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A Suitable Thermal Stress Index for the Elderly in Summer Tropical Climates

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Abstract

The elderly are particularly vulnerable to heatwaves and this research investigates the degree of thermal stress they experience and identifies a suitable index, using Thailand as the case study location. Several global heat stress indices were evaluated for their ability to predict thermal stress in the tropics: Universal Thermal Climate Index (UTCI), Heat Stress Index (HSI), Tropical Summer Index (TSI), Wet-bulb Globe Temperature Index (WBGT) and Discomfort Index (DI). The UTCI, WBGT and DI group tropical conditions in the zone of greater thermal stress, while the HSI and TSI are clustered in the lower stress categories and are more similar to the thermal sensation vote (TSV) and thermal comfort vote (TCV) definitions. Most indices correlated with the TSV, while only HSI and WBGT show a correlation with TCV. The research concluded that the HSI is the most suitable thermal stress index, although it still does not completely explain tropical heat stress conditions.
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Keywords: thermal stress; older people; summer; tropical climates

1. Introduction

In 2010, Thailand suffered from the hottest summer period in 20 years. For close to three weeks, newspapers were reporting temperatures in excess of 38°C and also a number of heat-related deaths, particularly among the elderly. Although six reported heat-related deaths in three years (2010 - 2013) might not be construed to be significant, heat-related illnesses created 3,963 hospital visits, 20% from the elderly [1]. In 2016, Thailand recorded the hottest summer in 65 years with maximum temperature over 40°C for most days of two summer months and temperatures peaking at 44.6°C during the hottest part of one day in a city in Utaradit [2]. Thirty-four heat-related deaths were recorded during these two summer months in 2016. Sources have since commented that most victims were homeless children under 14 years and older people over 65 years or those with chronic diseases [1–3].

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These phenomena led this research to question why local people, who should have been acclimatised to a hot-humid climate, died due to the heat and whether many of the deaths could have been prevented. Thus it was decided to investigate the heat stress levels of the elderly during summer to identify their thresholds in both current and future conditions.

1.1. Elderly limits

To date, previous research has attempted to explain the thermal comfort of the elderly in subtropical climates but few studies have covered this group of people in tropical climates. One issue is that the thermal sensitivity of the elderly has deteriorated, proven by numerous studies. The elderly's thermoregulation has diminished with age, leading to failure of sweat control [4–6]; reduction of thermal balance preservation [7, 8]; and a greater reduction of warm compared with cold receptors regarding thermosensitivity [7]. In addition, some of these characteristics can be exacerbated by chronic diseases such as diabetes [9], hypertension [10] and heart problems [11]. These symptoms lead to less accurate thermal sensation [12] and can lead to significantly different degrees of thermal consciousness expressed by the old and the young [13].

1.2. Heat stress in Thailand

Thailand defines a heatwave as the maximum temperature constantly exceeding 40°C for over three days [14]. Heatwaves have not often occurred in Thailand while heat stress is more common. Heat stress is a stage when the body cannot maintain normal thermoregulation, normally by sweating, from excessive heat gain. Generally, heatwave is more likely to happen in two ways: first, it occurs when average maximum and minimum temperatures exceed those of the past three days. Second, it happens when average temperatures exceed those of the past 30 days [15]. From 2010 – 2015, Thailand has experienced heat stress risk every summer [16]. The simulation system for heat stress investigation using the Heat Index (HI) found that Bangkok experienced 49% of the year with 'moderate' heat stress in 2014, the highest proportion of all cities in Thailand [17].

Researchers have paid little attention to heat stress in hot-humid climates. However, recent research has reported heat stress in peninsular Malaysia in more extreme conditions when the UTCI reflected 51.2°C, a unit which combines temperature, humidity and water vapour pressure [18]. In Thailand, a few studies have investigated the effects of heat on occupational environments and found that Thai workers produced 25-30% faster heart rates in the heat than western workers at the same level of oxygen consumption [19–21]. Two recent studies are convinced that heat-related deaths and illness have increased among the Thai people in 1999 - 2008, in particular those who are elderly [22, 23].

