Analysis of Human Heat Stress in Sri Lanka: Using Temperature Humidity Index (THI)

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Abstract **-** The Human Comfort Index (HCI) is known as the apparent temperature of the human body which is used to calculate Human Heat Stress (HHS). This is how the human body feels effects of the combination of Relative Humidity (RH) and Air Temperature (AT). This index is very important for human health, recreation activities, human productivity, tourism, urban planning and etc. Climate change is likely to bring mainly temperature increases in Sri Lanka – It might increase the HHS in the island. Analysis of HHS in Sri Lanka is limited and even today bioclimatic map has not been introduced for the country. The primary objective of this study was to calculate the HHS by Temperature Humidly Index (THI) which is one of the calculation methods of HCI. RH and AT data have been collected from Meteorology Department. The linear regression analysis, Arc GIS 10.4: Interpolation analyses of Radial basis function and Universal Kriging method, Mann-Kendall statistical test have been engaged in data analysis. HHS is calculated from 2006 to 2016 for 35 temperature stations. According to the annual THI, 04 stations are found as Comfort with Cold (THI=14.2-22.3), 04 stations are found as Extremely Comfort (THI=22.4–25.1), 05 stations are found as Comfort (THI=25.2–26.3), 12 stations are found as Slightly Comfort (THI=26.4–26.8) and 10 stations are found as Moderately Comfort (THI=26.9–27.5). Comfort with Cold and Extremely Comfort THI are located in the Central Highland where this range is sustained throughout the year. Out of 12 stations, 09 are located in the Intermediate Zone with Slightly Comfort range. Out of 10 stations, 08 stations are found in the Coastal Zone with Moderately Comfort range. HHS is also compared with two standard periods (1931-1961) and (2006-2016) for 15 main stations. Results revealed that the highest increase of THI is noticed in Anuradhapura (+ by 1.0) and the lowest THI is noticed in Badulla (+ by 0.2). The highest positive significant increasing trend of THI was noticed in Rathnapura (R^2 0.80) and Kundasale (R^2 0.83). Based on the THI, the spatial and temporal Bioclimatic maps have been created to show comfortable and less comfortable zones in Sri Lanka.

Index Terms- Temperature Humidly Index, Human Comfort Index, Human Heat Stress

I. INTRODUCTION

The theme of geography consists of inter-relation activities among, man, society, and environment (Mackinder, 1951). Climatology is the very specific field of Geography. Ellan (1932) stated that climate is one of the physical sources extremely affect not only for thinking but also the behaviors and activities of the human being and their cultural landscape. Howard (1995) explained that human health, energy, and comfort are determined by climate in the physical environment. Physiological functions of the human body respond to changes of the weather and some certain diseases are occurred due to the climate and climatic seasons. The condition of the atmosphere is also influenced to our mental and emotional outlook.

With global climatic change, Sri Lanka climate has also been changing. The temperature has an increasing trend and rainfall and humidity level have a decreasing trend. Annual mean, maximum and minimum air temperature anomalies have shown significant increasing trends during the past few decades in Sri Lanka (Rekha, 2003). This condition may highly influences to increase the Heat Stress in Sri Lanka. This research tried to analyses the spatially varied heat stress in Sri Lanka. The Human Comfort Index (HCI) is known as the apparent temperature of the human body which is used to calculate Human Heat Stress (HHS). This is how the human body feels the effects of the combination of Relative Humidity (RH) and Air Temperature (AT). In this contest, the pattern of behavior of temperature and humidity of atmosphere are very important sources for all the beings. These climatic elements are considered as determinants of comfortable and uncomfortable of the environment. This index is very important for human health, recreation activities, human productivity, tourism, urban planning and etc. The trend of temperature has been increasing in Sri Lanka and it might impact to the well-being of the nation. People could be suffering from the heat stroke, heat rash (skin), and dehydration in future (Sathyamoorthy, 2016). Ajith (2016) stated that heatstroke is a possible hazard to the current weather conditions in Sri Lanka. Emmanuel (2004) mainly focused Thermal Heat Index (THI) in Colombo city and found that THI has continuously increased in the daytime as well as in the night time.

