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ARTICLE

Study of Cold Wave and Cold Stress in the Four Metropolitan Cities of India for the Period 1985–2020

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ABSTRACT

Cold waves, cold nights and warm nights are major threats to human beings during winter due to climate change in different parts of India. The analysis of these has been studied for four major metropolitan cities (Chennai, Mumbai, Kolkata, and Delhi) of India during the period 1985–2020. The authors have used the 90th and 10th percentile threshold to identify the cold nights, warm nights and cold waves during the winter season. The degree of discomfort and cold stress category are identified using the Humidity Index (HD), and the Universal Thermal Climate Index (UTCI). The results indicate that the cold night event in Mumbai is ~0.36% higher than both Kolkata and Chennai cities but it is ~0.42% higher than Delhi. The number of cold wave events in Delhi is 53.5% higher than in Kolkata during the period of the study. It is also observed from the study of UTCI that the possibility of slight cold stress in the Delhi region during cold nights is 59.36% more than in other metropolitan cities. The study indicates that in the winter season, the climate of Delhi is more dynamic but for Kolkata it is relatively less dynamic.

Keywords: Thermal stress; Cold wave; Humidity index (HD); Universal Thermal Climate Index (UTCI)

1. Introduction

The effect of cold waves, cold nights and warm nights during winter badly affects human health. In northern India, the cold weather usually occurs from November to February. During the winter

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season, surface and near surface air temperatures significantly fall below the normal threshold based on climatology and last for two or more consecutive days as cold waves [1]. The appearance of westerly disturbances is frequently linked to the cold wave conditions across northern India [2–5]. During this period, the wind in the lower levels of the atmosphere is primarily from northern latitudes and the prevailing winds during this period are mostly dry and cold. Along with that, these winds are also responsible for occasionally cold and thus bring the condition of cold spells. These cold spells might gradually move from one region to another and are considered to be severe cold wave, when the night time temperature falls by at least 8 °C from its daily average. In this period, people experience significant cold stress due to cold waves [2,5,6].

In January 2016, a rare cold wave traversed through the majority of East Asia, setting records for cold temperatures and causing significant snowstorms throughout various zones [7]. Another unusual cold wave early in January 2021 invaded East Asia and North America resulting in historically intense low temperatures across wide regions. This study demonstrated that a significant stratospheric abrupt warming (SSW) occurrence at the start of January 2021 had a significant impact on this extremely cold wave. This significant SSW episode emerged on 2 January 2021 and caused the stratospheric polar vortex to shift to the eastern side of Asia [8]. Throughout the winter months of 2020/2021 between December 28th and 31st, 2020 and between January 5th and 8th, and January 14th and 17th, 2021, there were three instances of cold waves across the northern and eastern regions of China which led to the manifestation of severe cold climatic conditions. The historic freezing temperatures in central and eastern China during the initial winter months of 2020–2021 also sparked considerable panic in public [9–14]. Significant issues arise due to cold and heat waves in the sector of electricity generation [1]. There have been multiple and frequent instances of occurrences of severe, cold, and snowy winters over the parts of North America and Eurasia such as the one in 2009/2010, 2010/2011, and 2013/2014 [15,16]. The effect of extreme cold waves adversely affects human health and certain sections of people are more prone to cold-related deaths than others, controlled by factors such as old age, and chronic illness aggravates the chances of death due to a potential cold [17]. During winter, thermal sensations that are caused by cold stress are also affected school children [18]. Europe has experienced warmer climates in the late 20th and early 21st centuries than the previous centuries [19–21]. The reduction of thermal energy to the surroundings is called cold stress and under such circumstances, the body's first response is to reduce blood flow through the skin in order to conserve heat. The other factors that are also contributing to cold stress are low temperatures, wind, and moisture [22].

The trend analysis of cold events [23] indicating the cold, very cold and extremely cold nights has shown a declining pattern for the month of December, whereas for the North India in the months of January and February, a mixed trend has been observed with a significant decrease. The recent study [24] showed that during 2001–2010, cold waves in the winter season increased over the northern part of India (eastern Uttar Pradesh, Khiri, Lucknow, Baharaich, Gorakhpur, Allahabad). An increase in the intensity and frequency of cold waves has been observed in multiple locations in India in the recent period [25–27]. They showed that the Jammu and Kashmir regions experience the coldest waves, followed by Rajasthan and Uttar Pradesh. Even though Gujarat and Maharashtra are located in a more southern region, it is possible to discern that the average frequency of cold waves in those states is approximately one each year [5]. Cold wave-induced severe storm and hurricane surges have a significant impact on nautical engineering, maritime operations, and the coastal industry [28]. Chennai experienced an increase of 1.0 °C in the average *Tmin* from 1951–2010 and a considerable increase during the winter seasons. The changes of the difference between maximum temperature (T_{max}) and minimum temperature (T_{min}) affect human health [29]. However, the spatio-temporal changes in the minimum temperature were reported to be more dynamic than the maximum temperature over India [26,30] reported that India witnessed a rise of 0.4 °C/century during the 20th century.

Generally, cold wave impacts the region 20°N of the equator; however, due to the association of large amplitude troughs; states like Maharashtra and Karnataka have also reported cold wave events in the recent period [5]. The current era of Global warming has given impetus to several scientists and researchers for the study of extreme events such as heat waves, cold waves, and other temperature extremes [31,32]. Recently, Kumar et al. [33] investigated the heat stress and heat waves in the four metropolitan cities of India and concluded that the number of heatwave events in the Delhi region was significantly higher as compared to the other three metropolitan cities. They also concluded that the risk of extreme heat stress and dangerous heat stress was found to be higher in Chennai than in the metropolitan cities of India.

Previous research has demonstrated that cold waves are primarily caused by the movement of cold air from northern latitudes into the north-western regions of India [34]. Western disturbances, which carry cold air from northern latitudes into India, are characterized by well-marked troughs that move eastward and are in the upper tropospheric westerlies north of 20°N. These disturbances are frequently observed extending to the lower troposphere [34,35]. The months of December and January are the months that see the highest incidence of cold wave events and the mortality that is associated with them is primarily observed in the northwest and central northeast regions of India [36]. During the northern winter, when the occurrence of western disturbances takes place, the general circulation tends to shift towards the equator [37]. A decreasing trend of minimum temperature is generally observed in the states of Odisha, Chhattisgarh, parts of Andhra Pradesh and Karnataka which are also the regions where there is an increasing trend of cold wave events [37]. However, there are no studies related to cold waves, cold nights and warm nights during winter are not studied yet over the major metropolitan cities in India, although the land use, land cover and population density over these regions are changing rapidly. The selection of these regions was primarily motivated by the fact that Kolkata, Mumbai, and Chennai are situated near the coastal regions and are subject to significant influence from the ocean, which in turn influences the climate of these areas. Chennai, which is located on the eastern coast and influenced by north-easterly winds in winter from November to February. The capital city of Delhi has a typical tropical climate, with winters that are extremely cold and can sometimes drop to temperatures as low as 2 degrees Celsius and often experiences cold stress.

This paper investigates the pattern and the trend of temperature change in four metropolitan cities of India using 36 years of datasets from 1985 to 2020 during the winter period. This study also aims to quantify the cold wave, cold stress, and cold comfort categories during winter using Humidity-index (HD) and Universal Thermal Climate Indices (UTCI). This study will be beneficial for future prediction and modeling of cold wave and cold stress events. It will also be beneficial to aid the planning and management of major metropolitan cities in India.

2. Study area

Four metropolitan cities with varied climatic conditions, namely Delhi, Kolkata, Chennai, and Mumbai (**Figure 1**) are considered for this study. The diverse climatic conditions are primarily due to the location and other factors that influence the climatic conditions [38]. Kolkata, Mumbai, and Chennai are near the coastal regions and have a significant oceanic influence on their climatic condition. Chennai and Mumbai lie on the eastern and western coasts of the Indian sub-continent [39]. Chennai has a dry summer season where winter starts from November and lasts until February, with maximum and minimum temperatures of 28.9 °C and 21.9 °C, respectively [39]. In Mumbai, January is the coldest month, with air temperature slightly above 24 °C [40]. Kolkata is subject to a tropical wet-and-dry climate, having a short winter spell. The seasonally low temperatures range between 9 to 11 °C [41]. Delhi, the capital city of India, has a typical tropical climate where winters are extremely cold, with temperatures going down to 2 °C or even less in extreme cases [42]. In terms of population, Chennai has a high population density in India, having a population density of 26903 per square kilometer. In contrast, Delhi, Mumbai, and Kolkata have 11,297, 20,038, and 24,252 persons per square kilometer, respectively [43]. It is observed that in recent periods the daily temperature difference has increased in the southern India, northeastern part of India, and Jammu and Kashmir regions. However, Delhi, Punjab, some parts of Rajasthan, southern part of Gujrat and west Bengal regions show a declining trend.

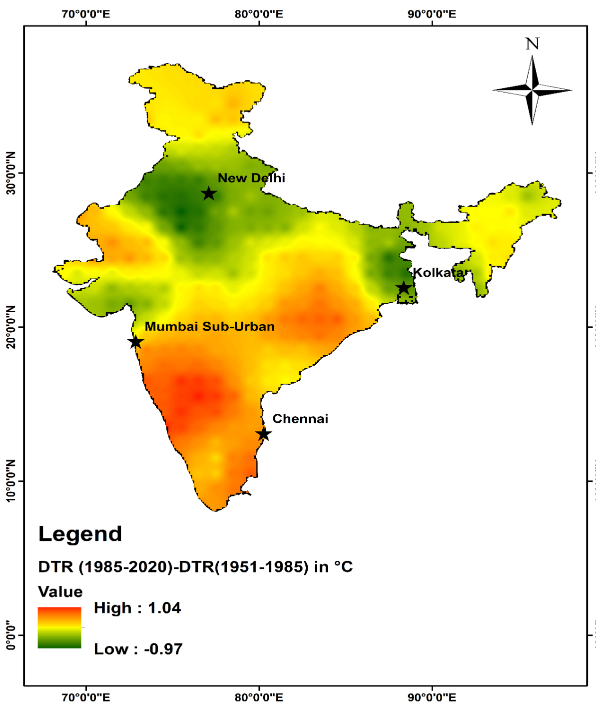


Figure 1. Locations of the cities of study regions on the India map. Color shading showing the changes of DTR values after 1985.

