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LETTER

Quantifying the shifts and intensification in the annual cycles of diurnal temperature extremes for human comfort and crop production

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Abstract
Any significant change in climate is known to have a significant impact on crop production and human resources, which are generally difficult to quantify. In the present study, two indices are defined: (i) refined growing season (GS) characteristics and (ii) transition period, based on the annual cycles of diurnal temperature extremes, to unravel any possible impact on these productive elements. Multi-dimensional ensemble empirical mode decomposition, a nonlinear, non-stationary approach is used to extract the annual cycles of diurnal temperature extremes. Since the adverse impact is reportedly more critical over tropical regions, the Indian region is chosen as the study area, and 1° × 1° gridded daily minimum and daily maximum temperature data are used. Results reveal earlier onset and lengthening of GS, with notable spatial variations. Further, a drastic reduction in the transition (i.e. comfortable) period is observed over the warm humid regions, majorly due to the encroachment of summer days. On the contrary, over semi-arid regions, the transition period is found to be increasing, majorly due to the shortening of winter. The quantification of these changes may aid in implementing regional adaptation strategies related to the two productive elements.

1. Introduction

Intensification of the global temperature associated with global warming is reportedly triggering catastrophic effects on the environment, in the forms of frequent floods and droughts (GuhaThakurta et al 2010, Giorgi et al 2011), deficit in crop productivity (Saseendran et al 2000, Peng et al 2004, Battisti and Naylor 2009), threat to human and animal health (Crick and Sparks 1999, Cotton 2003, Myers et al 2013), and human conflicts (Hsiang et al 2013). The increasing temperatures have a direct impact on the functioning of a country’s economy and human activities, which is complex to quantify because of its nonlinear behaviour (Dell et al 2012, Schlenker and Roberts 2009). While contradictory analyses (Dell et al 2012, Schlenker and Roberts 2009) have been reported on the response of the economy of wealthy countries to changes in temperature characteristics, a substantial adverse impact is evident on the economy of developing countries in response to the increased temperatures (Burke et al 2015). Quite alarming though, reportedly, economic growth of developing countries in tropics, will decrease by 1.3% per year with a mere 1° rise in the mean temperature (Dell et al 2012). While the global temperature distribution and its nonlinear effect on economic productivity is notable (Burke et al 2015), the temperature bell curve shifts are found to be larger in India and China, with the shift being relatively higher during summer than during winter.

The unquestionable influence of temperature in the dynamics of the ecosystem processes and thereby economy, may be quantified by characterising its impacts on the two fundamental productive elements such as crops and workers. Apparently, the regions over the tropics (Battisti and Naylor 2009, Hansen and Sata 2016) are observed/ projected to endure the persistent impact of climatic change, with the uncertain weather aggravating the (existing) food crisis and the
human hardships (Saseendran et al 2000, Peng et al 2004, Battisti and Naylor 2009). Considering the fact that the magnitude of the temperature extremes is rising at a faster rate than the average temperature (Robeson et al 2018), mere analysis of annual mean temperature which is the universal indicator of global warming may not be adequate to reveal the actual impact of rising temperature on these productive elements. The spatio-temporal (Vose et al 2005) differences and the varying rate of increase of minimum and maximum temperature with winter reportedly getting warmer at a rate higher than summer (Meehl et al 2007, Vinnarasi et al 2017), are expected to influence the crop productivity and sowing season directly.

Formulation of any mitigation strategies on the productive elements, hence, need comprehensive information about the evolution of the temperature variations (Reside et al 2010) to understand the change in the seasons and phenologies (Karl et al 1995). Detailed investigations of historic regional temperature variations are mandatory before putting confidence into the climate model projections, to devise future adaptation strategies (like a possible shift in the sowing time, change in cropping pattern and work scheduling of human resources) to tackle the altered temperature patterns.

Here, we investigate the possible influence of temperature variations in these two productive elements (i.e. crops and workers), by analysing the variation in the annual cycles of the diurnal temperature extremes through two main characteristics, i.e. growing season (GS) and transition period. GS is defined as a period favourable for plant growth and any change in the growing season length (GSL) is expected to severely affect crop productivity (Chmielewski et al 2004, Qian et al 2010, Xia et al 2013), hydrological cycle (Peterson 2002), carbon cycle, viniculture (Xia et al 2013), etc. This study is restricted to India, a tropical country, which is characterised by its diverse climate, dense population and agriculture-dependent economy.

