MAUSAM, **73**, 1 (January 2022), 105-114

551.524 : 551.583.16

Inter-spatial heat vulnerability assessment of Summer - 2018 over Madhya Pradesh using discomfort (wind and thermal) indices

VED PRAKASH SINGH, JIMSON MATHEW* and I. J. VERMA**

India Meteorological Department, Ministry of Earth Sciences,

Bhopal, Madhya Pradesh – 462 011, India

**Department of Computer Science and Engineering, Indian Institute of Technology,*

Patna, Bihar – 801106, India

***India Meteorological Department, Ministry of Earth Sciences, New Delhi – 110 003, India*

(*Received 29 November 2018, Accepted 2 November 2021*)

e mail : kvpssc@gmail.com

सार – वैश्विकतापन के कारण हवा के तापमान में वृद्धि इस समय एक चिंता का विषय बनता जा रहा है। यह तापवृद्धि अधिकांशतः उन लोगों के लिए हल्के से गंभीर तापजनित विकलता और गर्मी से संबंधित खतरे पैदा कर सकती है, जो पूरे दिन बाहरी गतिविधियों में लगे रहते हैं। वर्तमान अध्ययन मध्य प्रदेश के प्रमुख स्टेशनों पर तापीय प्रक्षेत्रों के अंतर-स्थानिक मासिक वितरण को दर्शाता है, जैसे - भोपाल, ग्वालियर, इंदौर, जबलपुर, होशंगाबाद, रीवा, रतलाम, उज्जैन, धार आदि। इस अध्ययन में, तापीय तनाव का अनुमान लगाने के लिए वेट बल्ब ग्लोब तापमान (डब्ल्यूबीजीटी) सहित उष्णकटिबंधीय जलवायु के लिए उचित विभिन्न उष्ण-सूचकांकों का उपयोग करके मौसमीय आंकड़ों का विश्लेषण किया गया है। मध्य प्रदेश में वर्ष 2018 में मार्च, अप्रैल और मई के महीने में गंभीर हीट स्ट्रोक की चपेट में आने वाले स्थानों की पहचान करने के लिए इनडोर, छायादार और बाहरी हीट स्ट्रेस की अलग-अलग और तापांतरण दरों की गणना करके अध्ययन किया गया था। यह देखा गया है कि किसी भी स्टेशन पर एहतियाती कदम उठाने हेतु केवल लू (हीट वेव) की घोषणा प्रशासन और स्वास्थ्य संगठनों के लिए पर्याप्त नहीं है; अपितु इसके साथ साथ, प्रभाव आधारित निगरानी और कार्य-समयसूची बनाने के लिए विकलता सूचकांकों (डिस्कम्फर्ट इंडेक्स) को संदर्भित किया जाना चाहिए। यह पाया गया है कि मार्च और अप्रैल में मध्य प्रदेश के कम से कम आधे जिले आंशिक असुविधा की श्रेणी में आते हैं। यह भी दिलचस्प पहलू है कि मई महीने में कई जिले बाहरी परिस्थितियों में असुविधा की श्रेणी में आते हैं, जबकि इनडोर या छायादार परिस्थितियों में नहीं। मुख्य रूप से मध्य पदेश के पश्चिम और मध्य क्षेत्रों में अप्रैल और मई के महीनों के दौरान गंभीर तनाव देखा जाता है। मध्य प्रदेश में अत्यधिक तापमानों के दौरान वास्तविक अनुभव-जैसे तापमानों को इंगित करने के लिए उष्णकटिबंधीय ग्रीष्म-सूचकांक (टीएसआई) और आभासी तापमान (एटी) की गणना के साथ विभिन्न उष्ण-सूचकांकों की तुलना भी की गयी है।

ABSTRACT. Due to global warming, increase in air temperature is a growing concern at present. This rise in temperature may cause mild to severe thermal discomfort and heat related hazards mostly for the people who are engaged in outside activities throughout the day. The present study shows the inter-spatial monthly distribution of thermal patches over major stations of Madhya Pradesh, *viz.*, Bhopal, Gwalior, Indore, Jabalpur, Hoshangabad, Rewa, Ratlam, Ujjain, Dhar etc. In this study, various Heat Indices applicable for tropical climate including Wet Bulb Globe Temperature (WBGT) are used to estimate the thermal stress by analyzing the meteorological data of Summer-2018 in Madhya Pradesh. Study was carried out for computing indoor, shady and outdoor heat stress separately and heat transfer rates to identify the places vulnerable to severe heat stroke in the month of March, April and May in 2018.It is observed that declaration of heat wave alone at any station is not sufficient for the administration and health organizations to take precautionary actions; also, discomfort indices should be referred for impact based monitoring and making work schedules. It is found that March and April fall in the partial discomfort category for at least half of the districts in Madhya Pradesh. It is interesting to note that several districts fall in discomfort category in outdoor conditions but not in indoor or shady conditions in May month. Severe stresses are observed mainly in the West and Central Madhya Pradesh during April and May months. Comparison of various Heat Indices is too performed along with computing Tropical Summer Index (TSI) and Apparent Temperature (AT) to indicate real feel-like temperatures in Madhya Pradesh during extreme temperature events.

Key words – Impact based monitoring, Wind-chill factor, HI (Heat Index), WBGT, TSI, Discomfort index.