3. Data and methodology

3.1 Data

We have used the climatic parameters namely, temperature, relative humidity, solar radiance, and wind speed [33,44,45] in this study. The datasets were collected from 1985 to 2020 the climate forecast system reanalysis (CFSR) of global weather data for soil and water assessment tools (https://swat.tamu.edu/data/cfsr) and modern-era retrospective analysis for research and applications, version 2 (MEERA-2) (https://gmao.gsfc.nasa.gov/reanalysis/MERRA-2/), depending upon the availability of the datasets. The CFSR data are produced using a cutting-edge data-assimilation technique with a horizontal resolution of ~38 km and a time step of 1 hour [46], while the output collections of MERRA-2 are on the regular grid of 0.625° × 0.5° [47]. Generally, in India, the cold wave and cold stress occur in the winter seasons. Hence, we have selected the months of November, December, January, and February for our analysis of the chosen study area.

3.2 Methods

Climatic variables trend analysis

We have performed the Mann-Kendall test [48,49] to analyze trends of climatic variables time series datasets in this study. Mann-Kendall test is a non-parametric test with no prerequisite conditions for the normally distributed data [50]. This test is grounded on a null hypothesis (H_0), indicating that there is no trend and the data are independent as well as randomly ordered. This is verified against the alternative hypothesis (H_a), which presumes that there is a trend [51]. The basic formulation of the Mann-Kendall test is in Equation (1) and as follows:

$$S = \sum_{j=1}^{m-1} \sum_{k=j+1}^{m} \text{sgn}\,(X_k - X_j) \tag{1}$$

where, $sgn(X_k - X_j) = \begin{cases} +1, \text{ if } (X_k - X_j) > 0 \\ 0, \text{if } (X_k - X_j) = 0 \\ -1, \text{if } (X_k - X_j) < 0 \end{cases}$ and

m is the length of data or sample and $j = 1, 2, 3..., m–1$ and $k = j+1,\ldots\ldots, m$. If $m > 10$, then S will become approximately normal distribution. If the S value is positive, it indicates an upward trend, whereas, a negative value indicates a downward trend. The variance is calculated to obtain the Z value is in Equation (2) and is,

$$Variance\ (V) = \frac{[m\,(m-1)(2m+5) - \sum_t f_t(f_t-1)(2f_t+5)]}{18} \tag{2}$$

where, the rank of the tied group and f_t is the frequency at which the rank is t. The equation calculates the normal Z test statistic is given in Equation (3) as,

$$Z = \begin{bmatrix} \frac{S-1}{\sqrt{\text{variance of S}}}, S > 0 \\ 0, S = 0 \\ \frac{S+1}{\sqrt{\text{variance of S}}}, S < 0 \end{bmatrix} \quad (3)$$

We have also determined the regression equations and slope. A negative slope indicates a downward trend, whereas, a positive value indicates an upward trend.

Evaluation of cold wave

A percentile-based methodology has been used to identify cold and warm nights [52], whereas, the cold wave is determined based on IMD criterion (https://img.indiaonline.in/weather/Weather-Glossary.pdf). The climatic situation is given by,

i) Cold night, if T_{min} < 10th percentile

ii) Warm night, if T_{min} > 90th percentile

iii) Cold wave, if $T_{min} < 10\ °C$ and T_{min} is –4.5 °C or –5 °C less than normal temperature. Here, the normal temperature is the average temperature of a station for the past 30 years.

The intensity of warm night, cold night and cold waves are calculated based on Cumulative Exceedance (CumExc) and Absolute Exceedance (AbsExc), which is comprehensively discussed [33] and can be expressed during cold night or cold waves as in Equation (4),

$$CumExc = \sum_{i=1}^{n} \Delta T_i$$
$$AbsExc = \pm\ (max\ [\Delta T_i]) \quad (4)$$

where, $\Delta T_i = (T_{min}$—*percentile (or mean) of* $T_{min})$ for the i^{th} day and percentile indicates as per the definition mentioned above. The plus and minus sign in the above equation indicates for warm and cold nights respectively.

The daily temperature range (DTR) is calculated following the Equation (5) and is given by,

$$DTR = T_{max} - T_{min} \quad (5)$$

Evaluation of cold stress

Cold stress evaluation was done using Humidity-index (*HD*) and Universal Thermal Climate Index (*UTCI*) following [33] the degree of discomfort and stress category due to cold are shown in **Table 1**.

Table 1. Thermal discomfort and thermal stress category.

Humidity index (HD)	**Degree of comfort**
>45	Dangerous – heat stroke possible
40–45	Great discomfort-avoid exertion
30–39	Some discomfort
≤29	No discomfort
UTCI (°C)	**Stress Category**
>46	Extreme heat stress
38–46	Very strong heat stress
32–38	Strong heat stress
26–32	Moderate heat stress
9–26	No thermal stress
0–9	Slight cold stress
–13–0	Moderate cold stress
–27—13	Strong cold stress
–40—27	Very strong cold stress
<–40	Extreme cold stress

Source: Masterson et al. [53] and Błażejczyk et al. [54].

4. Results

4.1 Trend analysis

We applied the Mann-Kendall test for the winter seasons (November to February) average of T_{max}, T_{min} (**Figure 2**) and their difference as *DTR* (**Figure 3**) to understand the trend in four metropolitan cities i.e., Kolkata, Chennai, Delhi, and Mumbai in the recent period from 1985 to 2020. To understand the changes in the above cities compared to the period prior to 1985, we have also conducted a similar test for the period from 1951 to 1985 shown in the upper panels of the figures (**Figures 2a, 2c** and **Figure 3a**). A brief overview of the trend analysis has been presented in **Table S1** and **Table S2** for the above two time periods.

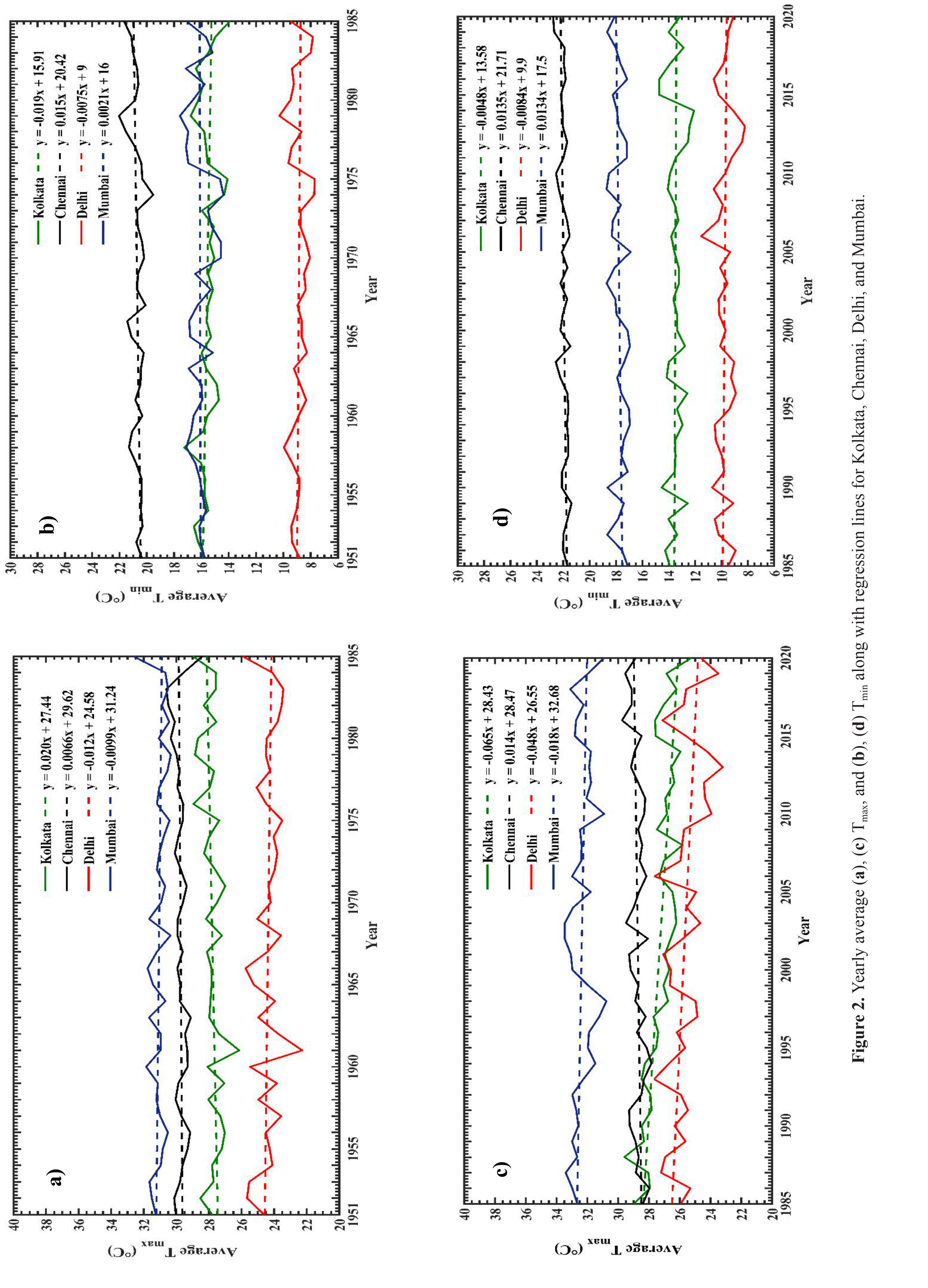


Figure 2. Yearly average (**a**), (**c**) T_{max}, and (**b**), (**d**) T_{min} along with regression lines for Kolkata, Chennai, Delhi, and Mumbai.

