based on the quality control checks, no missing data or outlier data was found. All 30-minute records of HI which have passed the quality control tests were averaged as hourly data. Pearson's correlation analysis was used to evaluate association between the HI values measured from EHT (HI_{EHT}) and those measured from QT36 (HI_{QT36}). The Pearson's correlation coefficient is shown in Equation 1.[28] In addition, to validate the HI data of the EHT and those of the QT36, bias (Equation 2), Root Mean Square Error (RMSE) (Equation 3), percentage error (Equation 4), and accuracy (Equation 5) were then used.[29-30] These statistics were tested based on a set of measured long-term data when compared with related previous studies.[31-33]

$$r = \frac{n(\sum xy)-(\sum x)(\sum y)}{\sqrt{[n\sum x^2-(\sum x)^2]\,[n\sum y^2-(\sum y)^2]}} \quad \text{(Eq. 1)}$$

where r is Pearson's correlation coefficient, while x and y represent values of the x and y variables

$$bias = \frac{1}{n}\sum_{i=1}^{n}(X\mathrm{i} - x) \quad \text{(Eq. 2)}$$

RMSE often measures the deviation between the observed and true values.[34] Its calculation formula is as follows:

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(y_i - \hat{y}_i)^2} \quad \text{(Eq. 3)}$$

In this study, *yi* is the measured value by the EHT, ˆ *yi* is the measured value by the QT36, and n is the total number of measurements.

$$Percentage\ Error = \frac{\text{Approximate Value} - \text{Exact Value}}{\text{Exact Value}} \text{x100} \quad \text{(Eq. 4)}$$

where approximate value is the measured value of HI by ETH and exact value is the measured value of HI by QT36.

$$Accuracy\ (\%) = \frac{\text{Observed Value} - \text{Theoritical Value}}{\text{Theoritical Value}} \quad \text{(Eq. 5)}$$

For this study, observed value is the measured value by the EHT and theoretical value is the measured value by the QT36, and n is the total number of measurements.

Heat Index

Air temperature and humidity are important determinants of heat stress and can have a great impact on public health.[16] The US National Weather Service (NWS) uses temperature and relative humidity to calculate a HI as a metric to identify the thresholds for heat stress as felt by the public.[35] This index is based on the human energy balance and is determined by the results of various extensive biometeorological studies.[36] HI is an attempt to estimate what humans feel as an apparent temperature. When the relative humidity is high, the loss rate of water is reduced which means that heat is reduced from the body at a lower rate, this causes the body to retain more heat than it would in dry air. HI is often used by public service advisories and is effective when the temperature is greater than 26ºC or 80ºF and humidity is at least 40%.[37] We applied Steadman's apparent equation based on a multiple regression analysis, for which the formula is as follows (Equation 4 and Equation 5)[38]

$$\text{HI} = -42.379 + 2.04901523\text{T} + 10.14333127\text{R} - 0.22475541\text{TR} \quad \text{(Eq. 4)}$$
$$-6.83783 \times 10^{-3}\text{T}^2\ 5.481717 \times 10^{-2}\text{R}^2 + 1.22874$$
$$\times 10^{-3}\text{T}^2\text{R}\ 8.5282 \times 10^{-4}\text{TR}^2$$
$$°\text{C} = (°\text{F} - 32) \times \frac{5}{9} \quad \text{(Eq. 5)}$$

where T denotes the air temperature (°C) and RH represents the relative humidity (%). HI values calculated from this equation have an error of ±0.08°C[39-40] and can be classified into five levels as shown in Table 1. It should be noted that these criteria are general guidelines for monitoring potential health impacts that may occur. They do not represent exact heat-related effects or illness.

Table 1. Risk to human health from continued exposure to excessive heat.[41-43]

HI (ºC)	Level	Description
<27	Normal	Fatigue with prolonged exposure
27 to <32	Caution	Fatigue possible with prolonged exposure and/or physical activity.
32 to <41	Extreme Caution	Heat stroke, heat cramps, or heat exhaustion possible with prolonged exposure and/or physical activity.
41 to <54	Danger	Heat cramps or heat exhaustion likely, and heat stroke possible with prolonged exposure and/or physical activity.
>54	Extreme Danger	Heat stroke is likely high.