1. Introduction

Climate change, which increases the global temperature, is one of the most concerned subjects now a day. Rapidurbanization and industrialization alters radiation balance, which changes the airflow and turbulence. Moreover, increased air pollution by human activities cumulatively rise the surrounding air temperature; concluded by Unger (1999). This rise in temperature leads to thermal discomfort and several heat related illness such as heat rashes, heat cramps, heat exhaustion and even severe heat stroke. According to J. F. Wing (1965) and Bell (1981), thermal stress affects the people most, who are exposed directly to the sun such as soldiers, athletes, farmers, travelers and open field workers. Moreover, Das *et al.* (2011) inferred that heat stress directly affects the individual's health; reduces worker's performance and productivity, which may have negative impact on socio-economic status and development. Comfort is a sensation and thermal comfort is the pleasant state of mind of an individual to his/her surrounding thermal environment as per ISO (1984) and ASHRAE standards (1996). Further, Fanger (1970) indicated that thermal sensation depends upon two factors such as environmental factors, *viz.*, air temperature, radiant heat, wind speed, relative humidity and behavioral factors, *viz.*, total metabolic rate, clothing, *etc*. As this thermal comfort is also an acceptable temperature zone, it ranges 23 °C to 27 °C during summer and 20 °C to 25 °C during winter, accepted in ANSI/ASHRAE standards (1992). Thermal stress is the balance between a worker's net thermal load (by the work and environment) and the capacity of eliminating the heat. Moreover, Jones *et al.* (1992); Mann *et al.* (1998) and Bhattacharya *et al.* (2010) concluded that rise in global mean temperature with very fast urban and industrial development has led to increase the heat stress mostly during the summer season in last few decades. Workers from construction industries, agricultural sectors, pottery industry, power plants and different unorganized sectors are mostly affected by the summer thermal stress. Active researches are going on throughout the world to indexing the thermal stress and more accurately grade it according to different climatic zones as pointed out by Chakrabarty *et al.* (1982); Epstein *et al.* (2006) and Miller *et al.* (2007). In this paper, an attempt is made to evaluate the thermal comfortability of all stations / subdivisions of Madhya Pradesh first time for year 2018 to suggest scientific work-rest plan throughout the summer season for outdoor, shady and indoor workers/activities as *ab-initio* guidelines for upcoming years.

While performing the current study, the selection of well-suited heat indices for Madhya Pradesh was very crucial task, so various universal heat indices were analyzed and their inter-spatial comparison with Tropical Summer Index was performed. There are several approaches to quantify comfort levels in terms of temperature and other meteorological variables in different regions of the globe. The American Society of Heating, Refrigeration and Air-Conditioning Engineers (ASHRAE) developed the concept of "effective temperature" as "an empirically determined index of the degree of warmth perceived on exposure to different combinations of temperature, humidity and air movement" in 1955. Different bioclimatic indices have also been proposed to integrate the effect of environment on the human thermal comfort. According to the guidelines of NIOSH (1986) and Miller *et al.* (2007), these indices can becategorized into three different groups, *viz.*, "rational indices", "empirical indices" and "direct indices".

Rational indices are based on heat balance equation of the human body, which accounts for the environmental variables such as ambient temperature, radiation temperature, humidity and air movement as well as metabolic processes and clothing insulation for human body. Most commonly used such recent indices are physiological equivalent temperature (PET) and Universal Thermal Climate Index (UTCI).Empirical indices are based on objective and subjective strain response data obtained on individuals and group of individuals exposed to various levels and combinations of environmental and metabolic heat stress factors, *e.g.*, Effective Temperature or Apparent Temperature and Wet Bulb Globe Temperature,described by Houghton *et al.* (1923) and Yaglou *et al.* (1957) respectively. Direct indices are based on direct measurements of environmental variables. Popular direct indices include Discomfort Index (DI) defined by Thom (1959) to indicate proportional effect of dry bulb temperature and wet bulb temperature over human thermal comfort, Humisery defined by Weiss (1983), Wind Chill Index created by Siple *et al.* (1945) and later on refined by Steadman (1971). In addition, Steadman (1979) created the apparent temperature / heat index. Giles *et al.* (1990) revised the work of Thom (1959) and proposed an alternative version of DI defined in terms of temperature in degree Celsius and relative humidity in percentage. Thom's Discomfort Index and its alternative version in °C (Thermo-hygrometric index) have been suggested as universal heat stress indices by Epstein *et al.* (2006) and Chronopoulos *et al.* (2012) respectively.

Among all these indices, direct indices mentioned above signify that essentially, wind and relative humidity play pivotal role in determining how cool or warm it might appear for a given temperature level. This is because the rate at which heat is dissipated from the human body through skin determines how warm one feels in summer season or how cold one feels in winter. Thus, it is important to have knowledge of this "apparent temperature" as it often aids in scheduling outdoor activities and deciding optimum temperature levels in many workplaces. Therefore, all five popular indices, *viz.*, Temperature Humidity Index (THI),Wet Bulb Globe Temperature (WBGT), Apparent Temperature, Thermo-hygrometric index (THygI) and Thermal Comfort were computed along with Tropical Summer Index (TSI)while studying Summer-2018 in Madhya Pradesh. The study was performed to find out - (*i*) the places vulnerable for severe heat stroke, (*ii*) comparison of indoor and outdoor indices to suggest what places are suitable for indoor or outdoor works.

2. Area of study

Qualitative analysis of heat indices has been performed for 33 stations out of 52 districts in the State of Madhya Pradesh (including all major cities), where full-time or part-time meteorological observations are operational on regular basis. Here, total nine (10) stations are classified with regular hourly or 3-hourly synoptic/ autographic observations, *viz.*, Bhopal, Indore, Guna, Sagar, Satna, Jabalpur, Hoshangabad, Khajuraho, Chhindwada and Gwalior.However, rest of the twenty-four (23) stations fall under the category of part-time surface observatories (6-hurly or 12-hourly synoptic observations), *viz.*, Tikamgarh, Rajgarh, Raisen, Dhar, Khandwa, Khargone, Ratlam, Shajapur, Ujjain, Rewa, Sidhi, Umaria, Mandla, Balaghat (Malajkhand), Narsingpur, Seoni, Chhatarpur (Nowgaon), Damoh, Sheopur Kalan, Datia, Shivpuri, Betul, Pachmarhi.

3. Data / Material

To carry on the study in the areas mentioned above, following dataset of primary and derived parameters were collected from respective sources:

(*i*) Weather Normals of all districts in Madhya Pradesh were collected from National Data Center (NDC), IMD, Pune.

(*ii*) Hourly / 3-hourly / 6-hourly meteorological (synoptic / autographic) observations were collected from Meteorological Centre, IMD, Bhopal for the months of March, April and May in year 2018 for 33 stations of Madhya Pradesh.

(*iii*) *Statistical Tools* : Excel for data analytics.

(*iv*) *Visual Tools* : Excel and Py-chart for infographic analytics.