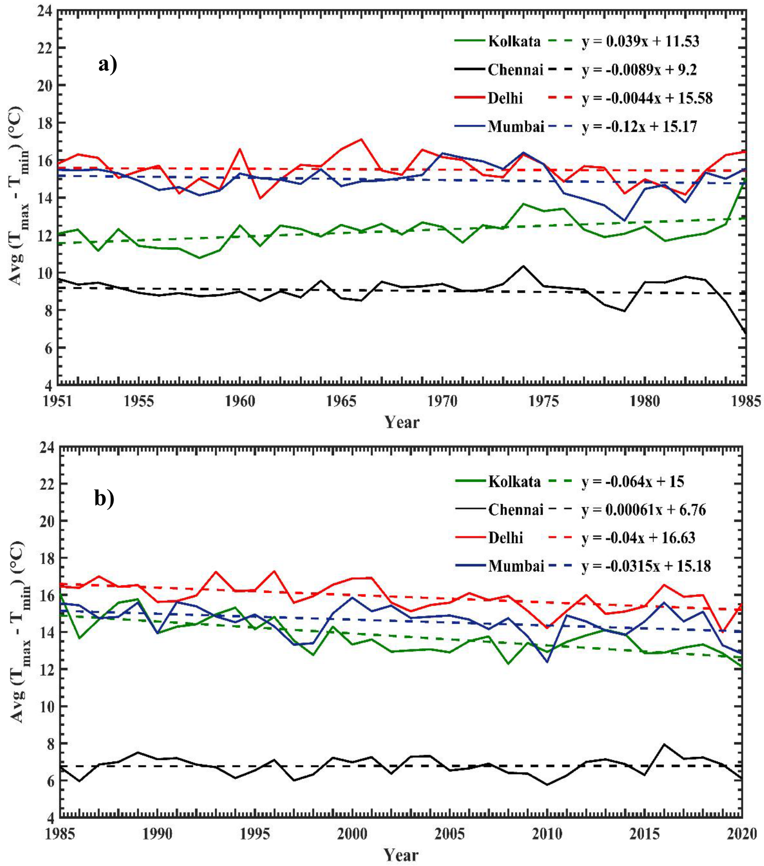


Figure 3. Yearly Average DTR with regression line for Kolkata, Chennai, Delhi, and Mumbai. Upper panel is for the period 1951 to 1985 and lower panel is for the period 1985 to 2020.

Using the Mann-Kendall test, we found that the Z value for T_{max} and DTR in winter for Kolkata is lower than $Z_{critical}$ (At α= 5%, $Z_{critical}$ = –1.65 for the left-hand test). Hence, it is rejecting the null hypothesis and accepting alternative hypothesis (H_1) at = 5%. The probability of accepting the null hypothesis is 0.00000182 and 0.00000948 for T_{max} and DTR respectively (**Table S1**) and the rejecting of the null hypothesis is 0.9999. Since the possibility of rejecting the null hypothesis is more significant than accepted, it indicates the decreasing trends of T_{max} and DTR for the period of the study, but for T_{min} at α = 5%, the trend is insignificant or negligible. A decreasing trend of DTR reveals that the difference between day and night temperature decreases, directly indicating that winter feeling of coldness decreases. A regression line presented in **Figures 2 and 3** also depicts similar trends for the winter season in the Kolkata region, indicating that the rate of decrease in annual average maximum, and minimum temperatures, and their difference, DTR for the winter season are 0.065, 0.0048, and 0.064 signifying that the rate of the feeling of coldness in winter is 0.064 (**Figures 2 and 3**) per year.

For Chennai, the Mann-Kendall test shows that the Z value for T_{max} and T_{min} during winter is more significant than $Z_{critical}$ (at α = 5% $Z_{critical}$ = 1.65 for the right-hand test). The accepted alternative hypothesis H_1 at α = 5%, and the probability of accepting and rejecting the null hypothesis is shown in **Table S1**. Therefore, it may be concluded that the trend of T_{max} and T_{min} is upward during this period, but for DTR, no upward or downward trend can be seen for α = 5% (**Table S1**). The result of linear regression for Chennai can be seen in **Figures 2 and 3** for the winter season. The results indicate that the rate of increase in annual average maximum temperature and average yearly minimum temperature and their difference are 0.014, 0.0135, and 0.00061, (**Figures 2b, 2d and 3b**) respectively, which signifies that the rate of felling of the increases of coldness is 0.00061 per year.

For the capital city of India, Delhi has the Z value of T_{max}, and DTR in winter is less than $Z_{critical}$ (at α = 5% $Z_{critical}$ = –1.65 for the left-hand test). The accepted alternative hypothesis H_1 at α = 5%, and the probability of accepting and rejecting the null hypothesis is mentioned in **Table S2**. The values reveal that the T_{max}, and DTR show a downward trend during this period, whereas, α = 5%, the T_{min} shows no trend. The linear regression for the Delhi region shows that the rate of decrease in annual average maximum temperature and average yearly minimum temperature and their difference in the winter season are 0.048, 0.0084, and 0.04 (**Figures 2b, 2d and 3b**). These results indicate that the rate of the decrease of the feeling of coldness is 0.04 per year.

The financial city of India, Mumbai, has a Z value for T_{max}, and DTR in winter is less than $Z_{critical}$ (at α = 5% $Z_{critical}$ = –1.65 for the left-hand test). The accepted alternative hypothesis H_1 at α = 5% and the probability of accepting and rejecting the null hypothesis are presented in **Table S1**. Hence, from the Mann-Kendall test, we can conclude that the trend of T_{max} and DTR is downward during this period; in contrast, for T_{min} at α = 5% upward trend can be observed. The rate of decreasing annual average maximum temperature, increasing average yearly minimum temperature, and decreasing their difference for the winter season are 0.018, 0.0134, and 0.0315. These values have been predicted using the linear regression mentioned in **Figures 2b, 2d and 3b**, which finally indicates the decrease of the feeling of the coldness in winter at the rate of 0.0315 per year for Mumbai city.

The 10th and 90th percentile of T_{min} base thresholds have been used to analyze cold and warm nights (**Figure 4**) and are also presented for the period from 1985 to 2020. Cold wave events arranged in terms of CumExc that are observed only for the Kolkata and Delhi cities are shown in **Table S11** and **Table S12** respectively. The 10th and 90th percentiles of T_{min} thresholds for Kolkata city vary from 6.93 to 16.38 (**Figure 4a**) and 13.31 to 21.9 (**Figure 4b**). The 10th and 90th percentiles of T_{min} thresholds for Chennai city vary from 19.01 and 23.21 to 22.26 and 25.41 (**Figure 4**) respectively. The percentile-based threshold shows that the 10th and 90th percentiles of T_{min} for Delhi region are varying from 3.02 to 13.25 and 9.02 to 17.98 (**Figure 4**). The 10th and 90th percentiles of T_{min} thresholds for Mumbai city vary from 13.23 to 17.32 and 17.37 to 23.3 (**Figure 4**).

The winter season from 1985 to 2020 witnessed notable warm night events and cold night events across Kolkata (**Figure 5a**), Chennai (**Figure 5b**), Delhi (**Figure 5c**), and Mumbai (**Figure 5d**). The figure also illustrates a detailed ranking of warm night events and cold night events in the four cities based on their cumulative exceedance (CumExc in °C) and the absolute exceedance (AbsExc in °C). From **Table S3**, we observe that the year 2012 has the maximum number of the cold night whereas the year 1988 has a minimum. Similarly, the number of warm nights is maximum in 2015 and minimum in 2014 (**Table S4**). It can be noted that for Kolkata region during the year 2015 experiences the most significant with 22 warm nights contributing to a CumExc of 43.58 °C, and an AbsExc peaking at 5.14 °C, indicating severity in warm nights (**Figure 5a**). During 2010, Kolkata experienced 20 warm nights (**Table S4**) and a CumExc of 28.81 °C, whereas, for the year 2016 has recorded the highest number of warm nights (27), with a slightly lower CumExc of 27.10 °C compared to the year 2015. The characteristics of cold night events in Kolkata, for the year 2012, are notable for its 33 cold nights (**Table S3**), resulting in a CumExc of –39.44 °C and an AbsExc of –2.74 °C, signifying cold conditions. Following closely one can observe that the years 1996 and 2008 are characterized by 27 and 15 cold nights respectively, with corresponding CumExc values of -35.18 °C and –24.87 °C.

Similarly for Chennai, in **Figure 5b** during the year 2019 emerges as the warmest nights (31) contributing to a CumExc of 14.65 °C and an AbsExc of 1.64 °C. The maximum number of cold nights were observed in 1989, 1999, and 2006 having 22 cold nights, whereas the minimum number of cold nights were observed in 1998 and 2020 (**Table S5**). For warm nights, the maximum was reported in 2019,

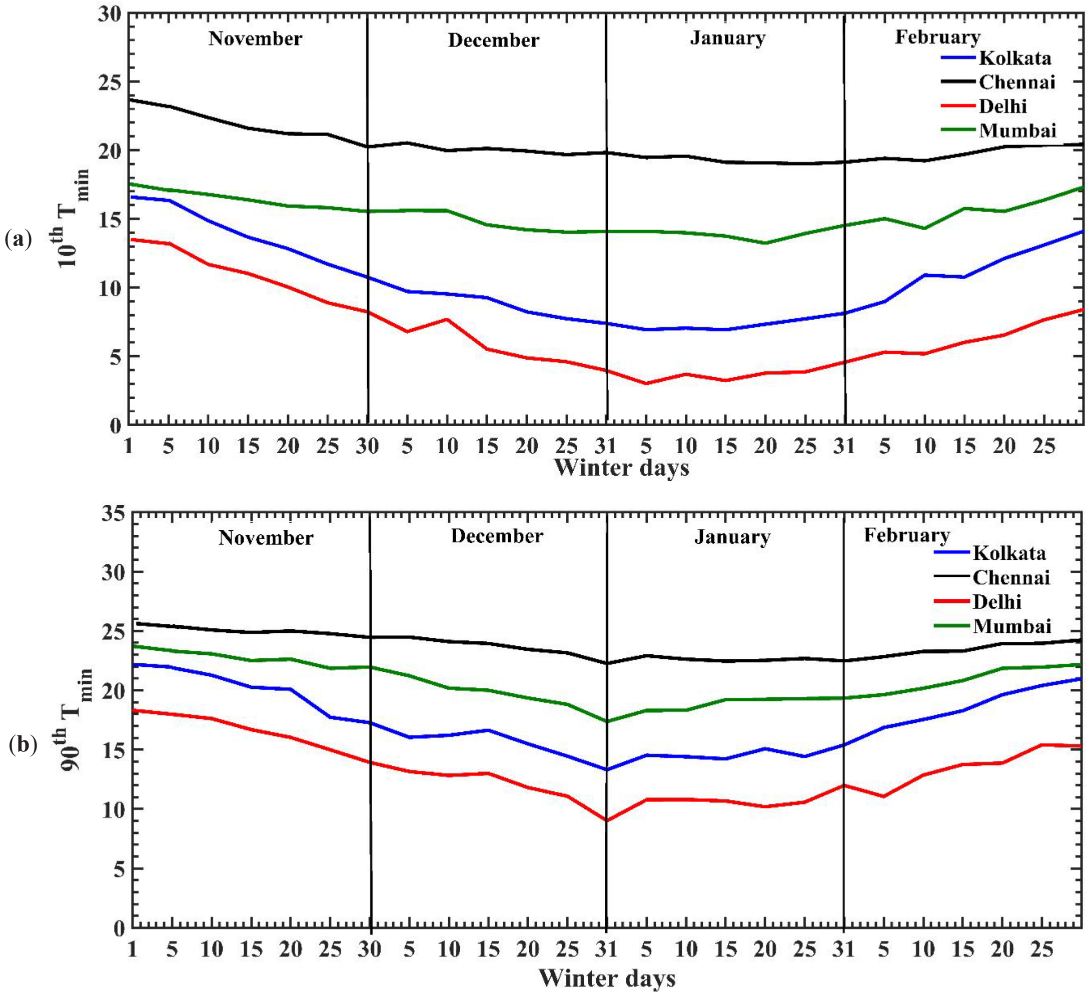


Figure 4. (**a**) 10th and (**b**) 90th percentile of T_{min} (5 days window) for the reference period (1985–2020) of the four metropolitan cities for the four winter months of our study.