2. Methods

2.1 Survey

This research focuses on the heat stress of the elderly in summer in hot-humid Thailand, using Chiangmai as the study site since it is one of the extreme cases of heat exposure during summer. The participants were aged 60 years old and over. The participating elderly were low income residents in four retirement homes in Chiangmai, three urban homes and one rural home. The main survey was conducted during the day from 9 am to 6 pm in semi-outdoor spaces (veranda, pavilion) associated with the retirement homes. Total numbers of the senior participants in the main survey in April to May 2015 translated into 135 datasets. Four physical environment parameters were measured using the Kimo AQ200 meter (OneTemp Pty Ltd): air temperature, globe temperature, wind speed and relative humidity.

2.2 Heat stress indices

Many heat stress indices have been established by scholars and several have been used in hot-humid climates. However, the most suitable index for these climates remains uncertain. The UTCI is the latest index covering universal climates [24]. Even though it considers the physical environment and physiological parameters and is used for heat stress assessment in a variety of built environment scales, many researchers have employed the UTCI for outdoor assessment rather than the indoors [25–27]. A possible reason for outdoor use only is the UTCI definition which is imprecise for thermal comfort levels. For example, ‘no thermal stress’ is recorded with a UTCI of 9 – 26°C [28] which seems unrealistic for world-wide application.

In hot-humid climates, some researchers have justified heat stress indices based on thermal perception and sweating rates of local people [29–31]. The TSI was created from physiological parameters sourced from the thermal sensation vote of Asian Indians [32]. The HSI was generated from the heat balance equation and calculated based on sweating levels of a standard American man [33]. Although these two indices are not often employed for heat stress assessment in the tropics, they are worth analysing in this research since they were formulated for people who are acclimatised to hot and humid environments.

The WBGT index is one of the oldest heat stress indices, created for people over 60 years old. It is formally employed in ISO standard 7243: 1989 [34]. Public health authorities of developed countries have used WBGT for heat stroke investigation such as in the USA [35]. The WBGT may not be reliable in very hot climates since local people usually experience 30°C and do not consider it as a severe heat stress condition as defined in the WBGT categories [36]. However, a few government reports in Thailand still use this index to define heat stress for industrial environments [20, 37].

The DI was established at the time of the WBGT [38]. Although the DI includes the sweat rate, it is used to determine heat stress during exercise or work in hot environments in industries [39] rather than a residential environment. Recently, some researchers have employed the DI in the studies in hot-humid environments such as Malaysia [40].

3. Results

The categories of five global heat stress indices are compared with one another in the different thermal stress zones and to the subjective thermal responses of TSV and TCV in Table 1. The ‘very strong’ heat stress category is higher than the TSV categories and represents conditions leading to humans being at risk.

Table 1. Thermal stress indices normalised to the thermal sensation and comfort votes

TSV	***TCV***	***Heat stress categories***	**UTCI**	**TSI**	**HSI**	**WBGT**	**DI**
		Very strong	38 - 46°C	> 42°C	> 80%	> 28°C	> 28°C
+3		*Strong*	32 - 38°C	37 - 42°C	40 - 80%	23 - 28°C	24 - 28°C
+2	***+2***	*Moderate*	26 - 32°C	34 - 37°C	20 - 40%	18 - 23°C	22 - 24°C
+1	***+1***	*Mild*		30 - 34°C			
0	***0***	*No heat stress*	9 - 26°C	25 - 30°C	0 - 20%	< 18°C	< 22°C
-1	***-1***			19 - 25°C			
-2	***-2***			< 19°C			
-3							

Note: All definitions are different so the five indices were normalised on a five and a seven point scale. WBGT, DI, UTCI and TSI units are in degree Celsius. The HSI is given as a percentage and is the proportion of the evaporative cooling in each condition to the maximum possible evaporative cooling.

3.1. Five heat stress indices

UTCI

The UTCI shows that weather conditions are perceived to be hotter in high humidity conditions. The scale is calculated from temperature, relative humidity and wind speed. The UTCI scale identifies 'strong heat stress' from 32°C or higher, and 'very strong heat stress' from 38°C. Regarding TCV, the majority of respondents to the survey felt 'uncomfortable' due to 'warm' weather and their thermal reaction is in the 'strong' to 'very strong heat stress' zone of UTCI. Interestingly, with the UTCI when the temperature is over 38°C, one-fourth of respondents still voted 'comfortably warm' to 'comfortable'. Moreover, the rural retirement home illustrates a greater degree of heat stress than the urban areas. It can be seen that UTCI may estimate an excessive heat stress impact compared to the TCV in the survey responses.