An attempt of measuring the heat stress using annual average temperature and relative humidity are very rare in Sri Lanka. All the attempts made in Sri Lanka for measuring heat stress were limited to a certain framework, and so far no individual or institutional level efforts to do any research on the overall heat stress by using the human comfort index in Sri Lanka. A bioclimatic map was not created to identify the comfortable and uncomfortable zones so far in Sri Lanka. It seems to be a big shortcoming in the metrological analysis in the country. This

study focuses to observe the geographical formation, measure the prevailing climatic tendencies, human heat stress of Sri Lanka. The study analyses the spatially and temporal variations of THI by using Human Comfort Index to create a bioclimatic map. It would be very useful for future studies, planning purposes and making policies for various sectors of development activities in Sri Lanka.

II. MATERIALS AND METHODS

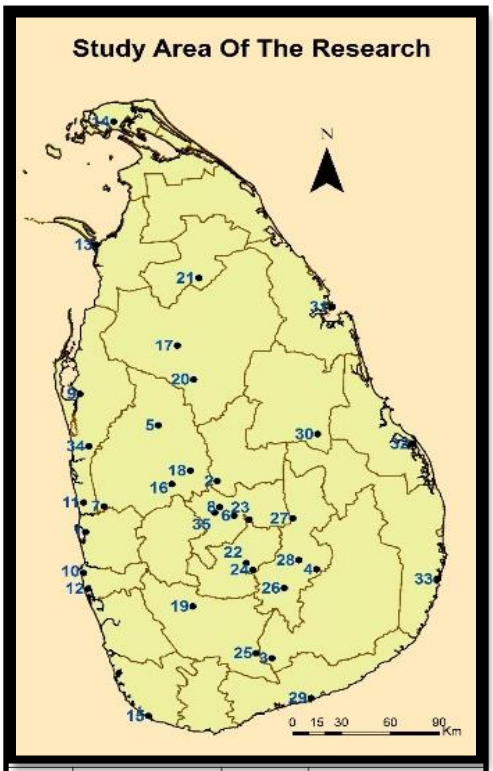
The primary objective of this study was to calculate the HHS by THI which is one of the calculation methods of HCI. These indexes express thermal stress by indicating the temperature which combines with the relative humidity of the atmosphere; it measures three thermal reactions, such as *too warm*, *comfortable* and *too cool* of atmosphere. As Sri Lanka is a tropical country, this Temperature – Humidity Index is more suitable for calculating the HHS. This index was invented by Nievwolt in 1975; (THI=0.8T+(T×RH)/500). Normally THI values were classified under the following intervals (McGregor & Nievwolt, 1998);

i. $21 \leq THI \leq 24$ = 100% of the subjects felt comfortable.
ii. $24 \leq THI \leq 26$ = 50% of the subjects felt comfortable.
iii. THI > 26 = 100% of the subjects felt uncomfortable and hot.

These results are based on experiments in the mid-latitude countries. People who live constantly in tropical lowlands probably can tolerate higher values of the THI or ET somewhat better, as nutrition, clothing and general speed of physical activities are all adjusted to a hot climate (Howard, 1995).

For this study spatial data was collected by using secondary sources and acquired from; Colombo Meteorology Department, Statistical abstracts of the Statistical Department, Long-term Hydro-Meteorological data book (Nakagawa et al, 1995) and various research articles. The data used from 1931 to1960 to analyse the previous situation in human heat stress and data from 2006 to 2016 is used to calculate the existing situation and forecast the future trends of heat stress in Sri Lanka. 35 stations are selected for collecting data. 16 stations out of 35 stations are agro-meteorological stations and 19 of them are belongs to the main meteorological stations in Sri Lanka. The main objective of this study was to analyses the human heat stress in Sri Lanka by using HCI. The methodology had the following steps for analysing the indices.

i. The bioclimatic map is created by using the isotherm method to identify comfortable zones of Sri Lanka. Tools of radial basis function and universal cringing kriging methods under interpolation analysis in Arc map 10.4.
ii. The seasonal temperature and relative humidity variations are observed in Sri Lanka. Spatial and temporal heat stress is also analysed with respect to the four main seasons in the country.
iii. For each month, human comfort index was calculated in order to identify the spatial changes occurred in heat stress during the 12 months in the selected years to identify the spatial patterns with time periods.
iv. 19 Meteorological stations and 16 Agro-Meteorological stations are selected for this study (Figure 1).