4. Methodology

Methods involved in current study can be described in three (3) stages- preparation of primary dataset, deriving secondary and estimated dataset, computation of empirically devised direct thermal loads, *viz.*, indoor, shady and outdoor heat indices.

4.1. *Preparation of thermal dataset*

As described previously, synoptic or part-time observations are discrete w.r.t. to time and have time-interval of minimum 3 hours between two (2) synoptic observations recorded at each station except few Meteorological offices (Bhopal, Indore, Jabalpur, Khajuraho, Gwalior), where hourly autographic observations are too recorded. Thus, getting the continuous profiles of temperature, wind speed and humidity w.r.t. time is not possible universally from primary dataset. Since, we need discomfort analytics of any station at the time when temperature reaches its peak in afternoon hours to quantify worst possible impact of heat on human body throughout the day; therefore, interpolation technique was followed to prepare humidity and wind dataset at desired points of time. However, maximum temperature is exclusively reported in evening synoptic observation, so it was directly used in the equations of heat indices but for humidity and wind, following two interpolation techniques were used on regional basis:

(*i*) *Linear Mean* **-** In several stations, it is found from scientific experiments performed locally that humidity and wind speed at the time of maximum air temperature (approximately between 14:30 IST to 15:30 IST), are almost equal to the arithmetic mean of the two values of respective parameter recorded in preceding and succeeding synoptic hours (at 11:30 IST and 17:30 IST). Usually, such stations are linked with semi-arid plain like climatic features, which are far from water bodies and having almost linear variation of meteorological variables throughout the day, especially between 08:30 IST and 17:30 IST. There are total eight (8) stations, which fall under this category, *viz.*, Tikamgarh, Shivpuri, Ratlam, Shajapur, Chhatarpur, Seopur Kalan, Datia, Balaghat (Malajkhand). For these stations, Relative Humidity (RH) and Wind Speed (V) [at the time of air temperature reaching its peak]are computed by taking statistical mean of two (2)values of respective variable, reported in11:30 IST and 17:30 IST synoptic observations respectively.

(*ii*) *Polynomial function in meteorological variable* **-** There are few stations [except mentioned in previous method and full-time observatories], where only part-time observations are recorded in morning (08:30 IST) and evening (17:30 IST) hours. In such scenario, several experiments were followed for devising polynomial function of morning and evening values of any parameter ($P_{morning}$ and $P_{evening}$) to find out afternoon values of weather parameters, *i.e.*, when $T = T$max as given below:

$$P_{(\text{when } T = T\max)} = A_1 \times P_{morning} + A_2 \times P_{evening} + A_3$$

where, constants A_1, A_2 and A_3 are fixed by empirical data analytics using excel tools using polynomial fitment criteria for a particular station in summer season. After deriving RH at desired point of time using this method, dew point temperature is also calculated using *T*max and derived RH. Further, the same is verified through INSAT-3D sounder facilitated dew-point temperature profiles. The error constant A_3 is retuned in such a way that dew point temperature (computed with the help of *T*max & derived RH above) and INSAT-3D derived dew point temperature (at time when $T = T$max) are close enough, to minimize the error in derived RH.

Above method was followed to compute RH and wind speed for sixteen (16) stations, *viz.*, Rajgarh, Raisen, Dhar, Khandwa, Khargone, Ujjain, Rewa, Sidhi, Umaria, Chhindwada, Mandla, Narsingpur, Seoni, Damoh, Betul, Pachmarhi, where only morning and evening synoptic observations are recorded.

4.2. *Computation of dew point and wet bulb temperature*

In previous section, required thermal dataset was prepared which is comprised of RH, wind speed (*V*) and dry bulb temperature at time, whenever it reaches its peak (*T*max). However, for performing the thermal comfort analysis, we also need wet bulb temperature (T_{wet}) as well as dew point temperature (T_{dew}) profiles. To resolve these dataset, RH and *T* (or T_{dry}) are used to derive other parameters at the time when $T = T$max.

If dry bulb temperature (ambient air temperature measured through laboratory thermometer) is *T* (in °C) at a given time and actual vapor pressure and saturated vapor pressure are *e* and e_s respectively, then e_s (in hPa) and RH (in %) can be computed as mentioned below:

$$e_s = 6.11 \times 10^{[(7.5 \times T) / (237.3 + T)]}$$

and

$$RH = e / e_s \times 100 \qquad \text{or } e = e_s \times RH / 100$$

Using above two equations, actual vapor pressure can be estimated with the help of dry bulb temperature and RH. Further, dew point temperature (T_{dew} in °C) may also be computed using following equation:

$$T_{dew} = \frac{237.3 \times \ln(e/6.11)}{7.5 \times \ln 10 + \ln(e/6.11)}$$

Moreover, according to Engineering Tool Box (2011), Discomfort Index (DI in °F) can be expressed in terms of dry bulb temperature (*T*) and either of dew point (T_{dew}) & wet bulb temperature (T_{wet}) using following two equations (valid for *T* in range of 0 °C to 50 °C):

$$DI = 0.55 \times T + 0.2 \times T_{dew} + 17.5 \tag{1}$$

where, DI, *T* and T_{dew} all three are in °F

Or alternatively,

$$DI = 0.4 \times (T + T_{wet}) + 15 \text{ or } T_{wet} = (DI - 15)/0.4 - T \tag{2}$$

where, T_{wet}, *T* and DI all three are in °F

Using equation (1) above, firstly, DI is computed and then by putting this value in equation (2), T_{wet} is estimated in °F, which is further converted back into in °C.

4.3. *Indoor thermal indices*

Based on bio-climatic features of various stations in Madhya Pradesh, selected heat indices in current study for indoor comfort analysis are being mentioned below:

(*i*) *Temperature Humidity Index (THI)* – Temperature Humidity Index (THI) is the combination of temperature and humidity that is a measure of the degree of discomfort. Temperature Humidity Index (THI) is also referred as Thermal Discomfort Index (DI) according to Kakon *et al.* (2010). It is measured inside the room. By empirically testing the THI values on human objects, the comfort limits are defined as–21≤THI≤24 => 100% of the subjects will feel comfortable, 24<THI≤26 => 50% of the subjects will feel comfortable and THI>26 => 100% of the subjects will feel uncomfortably hot.

$$THI = 0.8 \times T + RH \times T / 500 \tag{3}$$

where, *T* is air temperature in °C and RH is relative humidity in percentage at any point of time.