RESULT

Component selection and description

1. Microcontroller

The Node MCU ESP8266 is the most popular microcontroller board for environmental health research (Figure 3A).[44-45] It consists of an analog input pin, 17 general purpose digital input-output pins, and an inbuilt analog to digital converter (ADC). The Node MCU is equipped with 128 MB RAM and a flash memory of 4 MB to save the code written to obtain the required data and store the fetched information.[46-47]

2. Temperature and humidity sensor

The DHT22 is an inexpensive digital temperature and humidity sensor (Figure 3B). It is widely used mainly due to its user-friendly nature and being robust.[48] The output of the sensor is a digital signal that is to be transferred to the appropriate data pin. The working temperature is -40°C to 80°C and the humidity range is 0 to 100%. The temperature has an accuracy of ±0.5°C, and the humidity ±2%.[49-50] Unlike the DHT11 sensor, the DHT22 sensor provides better accuracy for temperature and humidity.[51]

3. Real time clock

The DS3231 module is a highly accurate real-time clock that can maintain time in hours, minutes, and seconds as well as the day, month, and year information (Figure 3C).[52] It has automatic compensation for leap years and months with less than 31 days. The clock has an AM/PM indication and works in either a 24-hour or 12-hour mode. The battery input is 3V and provides power to the module.[53]

4. Display module

The LCD 2004A is a display of liquid crystal material which is operated using a dot matrix system. LCD can display 40 characters consisting of four lines, and each line can display 20 characters (Figure 3D). Simplification of the circuit connections is the real significant advantage of this I2C Serial LCD module.[54]

5. SD-card adapter

The HW-125 is a Micro-SD-card reader module for reading and writing through the file system and the SPI interface driver (Figure 3E). It supports high-speed Micro SD-card (SDHC) and power supply input is in the range of 4.5V to 5.5V.[55]

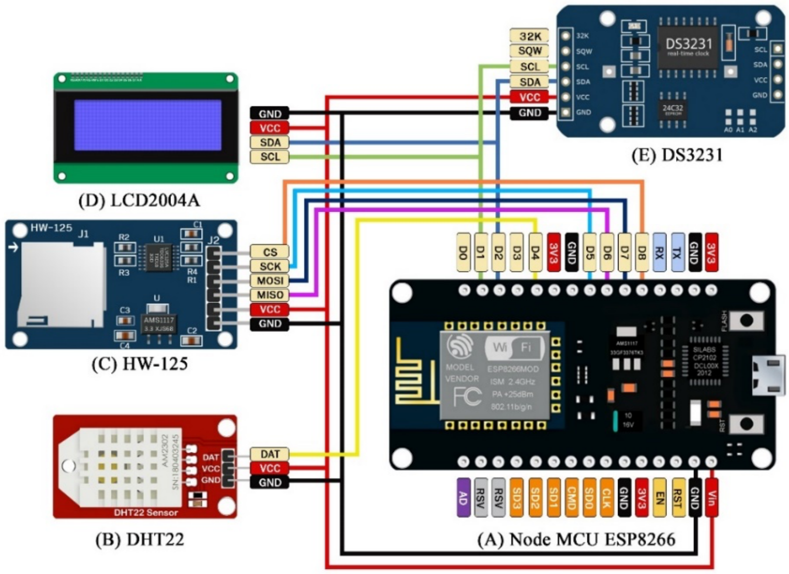

Figure 3. The architecture of the hardware and wiring diagram for EHT

Configuration of the EHT system

The software used is the Arduino IDE program available for extension by experienced programmers. It is easy to write and upload code to boards especially Node MCU ESP8266.[56] The Arduino IDE software consists of three phases: 1) program, 2) compiler, and 3) uploader.[57]