NO	Station Name	NO	Station Name
1	Katunayake	19	Ratnapura
2	Agalawatta	20	Mahailluppallama
3	Sewanagala	21	Vavuniya
4	Passara	22	Nuwara Eliya
5	Mahawa	23	Victoria
6	Kundasale	24	Seetha Eliya
7	Makadura	25	Udawalawa
8	Katugastota	26	Bandarawela
9	Puttalama	27	Giradurukotte
10	Colombo	28	Badulla
11	Lunuvila	29	Hambantota
12	Ratmalana	30	Aralaganvila
13	Mannar	31	Trincomalee
14	Jaffana	32	Baticaloa
15	Galle	33	Pottuvil
16	Kurunegala	34	Ambekelle
17	Anuradhapura	35	Gannoruwa
18	Bathalagoda		

Figure 1: Locations of the 35 Meteorological and Agro-Meteorological stations

Human heat stress has been observed relatively under two periods. Data related to temperature and humidity is used from 1931 to 1960 and from 2006 to 2016 to calculate the central tendency and Disperse measurement. These comparative two sets of periods provide the past and current situation of human heat

stress. This observation tries to identify the new trends of the heat stress in Sri Lanka. This analysis also tries to forecast the future trends of heat stress in Sri Lanka. The linear regression analysis has been applied to visualize the trends. The Mann-Kendall statistical test was engaged to examine the significant of THI trends. Existing trends in human heat stress has identified the negative and positive future trends. Various types of statistical methods were used with the computer soft wares to analyse the data. In addition to that, cartographical methods, display maps, and charts have been used in this context.

III RESULTS AND DISCUSSION

THI classification of Nievwolt (1975) does not show a much spatial variation of the heat stress in Sri Lanka. Therefore taking this classification as the basic taxonomy, new classification was separated into 06 class intervals to identify spatial variation of THI more clearly. This research introduced new THI classification system for Sri Lanka (Figure 2).

Temperature °C	Relative Humidity 100%							
(THI)	75	76	77	78	79	80	81	82
14.8	14.1	14.1	41.1	14.1	14.2	14.2	14.2	14.3
23.5	22.3	22.4	22.4	22.5	22.5	22.6	22.6	22.7
26.0	24.7	24.8	24.8	24.9	24.9	25.0	25.0	25.1
27.1	25.7	25.8	25.9	25.9	26.0	26.0	26.1	26.1
27.6	26.2	26.3	26.3	26.4	26.4	26.5	26.6	26.6
27.8	26.4	26.5	26.5	26.6	26.6	26.7	26.7	26.8
27.9	26.5	26.6	26.6	26.7	26.7	26.8	26.8	26.9
28.8	27.4	27.4	27.5	27.5	27.6	27.6	27.7	27.8

Cold and Comfort (THI=14.2-22.3)

Comfort (THI=25.2–26.3)

Extremely Comfort (THI=22.4–25.1)

Slightly Comfort (THI=26.4–26.8)

Moderately Comfort (THI=26.9–27.5)

Warm/ Humid and Discomfort (THI=27.5<)

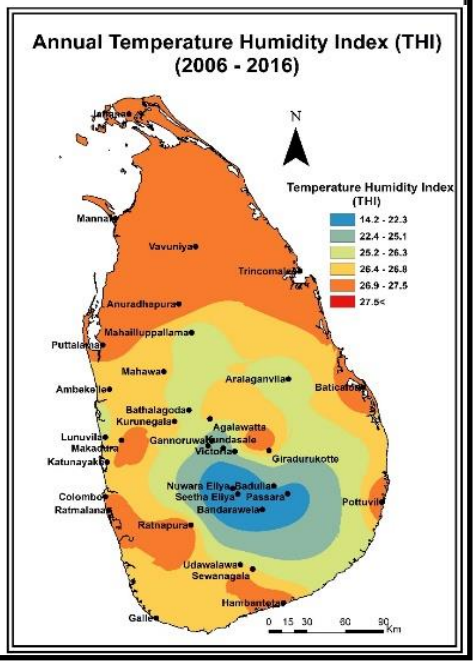


Figure 2: Classification of Temperature Humidity Index and introduce the Bio Climatic Map for Sri Lanka

