Chapter -2

Cold and Heat Wave Indices and Methodology

There are no universal definition of heat and cold waves. Heat and Cold wave events are anomalous situations with above (below) normal temperatures respectively. The criteria used to define how much above/below normal could differ. India Meteorological Department (IMD) uses criteria for heat and cold waves using station temperature data. Definitions of heat and cold waves based on area average or gridded temperature data are however different but very similar.

Heat waves have wide range of impacts on different sectors. Because of this, the definition of heat waves will be different for different applications. Some studies (Alexander et al. 2006, 2007; Fischer and Schar 2010; Fischer et al. 2011; Avila et al. 2012; Jiang et al. 2012; Perkin and Alexander 2013) used ETCCDI indices for heat wave analysis and these indices are not good enough to heat stress related studies. The indices like Predicted Mean Vote (PMV) and the Physiological Equivalent Temperature (PET) are used for the health related studies (Matzarakis et al. 1999; McGregor et al. 2002; Pantavou et al. 2008). Another index named Heat Index (HI) also known as apparent temperature (Steadman 1979, Steadman 1984) used for heat stress related studies in many regions (Zahid and Rasul 2009; Rajib et al. 2011; Rakib 2013; Opitz-Stapleton et al. 2016; Jaswal et al. 2017) as it combines air temperature and relative humidity.

There are some similarities across these heat wave matrices, all definitions include at least one form of temperature (maximum, minimum or average temperature) (Perkin 2015). A recent study (Perkin et al. 2012) compared the various heat wave characteristics obtained from 3 different indices (90th percentile for maximum temperature, the 90th percentile for minimum temperature, and positive extreme heat factor (EHF)) and it indicates that qualitative measurements across the indices are similar but the quantitative values are different. This implies the importance of selecting an appropriate index for the impacted region.

People residing in a place for sufficiently long time get more or less acclimatized to the normal weather conditions of that place. Human body is quite sensitive to any physiological change which takes place due to significant departure of weather conditions from normal. These definitions are designed to take the physiological changes also into account.

2.1 **Heat wave Indices.**

India Meteorological Department (IMD) considers only maximum temperatures (Tmax) for defining heat waves. They define heat wave as " if the maximum temperature of a station reaches at least 40°C or more for Plains, 37°C or more for coastal station and at least 30°C or more for Hilly region ". The detailed IMD criteria of heat waves are given below (Table 2.1).

Table 2.1

Criteria used for declaring Heat Wave by India Meteorological Department (IMD)

Nomenclature	Departure from Normal Temperature
Criteria for Heat Wave/Severe Heat Wave	
a) When normal maximum temperature of station is 40°C or less	
Normal	-1^0 C to 1^o C
Above normal	2^0C
Appreciably Above Normal	3^o C to 4^o C
Markedly above normal/Moderate Heat Wave	5^0 C to 6^o C
Severe Heat Wave	7^o C or above
b) When normal maximum temperature of station is more than 40°C (The term moderate heat wave will not be used)	

Normal	-1^0 C to 1^o C
Above normal	2^0C
Heat Wave	3^o C to 4^o C
Severe Heat Wave	More than 5^0 C
c) When normal maximum temperature of station is 45^0C or more for two days or more	
The condition may be declared as Heat Wave	

To declare a heat wave, the above criteria should be met at least in 2 stations in the meteorological sub-division for at least two consecutive days.

For defining heat waves, there are more indices used in scientific literature, especially with area averaged or gridded data. The first one is the **90th percentile threshold of maximum temperature (Tmax90)** based on a 5-day window (Rohini et al. 2016).

The second index considered is the **Excessive Heat Factor (EHF)** (Nairn and Fawcett 2013; Perkins and Alexander 2013, Rohini et al. 2016). This index is based on two excessive heat indices, namely Excess Heat (EHI_{sig}) and Heat Stress (EHIaccl). The unit of EHF is $^oC^2$.

The Excess heat represents unusually high heat arising from a daytime temperature that is not sufficiently discharged overnight due to unusually high overnight temperatures. The Daily Mean Temperature (DMT) averaged over a three-day period is compared against a climate reference value to characterize this index. The unit of EHI_{sig} is ^oC.