(*ii*) *Thermal Comfort (ThC)* - Thermal comfort refers specifically to thermal perception of our surroundings according to Toolkit *et al.* (2008). Human thermal comfort is defined universally by ASHRAE (1955, 1992 and 1996) as the state of mind that expresses satisfaction with the surrounding environment. Acceptable thermal environment is an environment, in which at least 80% of the occupants would find thermally acceptable as per the ISO (1955) standards. ThC is expressed as

$$\text{ThC} = 19.7 + 0.30 \times T \quad (4)$$

In India, National Building Code (2005) mentions that thermal comfort of a person lies between 25 °C and 30 °C, with optimum condition at 27.5 °C as the normal skin temperature is 31 °C to 34 °C.

4.4. *Shady thermal comfort indices*

Based on climatic features (under cloudy conditions) of various stations in Madhya Pradesh, selected heat indices in current study for shady comfort analysis are being mentioned below:

(*i*) *Heat Index (HI)*-According to Sohar *et al.* (1963) and mentions of American College of Sports Medicine (1984), Heat Index combines air temperature and relative humidity in an attempt to determine the human-perceived equivalent temperature. When the heat gain is greater than the level of heat, which can be removed by the body, the body temperature is increased which results in illness and disorders. HI may be expressed as empirical relation given below:

$$\text{HI} = -42.379 + 2.04901523 \times \text{T} + 10.14333127 \times \text{RH} - 0.22475541 \times \text{T} \times \text{RH} - 6.83783 \times 0.001 \times \text{T}^2 - 5.481717 \times 0.01 \times \text{RH}^2 + 1.22874 \times 0.001 \times \text{T}^2 \times \text{RH} + 8.5282 \times 0.0001 \times \text{T} \times \text{RH}^2 - 1.99 \times 0.000001 \times \text{T}^2 \times \text{RH}^2 \quad (5)$$

where, T is dry bulb temperature in °F and RH is relative humidity in percentage. Places with significantly higher heat indices are not suitable for the workers performing outdoor activities in shady environment.

(*ii*) *Thermo-Hygrometric Index (THygI)* - It is the most widely used empirical heat index, which was developed by Thom (1957, 1959), expressed as :

$$\text{THygI} = 0.72\,(T + T_{wet}) + 40.6 \quad (6)$$

where, T and T_{wet} are the ambient air temperature and wet bulb temperature in °C respectively. Several categories of degree of comfort in ThI ranges are described as - Partial discomfort if 60 ≤ ThI <65, Comfortable if 65≤ ThI <75, Partial discomfort if 75≤ ThI <80, Discomfort if 80 ≤ ThI < 85 and Severe stress if ThI≥85.

(*iii*) *Tropical Summer Index (TSI)* - According toNational Building Code of India (2005), Tropical Summer Index is the temperature of calm air at 50% relative humidity, which imparts the same thermal sensation as the given environment. TSI also evaluates indoor thermal comfort level according to Suman *et al.* (2007).

$$\text{TSI} = 0.745 \times T + 0.308 \times T_{wet} - 2.060 \times V \quad (7)$$

where, T is dry bulb temperature in °C, T_{wet} is wet bulb temperature in °C and V is wind speed in m/s.

4.5. *Outdoor thermal indices*

Based on dynamic meteorological features (mentioned in ACGIH Signature Publications, 2004) of various stations in Madhya Pradesh, selected heat indices in current study for outdoor comfort analysis are being mentioned below:

(*i*) *Wet Bulb Globe Temperature (WBGT)* - The wet-bulb temperature is a type of temperature measurement that reflects the physical properties of a system with a mixture of a gas and a vapor, usually air and water vapor. Wet bulb temperature is the lowest temperature that can be reached by the evaporation of water only. It is the temperature one feels when his / her skin is wet and is exposed to moving air and it should not be greater than 29 °C as inferred in National Building Code of India (2005). Unlike dry bulb temperature, wet bulb temperature is an indication of the amount of moisture in the air. The Wet Bulb Globe Temperature (WBGT) is a measure of the heat stress in direct sunlight, which takes into account: temperature, humidity, wind speed, sun angle and cloud cover (or solar radiation). However, using water vapor pressure (e given in hPa) in partially cloudy conditions, WBGT may be expressed in °C as:

$$\text{WBGT} = 0.567 \times T + 0.393 \times e + 3.94 \quad (8)$$

(*ii*) *Apparent Temperature (AT)* - Apparent Temperature is defined as the temperature, at the reference humidity level, producing the same amount of discomfort as that experienced under the current ambient temperature and humidity. Using the Steadman table, the apparent temperature is calculated as:

$$\text{AT} = T + 0.33 \times e - 0.70 \times V - 4 \quad (9)$$

where, T is dry bulb temperature in °C, e is water vapor pressure in hPa and V is wind speed in m/s.