and the minimum number was noticed in 1992, 1995, and 2006 (**Table S6**). Following closely are the years 2020 and 1997, which also recorded high numbers of warm nights, with 29 and 27 nights respectively (**Table S6**), and notable CumExc values. In contrast, the ranking of cold night events in Chennai during the same period highlights varying degrees of cold intensity over the years. Topping the list is the year 2012, notable for its 18 cold nights contributing to a CumExc of –19.10 °C and an AbsExc of –3.14 °C, indicative of cold night conditions. Following closely are years like 1989 and 2006, characterized by 22 cold nights respectively (**Table S5**), with corresponding lower CumExc values of –14.51 °C and –14.40 °C demonstrating fluctuations in the intensity and frequency of cold night events.

Whereas, in **Figure 5c** for Delhi, the data reveal notable years such as 2006 and 1990, which top the list with high CumExc values of 67.76 °C and 32.97 °C respectively holding 35 and 22 warm nights. The maximum and the minimum number of cold nights were observed in 2013 and 2016 (**Table S7**), while the maximum and the minimum number of warm nights were in 2006 and 2012 (**Table S8**). Conversely, the consecutive years like 2012 and 1986 exhibited lower CumExc value. Topping the list is the year 2013, notable for its 29 cold nights contributing to a CumExc of –41.64 °C and an AbsExc of –3.97 °C, indicative of cold night conditions. Following closely are years like 1996 and 2019, characterized by substantial numbers of cold nights and notable CumExc values (**Table S7**).

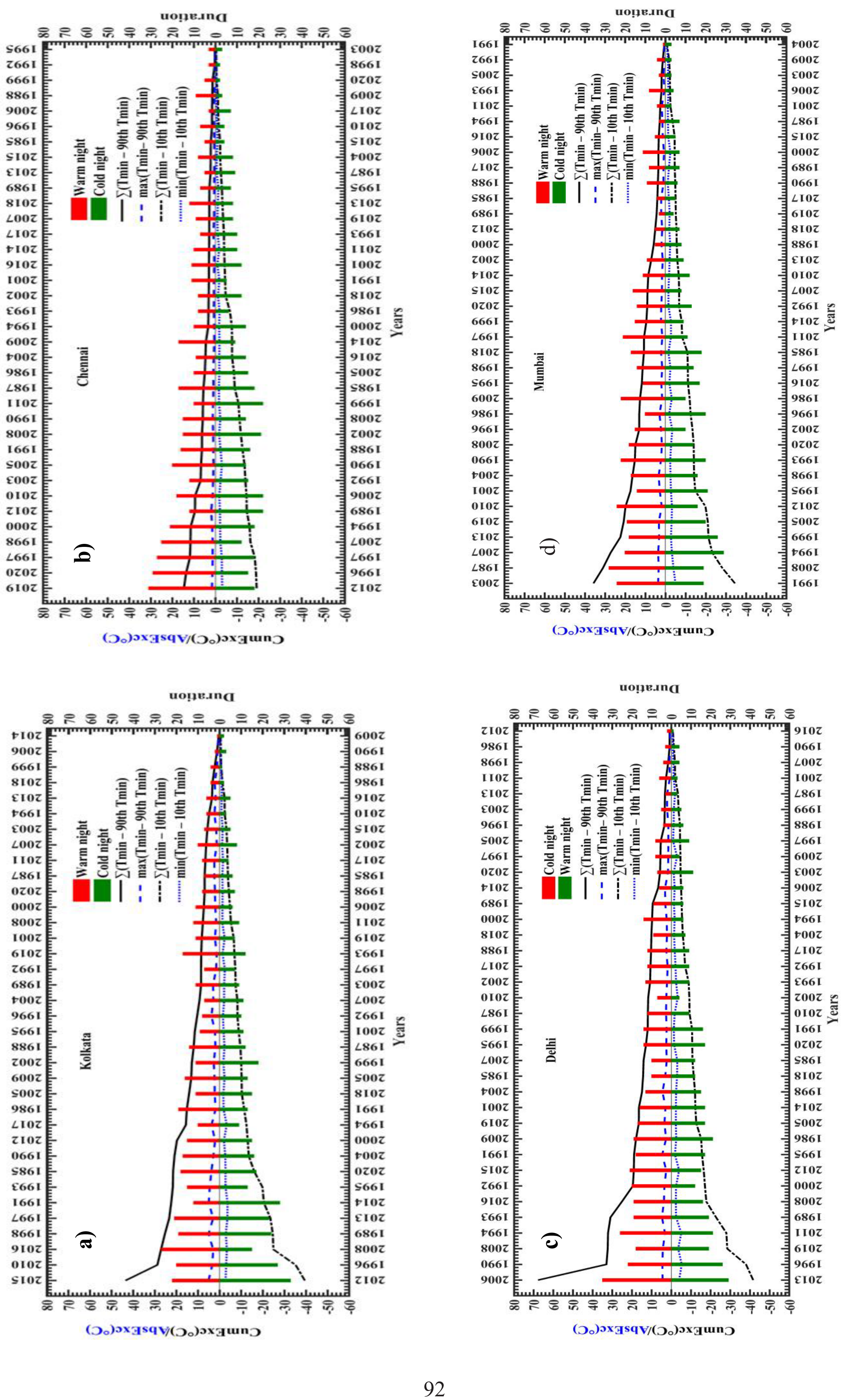


Figure 5. CumExc, (arrange from highest to lowest) and AbsExc during (a) cold and warm night events during 1985 to 2020 for **a**) Kolkata, **b**) Chennai, **c**) Delhi, and **d**) Mumbai.

For Mumbai as depicted in **Figure 5d**, the notable years like 2003 and 1987 top the list with significant CumExc values of 35.80 °C and 31.09 °C respectively. In 1994 the maximum number of cold nights was observed, while the minimum number was reported in 2001, 2003, 2004, and 2009 (**Table S9**). In contrast, the maximum number of warm nights was observed in 1987 and the minimum was reported in 1991 (**Table S10**). These years experienced a considerable number of warm nights (**Table S10**), aligning with their high CumExc values and suggesting sustained warmth throughout the winter season. Conversely, years such as 1991 and 1992 exhibited minimal CumExc values. Whereas the year 1991 was characterized by 19 cold nights contributing to a CumExc of –34.41 °C and an AbsExc of –4.87 °C, signifying particularly cold conditions (**Table S9**). The years 2008 and 1994 are notable for their high numbers of cold nights and substantial CumExc values for Mumbai region.

The CumExe and AbsExe during cold wave events for Kolkata and Delhi are shown in **Figure 6a** and **Figure 6b** respectively. It is also observed that 17 categories of cold wave events with 0.472 per year occurred in Kolkata during the 36 years of our study period (**Table S11**). The number of cold waves is observed to be the highest in 2012, 2013, and 2020, with a total of 2 episodes. Simultaneously the minimum value of CumExc is in the year 2012, and for AbsExc, the years are 2013 and 1996. It has also been observed that 31 categories of cold wave events with 0.861 per year occurred in Delhi during the study period using a methodological approach (**Table S12**). The number of cold wave episodes is reported to be the highest in the years 1986 and 2014, having four and three episodes respectively. The minimum value of CumExc is in the year 2019, and the minimum value of AbsExc is noted in 1996, 2011, and 2013 (**Table S12**).

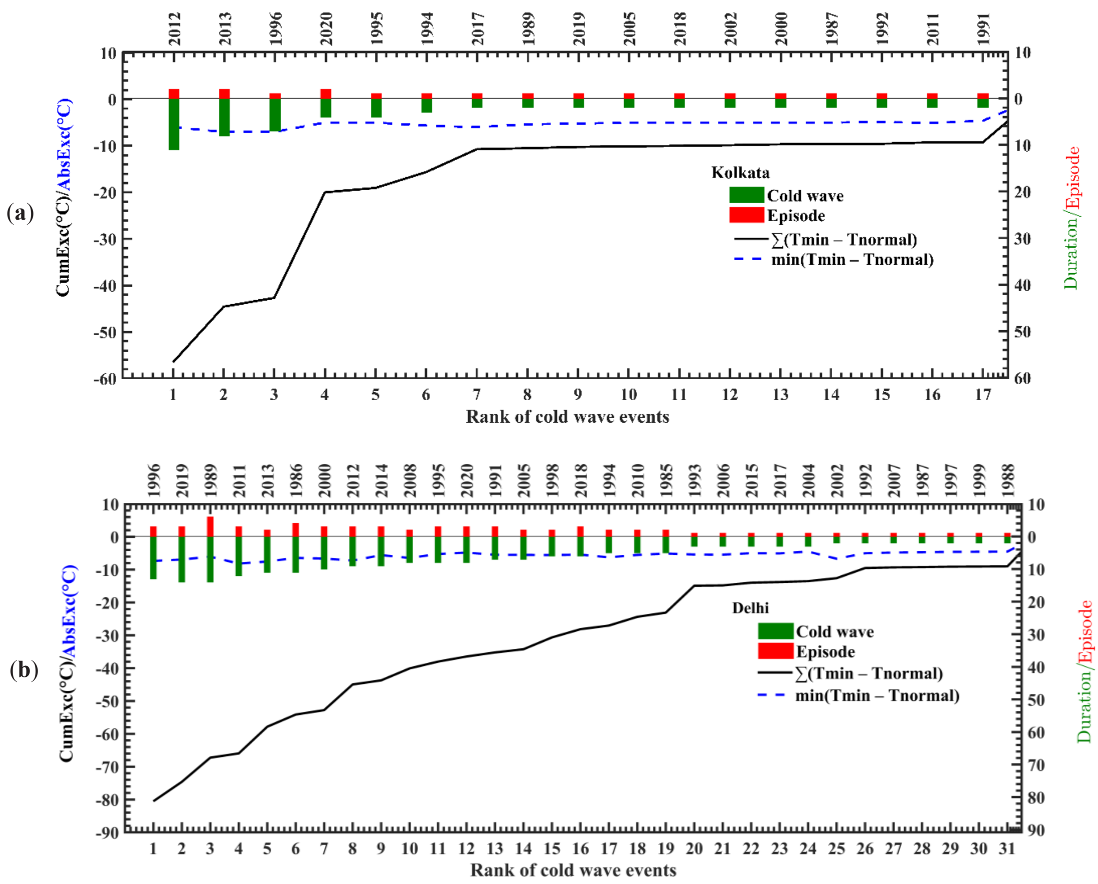


Figure 6. CumExc (arrange from highest to lowest magnitude) and AbsExc during cold wave events during 1985 to 2020 for (**a**) Kolkata, and (**b**) Delhi.