TSI

The TSI index is a heat stress predictor available for people in tropical summer conditions [32], TSI places responses in a lower intensity heat stress zone than the other indices. The TSI scale defines 'moderate heat stress' at over 34°C and 'strong heat stress' over 37°C.

Regarding the TSI and the TCV (Fig. 1), over half of the thermal responses are distributed in the 'moderate heat stress' zone. Although stated comfort levels are spread along the moderate zone, 26% being 'comfortably warm' seems to appear with the most frequency. It is significant that the TSI places the survey results in a lower heat stress category than the UTCI does, since it is established for the tropical summer heat stress assessment. The majority of participants fall into the 'moderate heat stress' zone, whereas most TCV results are in the 'strong heat stress' zone on the UTCI scale.

HSI

The percentage based HSI scale determines heat stress through examining the ratio between demand and capacity of evaporative cooling[1] to maintain body thermal regulation. It is categorized in three levels [33]. First, at over 80% of the HSI scale, there is a large demand for evaporation to maintain thermoregulation since conditions reflect high temperatures (36.5°C), high relative humidity (42%) and very low wind speed (0.01 m/s). Such conditions are considered as leading to 'very strong heat stress'. Second, 40-80% on the HSI scale, equates to 'strong heat stress'. It can be seen that the evaporation demand and capacity scale covers temperature at over 34°C and most survey respondents at that point sensed that it was 'hot'. Third, 20-40% on the scale is referred to as 'moderate heat stress' since it requires just a small amount of sweating to be balanced. Although the temperature is high, low humidity and a high wind speed can raise evaporative capacity. Moreover, the HSI impact seems to be stronger over 34°C, comparing both TSV and TCV. There is a distinct increase in warm perception in both TSV and TCV responses in excess of this temperature which equates to the strong HSI heat stress zone (Fig 2).

A comparison between urban and rural conditions in Fig. 2 illustrates that the rural areas do not experience a significantly higher degree of heat stress than urban areas, even though the rural area was hotter.

Overall, the HSI shows that the elderly need to sweat profusely in order to deal with the hot summer conditions. Most conditions as identified in the survey are in the 'moderate' to 'very strong' heat stress zones, even though respondents do not feel heat stress. The HSI can also take into account the degree of heat stress when heat is being lost by evaporation in the hot-humid climate zone. Therefore, the HSI is a very important index for these climatic latitudes, particularly for the elderly.

WBGT

Even though WGBT was the most widely used index before UTCI was created, it seems to overestimate heat stress conditions in hot-humid climates. WBGT defines a temperature of 28°C and over as 'very high' heat stress. Most conditions, according to the WBGT during the survey are in the 'very high heat stress' zone, including all weather conditions in the rural area. Just one-fourth of the prevailing weather conditions were voted by the elderly as 'too warm' (TCV +2).

DI

Like the WGBT, DI seems to overestimate heat stress in the hot-humid climate, since it defines 28°C and over as a 'very high' heat stress. Most weather conditions during the survey (95%) are classed as 'very high' heat stress,

[1] The percentage-based HSI is the proportion of the evaporative cooling in each category to the maximum possible evaporative cooling. For example, 80% refers to the proportion of evaporative cooling required to maintain thermal regulation which means it is almost at the maximum capacity of evaporation.

although rural conditions are only slightly more extreme than urban ones. DI may overestimate heat stress more than the other indices in this research since half of the weather conditions during the survey are classed at the extreme of the 'very high heat stress' band.