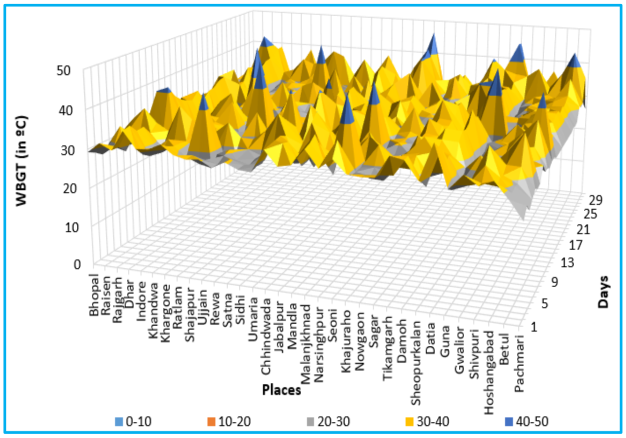

Fig. 1. WBGT for the stations of Madhya Pradesh in March-2018

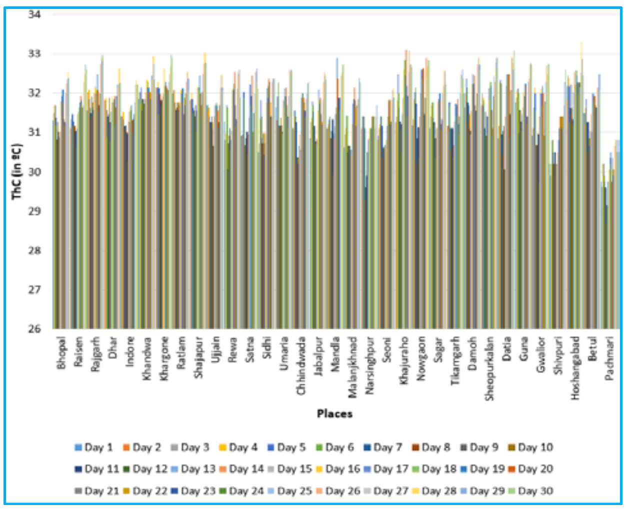

Fig. 2. Thermal comfort for the stations of Madhya Pradesh in April-2018

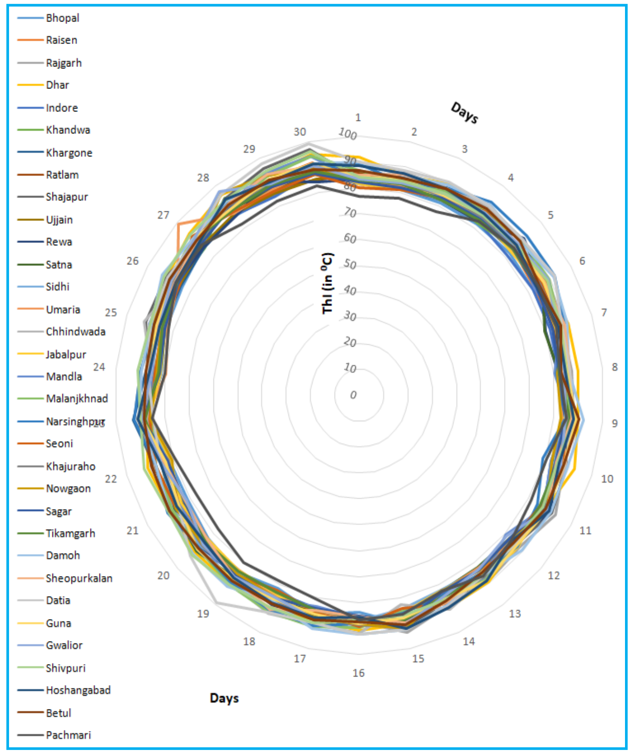

Fig. 3. Thermo-Hygrometric Index (ThI) for the stations of Madhya Pradesh in April-2018

Apparent temperature (AT) may be greater or lower than *T* depending upon wind speed, that means, one will feel less heat if wind speed is higher due to higher rate of evaporation from body skin.

5. Results

Various heat indices mentioned in section 4.3, 4.4 and 4.5 were computed for all 33 stations of Madhya Pradesh in year 2008 separately for the months March, April and May (*i.e.*, summer season). Month wise results for maximum possible stress (in day time when temperature reaches its peak, *i.e.*, $T = T$max) are shown below:

5.1. *March-2018*

In year 2018, maximum temperatures of March month in almost each station of Madhya Pradesh were in range of 32 °C to 40 °C, *i.e.*, near to normal human body temperature (37 °C). Hence, indoor or shady heat indices analytics did not infer any significant thermal stress information in the month of March but outdoor heat indices are linked with stressed heat loads for few stations as shown in Fig. 1.

From Fig. 1, it is clearly inferred that majority of the cities marked with WBGT > 40 °C (blue coloured peaks) fall in second fortnight of March-2018. Cities vulnerable to severe heat loads are Rajgarh, Narsingpur, Datia, Betul, Damoh and Rewa. Moreover, the maximum possible WBGT went beyond 40 °C for these cities on isolated days only.

5.2. *April-2018*

In year 2018, maximum temperatures of April month in almost each station of Madhya Pradesh were in range of 40 °C to 44 °C, *i.e.*, 3 °C to 7 °C above normal human body temperature (37 °C).

Here, indoor heat indices analytics inferred that thermal comfort level in all days of April month was slightly higher than normal skin temperature (33°C) for majority of the cities during last week of the month end as shown in Fig. 2.

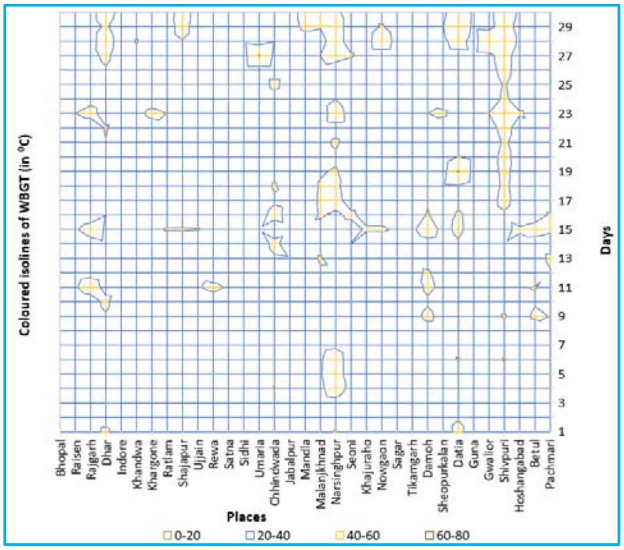

Fig. 4. Wet bulb globe temperature (WBGT) for the stations of Madhya Pradesh in April-2018