The Excess Heat Index is calculated as

$$EHI_{\mathrm{sig}} = \frac{(\mathrm{T_i} + \mathrm{T_{i-1}} + \mathrm{T_{i-2}})}{3} - \mathrm{T_{95}}$$

where T_{95} is the 95^{th} percentile of DMT (T_i) for the climate reference period of 1961-

1990. The daily mean temperature is the average of maximum and minimum temperatures as defined by

$$T = \frac{(T_{max} \; + \; T_{min})}{2}$$

The heat stress which arises from a period where the temperature is warmer, on average than the recent past. Maximum and subsequent minimum temperatures averaged over a three-day period and the previous 30 days are compared to characterize the heat stress. This is expressed as a short term (acclimatization) temperature anomaly. The unit of EHIaccl is °C. The heat stress is defined as

$$EHI_{accl} = \frac{(T_i \; + T_{i-1} + T_{i-2})}{3} - \frac{(T_{i-3} + \ldots + T_{i-32})}{30}$$

where Ti is the DMT on i^{th} day.

The Excess Heat Factor (EHF) is defined as follows:

$$EHF = EHF_{sig} \times \max(1, EHI_{accl})$$

A heat wave is considered when the value of EHF is positive, and the daily climatological Tmax is greater than 35°C for consecutive three days or more. These criteria were selected carefully to choose the heat wave events occurring over the Indian sub-continent. The 35 °C criterion was used to restrict such events occurring over the hilly regions.

The significant associations between high temperature and mortality and morbidity have been studied in many parts of the world (Heo et al. 2019). Therefore, understanding associations between heat waves and various health outcomes is essential to prevent the current and future burden of heat impacts on human health. In many countries, the Heat-Health Warning Systems (HHWS) adopted thermal comfort indices, which quantify a combined effect of a series of meteorological factors (air temperature, humidity and wind) on perceived temperature, to represent the actual human thermal situation during heat waves. The effectiveness of a HHWS using a thermal index (including ambient temperature) depends on how properly the heat wave definition can relate heat wave periods and related health problems, and choice of which thermal index to use is a critical public health issue for policy (Heo et al. 2019).

There are such indices to define and monitor heat waves in the context of its health impacts. Some of such indices are Heat Index (HI) and Wet Bulb Global Temperature (WBGT) (Heo et al. 2019). HI attempts to represent the human perceived temperatures by the impact of humidity. HI is an index that combines air temperature and relative humidity to determine a human-perceived apparent temperature to determine how hot it actually feels. It is a measure of the stress placed on humans by elevated levels of atmospheric temperature and moisture. It implies that an extended period of unusually high heat stress may have adverse health consequences for the affected population. The computation of HI is based upon the formula given by Steadman (1979) where the author has quantified the physiological effects of high heat and humidity on human being. The variables used in the formula include heat generation and loss, fabric resistance, vapour pressure, wind speed, solar radiation, terrestrial radiation, proportion of body clothed and other factors (Steadman, 1984). The Steadman's equation was further modified by Rothfusz (1990) by performing multiple regression analysis on the data from Steadman's table. Jaswal et al. (2017) used this index to study long term trends using IMD station data. More details of the index are available in Jaswal et al. (2017).

The equation used by the National Weather Service of the National Oceanographic and Atmospheric Administration (NOAA) is given below.

$$\mathbf{HI = -42.379 + 2.04901523*T + 10.14333127*R - 0.22475541*T*R - 6.83783\times10^{-3}*T^2 - 5.481717\times10^{-2}*R^2 + 1.22874\times10^{-3}*T^2*R + 8.5282\times10^{-4}*T*R^2 - 1.99\times10^{-6}*T^2*R^2}$$

where, T= Ambient dry bulb temperature (^{0}F) and

R= Relative Humidity (Integer percentage).

Wet-bulb globe temperature (WBGT) is one of the most commonly used indices by many organizations since the 1960s. This index was originally invented in the 1950s in efforts to lower the risk of heat disorders during the training of the US Army and Marine troops. Since that time, WBGT has been applied in other settings, and is widely used for the evaluation of occupational heat stress exposure (Budd 2008; Alfano et al., 2014). WBGT is a weighted average of dry bulb (air) temperature, natural wet-bulb temperature and black globe temperature. Black globe temperature is a function of radiant heat, temperature, and wind while natural wet blub temperature measures the amount of cooling by humidity and wind (Budd, 2008). By incorporating black globe temperature, WBGT considers radiation effect whereas many other simplified thermal comfort indices do not. In sunny conditions, the weighting coefficients are 0.7, 0.2, and 0.1 for natural wet temperature, globe temperature, and dry-bulb temperature, respectively. At other times, the weighting coefficients are 0.7 and 0.3 for natural wet temperature and dry-bulb temperature, respectively, while the globe temperature is not considered in the calculation. Until recently, several approximation formulas of WBGT using readily available meteorological data (e.g., temperature, humidity, wind, and radiation) have been suggested for practical use as the original components for calculating WBGT are not standard meteorological monitoring data. Further details of WBGT are available in Heo et al. (2019).