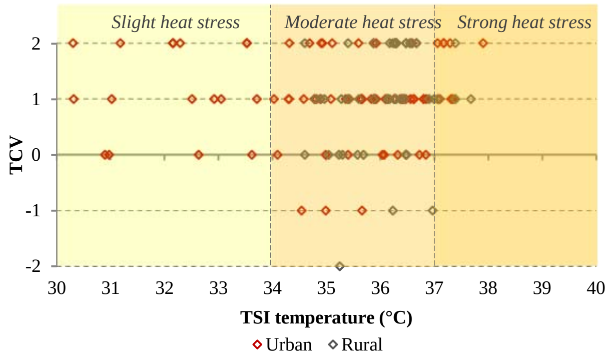

Fig. 1 The TSI and TCV scale in the urban and rural areas

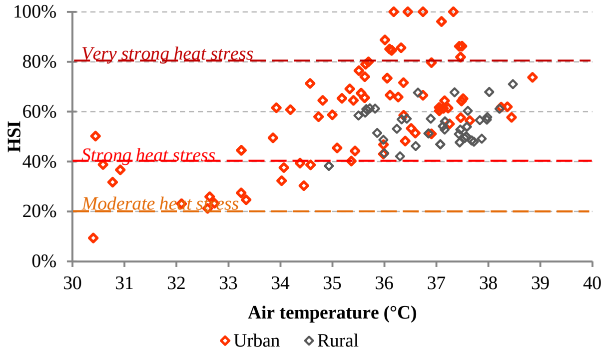

Fig. 2 The HSI and the TCV in urban and rural areas

3.2. The best heat stress index

The HSI index is determined as the best heat stress index for the elderly in hot, humid climates and this section explains three reasons for that determination. First, the definition of heat stress categories should relate to the real situation in hot-humid climates. Heat stress indices' assessment should not overestimate the hot-humid conditions of Thailand since most TCV votes of the elderly in this study indicate 'comfortably warm'. Table 2 shows that WBGT and DI may overestimate the summer hot-humid conditions since both indices categorise that most elderly experience a 'very high' heat stress while most voted 'comfortably warm'.

Second, a suitable heat stress index should show a significant relationship to subjective thermal responses like TSV and TCV. Each heat stress index has a different definition so the five indices were normalised on a seven-point scale related to the subjective thermal responses to establish a correlation with the TSV and TCV. Most indices correlated with the TSV, while only HSI and WBGT show a correlation with TCV (Table 3). However, the WBGT index was distinguished by overestimation in the first criterion.

Lastly, the correlation between heat stress indices and physical parameters should be identifiable. For example, the four indices based on air temperature should show progressive heat stress levels with a higher air temperature. Fig. 3 illustrates that the DI does not increase with higher temperature, while UTCI, TSI and WGBT show a greater response to air temperature. The HSI shows the greatest sensitivity to rising air temperature, although the HSI is based on humidity and evaporation. The relationship between HSI and relative humidity is shown in Fig. 4.

Table 2. Summary of five thermal stress indices

	UTCI	*TSI*	*HSI*	*WBGT*	*DI*
Mean	37.45	35.52	58.00	29.66	31.36
SD	1.78	1.56	0.18	0.96	1.16
Coefficient of variance (CV)	4.77%	4.38%	30.40%	3.23%	3.70%
Mean heat stress zone	Strong	Moderate	Strong	Very high	Very high

Note: UTCI, TSI, WBGT and DI units are in °C. HSI unit is percentages.

Table 3. Correlation coefficient of the nonparametric analysis of TSV and TCV on the heat stress indices

	UTCI	*TSI*	*HSI*	*WBGT*	*DI*
TSV	0.100	0.195*	0.230**	0.306**	0.232**
TCV	0.107	0.130	*0.310***	0.239**	0.171*

*Note: * and ** correlations are significant at the 0.05 and 0.01 level, respectively.*