When consider about the annual pattern of THI in the island, Comfort with Cold Level can be recognized only the stations situated in Central Highland mainly at Nuwara-Eliya, Seethaeliya, Bandarawela, and Passara stations. Many stations with Extremely Comfort Level are gather round the Central Highland at Katugastota, Badulla, Kundasale and Gannoruwa stations. Out of 12 stations, 09 are located in the Intermediate Zone (elevation 30-300 m) with Slightly Comfort Level range and out of 10 stations, 08 stations are found in the Coastal Zone with Moderately Comfort Level. THI values are changing with the seasonal rainfall, environment lapse rate and effect of Kachchan wind which are occurring with the nature of the topography and orography. There is a strong relationship found in between THI and elevation. The Comfortable level has been changing along the slope of the Central Highland. The study revealed that when elevation increases the THI decreases in Sri Lanka. An important fact is that one of the cooling mechanisms called laps rates and it functions in every 1000m from sea level to highland the temperature is falling down by 6.5^{o}C, as a result, the temperature is decreasing. On the other hand low temperature is reported in Central Mountains than sea level and intermediate zones. With the low temperature, the higher value of humidity is noticed in this area with the elevation is increasing; the decrease of the THI value is also recorded.

The distribution pattern of wet zone and dry zone also affect by the THI value. Normally higher THI values are recorded from the coastal zones and intermediate zones. But the highest THI value is recorded from the stations which are located in the dry zone than from wet zone. Central Highland in Sri Lanka is performing a significant role in changing climatic elements. This also strongly affects the change of spatial THI values in the country. In considering the above facts the south-western part is more comfortable than north-eastern part of Sri Lanka. One of the reasons for this pattern is the higher humidity level on the south-western side than on the north-eastern side and the temperature is lower on the western side than the north-eastern side. As a result of this distinction the comfort level in the wet zone is greater than in the dry zone. The wind lifting mechanisms, called orographic lifting and blowing of Kachchan wind also greatly affected this situation. As a result, the windward side is experienced heavy rain and the leeward side experience as the rainy shadows. Further, this performance controls humidity and temperature in both sides of central mountains. Owing to this process uncomfortable environment is created in the leeward side, and body convenience in the environment is created in the windward side. As a consequence, seasonal rainfall pattern are highly affected for the variation of THI over the land (Figure 3).

Higher THI value was recorded in the First Inter-Monsoon (FIM) and the South West Monsoon (SWM) seasons. A quite uncomfortable situation was observed from many stations in North part of the country. For an example during the FIM season, warm/humid and discomfort level was observed from 6 stations and during the SWM from 7 stations except for south-western part. During the both FIM and SWM seasons, out of 35 stations, only 3 stations recorded extremely comfort level. Even though slightly comfort was visible entire Sri Lanka during the Second

Inter-Monsoon (SIM) season, it is not much comfortable like in North East Monsoon (NEM). During this season, no any other stations recorded the state of warm/humid and discomfort level. This study revealed that, NEM season as the common comfortable season for entire Sri Lanka and in this period no any other station observed discomfort level. 11 stations are recorded as extremely comfort level in this season. Many of the stations which recorded comfort level are also visible in this season. They are 17 in number.