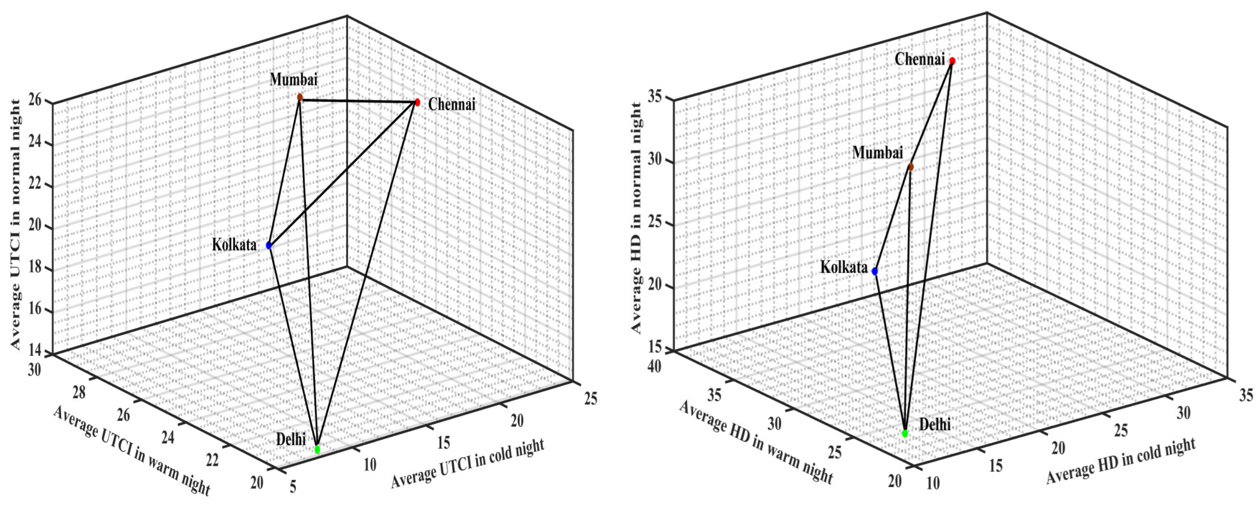
4.2 Changes in cold/heat stress between cold, warm nights and cold waves

Figure 7a and **Figure 7b** represented the average UTCI and average HD of four metropolitan cities on cold, warm, and normal days and how they change over 36-year periods, with the calculation of the Euclidian distance. We see that Euclidian distance from the centroid of all UTCI and HD (cold, warm, normal) in Delhi is highest in average UTCI and HD and is more as compared to other cities (**Table 2**). The variations of daily HD and UTCI are shown in **Tables S3–S12**. It is noted that during cold nights people do not experience discomfort due to coldness and cold stress in Kolkata, Chennai, and Mumbai but during warm nights in winter people experience discomfort due to hotness and heat stress. In Kolkata and Delhi, people are experiencing slightly cold stress during cold waves. Mostly in November, people experience discomfort/thermal stress in all cities during warm nights. During cold nights, the total number of nights in which people do not feel discomfort due to coldness or cold stress is 417, 417, and 423 in Kolkata, Chennai, and Mumbai cities respectively. However, the value of HD and UTCI is the lowest in Delhi; therefore, people experience slight cold stress. On the other hand, the total number of days during the warm nights in which people experience hot, discomfort/stress are 423, 445, 455, and 452 in Kolkata, Chennai, Delhi, and Mumbai. It is observed from our study that only the Kolkata and Delhi cities experience cold wave events. There are 59 and 197 cold wave days occurred in the cities of Kolkata and Delhi respectively during the 36 years of the study (**Table 2**).

Figure 8 represented the Euclidian distance variations of cold and warm nights and cold waves in the four metropolitan cities over 36 years. We also see from **Table 2** that the Euclidian distance from the centroid of the night (cold, warm, and cold wave) in Delhi is highest as compared to other cities indicating the dynamic nature of the variation of the cold and warm and cold wave is more as compared to other cities.

5. Discussion

The severity of cold waves, warm nights, and cold nights during winter causes discomfort to human and their health. The analysis of the 36 years of datasets for the four cities reveals that warm nights during winter seasons are experienced by all cities, whereas, cold waves and cold nights are experienced by Delhi and Kolkata during winter seasons. In order to understand the cold wave and associated cold stress, warm night and cold night events during the



(**a**) (**b**)

Figure 7. Variation in (**a**) average UTCI and (**b**) average HD in the four metropolitan cities using the Euclidian distance.

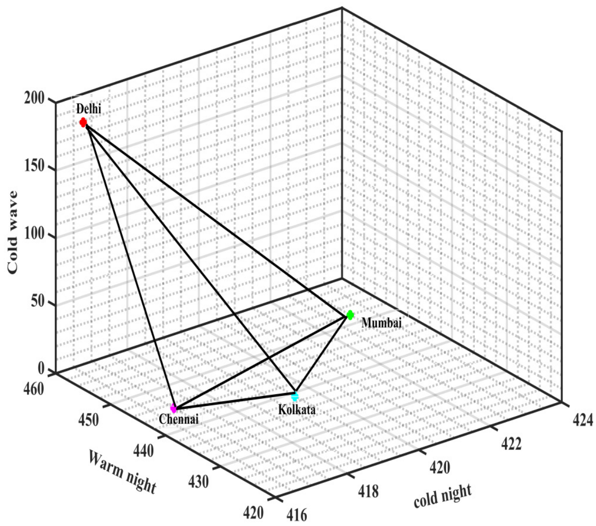


Figure 8. Variation in the cold night, warm night and cold waves in the four metropolitan cities using the Euclidian distance.

Table 2. Euclidean distance from centroid of UTCI, HD, and T_{min}.

Cities	Euclidean distance from centroid					
	UTCI	**HD**	T_{min}	Cold night	Warm night	Cold wave
Kolkata	2.85	3.79	21.4	417	423	59
Chennai	8.21	13.96	64.02	417	445	0
Delhi	11.53	15.91	133.5	416	455	197
Mumbai	6.04	5.29	64.7	423	452	0

study period, we have presented the probability of the degree of discomfort in terms of the percentage of frequency in **Tables 3–6**. The probability of great discomfort (based on HD) during warm nights for Kolkata, Chennai, Delhi, and Mumbai are 0, 3.15%, 0, and 1.33% respectively. There is no great discomfort level during cold nights for all the cities during the 36 years of the study. Some discomfort level is maximum for Mumbai (98.67%) followed by Chennai (96.85%) and Kolkata (52.25%) but for Delhi is minimum (0.44%) during warm nights in the winter seasons (**Table 3**). During cold nights, some discomfort is observed for only Chennai with the highest in Chennai city (**Table 4**). During normal nights in cold seasons (**Table 5**), some discomfort is maximum in Chennai (99.45%) followed by Mumbai (33.35%), Kolkata (10.83%) and Delhi (0%).

According to UTCI (**Tables 3–5**) for Kolkata, Chennai, Delhi, and Mumbai, the probability of moderate heat stress is 48.70%, 23.60%, 0.66%, and 94.91% during warm nights with a maximum in Mumbai (**Table 3**). During cold nights, there is no thermal stress in all cities. Only Delhi city where slight cold stress is present on cold or normal nights during winter seasons (**Tables 4 and 5**). The probability of slight cold stress (Delhi) is 59.36%, 17.32%, and 100% during cold night, normal night, and cold wave periods in the winter seasons. It is to be noted that slight cold stress is observed in Delhi (100%) only during cold wave period. The nonexistence of cold stress during cold wave period in Chennai and Mumbai may be due to their position near coastal area, but Kolkata is near the coastal area and close to the northern part of India, therefore cold waves are observed in this region. However, during cold waves in Kolkata, there is slight cold stress (50.85%) present (**Table 6**). Another significant observation of our study is to identify the most dynamic climate of a city using the average UTCI and HD during cold, warm, and normal nights (**Figures 7a, 7b** and **Figure 8**) based on T_{min}, which is used to decide the cold night, warm night, and cold wave. We note that overall Euclidian distances from the centroid of UTCI, HD and T_{min} (**Table 2**) are more for Delhi (11.53, 15.91, and 133.5). Therefore, one can say that Delhi's winter climate is more dynamic in nature compared to Kolkata, Chennai, and Mumbai regions which are relatively less dynamic in nature as per the Euclidian distance estimates [55–57] during the last 36 years, period of our study.

Table 3. Probability of the degree of discomfort and thermal stress (based on % frequency in the range) for the four cities during warm day periods only.

Category		Kolkata	Chennai	Delhi	Mumbai
Degree of comfort (% frequency of HD)	No discomfort	47.75	0	99.56	0
	Some discomfort	52.25	96.85	0.44	98.67
	Great discomfort	0	3.15	0	1.33
	Dangerous	0	0	0	0
Thermal stress (% frequency of UTCI)	No thermal stress	51.30	76.40	99.34	5.09
	Moderate heat stress	48.70	23.60	0.66	94.91
	Strong heat stress	0	0	0	0
	Very strong heat stress	0	0	0	0
	Extreme heat stress	0	0	0	0

Table 4. Probability of the degree of discomfort and thermal stress (based on % frequency in the range) for the four cities during cold day periods only.