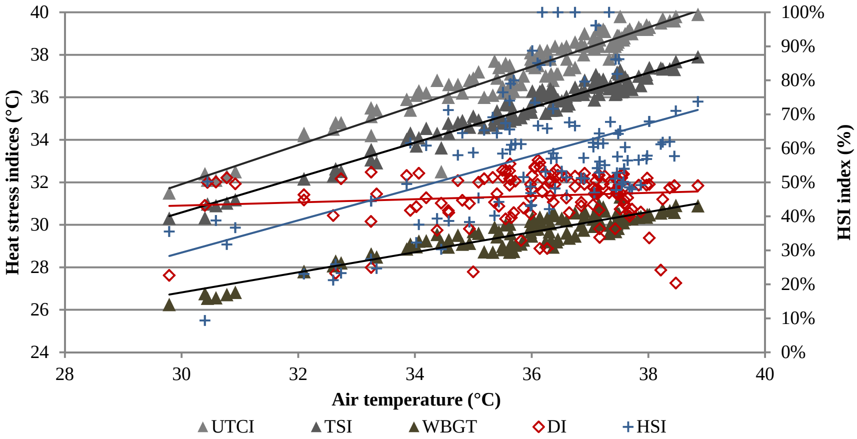

Fig. 3. Relationship between heat stress indices and air temperature

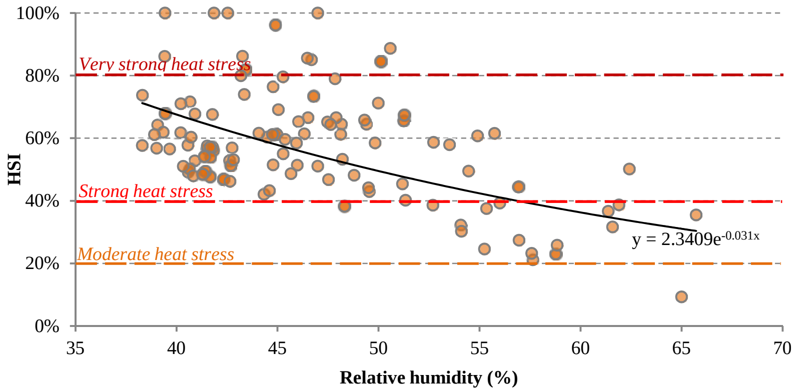

Fig. 4. Relationship between HSI and relative humidity

Therefore, this research concluded that HSI is the most suitable thermal stress index for the elderly in the summer hot-humid climate for these reasons:

- HSI categorizes more realistically the hot-humid condition, determining most recordings in the ‘strong heat stress’ category.

- HSI does not only show a strong correlation to both TSV and TCV, it also relates to both air temperature and relative humidity.

In addition, besides the above criteria, HSI has proved to be the best index for the hot-humid climate because its calculation is fundamentally related to hot-humid conditions and the elderly’s physiology. As HSI is based on the proportion of evaporation required to maintain thermoregulation and the maximum possible evaporation rate in local conditions, it is similar to the body’s thermoregulation principles in hot-humid climates. Sweating and evaporative functions are keys to avoiding heat stress in the hot-humid climate. If people sweat enough and their sweat could sufficiently evaporate, they would reduce the risk of heat stress. The elderly in the hot-humid climates who cannot maintain normal sweating levels, may not be comfortable in extremely hot and humid conditions. It does seem that HSI is the most relevant index to reflect physiological conditions in hot-humid climates, in particular the elderly’s physiology.

Moreover, HSI is the only index that can distinguish different conditions prevailing in urban and rural areas. Since the HSI fundamentally emphasizes the physiological issue of sweating in the hot-humid climate, it can differentiate a hot condition from a hot and humid condition. For example, average conditions in the rural area were hotter (+1°C), breezier (wind speed +0.1 m/s) and drier (relative humidity 5% lower), compared to the urban area. The HSI can recognize that conditions in the rural area will have less severe heat stress impact than those in the urban area in this study, due to a greater potential for evaporation.

However, HSI also has some flaws. When the coefficient of variance (CV) was tested, HSI shows the largest value of all five indices (Table 2) which means that HSI data is less consistent than other indices. Also, the physiological condition of the elderly is excluded in the HSI calculation. Therefore, if the HSI could be adjusted to include physiological parameters like measured sweating level, the HSI would become an even more accurate index for measuring the elderly's heat stress in the tropics.