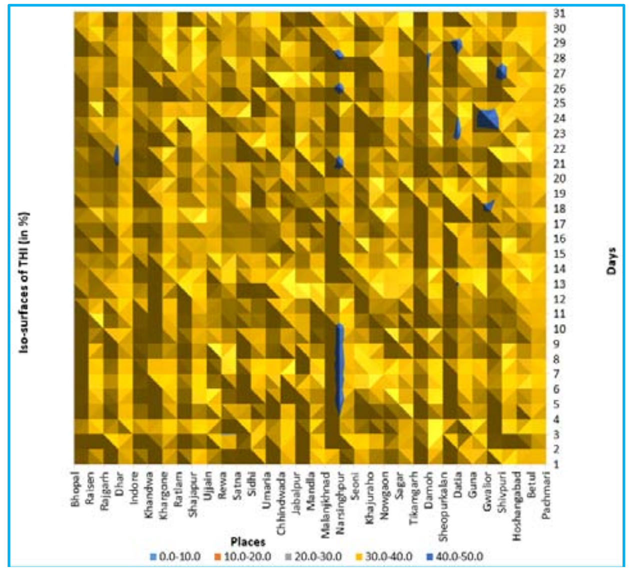

Fig. 5. Temperature-Humidity Index (THI) for the stations of Madhya Pradesh in May-2018

From Fig. 2, cities with best comfort zones (ThC ≤ 31.9 °C) are Pachmarhi, Narsingpur and Seoni in all 30 days, while other cities such as Bhopal, Raisen, Indore, Ujjain, Chhindwada, Betul, Shivpuri, Balaghat (Malajkhand), Mandla and Jabalpur are in comfort zone upto first fortnight of April month. However, rest of the cities are slightly deviating from the comfort zone but none of them are reaching beyond severe indoor discomfort level (ThC > 34 °C).

Shady thermal indices analytics is shown in Fig. 3 with the help of Thermo-hygrometric Index (THygI or ThI). ThI beyond 85 °C falls under severe stress zone.

From Fig. 3, it can be concluded directly that all the cities except Pachmarhi fall under the category of discomfort zone (80 °C <ThI ≤85 °C) and above (severe or very severe stress). However, cities under very severe stress (ThI >90 °C) in shady environment are Datia, Umaria, Shivpuri and Dhar in many days, while Hoshangabad falls under very severe stress zone in second fortnight of April month. On other hand, Raisen, Rajgarh, Betul, Gwalior, Guna, Chhatarpur (Nowgaon), Mandla, Satna, Sidhi, Shajapur and Khandawa cities are under severe stress zone (85 °C< ThI ≤90 °C) and rest of the places are in discomfort zone (80 °C <ThI ≤85 °C).

Moreover, while analyzing outdoor thermal indices (WBGT) as shown in Fig. 4, it was found that almost every city of Madhya Pradesh in the month of April-2018is not suitable for outdoor workers/ activities, even in partially cloudy conditions as WBGT is either near to skin comfort level 29 °C or higher. However, few cities linked to dangerous level of WBGT (40 °C or above, marked by yellow colour) in many days, that means these locations are not even suitable for open walking. These cities are Shivpuri, Gwalior, Narsingpur, Dhar, Shajapur, Rajgarh, Balaghat (Malajkhand) and Damoh, however rest of cities are in discomfort zone but with lower WBGT.

5.3. *May-2018*

In year 2018, maximum temperatures of May month in almost each station of Madhya Pradesh (except Pachmarhi - hill station) were in range of 41 °C to 46 °C, *i.e.*, 4 °C to 8 °C above normal human body temperature (37 °C) but with higher RH levels. However, normal maximum temperatures of May month are either 41 °C or above in most of the places in Madhya Pradesh, leading to non-issuance of heat waves (as departures from normal were in lower side, *i.e.*, range of +0.5 °C to +4 °C mostly except last few days of 2^{nd} fortnight of May month). Hence, issuing heat wave warnings could not serve the purpose to take suitable precautions for heat hazards.

From Fig. 5, indoor thermal index analytics (based on THI in %) is depicted and observed that all the stations throughout the May month are in discomfort zone (THI > 26%) but there are few cities (THI > 40%, marked with blue colour) also falling under severe thermal stress in indoor conditions at isolated occasions. These cities are Narsingpur, Gwalior, Datia, Shivpuri and Dhar; among them Narsingpur affected most.

Further, Tropical Summer Index (TSI) was analyzed in May-2018 for all 33 stations of Madhya Pradesh to get

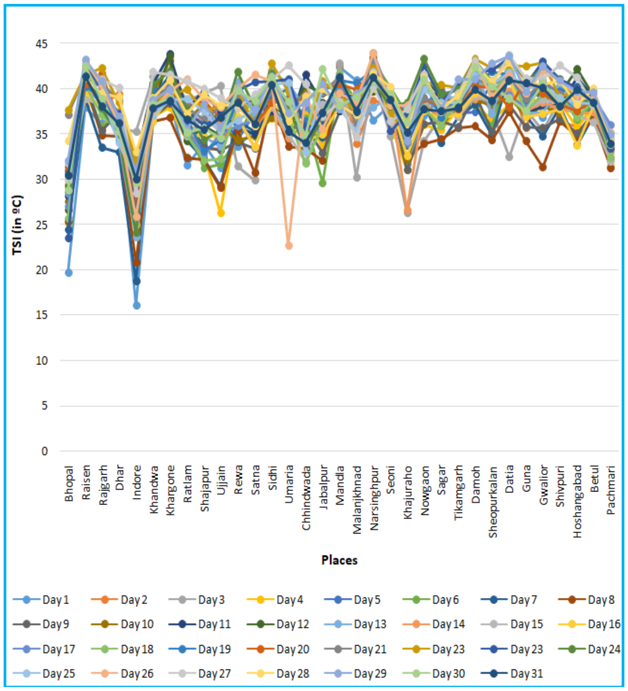

Fig. 6. Tropical Summer Index (TSI) for the stations of Madhya Pradesh in May-2018