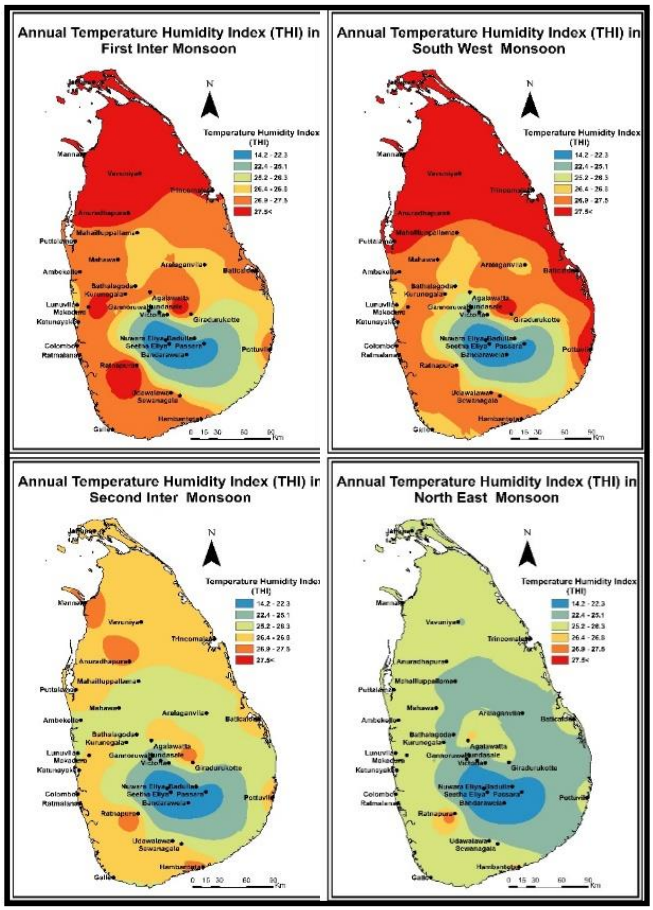


Figure 3: Seasonal variation of THI in Sri Lanka

Season	Maximum		Minimum	
	THI	Station	THI	Station
FIM	28.0	Anuradhapura	16.0	Nuwara-Eliya
SWM	28.8	Trincomalee	16.1	Nuwara-Eliya
SIM	26.8	Trincomalee	15.8	Nuwara-Eliya
NEM	26.4	Ratnapura, Hambantota	14.7	Seetha-Eliya

According to the seasons, table 1 shows the minimum and maximum THI values with the locations.

Table 1: Seasonal THI (Maximum and Minimum) with stations

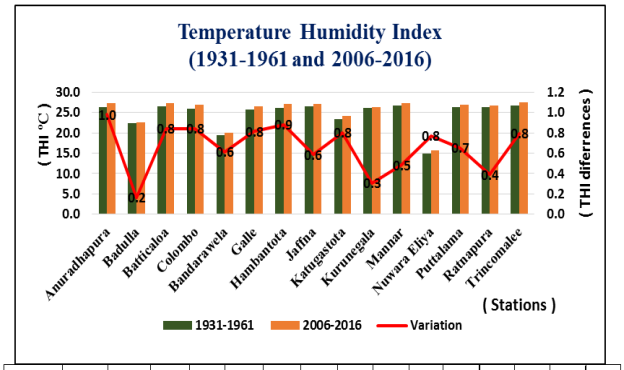
THI variation can be observed for each month (Table 2). February is the most comfortable month and May is the uncomfortable and hottest month on the island. When compared with two standard periods (1931-1961 and 2006-2016) for 15 main stations, it is identified an increasing trend of HHS in Sri Lanka.

Table 2: THI comfort levels, with monthly classification

Months	Comfort with Cold	Extremely Comfort	Comfort	Slightly Comfort	Moderately Comfort	Warm/Humid and Discomfort
Dec	5	9	19	2	0	0
Jan	6	17	12	1	0	0
Feb	5	8	17	4	1	0
Mar	5	3	3	12	11	1
Apr	4	2	2	2	13	12
May	4	3	1	2	10	15
Jun	4	4	1	5	10	11
Jul	4	4	4	6	9	8
Aug	4	4	3	8	8	8
Sep	4	4	3	11	6	7
Oct	4	4	6	11	10	0
Nov	5	4	16	10	0	0

Comfortable Uncomfortable

According to figure 4, a considerable variation of THI is recorded from Anuradhapura station and it increased by 1.0^{o}C from 1931-1961 to 2006-2016. Badulla station is recorded minimum variation between above two periods and its differences is 0.1^{o}C. The large variation of THI, are shown at Hambantota, Batticaloa, Colombo, Galle, and Trincomalee. It was found that, even though the Kandy and Nuwara-Eliya are situated in the central highland the THI has increased with similar to the other stations which are located in the dry and coastal zone. The Nuwara-Eliya THI is increased by 0.8^{o}C. According to that graphical information, THI values are increased with respect to the changing of other climatic parameters too i.e. Temperature and Relative Humidity.