The health risk assessment is subject to the designated heat wave periods, and more extreme heat wave definitions with the higher thresholds generally identify fewer heat waves of shorter duration and higher intensity. Thus, the definitions with higher thresholds, which reflect the most intense heat waves but also lead to the shortest heat wave periods and fewer designated heat waves, may not necessarily result in the strongest or the most significant health effect estimate.

Effectiveness of a HHWS to prevent health risks from heat exposure is subject to the precision of weather forecast. Temperature tends to be more accurately forecast than other weather components, which may hinder the use of thermal indices that use other weather components for heat wave warnings. Currently, historical forecast data are available through an open data source for everywhere for components including temperature, humidity and wind speed.

Russo et al. (2014) introduced another index for heat wave activity, namely the Heat Wave Magnitude Index (HWMI). The computation of HWMI involves multiple stages that begin with the computation of daily threshold (90^{th} percentile) with reference to the baseline period (Das and Umamahesh, 2022). Next, the selection of heat wave events is carried out according to the minimum three consecutive days Tmax above the threshold. The selected heat wave is then grouped into sub-heat waves, where each sub-heat wave is a heat wave of three consecutive days. More details of this index are available in Russo et al. (2014).

2.2 **Cold Wave Indices**

Based on station temperature data, India Meteorological Department (IMD) uses the following definition of cold waves over India, as shown in Table-2.2

Table 2.2

Criteria for Cold Wave/Severe Cold Wave

Nomenclature	Departure from Normal Temperature
Criteria for Cold Wave/Severe Cold Wave	
a) When normal minimum temperature of station is 10^{o}C or more	
Normal	-1^{0} C to 1^{o} C
Below normal	-2^{0}C
Appreciably Below Normal	-3^{o} C to -4^{o} C
Markedly Below normal/Moderate Cold Wave	-5^{0} C to -6^{o} C
Severe Cold Wave	-7^{o} C or above
b) When normal maximum temperature of station is less than 10^{0}C (The term	

moderate cold wave will not be used)	
Normal	-1^{0} C to 1^{o} C
Below normal	-2^{0}C
Cold Wave	-3^{o} C to -4^{o} C
Severe Cold Wave	-5^{o} C or less

Ratnam et al. (2016 b) considered cold wave events over India when the normalized area average Tmin anomalies are less than one standard deviation for four or more days. Some researchers used the 10^{th} percentile criteria for defining cold waves.

2.3 Temperature data

For studying heat and cold waves over India, researchers generally make use of IMD station data or IMD Gridded daily temperature data set. The IMD gridded temperature data set was prepared indigenously by IMD researchers in 2009 (Srivastava et al. 2009). The details of the IMD gridded temperature data set are given below.

IMD maintains around 550 surface observatories in the country, where daily surface air temperature observations (maximum and minimum) are taken. These data are compiled, digitized, quality controlled and archived at the National Data Centre (NDC) of IMD. However, daily data from 1969 onwards only are digitized and archived at NDC. Later this data set was updated with the daily temperature data from 1961. From the list of stations for which daily data are available, only those stations which have minimum 10 years of data, at least for 300 days in a year during the period 1971–2000, were selected for further analysis. The data were subjected to basic quality checks like rejecting values, greater than exceeding known extreme values, minimum temperature greater than maximum temperature, same temperature values for many consecutive days etc. Unusual high values were flagged by putting a filter which allowed values only in the range mean±(1.76+0.8 N) standard deviation for further data analysis.

The interpolation was used a modified version of the Shepard's angular distance weighting algorithm for the present analysis. In order to avoid biases in the gridding, daily anomalies were used instead of the absolute values. For this purpose, climatological normal of maximum and minimum temperatures for the period 1971–2000 was calculated for each station. The daily anomalies were calculated as the difference of each daily temperature from its daily normal values. The present interpolation method requires an under-standing of the spatial correlation structure of the station data. Therefore, the interstation correlations were calculated to determine the distances over which observed temperature anomalies are related. For each month, for each pair of 395 stations lying within 2000 km, correlation was calculated and then binned according to their separation over intervals of 100 km. The mean correlation was estimated over each 100-km interval and a two-degree polynomial function was fitted to these values. For interpolating the station data, we have to define the radius of influence. This was estimated as the correlation length scale (CLS), which is defined as the distance at which the mean correlation, represented by the fitted function, fell below 1/e.

More details of this data set are available in Srivastava et al. (2009). This data set is being used very extensively by researchers worldwide.