3.3. Future scenarios

According to the Intergovernmental Panel on Climate Change, IPCC report 2013 [41], temperature and precipitation in the tropics are projected to change in the future. Near-term projections suggest that the overall temperature in the hot-humid tropics is expected to increase 0.3-1°C and precipitation decrease 10% by the end of 2035 based on 1850-1900 data [42]. Long-term projections state that the average temperature is very likely to increase by 1.5°C [43]. Although the overall temperature is unlikely to increase by 2°C by 2081, the worst case scenario assisted by high emissions of carbon pollution, predicts a 2.6-4.8°C increase. Moreover, in the hot-dry season (March to May [41]), Thailand in the long-term would experience a greater average temperature such as +0.3°C with -10% precipitation by 2035, +1°C with -20% precipitation by 2065, +1°C with -10% precipitation by 2100 and +1°C with -30% precipitation by 2200. An increase of 3°C on the warmest days by 2081-2200 is also expected [43]. The IPCC [41] also suggests that there will be at least a 10% increase in 'hot days' and 'extremely hot days' by 2200. A summary of projected changes in Thailand is shown in Table 4. There are no comments in the IPCC report about wind speed projections.

Climate change scenarios in the future cover both hotter and dryer cases. Although higher temperature definitely impacts people, lowered levels of humidity may help reduce discomfort in the hot-humid climate. When superimposed on the HSI, the five climate change scenarios in Table 4 show a greater heat stress impact than the current climate situation. Given a 0.5°C increase in temperature Scenario-1 [41], Scenario-1 shows a significant impact from 'strong' to 'very strong' on the HSI chart (see the blue dot symbols in Fig. 5). Compared to other scenarios, Scenario-1 illustrates the second greatest change from the current situation. Scenario-1 is influenced by an increase in temperature without a decrease in humidity.

Table 4. Projected climate changes in Thailand summarized from the IPCC report (2013)

Climate Change Scenarios	**1** 2015-2035 Current	**2** 2035 +20 years	**3** 2046-2065 +30-50 years	**4** 2081-2100 +65-85 years	**5** 2081-2200 +85-185 years
Temperature	+0.5°C	+0.3°C	+1°C	+1°C	+1°C
Precipitation	-	-10%	-20%	-10%	-30%
Estimated mean RH[1]	-	-4%	-8%	-4%	-14%
T_{max} in warmest days[2]	-	-	-	+3°C	+3°C

Notes: The data is not a cumulative increase but the expected increments over the scenario period. [1]Estimated mean relative humidity is calculated from relative humidity changes by a decrease in precipitation, based on a psychrometric chart in Chiangmai. [2]Warmest days refer to a day over 34°C.

Other scenarios have lower humidity levels than current conditions which helps to reduce heat stress levels. More than half of the Scenario-2 data is distributed in the HSI 'strong heat stress' zone. This scenario also shows that 10% lower humidity results in less impact on the HSI heat stress index than in Scenario-1, even though there is a 0.3°C temperature increase. However, when both rise of temperature and lower humidity are superimposed on the HSI, the majority of Scenario-3, 4 and 5 results are categorized in the 'very strong' heat stress zone. Scenario-4 has the highest change in temperature (+3°C on the warmest days) with just a 10% decrease in humidity and has the greatest HSI heat stress impact since almost half of the conditions are at the maximum HSI load. Lastly, Scenario-5 experiences higher temperatures but 30% lower humidity and appears to have less HSI heat stress impact than Scenario-4.

Placing all five scenarios on the HSI chart confirms that the elderly will suffer greatly in the future. More than half of these five scenarios are distributed in the HSI 'very strong' heat stress category and the elderly who have limited sweating capacity, will be a group at considerable risk over the long term.