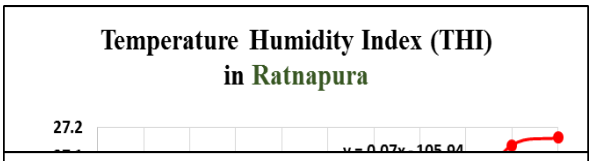


Station	Anuradhapura	Badulla	Batticaloa	Colombo	Diyathalawa	Galle	Hambantota	Jaffna	Kandy	Kurunegala	Mannar	Nuwara Eliya	Puttalama	Ratnapura	Trincomalee
1931-1961	26.3	22.4	26.4	26.0	19.4	25.7	26.2	26.6	23.4	26.0	26.8	15.0	26.3	26.4	26.7
2006-2016	27.3	22.6	27.3	26.8	20.0	26.5	27.1	27.2	24.2	26.4	27.2	15.7	27.0	26.8	27.5
Varition	1.0	0.2	0.8	0.8	0.6	0.8	0.9	0.6	0.8	0.3	0.5	0.8	0.7	0.4	0.8

Figure 4: THI differences from 1931-1961 to 2006-2016

One or two degrees of temperature have increased for a long time period but this small change makes big issues on the heat stress of THI which may create large changes in the human body and sensitive environment.

The annual trend of THI, the positive increasing trend of the heat stress, as well as the decreasing trend of the THI, can be observed from 2006 to 2016 in selected 35 stations. Out of 35 stations 30 stations had recorded increasing trend of THI and 5 of them showed a decreasing trend of THI. Hambantota, Ratnapura, Puttalama, Kundasale and Mahawa stations show clear increasing tends (R^2 0.50) and the stations of Ratnapura and Kundasale recorded greater than R^2 0.80. These both stations have strong positive increasing trend of THI than other stations. Among the 35 stations, Badulla, Katunayake, Aralaganvila, Gannoruwa and Victoria stations are showing a decreasing trend and Aralaganvila is showing a clear negative decreasing trend (R^2 0.67).



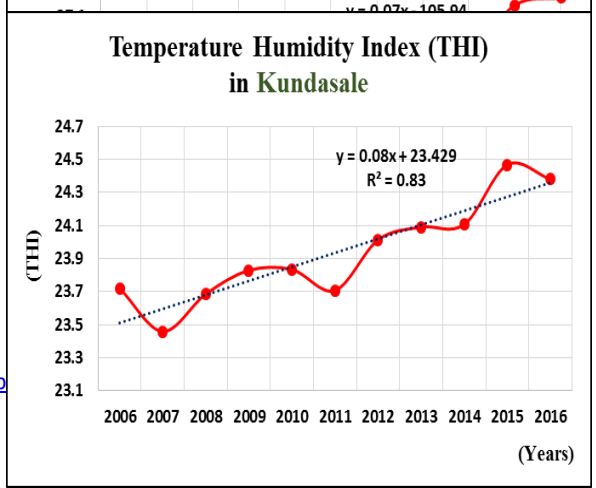


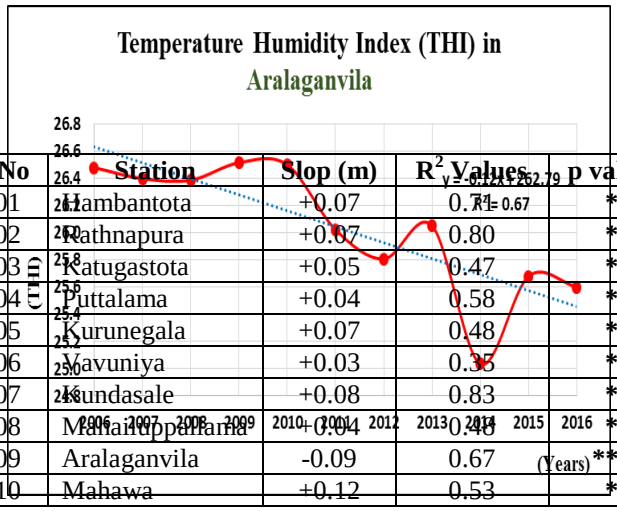
Figure 5: Increasing trend of THI in Rathnapura and Kundasale

Figure 6: Decreasing trend of THI in Aralaganvila

To observe the significant level of THI the Mann-Kendall statistical analysis has been applied. The calculated p-value shows the significant level of THI in each station and found that the $p < 0.05$. Table 3 visualizes the significant trend of THI in 10 specific stations annually.