After programming, the Node MCU can connect to the other sensors, gather inputs, and control a variety of physical outputs. The library must be installed before using the sensors or parts with the Node MCU. It has all the functions essential to get the value readings from the accessories.[58] There are three steps to interface the main components of EHT as follows: 1) DHT22 sensor is connected to pins D4, Vin, and GND for measuring as shown in Figure 3, and the ADC converts the corresponding sensor reading to its digital values and from those values the corresponding temperature and humidity parameters are evaluated, 2) DS3231 and LCD2004A are connected to pins SCL-D1, SDA-D2, Vin, and GND, and 3) HW-125 is linked to pins SCK-D5, MISO-D6, MOSI-D7, CS-D8, Vin, and GND. A power supply is created for the Node MCU board by using an adapter charger with an input range of 100-240V and an output of 5V-1.0A, which can accept a wide range of voltage inputs. It is used to supply voltage to all parts expect the DS3231 due to the built-in 3V backup battery.[53]

EHT tool

An overview of the assembly EHT tool is shown in Figure 4A. All components fit into the waterproof electrical junction box.[59] The Node MCU, SD-card adapter, and real time clock were installed at the upper-left, lower-right, and upper-right corners inside the box respectively. Meanwhile, the outside of the box is equipped with the DHT22 at the upper-right part and LCD size 10*4 centimeters in the front center of the box. Two holes, 2-millimeter in diameter, were drilled at the lower-right part of the box. Both holes were used for the output cable of the DHT22 and power supply input cable for the microcontroller. Figure 4B presents a simple EHT tool. The EHT is designed for general use to measure T, RH, and HI. The units measured temperature over a range of <10°C to >50°C, 0 to 100% RH, and <27°C to >50°C, respectively. It incorporates a custom LCD, displaying T (°C), RH (%) in Line-1, HI (°C) in Line-2, level of health impact from HI (5 levels) in Line-3, and date and time in the last line. The advantage of a single screen display is that the user can easily read the values without pressing buttons to read the values on other screens.[60] It was programmed to show 30-minute interval updates, providing the potential for information to be quickly shared with public health officers and to communicate effectively in emergency situations.

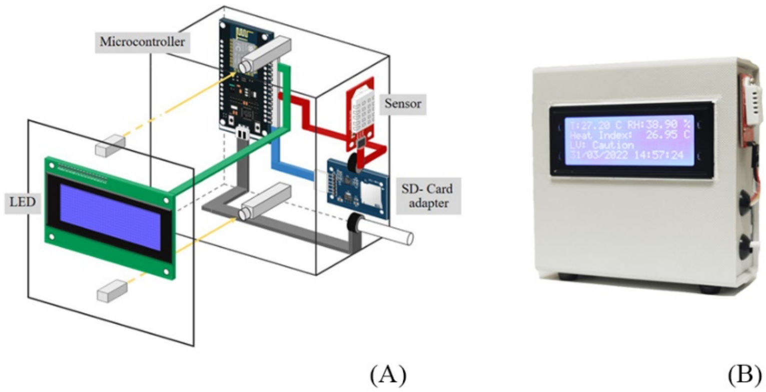

Figure 4. EHT tool and its installed components.

The defined range of health impact levels from the HI is shown in Table 2. Normally, NWS classifies health risk of HI into four levels, but this study adds a normal level when HI is lower than 27°C. Due to long-term measurements of climate variables, the range of HI values may be lower than those specified.[61-62] In addition, the monitored readings could directly be stored in the SDHC-card (16 GB) in text file format. It can record up to 8 million datasets at 30-minute intervals. Users can directly save and send data to a PC via an adapter card, which may be further imported into Microsoft Excel for data analysis. It can be stored as a high-resolution local climate variable database and linked to the Thailand government's Big Data system, which will be a part of further research in other sectors.[63-64]

Table 2. EHT technical specifications.

Temperature range	<10 ºC to >50 ºC
Humidity range	0 to 100 %
Heat index range	<27 ºC to >50 ºC
Data storage capacity	SDHC-card 16 GB
Recording intervals	1 min. to 24 Hrs.
Recording type	Text file
LCD size	9.5(L) * 4(W) cm.
Dimension	12(L) * 5(W) * 12(H) cm.
Net weight	290 g.