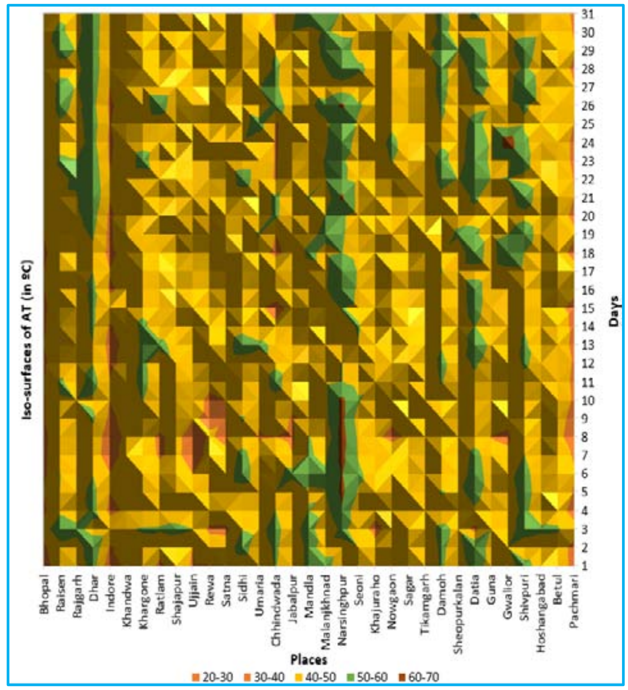

Fig. 7. Apparent Temperature (AT) for the stations of Madhya Pradesh in May-2018

thermal stress information in shady conditions as shown in following Fig. 6.

From Fig. 6, it is inferred that cities such as Sheopur Kalan, Datia, Guna, Gwalior, Shivpuri, Hoshangabad, Chhatarpur (Nowgaon), Khargone, Rajgarh, Raisen, Rewa, Mandla and Narsingpur fall under the category of severe stress (TSI > 37 °C) in 20 days ormore. However, several cities such as Indore, Ujjain, Bhopal, Khajuraho, Betul, Pachmarhi and Sagar fall under the limiting comfort (TSI ≤ 37 °C) in shady conditions.

Since, May month is considered as severe hot period of summer season, therefore studying the stress indices in outdoor conditions is essential here to point out the places vulnerable to severe heat stroke. In Fig. 7, the same has been depicted using feel-like temperature, *i.e.*,Apparent Temperature (AT).

From Fig. 7, it may be concluded that few cities such as Raisen, Rajgarh, Khargone, Chindwada, Mandla, Narsingpur, Balaghat (Malajkhand), Damoh, Datia, Shivpuri, Guna and Gwalior witnessed severe thermal stress (Feel-like temperature > 50 °C, near to breakdown temperature of human cells or heat stroke threshold) in at least 10 days of May month. However, Narsingpur and Gwalior cities also witnessed most dangerous level of thermal stress (sudden stroke, shown in dark magenta coloured) in isolated occasions.

6. Discussion

Based on the diversity of various thermal data analytics shown in section 5 for indoor, shady and outdoor conditions, current study deterministically settles that declaration of heat waves alone may not serve the purpose to take categorized precautions in summer season or to propose suitable work plans for miscellaneous activities (region wise). This is because of the fact that effect of humidity, wind is not included while issuing warnings for heat waves. Therefore, utilization of various heat indices can play deciding role to plan/ schedule activities in indoor, shady and outdoor conditions at different locations.

Moreover, the various health/work precautions may be proposed based on the analysis of summer-2018 for different locations of Madhya Pradesh as mentioned in Table 1.

7. Conclusions

It is concluded that the comfort levels were unsatisfactory (high stress) during most of the days in Summer - 2018 in many stations of Madhya Pradesh, especially from second fortnight of April month onward. However, indoor thermal comfort conditions remained within satisfactory limits during most of the days for the same season but essential cooling may be required for

TABLE 1

Classification of major cities of Madhya Pradesh based on suitability of work/ activity conditions (indoor, shady and outdoor) in Summer season of 2018as analytical application of various thermal indices, considerable in tropical climate

Month	Fortnight	Locations not suitable for any of outdoor or shady activities Cat. 1	Locations not suitable for outdoor activities but suitable for shady or indoor activities Cat. 2	Locations where indoor cooling is essential with air-conditioning Cat. 3
March	First	Nil	Nil	Nil
	Second	Nil	Rajgarh, Narsingpur, Datia, Betul, Damoh, Rewa	Nil
April	First	Shivpuri, Umaria, Dhar, Hoshangabad, Datia	Narsingpur, Gwalior, Damoh, Shajapur, Rajgarh, Balaghat	Nil
	Second	Gwalior, Datia, Umaria, Shivpuri, Hoshangabad, Guna, Mandla, Raisen, Rajgarh, Betul, Khandawa, Chhatarpur, Satna, Sidhi	Narsingpur, Balaghat, Damoh, Shajapur, Dhar	Rajgarh, Khandwa, Shajapur, Datia, Hoshangabad, Mandla, Gwalior, Chhatarpur, Guna
May	First	Sheopur Kalan, Shivpuri, Guna, Gwalior, Narsingpur, Rewa, Hoshangabad, Chhatarpur, Datia, Khargone, Rajgarh, Raisen, Mandla	Chindwada, Balaghat, Damoh	Narsingpur, Gwalior, Datia, Shivpuri, Dhar, Khargone, Rajgarh
	Second	Sheopur Kalan, Shivpuri, Guna, Gwalior, Narsingpur, Hoshangabad, Rewa, Chhatarpur, Datia, Khargone, Rajgarh, Raisen, Mandla	Chindwada, Balaghat, Damoh	Narsingpur, Damoh, Khargone, Shajapur, Mandla, Rewa, Hoshangabad, Rajgarh, Gwalior, Guna, Chhatarpur, Datia, Shivpuri, Sheopur Kalan

optimal (stress-free) human body metabolism. Further, heat waves alone doesn't give enough indication to take precautions in summer season for workers/ farmers involved in miscellaneous activities in different locations because the effect of humidity, wind or direct solar radiation is not associated with heat waves warnings. Hence, application of various thermal indices applicable in tropical region (*viz.*, THI, AT, WBGT, THygI, ThC and TSI) can be used as more-realistic heat impact indicators to propose work plans and issue precautionary measures during summer season in upcoming years.

Acknowledgement

The authors acknowledge the National Data Centre, India Meteorological Department, Pune for providing weather data and Central Building Research Institute, Roorkee for providing standards and codes for various locations and building architectures regarding thermal comfort and ventilation.