Table 3: R^2 and p-value in each station

Note: Bold numbers are significant, *significant positive, **Significant negative



No	Station	Slop (m)	R^2 Values	p values
01	Hambantota	+0.07	0.71	***0.01**
02	Rathnapura	+0.07	0.80	***0.00**
03	Katugastota	+0.05	0.47	***0.02**
04	Puttalama	+0.04	0.58	***0.03**
05	Kurunegala	+0.07	0.48	***0.04**
06	Vavuniya	+0.03	0.35	***0.04**
07	Kundasale	+0.08	0.83	***0.00**
08	Mahaluppallama	+0.04	0.48	***0.04**
09	Aralaganvila	-0.09	0.67	****0.01**
10	Mahawa	+0.12	0.53	***0.01**

According to this graph, it is clear that 10 stations are showing the significant trend of the THI value in Sri Lanka. But among these 10 stations, 9 stations are showing increasing significant trend of the THI and only Aralaganvila station showing decreasing trend of the THI. Monthly trends also very important for identifying the significant negative and positive trends of the heat stress in the country (Table 4).

Table 4: Monthly significant trend of THI

Mo	Number of Stations			
	IT	Stations	DT	Stations
Jan	9	Hambantota, Ratnapura, Kurunegala, Mahaillukpallama, Kundasale, Makadura, Passara, Mahawa, Sewanagala	0	No
Feb	2	Hambantota, Lunuvila	1	Victoria
Mar	3	Katugastota, Puttalama, Mahawa	1	Aralaganvila
Apr	3	Ratnapura, Mahawa, Ambekelle	0	No
May	3	Pottuvil, Kundasale, Ambekelle	1	Aralaganvila
Jun	2	Ratnapura, Kurunegala,	1	Aralaganvila
Jul	8	Ratnapura, Katugastota, Puttalama, Kurunegala, Kundasale, Lunuvila, Mahawa, Ambekelle	1	Aralaganvila
Aug	4	Jaffna, Ratnapura, Mahawa, Sewanagala	1	Aralaganvila
Sep	0	No	1	Aralaganvila
Oct	3	Hambantota, Puttalama, Mahawa	1	Aralaganvila
Nov	1	Udawalawa	2	Aralaganvila, Victoria
Dec	3	Sewanagala, Kundasale,Hambantota	0	No

Note: IT: Increasing Trend, DT: Decreasing Trend

Aralaganvila is one and only station which recorded 8 out of 12 month as significant decreasing trend of heat stress. November and September months of this stations are more significant than other months. In this station, 6 months are visualized as the significant trend and January month is more significant than the other months because $p \leq 0.05$. In North East Monsoon season only the increasing trend of THI are observed. Hambantota, Kundasale, Ambekelle and Sewanagala stations showed the significant increasing trend of THI values because the $p \leq 0.05$. Hambantota station is special than other stations and it recorded strong significant increasing trend of THI than other stations. SWM period also recorded increasing trend, but in this time Badulla and Aralaganvila stations show significant decreasing trend of THI. FIM and SIM period couldn't identify significant increasing trend of IHT, but in the same season, Badulla and Aralaganvila stations show significant decreasing trend of the Human Heat Stress.

IV. CONCLUSION

The spatially and temporally the Temperature Humidity index (THI) is varied in Sri Lanka. It was clearly observed on monthly, seasonally and annually. The annual pattern of THI, of the most of the stations are noticed as a slightly comfort level. High THI values generate the stressful and uncomfortable conditions and most of the coastal and dry zones areas are found in this category. 100% of the comfort zones are gathered around the Central Highland and with the increases of elevation human body feel cold and comfort. There is a strong relationship among the elevation with environment lapse rate and Temperature Humidity Index in Sri Lanka and when elevation increases the THI decreases and vice versa. THI directly depends on monsoon wind and rainfall pattern in the island and it is controlled by Central Highland with the deferent elevation levels. With the effect of Kachchana wind, the wind-word side receive more rainfall and it becomes a comfortable than the leeward side. During the SWM period south-western part performance as the wind word side and this western slop get more comfortable condition than the northern side. SWM period recorded maximum THI in North part, but during the NEM period entire Sri Lanka tern to a comfortable situation. When considering the monthly pattern of THI, February is the most comfortable month and May is the uncomfortable and hottest month on the island. There is a positive increasing trend of the THI in the country (from 1931-1961 to 2006-2016). It is not a big issue today, but continues increasing trend of heat stress will make several complications of health of the nation in the country.

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