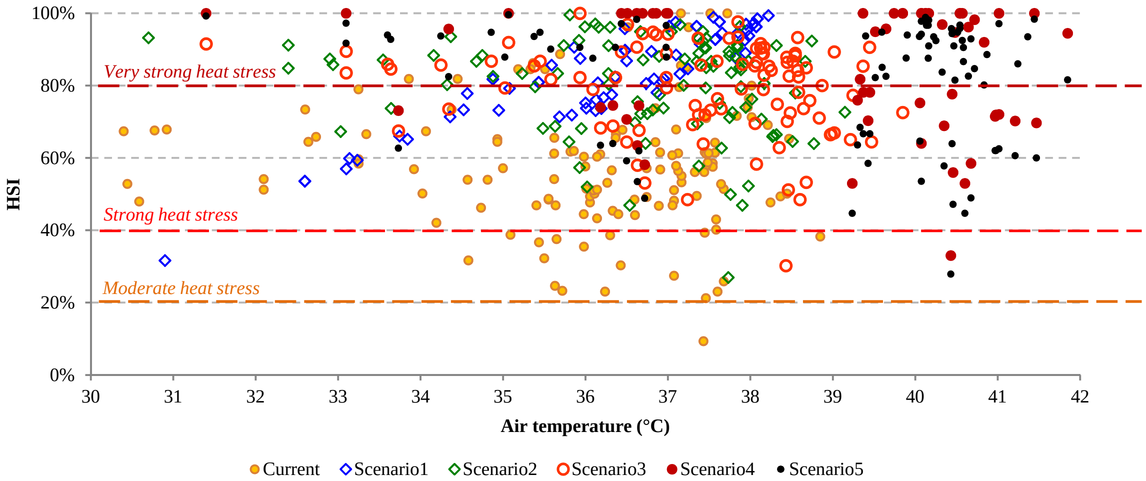

Fig. 5. HSI with climate change scenarios

4. Discussion

According to a comparison of comfort ranges in neighbouring climate zones, threshold temperatures related to discomfort and mortality during heat stress indicates that people in hotter climates could be more tolerant to heat than those who live in a cooler climate. There is little threshold temperature research available in the tropics so studies from the subtropics and some temperate zone cities are discussed in this section.

This research defines threshold temperature of discomfort at three levels, supported by the definition from the Thai Meteorology Department [16]. First, the threshold temperature for a hot day is defined as 31°C, is linked to a 'moderate heat stress' [16] and refers to the morbidity and mortality temperature for all Thai adults in Thailand [44]. The second threshold is defined at over 34°C and refers to a very hot day and as 'strong heat stress' by the same authority. This threshold is also observed in the heat stress indices assessment that heat stress is likely to increase when the air temperature exceeds 34°C.

The third threshold temperature is defined at over 38°C. It does not only refer to an extremely hot day [16], but also is categorized as 'very strong heat stress' in most heat stress indices and is voted by respondents as an 'unacceptable' temperature in this research. The new heat stress categories (Fig. 6) resulting from these three threshold temperatures identify a lower degree of heat stress compared to the existing categories from the universal heat stress standard for Westerners such as the UTCI. Fig. 6 also illustrates that the 'moderate' and 'strong' heat stress zones in this research are respectively defined as 3°C and 2°C higher than those defined for temperate climates. However, the 'very strong' heat stress zone is defined at the same 38°C temperature as in the UTCI category.

The threshold temperature of discomfort in summer for the Thai elderly was found to be 38°C in the research. The threshold temperature for Thai adults over the year was significantly lower at 31°C [44] which is similar to the threshold temperature of discomfort found in Australian adults [45]. The current research suggests that a 7°C difference may exist because the survey period was in summer as opposed to the average for the whole year and the participating elderly experience physiological response limitations and also psychological tolerance. Also, those studies were in naturally ventilated indoor spaces rather than the semi-outdoors. At 31°C, the temperature is higher than the mortality threshold (the temperature at which there is an increase in the mortality rate) of the elderly in Taiwan and temperate climates. Taiwan's mortality threshold for the elderly was 30°C [47] and in temperate climates it is 30-32.5°C [48] (Fig. 6).

The new heat stress categories were combined with the three threshold temperatures (31°C, 34°C and 38°C) from the above data. The new heat stress categories are more suitable for people who are habituated to a high temperature in hot and humid climates compared with the UTCI. It also provides a comparison of the results among several climate zones.