Usually, GSL is measured using the daily mean temperature, with numerous studies reporting an increase in GSL, owing it to an earlier (advancement) onset (start) (Christidis et al 2007, Qian et al 2009, Xia et al 2013). However, crop productivity may decline merely due to any increase in minimum temperature despite any considerable change in maximum temperature (Peng et al 2004, Nagai and Makino 2009). Both the productivity elements are influenced by the transition periods (i.e. periods of comfort) exhibited in the annual cycles of maximum and minimum temperature. With the reported increase in the days with high temperatures, the length of the transition period is expected to decline, which in turn will severely affect the productivity. Hence, this study aims to analyze the annual variation of diurnal extremes using four different indices for GS and transition period namely Onset of GS ($O_{GS}$), Length of GS ($L_{GS}$), transition period of winter to summer ($T_{WS}$) and transition period of summer to winter ($T_{SW}$), using the $1^\circ \times 1^\circ$ gridded dataset of daily maximum ($T_{\text{max}}$) and minimum ($T_{\text{min}}$) temperatures. A robust, multi-dimensional ensemble empirical mode decomposition (MEEMD) technique has been employed to extract the annual cycle and its longer timescale components (ALC) from the temperature data. The evolution of the trend in these indices is further assessed using the ensemble empirical mode decomposition (EEMD) trend.

2. Data and methods

2.1. Data description

This study uses daily maximum and minimum temperature gridded dataset for the period from 1951 to 2010, having a spatial domain of $7.5^\circ$ S–$37.5^\circ$ N and $67.5^\circ$ E–$97.5^\circ$ E, and with a spatial resolution of $1^\circ \times 1^\circ$, which is developed by the National Climate Center, Indian Meteorological Department (Srivastava et al 2009). A modified version of Shepherd’s angular distance weighing algorithm (Shepard 1968) was used to interpolate the daily temperature data from around 395 observation stations, to convert the irregularly spaced station data into gridded data (Srivastava et al 2009). The quality of the present data is found to be comparable with the monthly mean temperature dataset prepared by University of Delaware (Willmott and Matsuura 2001), with a correlation coefficient of around 0.8 in most of the grids (Srivastava et al 2009). Moreover, the accuracy of the gridded dataset is evaluated using cross-validation, and the Root Mean Square Error was found to be lesser than 0.5°C. This dataset is extensively used in the literature, especially to evaluate the warming scenario (e.g. Kothawale and Rupa Kumar 2005; Kothawale et al 2010, 2012).

2.2. GS and transition period

GS is generally described as the period in which the mean temperature is above 5°C (Alexander et al 2006, Qian et al 2010). This definition, however, may not be appropriate for tropical regions. Hence, Christidis et al (2007) proposed a definition for GS using local annual mean temperature as a threshold. Moreover, in India, most of the crops are sown when the temperature is below the annual average temperature. Therefore, to investigate the changes in the GSL, we have utilised a modified threshold for GS based on the temperature requirement for the major crops (like rice, wheat and maize) cultivated in India. So, the threshold is fixed as $T_{\text{max}}$ above $25^\circ$C and $T_{\text{min}}$ above $15^\circ$C (Nagai and Makino 2009, Hatfield and Prueger 2015). Further, GS is characterised by two indices, i.e. $O_{GS}$, $L_{GS}$.

Similarly, the transition period is a period of moderate weather between intense summer and winter and vice versa, when the temperature is optimum for crop growth and comfortable for workers. $T_{WS}$ and $T_{SW}$ are
2.3. Extraction of indices and its trend

The extraction of the indices $O_{GS}, L_{GS}, T_{WS}, T_{SW}$ (see table S1 which is available online: stacks.iop.org/ERL/14/054016/mmedia) is complicated due to the high-frequency fluctuations in the observed daily $T_{max}$ and $T_{min}$ data, which may yield false $O_{GS}$ and $L_{GS}$. To overcome this problem, a highly adaptive, nonlinear and non-stationary time domain decomposition method, known as MEEMD (Qian et al 2009, Wu et al 2009, Xia et al 2013) has been used, which is superior to other methods such as Fourier Transform and wavelet decomposition, and is an enhanced version of EEMD. The procedure of EEMD technique is shown in figure S1. Initially, the ALC is isolated using MEEMD, which represents the annual variation and long term changes with minimal distortion from the original data (Xia et al 2013). The steps involved in extracting ALC is described in supplementary section S1. After obtaining ALC from $T_{max}$ and $T_{min}$, the indices are extracted using the threshold mentioned above, as illustrated in figure S2, unlike the previous studies where the only mean temperature is analysed (Qian et al 2009, Xia et al 2013). Finally, EEMD method is applied to extract the grid-wise adaptive EEMD trend (Ji et al 2014, Vinnarasi et al 2017) of the computed indices from the ALC for four distinct time windows (1951–1980, 1951–1990, 1951–2000 and 1951–2010), to assess the spatio-temporal evolution of the EEMD trend. The statistical significance of EEMD trend is computed using Monte Carlo simulation (Ji et al 2014) (for more details see supplementary section S1).