Temperature range	<10 ºC to >50 ºC
Display	LED, 4 lines
Temperature (°C)	Line-1
Humidity (%RH)	Line-2
Heat Index (°C)	Line-3
Normal	< 27 ºC
Caution	27°C to <32 ºC
Extreme Caution	32°C to <41 ºC
Danger	41°C to <54 ºC
Extreme Danger	> 54 ºC
Date and time (HH: MM: SS)	Line-4
Software	Arduino version 1.8.16
Connection interface	Universal Serial Bus 2.0/3.0
Power supply	Adapter 100-240 V or Power bank

EHT performance testing

We assessed the reliability and consistency of the HI_{EHT} values by comparing them with HI_{QT36}. The results of the instrument performance test are shown in Figure 5. The HI_{EHT} demonstrated a highly positive correlation with the HI_{QT36} ($r=0.99$; $p<0.01$; $n=4,182$). From the temporal variation perspective, the HI_{EHT} and HI_{QT36} values show a strong coherent pattern (Figure 5). That is, on the diurnal cycle, both HI values correspondingly reached the highest levels in the afternoon and exhibited minima at night, demonstrating high consistency and acceptable reliability of the EHT with respect to the QT36 device.

The values of both measured HI were in the range of 19.4 to 50.9°C. By comparison, however, the HI_{EHT} values were relatively higher than the HI_{QT36} values. The lowest value of HI was recorded on 3 April 2022. This may be due to a strong high-pressure system originating from China which caused a cold spell to move southward to Thailand. This was unusually cold, especially the middle of Thailand's infamous hot season.[65] Our analysis shows that the maximum value of HI was found on 28 April 2022. This is probably because temperature and relative humidity were elevated during the hottest month in Thailand, leading to correspondingly high HI values.[66] In addition, analysis of bias, RMSE, percentage error, and accuracy as statistical techniques to evaluate the EHT skills shows relatively small errors of HI_{EHT} values in comparison to the HI_{QT36} values with the averages of bias (-0.54), RMSE (0.99), percentage error (2.5), and accuracy (97.5%).

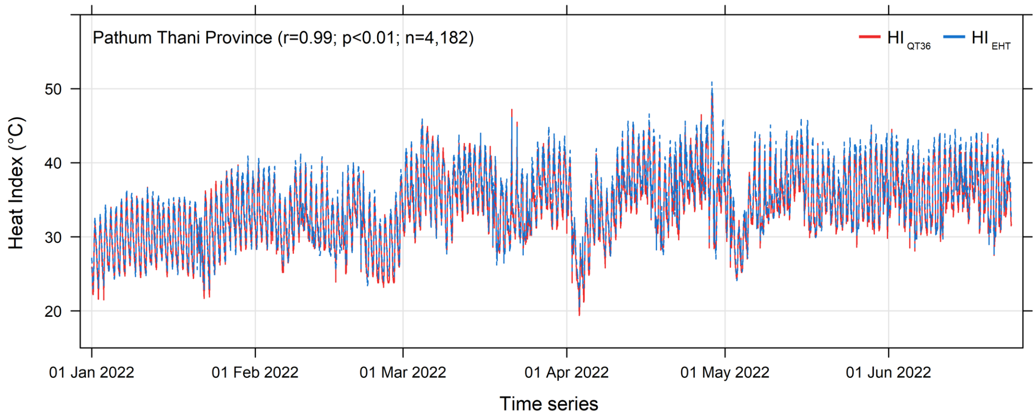

Figure 5. Temporal variation patterns of the HI_{EHT} and HI_{QT36} at the Pathum Thani station.