Category		Kolkata	Chennai	Delhi	Mumbai
Degree of comfort (% frequency of HD)	No discomfort	100	29.02	100	100
	Some discomfort	0	70.98	0	0
	Great discomfort	0	0	0	0
	Dangerous	0	0	0	0
Thermal stress (% frequency of UTCI)	No thermal stress	100	100	40.64	100
	Moderate heat stress	0	0	0	0
	Strong heat stress	0	0	0	0
	Very strong heat stress	0	0	0	0
	Extreme heat stress	0	0	0	0
	Slight cold stress	0	0	59.36	0

Table 5. Probability of the degree of discomfort and thermal stress (based on % frequency in the range) for the four cities during normal day periods only.

Category		Kolkata	Chennai	Delhi	Mumbai
Degree of comfort (%frequency of HD)	No discomfort	89.17	0.55	100	66.65
	Some discomfort	10.83	99.45	0	33.35
	Great discomfort	0	0	0	0
	Dangerous	0	0	0	0
Thermal stress (% frequency of UTCI)	No thermal stress	94.38	76.78	82.68	81.64
	Moderate heat stress	5.62	23.22	0	18.36
	Strong heat stress	0	0	0	0
	Very strong heat stress	0	0	0	0
	Extreme heat stress	0	0	0	0
	Slight cold stress	0	0	17.32	0

Table 6. Probability of the degree of discomfort and thermal stress (based on % frequency in the range) for the four cities during cold wave periods only.

Category		Kolkata	Chennai	Delhi	Mumbai
Degree of comfort (% frequency of HD)	No discomfort	100	0	100	0
	Some discomfort	0	0	0	0
	Great discomfort	0	0	0	0
	Dangerous	0	0	0	0
Thermal stress (% frequency of UTCI)	No thermal stress	49.15	0	0	0
	Slight cold stress	50.85	0	100	0
	Moderate cold stress	0	0	0	0
	Strong cold stress	0	0	0	0
	Very strong cold stress	0	0	0	0

6. Conclusions

In this paper, we have done a trend analysis of cold waves using various techniques in the four major metropolitan cities of India. The first step involves the detailed examination for trend analysis by the Mann-Kendall test and the existing important 10th and 90th percentiles method for finding the cold and warm night events as well as IMD rules for finding cold waves during winter season for 36 years of our study. The second step involved the usage of HD to find the degree of comfort, and in the third step, we used the UTCI to find the cold stress category. The current research focuses on four metropolitan cities in India viz., Kolkata, Chennai, Delhi, and Mumbai where the variation of discomfort/stress during cold/warm nights and during cold waves periods in the winter seasons.

We have examined cold stress and discomfort levels due to coldness by examining the trend, frequency, and patterns of cold nights, warm nights, and cold waves in four major metropolitan cities of India i.e., Kolkata, Chennai, Delhi, and Mumbai. Our analysis shows that the temperature in Kolkata, Delhi, and Mumbai has increased (**Table S1**). The temperature gap between days and night has decreased for Kolkata, Delhi and Mumbai regions except for Chennai, where no trend is observed during the winter season of the study period. Cold night events in Mumbai are 0.36%, 0.36%, and 0.42% higher than in Kolkata, Chennai, and Delhi and warm night events in Delhi are 1.80%, 0.56%, and 0.17% higher than in Kolkata, Chennai, and Mumbai and similarly total events of cold wave in Delhi are 53.5%, 100%, 100% higher than in Kolkata, Chennai, and Mumbai respectively (**Tables S3–S12**).

We have compared the discomfort due to coldness and cold stress among the four metropolitan cities (**Tables 3–6**). According to HD calculation in the tables, the possibility of great discomfort in the Chennai region during warm night is more as compared to Kolkata, Delhi, and Mumbai. The possibility of some discomfort in Chennai during warm, cold and normal nights during cold seasons is more as compared to Kolkata, Delhi, and Mumbai. According to UTCI calculations, the possibility of moderate heat stress in the Delhi region during warm night is low as compared to other metropolitan cities. Similarly, the possibility of moderate heat stress in the Mumbai region during warm night is higher than in Kolkata, Delhi, and Chennai but in normal night possibilities of moderate heat stress in Chennai region is higher compared to Kolkata, Delhi, and Mumbai. Similarly, the possibility of slight cold stress in the Delhi region during cold night and normal night are 59.36% and 17.32% more respectively with respect to Chennai or Mumbai or Kolkata city. However, the possibility of slight cold stress during cold wave period in the Delhi region is 100% more than Chennai or Mumbai regions and 49.15% more than Kolkata region.

The findings of this research will be useful for policymakers and government agencies to devise blueprints to mitigate the unfortunate impacts of climate change during the winter season. Future work needs to focus on predicting the trends of cold stress across many other vulnerable regions and cities using deep learning and machine learning algorithms in various RCP scenarios.

Author Contributions

PK is involved in conceptualization, methodology, software, validation, formal analysis, investigation, resources, data curation, writing-original draft, and visualization. SS took part in conceptualization, methodology, draft editing, data curation, and editing. MSH and AU contributed discussions, plotting, and draft editing. AC contributed to conceptualization, investigation, writing—review, editing, and supervision.

Conflict of Interest

The authors declare no conflict of interest in this study.

Data Availability Statement

The data used in this study are publicly available. The authors will be happy to share the data used in the manuscript upon request.

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Appendix

Table S1. Trend analysis of average yearly temperature in the winter season (Nov–Feb) over 1985–2020 using the Mann-Kendall test.

City	T_{max}	T_{min}	DTR ($T_{max} - T_{min}$)
Kolkata	n = 36 α = 5% S = –340 V = 5390 Z = –4.6311 P value = 0.00000182 Trend—Decreasing	n = 36 α = 26.58% S = –46 V = 5390 Z = –0.6265 P value = 0.26579 Trend—Decreasing but at α = 5% no downward trend	n = 36 α = 5% S = –314 V = 5390 Z = –4.277 P value = 0.00000948 Trend—Decreasing
Chennai	n = 36 α = 5% S = 126 V = 5390 Z = 1.716 P value = 0.04308 Trend—Increasing	n = 36 α = 5% S = 160 V = 5390 Z = 2.179 P value = 0.01465 Trend—Increasing	n = 36 α = 50% S = 1 V = 5390 Z = 0.0136 P value = 0.49457 Trend—Increasing but at 5% no upward trend
Delhi	n = 36 α = 5% S = –202 V = 5390 Z = –2.7514 P value = 0.002967 Trend—Decreasing	n = 36 α = 24.79% S = –50 V = 5390 Z = –0.6810 P value = 0.24792 Trend—Decreasing but at 5% no downward trend	n = 36 α = 5% S = –238 V = 5390 Z = –3.2418 P value = 0.000594 Trend—Decreasing
Mumbai	n = 36 α = 5%, 1% S = –122 V = 5390 Z = –1.6617 P value = 0.048282 Trend—Decreasing	n = 36 α = 5% S = 132 V = 5390 Z = 1.798 P value = 0.03609 Trend—Increasing	n = 36 α = 5% S = –184 V = 5390 Z = –2.5062 P value = 0.0061011 Trend—Decreasing

Table S2. Trend analysis of average yearly temperature in the winter season (Nov–Feb) over 1951–1985 using the Mann-Kendall test.

City	T_{max}	T_{min}	DTR ($T_{max} - T_{min}$)
Kolkata	n = 35 α = 4.159% S = 123 V = 4958.33 Z = 1.7326 P value = 0.04159 Trend—Increasing	n = 35 α = 6.6117% S = –107 V = 4958.33 Z = –1.505 P value = 0.066117 Trend—Decreasing but at 5% no downward trend	n = 35 α = 0.622% S = 177 V = 4958.33 Z = 2.499 P value = 0.00622 Trend—Increasing but at 5% no upward trend
Chennai	n = 35 α = 8.2% S = 99 V = 4958.33 Z = 1.3917 P value = 0.082 Trend—Increasing but at 5% no upward trend	n = 35 α = 2.501% S = 139 V = 4958.33 Z = 1.9598 P value = 0.02501 Trend—Increasing	n = 35 α = 46.605% S = 7 V = 4958.33 Z = –0.085208 P value = 0.46605 Trend—Increasing but at 5% no upward trend
Delhi	n = 35 α = 11.098% S = –87 V = 4958.33 Z = –1.2213 P value = 0.11098 Trend—Decreasing but at 5% no downward trend	n = 35 α = 15.327% S = –73 V =4958.33 Z = –1.0225 P value = 0.15327 Trend—Decreasing but at 5% no downward trend	n = 35 α = 24.772% S = –49 V = 4958.33 Z = –0.68167 P value = 0.24772 Trend—Decreasing but at 5% no downward trend
Mumbai	n = 35 α = 2.0427% S = –145 V = 4958.33 Z = –2.045 P value = 0.020427 Trend—Decreasing	n = 35 α= 27.543% S = 43 V = 4958.33 Z = 0.5965 P value = 0.27543 Trend—Increasing but at 5% no upward trend	n = 35 α = 35.598% S = –27 V = 4958.33 Z = –0.369237 P value = 0.35598 Trend—Decreasing but at 5% no upward trend

Table S3. Characteristics of cold night events in order of cumulative exceedance for Kolkata in the winter season (1985–2020).

Rank of events	Year	Number of cold night	CumExc (°C)	AbsExc (°C)	Range of HD	Range of UTCI
1	2012	33	–39.44	–2.74	10–20	9–17
2	1996	27	–35.18	–3.04	12–20	9–18
3	2008	15	–24.87	–3.35	12–20	9–18
4	1989	24	–24.62	–2.88	12–21	10–18
5	2013	23	–23.50	–3.61	13–21	10–18
6	2014	26	–21.60	–3.68	13–21	10–18
7	1995	13	–19.84	–2.73	13–21	10–18
8	2020	17	–16.06	–2.73	13–21	10–18
9	2004	16	–13.49	–2.63	13–22	10–19
10	2000	15	–13.01	–2.00	13–22	10–19
11	1994	09	–12.42	–3.29	13–22	10–19
12	1991	13	–11.36	–1.85	13–22	10–19
13	2018	15	–10.29	–1.74	13–22	10–19
14	2005	13	–10.17	–2.29	13–23	10–19
15	1999	18	–10.00	–1.75	13–23	10–19
16	1987	12	–9.63	–2.26	13–23	10–19
17	2001	11	–8.86	–1.86	13–23	10–19
18	1992	10	–8.26	–1.54	13–23	10–19
19	2007	11	–8.24	–2.12	13–23	10–19
20	2003	09	–7.35	–2.08	13–23	10–19
21	1997	07	–7.30	–2.43	13–23	10–19
22	1993	12	–6.84	–1.37	13–23	10–19
23	2019	07	–6.56	–2.32	13–23	10–19
24	2011	09	–5.22	–1.26	13–23	10–19
25	2006	06	–4.79	–1.32	13–23	10–19
26	1998	07	–4.30	–1.40	13–23	10–19
27	1985	06	–3.83	–1.26	13–23	10–19
28	2017	04	–3.67	–1.60	13–23	10–19
29	2002	08	–3.51	–1.16	14–23	10–19
30	2015	05	–3.17	–1.43	14–23	10–19
31	2010	03	–2.35	–0.87	14–23	10–19
32	2016	05	–2.32	–0.97	14–23	10–19
33	1986	02	–1.31	–0.95	14–23	10–19
34	1988	01	–0.75	–0.75	14–23	10–19
35	1990	03	–0.56	–0.27	14–23	10–19
36	2009	02	–0.48	–0.26	14–23	10–19

Table S4. Characteristics of warm night events in order of CumExc for Kolkata in the winter season (1985–2020).