Disclaimer : The contents and views expressed in this study are the views of the authors and do not necessarily reflect the views of the organizations they belong to.

References

ACGIH, 2004, "TLVs and BELs. Threshold limit values for chemical substances and physical agents and biological exposure indices", *ACGIHSignature Publications*, Cincinnati, 168-176.

American Society of Heating, Refrigeration and Air-Conditioning Engineers (ASHRAE), "Heating, Ventilating, Air-Conditioning Guide No. 33", 1955.

ASHRAE, "Thermal comfort conditions", *ASHRAE standard 55*, **66**, New York, 1996.

ASHRAE, "Thermal environmental conditions for human occupancy", *ANSI/ASHRAE standards*, Atlanta, 1992.

Bell, P. A., 1981, "Physiological comfort, performance and social effects of heat stress", *Journal of Social Issues*, **37**, 71-94.

Bhattacharya, R. and Biswas, G., 2010, "Physiological stress during hot weather months over Kolkata, West Bengal", *Proceeding Biodiversity, Water Resources and Climate Change Issues*, Kalyani University, 110-115.

Bhattacharya, R., Biswas, G. Guha, R., Pal, S. and Dey, S. S., 2010, "On the variation of summer thermal stress over Kolkata from 1995 to2009", *Vayumondal*, **36**, 16-21.

Chakrabarty, K. K., 1982, "A usual cold day in Calcutta in the third week of April", *Vayumandal*, **12**, 29-31.

Chronopoulos, K., Kamoutsis, A., Matsoukis, A. and Manoli, E., 2012, “An Artificial Neural Network Model Application for the Estimation of Thermal Comfort Conditions in Mountainous Regions, Greece”, *Atmósfera*, **25**, 171-181.

Dash, S. K. and Kjellstrom, T., 2011, “Workplace heat stress in the context of rising temperature in India”, *Current Science*, **101**, 4, 496-503.

Engineering ToolBox, 2011, “Human physiology, air quality and comfort temperatures, activity and metabolic rates”,*Discomfort Index*, Available at : https://www.engineeringtoolbox.com/ discomfort-index-d_1811.html, Dec 2011.

Epstein, Y. and Moran, D. S., 2006, “Thermal comfort and heat stress indices”, *Industrial Health*, **44**, 388-398.

Fanger, P. O., 1970, “Thermal comfort”, *Danish Technical Press*, Copenhagen.

Giles, B., Balafoutis, C. and Maheras, P., 1990, “Too Hot for Comfort: The Heat waves in Greece in 1987 and 1988”, *International Journal of Biometeorology*, **34**, 2, 98-104.

Houghton, F. C. and Yaglo, C. P., 1923, “Determining Equal Comfort Lines”, *Journal of the American Society of Heating and Ventilating Engineers*, **29**, 165-176.

ISO-7730, 1984, “Moderate thermal environments- determination of the PMV and PPD indices and specification of the conditions for thermal comfort”, ISO, Geneva, 1984.

ISO-7730, 1995, “Moderate thermal environments - determination of the PMV and PPD indices and specification of the conditions for thermal comfort”, ISO, Geneva, 1995.

Jones, P. D. and Briffa, K. R., 1992, “Global surface air temperature variations during the 20th century : Part I- Spatial, temporal and seasonal details”, *Holocene*, **2**, 165-179.

Kakon, Anisha Noori, Nobuo, Mishima, Kojima, Shoichi and Yoko, Taguchi, 2010, “Assessment of Thermal Comfort in Respect to Building Height in a High-Density City in the Tropics”, *American Journal of Engineering and Applied Sciences*, **3**, 3,545-551.

Mann, M. E., Brandley, R. S. and Hughes, M. K., 1998, “Global scale temperature patterns and climate forcing over the past six centuries”, *Nature*, **392**, 165-179.

Miller, V. and Bates, G., 2007, “Hydration of outdoor workers in northwest Australia”, *Journal of Occupational Health and Safety – Australia and New Zealand*, **23**, 79-87.

National Building Code of India (NBC - 2005).

National Institute of Occupational Safety and Health (NIOSH), “Occupational Exposure to Hot Environments”, 1986.

Position Stand, Med. J. Aust, 1984, “Prevention of thermal injuries during distance running”, *American College of Sports Medicine*, 876.

Siple, P. A. and Passel, C. F., 1945, “Measurements of Dry Atmospheric Cooling in Subfreezing Temperatures”, *Proceedings of the American Philosophical Society*, **89**, 177-199.

Sohar, E., Adar, R. and Kaly, J., 1963, “Comparison of the environmental heat load in various parts of Israel”, *Bulletin of the Research Council of Israel*, **10E**, 111-115.

Steadman, R. G., 1971, “Indices of Wind-chill of Clothed Perons”, *Journal of Applied Meteorology*, **10**, 674-683.

Steadman, R. G., 1979, “The Assessment of Sultriness. Part I: A Temperature-Humidity Index Based on Human Physiology and Clothing Science”, *Journal of Applied Meteorology*, **18**, 861-885.

Suman, B. M. and Srivastava, R. K., 2007, “Insulated Roof for Energy Saving and Thermal Comfort in Buildings”, Central Building Research Institute, Roorkee.

Thom, E. C., 1959, “The Discomfort Index”, *Weatherwise*, **12**, 2, 57-61.

Toolkit, Vladimir Mikler, Albert Bicol, Beth Breisnes Hughes Condon Marler, 2008, “Passive Design”, *Ventilation Architecture*, City of Vancouver.

Unger, J., 1999, “Comparisons of urban and rural bio-climatological conditions in the case of a Central-European city”, *International Journal of Biometeorology*, **43**, 139-144.

Weiss, M. H., 1983, “Quantifying Summer Discomfort”, *Bulletin of the American Meteorological Society*, **64**, 654-655.

Wing, J. F., 1965, “Upper thermal tolerance limits for unimpaired mental performance”, *Aerospace Medicine*, **36**, 960-964.

Yaglou, C. P. and Minard, D., 1957, “Control of Heat Casualties at Military Training Centers”, *Archives of Industrial Health*, **16**, 302-305.