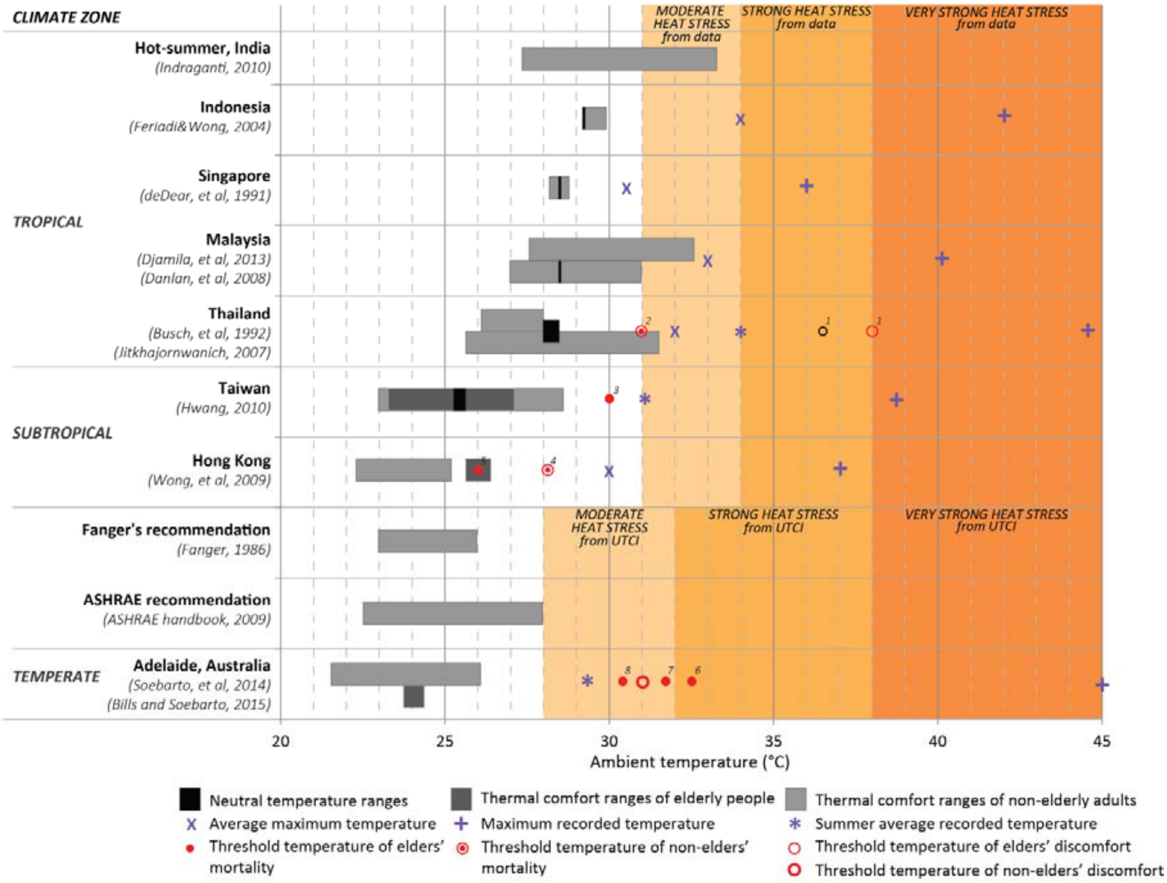

Fig. 6. Thermal comfort ranges and threshold temperatures in the neighbouring countries compared with the heat stress zones defined by data suggested in this research and by the UTCI index

Notes: [1]Threshold temperature of the elderly's discomfort in summer [50]; [2]Threshold temperature of the non-elders' discomfort (44); [3]Threshold temperature of the elderly's mortality in Taiwan [47] and [5]in Hong Kong [46]; [4]Threshold temperature of the non-elders' mortality [49]; Threshold temperature during heat stress in temperate climates; [6]Athens, [7]Milan, [8]Rome [48]; "o[1]" means comfort temperature of the elderly in summer identified in this research.

5. Conclusion

The heat stress levels of all adults in summer are in the HSI 'strong' to 'very strong' categories. However, people who have sweating limitations, like the elderly, tend to suffer a greater impact than adults in general. Moreover, the climate change scenarios suggest that the situation in the future will be worse, although an increase in temperature may be partially compensated by reduced humidity levels. The elderly who live in the tropics might experience two conditions in the summer in future. Firstly, the extremely high heat stress conditions may lead the elderly who cannot sweat sufficiently, into heat stroke more easily. Secondly, the elderly who can maintain sufficient sweat rate may experience dehydration. Since future physical climate conditions in Thailand will be hotter and drier, functional sweating rates will rise and people will need to drink more fluids, more frequently, than in current conditions. This might be a problem because their awareness of dehydration also deteriorates. Preparing guidelines for preventing or at least reducing the death rate during heatwaves and the costs of morbidity related to them should be formulated in terms of a heat-related warning system and design criteria for elderly housing.

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