Rank of events	Year	Number of warm night	CumExc (°C)	AbsExc (°C)	Range of HD	Range of UTCI
1	2015	22	43.58	5.14	25–39	21–31
2	2010	20	28.81	3.38	25–39	21–31
3	2016	27	27.10	2.98	25–39	21–31
4	1998	19	25.32	5.12	25–39	21–31
5	1997	21	23.33	3.00	25–39	21–31
6	1991	12	22.40	5.00	25–39	21–31
7	1993	15	21.66	4.58	25–39	21–31
8	1985	18	21.52	3.82	25–39	21–31
9	1990	17	20.90	2.90	25–39	21–31
10	2012	15	19.76	2.08	25–39	21–31
11	2017	10	15.61	3.73	25–39	21–31
12	1986	19	15.19	1.88	25–39	21–31
13	2005	11	14.14	2.26	25–39	21–31
14	2009	16	13.15	2.32	25–39	21–31
15	2002	11	12.85	2.72	25–39	21–31
16	1988	14	12.00	1.95	25–39	21–31
17	1995	09	11.48	2.13	25–39	21–31
18	1996	08	10.39	3.77	25–39	21–31
19	2004	07	9.31	2.92	25–39	21–31
20	1989	11	8.59	3.02	25–39	21–31
21	1992	07	8.59	1.62	25–39	21–31
22	2019	17	8.52	1.30	25–39	21–31
23	2001	11	8.26	2.18	25–39	21–30
24	2008	12	7.76	1.58	25–39	21–30
25	2000	11	7.30	2.02	25–39	21–29
26	2020	08	6.93	2.15	25–39	21–29
27	1987	07	6.93	2.43	25–39	21–29
28	2011	08	6.58	2.43	25–39	21–28
29	2007	10	6.24	1.30	25–39	21–28
30	2003	07	5.66	1.57	25–39	21–28
31	1994	06	4.88	2.39	25–39	21–28
32	2013	06	3.52	1.81	25–39	21–28
33	2018	04	3.29	2.29	25–39	21–28
34	1999	04	2.30	1.13	25–39	21–28
35	2006	02	1.17	1.05	25–39	21–28
36	2014	01	0.46	0.46	25–39	21–28

Table S5. Characteristics of cold night events in order of CumExc for Chennai in the winter season (1985–2020).

Rank of events	Year	Number of cold night	CumExc (°C)	AbsExc (°C)	Range of HD	Range of UTCI
1	2012	18	–19.10	–3.14	25–29	20–28
2	1996	15	–18.81	–2.99	26–29	20–25
3	1997	18	–18.23	–2.94	26–30	20–25
4	2007	12	–16.21	–2.26	26–30	20–25
5	1994	18	–15.84	–2.15	27–30	20–25
6	1989	22	–14.51	–2.08	27–30	20–25
7	2006	22	–14.40	–1.77	27–30	20–25
8	1992	15	–13.87	–2.35	27–31	21–25
9	1990	14	–13.51	–2.98	27–31	21–25
10	1988	16	–12.55	–2.35	27–31	21–25
11	2002	21	–11.78	–1.69	27–31	21–25
12	2008	14	–11.13	–2.24	27–31	21–25
13	1999	22	–10.70	–1.68	27–31	21–25
14	1985	18	–8.93	–1.58	27–31	21–25
15	2005	15	–8.61	–1.79	27–31	21–25
16	2016	14	–7.71	–1.77	28–31	21–25
17	2014	09	–7.69	–1.86	28–31	21–25
18	2000	14	–7.61	–1.69	28–32	21–25
19	1986	06	–6.69	–1.90	28–32	21–25
20	2018	12	–4.67	–1.14	28–32	21–25
21	1991	05	–4.49	–1.79	28–32	21–25
22	2001	12	–4.25	–0.85	28–32	21–25
23	2011	10	–4.02	–1.70	28–32	21–25
24	1993	10	–3.93	–1.06	28–32	21–25
25	2019	08	–3.55	–0.88	28–32	21–25
26	2013	08	–3.22	–1.09	28–32	21–25
27	1995	07	–2.97	–1.36	28–32	21–25
28	1987	09	–2.51	–0.57	28–32	21–25
29	2004	08	–2.17	–0.57	28–32	21–25
30	2015	04	–2.17	–0.99	28–32	21–25
31	2010	04	–1.52	–0.79	28–32	21–25
32	2017	07	–1.20	–0.48	28–32	21–26
33	2009	03	–1.14	–0.58	28–32	21–26
34	2020	02	–0.53	–0.44	28–32	21–26
35	1998	02	–0.41	–0.24	28–32	21–26
36	2003	03	–0.32	–0.23	28–32	21–26

Table S6. Characteristics of warm night events in order of CumExc for Chennai in the winter season (1985–2020).

Rank of events	Year	Number of warm night	CumExc (°C)	AbsExc (°C)	Range of HD	Range of UTCI
1	2019	31	14.65	1.64	34–41	22–31
2	2020	29	13.62	1.42	34–41	22–31
3	1997	27	11.84	1.30	34–41	22–31
4	1998	25	11.61	1.29	34–40	22–31
5	2000	21	11.49	1.53	34–40	22–31
6	2012	12	9.51	2.01	34–40	22–31
7	2010	18	9.45	1.29	34–40	22–31
8	2003	12	6.88	1.11	34–40	22–31
9	2005	20	6.71	0.91	34–40	22–31
10	1991	16	6.29	1.02	34–40	22–30
11	2008	15	6.26	1.06	34–40	22–30
12	1990	15	5.89	1.26	34–40	22–30
13	2011	10	5.80	1.14	34–40	22–30
14	1987	17	5.57	0.94	34–40	22–30
15	1986	10	4.94	1.00	34–40	22–30
16	2004	09	4.65	0.84	34–40	22–30
17	2009	17	4.46	0.55	34–40	22–30
18	1994	10	3.35	0.64	34–40	22–30
19	1993	08	3.24	0.77	34–40	22–30
20	2002	08	3.15	0.75	34–40	22–30
21	2001	11	3.04	0.75	34–40	22–30
22	2016	11	3.02	0.60	34–40	22–30
23	2014	10	2.95	0.68	34–40	22–30
24	2017	07	2.88	0.96	34–40	22–30
25	2007	09	2.87	0.71	34–40	22–30
26	2018	12	2.85	0.67	34–40	22–30
27	1989	07	2.81	0.63	34–40	22–30
28	2013	05	2.25	0.63	34–40	22–30
29	2015	08	2.23	0.58	34–40	22–30
30	1985	05	2.15	0.61	34–39	22–30
31	1996	07	1.61	0.70	34–39	22–30
32	2006	03	1.59	0.92	34–39	22–30
33	1988	09	1.46	0.57	34–39	22–30
34	1999	05	1.35	0.72	34–39	22–30
35	1992	03	0.32	0.15	34–39	22–30
36	1995	03	0.29	0.13	34–39	22–30

Table S7. Characteristics of cold night events in order of CumExc for Delhi in the winter season (1985–2020).

Rank of events	Year	Number of cold night	CumExc (°C)	AbsExc (°C)	Range of HD	Range of UTCI
1	2013	29	–41.64	–3.97	6–14	5–12
2	1996	26	–37.99	–5.3	6–15	5–12
3	2019	19	–28.45	–3.5	7–15	5–12
4	2011	21	–28.01	–5.06	7–15	5–12
5	1989	19	–22.76	–2.43	7–16	5–12
6	2008	16	–17.81	–2.32	7–16	5–13
7	2000	12	–17.1	–2.43	7–16	5–13
8	2012	15	–16.49	–3.98	7–16	5–13
9	1995	17	–15.61	–1.85	7–16	5–13
10	1986	21	–15.19	–2.52	7–16	5–13
11	2005	17	–12.69	–2.3	7–16	5–13
12	2014	17	–12.22	–2.38	7–16	5–13
13	1998	15	–12.06	–2.44	7–16	5–13
14	2018	12	–11.38	–2.93	7–16	5–13
15	1985	12	–10.75	–3.04	7–16	5–13
16	2020	17	–10.65	–1.44	7–16	5–13
17	1991	16	–10.56	–1.27	7–16	5–13
18	2010	9	–9.27	–1.71	7–16	6–13
19	2002	4	–9.18	–3.24	7–16	5–13
20	1993	9	–8.81	–2.43	8–16	5–13
21	1992	9	–7.03	–2.14	8–16	5–13
22	2017	9	–6.54	–1.73	8–16	5–13
23	2004	7	–5.87	–1.42	8–16	5–13
24	1994	6	–5.48	–1.69	8–16	5–13
25	2015	6	–5.23	–1.35	8–16	5–13
26	2006	6	–5	–1.7	8–16	5–13
27	2003	11	–4.7	–1.23	8–16	5–13
28	2009	4	–4.66	–2.92	8–16	5–13
29	1997	9	–4.46	–0.88	8–16	6–13
30	1988	6	–4.4	–1.19	8–16	6–13
31	1999	5	–3.66	–1.28	8–16	6–13
32	1987	3	–3.4	–1.91	8–16	5–13
33	2001	3	–1.97	–1.23	8–16	5–13
34	2007	4	–1.82	–1.07	8–17	6–13
35	1990	4	–1.32	–0.74	8–17	6–13
36	2016	1	–0.8	–0.8	8–17	6–13

Table S8. Characteristics of warm night events in order of CumExc for Delhi in the winter (1985–2020).