Pilot areas tested

The EHTs were used in pilot areas to further evaluate their performance in the summer season. The following steps were used with the EHT: 1) installing the EHT in an open-space indoor environment, 2) connecting the power supply to the EHT with an adapter, 3) waiting for 30 minutes, 4) reading the HI level on the screen, and 5) warning the public. To test the EHTs, HI data were collected from 25 March 2022 to 13 May 2022. Based on the quality control checks, no outliers or missing data were found. The EHTs measured and recorded 1,180 HI values at all stations. Overall, the average HI values of all stations were in the range of 33.6 to 36.8°C. The maximum average HI values were found at Phuket station. This may be due to its complex geographical setting characterized by mountainous and surrounded by the Andaman Sea, leading to hot temperatures and humidity throughout the year.[67]

When considering in the context of the health impact levels classified by NWS, it was found that more than 60% of HI in Maha Sarakham Province, Chaiyaphum Province, and Phuket Province were in the extreme caution and higher health-impact classes (Figure 6). However, the HI with the danger level was greater than 15%. A larger proportion of HI in these classes implies a higher exposure to hot weather for Thai people especially the vulnerable groups such as elderly persons, poor people and outdoor workers.[68-70] Therefore, the EHT will be a simple tool to provide appropriate warning for extremely hot weather situations in the form of HI, which is a suitable index since it is calculated from two variables, representing the heat stress and effects of hot weather and is better than the air temperature.