Rank of events	Year	Number of warm night	CumExc (°C)	AbsExc (°C)	Range of HD	Range of UTCI
1	2006	35	67.76	4.43	16–30	15–28
2	1990	22	32.97	4.55	16–30	15–27
3	2008	18	32.33	4.30	16–29	15–27
4	1994	26	32.17	3.23	16–29	15–26
5	1993	19	30.93	4.73	16–29	15–26
6	2016	19	25.12	3.75	16–29	15–26
7	1992	20	19.55	3.50	16–29	15–26
8	2015	21	19.05	2.59	16–28	15–26
9	1991	18	18.93	4.61	16–28	15–26
10	2009	19	17.95	2.66	16–28	15–26
11	2019	17	16.52	3.48	16–28	15–26
12	2001	16	16.46	2.98	16–28	15–26
13	2004	13	14.89	4.46	16–28	15–26
14	1985	10	14.34	3.08	16–28	15–26
15	2007	10	14.10	2.33	16–28	15–26
16	1995	14	12.87	2.59	16–29	15–26
17	1999	14	12.00	2.40	16–28	15–26
18	1987	12	11.92	2.68	16–28	15–26
19	2010	07	11.75	2.57	16–28	15–26
20	2002	13	10.79	2.15	16–28	15–26
21	2017	12	10.58	1.87	16–28	15–26
22	1988	12	10.27	2.54	16–29	15–26
23	2018	09	10.12	2.17	16–28	15–26
24	2000	14	9.78	2.35	16–28	15–26
25	1989	09	9.47	3.09	16–28	15–26
26	2014	06	6.70	3.17	16–28	15–26
27	2020	07	5.71	1.69	16–28	15–26
28	1997	08	5.53	1.53	16–28	15–26
29	2005	08	5.35	1.49	16–28	15–26
30	1996	04	3.47	1.51	16–28	15–26
31	2003	05	3.34	2.12	16–28	15–26
32	2013	03	3.21	2.11	16–28	15–26
33	2011	06	2.68	0.75	16–28	15–26
34	1998	04	1.57	0.94	16–28	15–26
35	1986	03	0.86	0.73	16–28	15–26
36	2012	02	0.86	0.70	16–28	15–26

Table S9. Characteristics of cold night events in order of CumExc for Mumbai in the winter season (1985–2020).

Rank of events	Year	Number of cold night	CumExc (°C)	AbsExc (°C)	Range of HD	Range of UTCI
1	1991	19	–34.41	–4.87	16–25	13–21
2	2008	19	–28.13	–3.89	16–25	13–21
3	1994	29	–23.14	–3.12	17–25	14–21
4	1999	26	–21.23	–2.64	17–25	14–21
5	2005	20	–20.95	–2.98	17–25	14–21
6	2012	16	–19.76	–3.13	17–26	14–21
7	1995	21	–14.72	–2.65	17–26	16–23
8	1998	16	–14.11	–2.42	17–26	16–23
9	1993	20	–14.02	–2.27	17–26	16–23
10	2020	14	–13.93	–2.72	17–26	16–23
11	2002	10	–13.33	–3.30	17–26	16–23
12	1996	20	–12.40	–1.74	17–26	16–23
13	1986	10	–11.93	–3.09	17–26	16–23
14	2016	17	–11.08	–1.85	17–26	16–23
15	1997	14	–11.02	–2.42	17–26	16–23
16	1985	18	–10.86	–1.39	17–26	16–23
17	2011	11	–8.19	–2.65	17–26	16–23
18	2014	09	–7.96	–2.67	17–26	16–23
19	1992	13	–6.70	–1.40	17–26	16–23
20	2007	08	–6.70	–1.42	17–26	16–23
21	2010	12	–6.52	–1.70	17–26	16–23
22	2013	09	–5.81	–1.98	17–26	16–23
23	1988	08	–5.51	–2.29	17–26	16–23
24	2018	07	–5.40	–1.81	17–26	16–23
25	2019	04	–5.05	–2.01	17–26	16–23
26	2017	05	–4.96	–1.62	17–26	16–23
27	1990	06	–4.79	–1.07	17–26	16–23
28	1989	07	–4.52	–1.63	17–26	16–23
29	2000	07	–4.49	–2.34	17–26	16–23
30	2015	05	–4.49	–1.31	17–26	16–23
31	1987	07	–3.46	–1.16	17–27	16–23
32	2001	03	–2.41	–1.09	17–27	16–23
33	2006	04	–2.18	–1.41	17–27	16–23
34	2003	03	–2.13	–1.18	17–27	16–23
35	2009	03	–1.74	–1.19	17–27	16–23
36	2004	03	–0.68	–0.55	17–28	16–23

Table S10. Characteristics of warm night eventsin order of CumExc for Mumbai in the winter season (1985–2020).

Rank of events	Year	Number of warm night	CumExc (°C)	AbsExc (°C)	Range of HD	Range of UTCI
1	2003	24	35.80	3.73	30–44	25–32
2	1987	28	31.09	3.43	30–43	25–32
3	2007	20	27.25	3.68	30–43	25–32
4	2013	18	22.45	3.21	30–43	25–32
5	2019	19	20.80	3.36	30–40	25–32
6	2010	24	19.89	1.94	30–40	25–32
7	2001	14	17.42	2.90	30–40	25–32
8	2004	17	16.42	3.46	30–40	25–32
9	1990	22	15.24	2.30	30–40	25–32
10	2008	18	15.01	1.85	30–39	25–31
11	1996	15	13.09	2.28	30–39	25–31
12	1986	10	13.08	3.05	30–39	25–31
13	2009	22	12.71	1.71	30–39	25–31
14	1995	11	11.79	2.16	30–39	25–31
15	1998	14	11.41	1.69	30–39	25–31
16	2018	17	10.76	2.26	30–39	25–31
17	1997	21	10.71	1.63	30–39	25–31
18	1999	15	9.55	2.27	30–39	25–31
19	2020	14	9.12	2.18	30–39	25–31
20	2015	16	8.98	1.83	30–39	25–31
21	2014	11	8.61	1.79	30–39	25–31
22	2002	09	7.17	1.42	30–39	25–31
23	2000	05	5.91	2.05	30–39	25–31
24	2012	05	5.16	1.70	30–39	25–31
25	1989	03	4.46	2.17	30–39	25–31
26	1985	04	4.10	2.21	30–39	25–31
27	1988	09	3.85	1.05	30–39	25–31
28	2017	08	3.57	1.09	30–39	25–31
29	2006	11	3.56	0.79	30–39	25–31
30	2016	05	3.39	1.45	30–39	25–31
31	1994	03	2.93	1.60	30–39	25–31
32	2011	04	2.64	1.90	30–39	25–31
33	1993	08	2.04	0.67	30–39	25–31
34	2005	03	1.99	1.06	30–39	25–31
35	1992	04	1.38	0.57	30–39	25–31
36	1991	01	0.67	0.67	30–39	25–31

Table S11. Characteristics of cold wave events in order of CumExc for Kolkata in the winter season (1985–2020).

Rank of events	Year	Duration of cold wave (in days)	Episode	CumExc (°C)	AbsExc (°C)	Range of HD	Range of UTCI
1	2012	11	2	–56.54	–6.00	10–13	5–10
2	2013	8	2	–44.58	–7.00	10–13	5–10
3	1996	7	1	–42.68	–7.00	10–12	5–10
4	2020	4	2	–20.00	–5.00	10–12	5–10
5	1995	4	1	–19.05	–5.00	10–12	5–10
6	1994	3	1	–15.64	–5.64	10–12	5–10
7	2017	2	1	–10.73	–6.00	10–12	5–10
8	1989	2	1	–10.51	–5.37	10–12	5–10
9	2019	2	1	–10.24	–5.23	10–12	5–10
10	2005	2	1	–10.10	–5.00	10–12	5–11
11	2018	2	1	–10.01	–5.00	10–12	5–11
12	2002	2	1	–9.87	–5.00	10–12	5–11
13	2000	2	1	–9.67	–5.00	10–12	5–11
14	1987	2	1	–9.65	–5.00	10–12	5–11
15	1992	2	1	–9.55	–4.87	10–12	5–11
16	2011	2	1	–9.25	–5.10	10–12	5–11
17	1991	2	1	–9.22	–4.61	10–12	5–11

Table S12. Characteristics of cold wave events in order of CumExc for Delhi in the winter season (1985–2020).

Rank of events	Year	Duration of cold wave (in days)	Episode	CumExc (°C)	AbsExc (°C)	Range of HD	Range of UTCI
1	1996	13	3	–80.53	–7.34	5–8	3–7
2	2019	14	3	–74.62	–6.92	4–9	3–6
3	1989	14	6	–67.25	–6.04	5–9	3–8
4	2011	12	3	–65.96	–8.15	5–9	3–8
5	2013	11	2	–57.83	–7.53	5–9	4–8
6	1986	11	4	–54.12	–6.42	5–10	4–8
7	2000	10	3	–52.77	–6.63	6–10	4–8
8	2012	9	3	–44.96	–7.23	6–10	4–8
9	2014	9	3	–43.72	–5.58	6–10	4–9
10	2008	8	2	–40.07	–6.44	6–10	4–9
11	1995	8	3	–38.00	–5.24	6–10	5–9
12	2020	8	3	–36.45	–4.81	6–10	5–9
13	1991	7	3	–35.21	–5.46	7–10	5–9
14	2005	7	2	–34.24	–5.51	7–10	5–9
15	1998	6	2	–30.64	–5.56	7–10	5–9
16	2018	6	3	–28.14	–5.43	7–11	5–9
17	1994	5	2	–27.03	–6.25	7–11	5–9
18	2010	5	2	–24.36	–5.52	7–11	5–9
19	1985	5	2	–23.08	–5.08	7–11	5–9
20	1993	3	1	–14.89	–5.39	7–11	5–9
21	2006	3	1	–14.80	–5.43	7–11	5–9
22	2015	3	1	–13.98	–4.98	8–11	5–9
23	2017	3	1	–13.76	–5.047	8–11	5–9
24	2004	3	1	–13.50	–4.50	8–11	5–9
25	2002	2	1	–12.60	–6.67	8–11	5–9
26	1992	2	1	–9.50	–5.00	8–11	5–9
27	2007	2	1	–9.30	–4.80	8–11	5–9
28	1987	2	1	–9.23	–4.70	8–11	6–10
29	1997	2	1	–9.10	–4.60	8–11	6–10
30	1999	2	1	–9.05	–4.55	8–11	6–10
31	1988	2	1	–9.00	–4.50	8–11	6–10