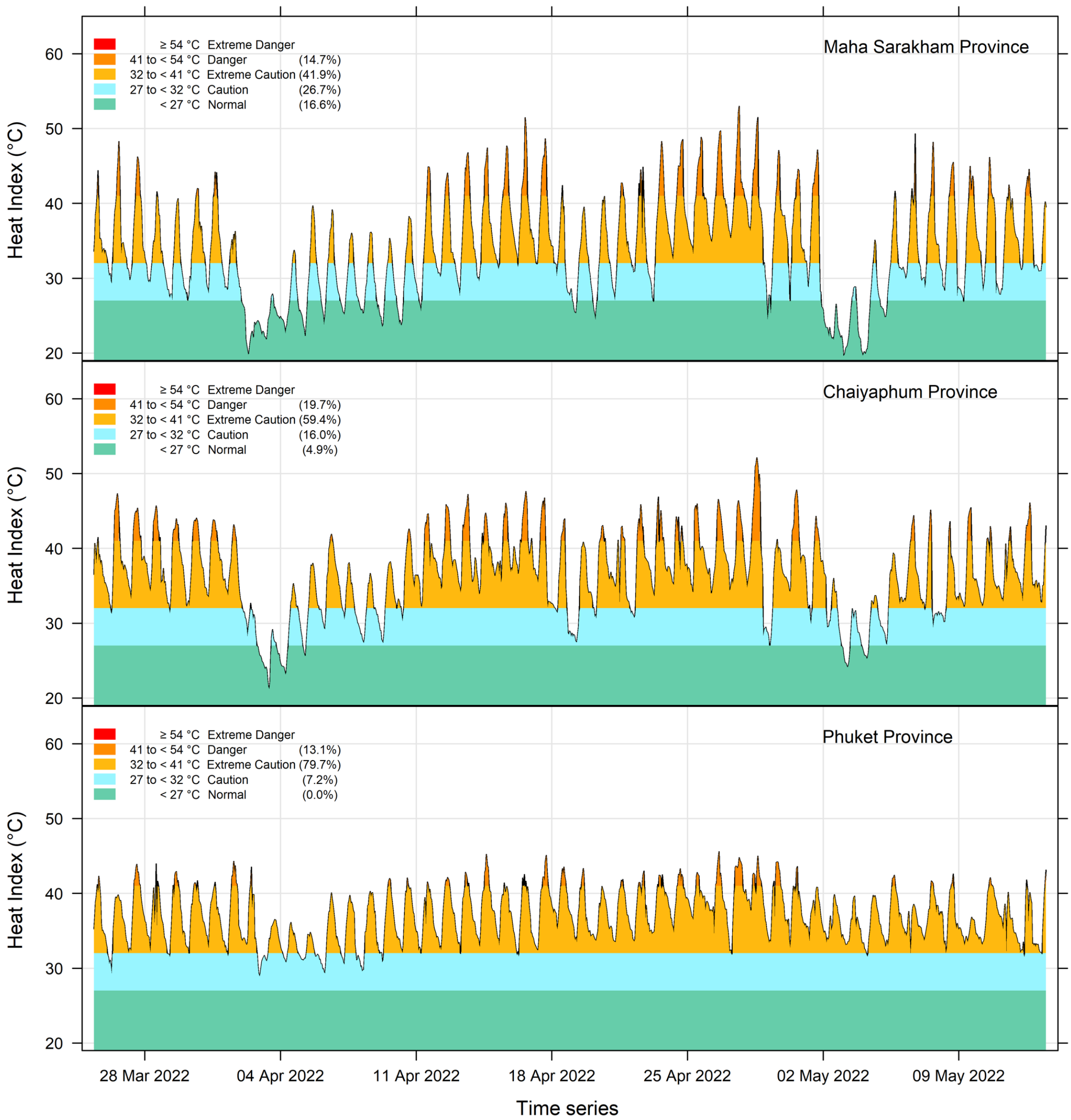

Figure 6. Temporal variation patterns of the HI_{EHT} in pilot areas.

DISCUSSION

From the above results, it is confirmed that the EHT has good performance. Validation with the statistical methods provides additional confidence that the simple EHT tool can be used to measure HI. When compared with the previous study that evaluated similar instrument accuracy, it was found that the bias (-0.64 and -0.54), RMSE 0.44 and 0.99), and %error (2.9 and 2.5) of EHT were approximately the smallest error.[59, 71] Nevertheless, there are a few issues to consider when assembling this tool. A normal breadboard is a simple device designed to create circuits without the need for soldering, but it may not tighten connections for wire jumps .[72] Thus, the shield breadboards which are durable connections and have far better current carrying capacity should be used. It is an essential part for connecting the microcontroller without using a Printed Circuit Board (PCB).[73] This will reduce cost and is different from other studies.[74] In terms of the display module, LCD 2004A is sufficient for displaying T, RH, HI, and health impact levels. However, TFT touch Screen LCD display is widely interesting at present. It not only features a backlight with four white LEDs but also offers colorful with 18-bit 262,000 different shades.[75] It can be adjusted for the properties of the visual components, like text color and color of health impact levels which make EHT more remarkable.

The simple EHT tool should be part of the Heat-Health Surveillance and Warning System (HHSW) developed by the Ministry of Public Health[76], and operated by the Public Health network. It consists of the Provincial Public Health Office (PHO), the District Public Health Office (DPHO), the Subdistrict Health Promoting Hospitals (SPH), and public health volunteers. The operation should be scheduled in the hottest month from March to mid-May.[77] It is recommended to frequently warn the public when the HI values reach the danger level (41 to <54°C), and extreme danger level (>54°C). Once the HI values are at the extreme caution level (32 to <41°C), the SPH will notify volunteers to prepare to cope with critical situations. When the HI values are at the danger level, the volunteers will announce extremely hot weather situation to the public and recommend actions needed to prevent heat-related illness. In the event of HI values reaching the extreme danger level, volunteers must communicate with caregivers and visit at risk people's houses, especially elderly persons, bed-bound patients, persons who are differently abled, and children. Meanwhile, the SPH will prepare to refer at risk groups and patients to community cooling centers and hospitals.[78] In addition, the volunteers and SPH will report the number of patients not only to the DPHO, but also to the PHO in order to evaluate the situation. Lastly, the EHT should be used to support the implementation of the the Health National Adaptation Plan (HNAP) Phase 1 (2021-2030).

Regarding the components of the EHT tool, the Node MCU is a microcontroller board that can function for Wi-Fi network connectivity with a Wi-Fi network[79]. It is useful for connecting to the internet of Things (IoT) by using various computer programs such as MySQL, Power BI and Cloud services.[80] When the EHT is connected with IoT, all measured data that is recorded in the database can be transmitted to mobile apps via the Node MCU using the Blynk app.[81] Once the EHT detects that the surrounding HI values are at the danger level, the buzzer will be then activated for alarm notifications. Vulnerable groups or caregivers can receive updates and data via the mobile application, anywhere and at any time. Thus, the EHT has the potential to play a critical role in the advancement of local health promotion in the future. In addition, the effects of water-salt metabolism system need to be considered for evaluation and prediction of the human thermal risk in hot and humid environments in further studies.

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