3. Results and discussion

As a preliminary investigation, the spatio-temporal long-term average ALC of $T_{max}$ and $T_{min}$ obtained using EEMD shown in figure 3(a), reveals a bimodal pattern of $T_{max}$, with the peak of $T_{max}$ appearing approximately one month earlier than that of $T_{min}$. The lag between the peaks of $T_{max}$ and $T_{min}$ is chiefly attributed to the monsoon, western disturbances (extratropical storm originating in the Mediterranean region that brings sudden winter rain to the northwestern parts of the Indian subcontinent), and expected higher night-time temperatures during monsoon/rainy days (Dai et al 1999, Rai et al 2012, He et al 2015, Vinnarasi et al 2017). The spatial variation of this peak value for $T_{max}$ and $T_{min}$ are shown in figures 1(b) and (c) respectively and the corresponding months of occurrences are shown in figures 1(d) and (e). Though there is spatial coherence in the grids exhibiting higher peak $T_{max}$ and $T_{min}$ values, it is worthwhile to note that the higher amplitudes of $T_{min}$ are observed in much higher number of grids than $T_{max}$, especially in north-west and Central India, which demonstrates that the night-time temperature is increasing at a faster rate than that of $T_{max}$ (Vinnarasi et al 2017). This supports the observation that the unusual warm period is not only due to the warm days, but rather aggravated due to warm nights (Meehl et al 2007), which ultimately leads to increased mortality rate (Mazdiyasni et al 2017). Further, the spatial variation of the peak values of $T_{max}$ and $T_{min}$ and their onsets over three different decadal time windows—first (1951–1960), middle (1976–1985) and last (2001–2010), are shown in figure S3, which further strengthens the above arguments. Hence, here we further concentrate our analyses on the joint behaviour of diurnal extremes using the extracted ALC.

3.1. Joint behaviour of diurnal extremes

Jointly, $T_{max}$ and $T_{min}$ exhibit a hysteresis loop like behaviour, highlighting the phase lag between them, as visible in figure 2(a) which demonstrates the joint probability of diurnal extremes spatially averaged for 60 years. Joint behaviour portrays a clockwise loop changing from summer to winter, displaying higher probability during intense winter and summer. Since the study area is comprised of diverse climatic regions such as arid and humid, in order to understand the spatial variation of the joint behaviour of the diurnal extremes, the joint probability is computed for each grid at different thresholds of $T_{max}$ and $T_{min}$. The thresholds of $T_{max}$ and $T_{min}$ are varied from 15 °C to 35 °C and from 5 °C to 25 °C respectively at increments of 5 °C, including the temperatures above and below the respective thresholds, i.e. $T_{max} < 15 \, ^\circ \text{C}$ and $T_{max} > 35 \, ^\circ \text{C}$; and $T_{min} < 5 \, ^\circ \text{C}$ and $T_{min} > 25 \, ^\circ \text{C}$. Spatial variations of the joint probability for each threshold ranges are shown in figure 2(b). The coldest diurnal extreme ($T_{max} < 15 \, ^\circ \text{C}$ and $T_{min} < 5 \, ^\circ \text{C}$) is observed only in very few grids of northernmost India and warmest diurnal extreme ($T_{max} > 35 \, ^\circ \text{C}$ and $T_{min} > 25 \, ^\circ \text{C}$) is observed in the northwest, central India, interior southern India and east-coast. Evidently, a majority of grids, especially in the coastal regions and northeast, which are highly humid zones with relative humidity above 70% (Jaswal and
northernmost and southern part of west-coast.

This raises the alarm about human comfort, and productivity during the humid summer days. This decrease of cold joint extremes and an increase of time windows, as mentioned earlier, clearly indicate respectively.

A clear indication of the shifting of both $T_{\text{max}}$ and $T_{\text{min}}$ towards hot joint extremes are visible overall. The analysis emphasises that the magnitude and density of lysis emphasises that the magnitude and density of towards hot joint extremes are visible overall. The analysis

time windows, as mentioned earlier, clearly indicate respectively.

The units are normalised. Spatial variation of the peak value of this average ALC of (b) $T_{\text{max}}$ and (c) $T_{\text{min}}$. White dots in (b) and (c) represents grids exhibiting bi-modal behaviour, while grids without a dot represent unimodal behaviour. Spatial information of the month exhibiting this peak in the average ALC of (d) $T_{\text{max}}$ and (e) $T_{\text{min}}$. Grids with inconsistent data are shown in dark grey colour (bottom), which is represented as NA (Not Analyzed) in the colorbar.

Koppar 2011, Jain et al 2013 (except northwest, northernmost and southern part of west-coast), display higher probability in the threshold ranges of $T_{\text{max}}$ between 30 °C and 35 °C and $T_{\text{min}}$ between 20 °C and 25 °C. This indicates a probable rise in the mortality rates in these regions, with high humidity and higher temperature occurring concurrently (Wehner et al 2016). We further dissected this range, and the analysis is repeated at a smaller increment of 2 °C for the above threshold (i.e. $T_{\text{max}}$ from 30 °C to 36 °C and $T_{\text{min}}$ from 20 °C to 26 °C), as demonstrated in figure 2(c). Higher probability in the northeast is observed for the range of $T_{\text{max}}$ as 30 °C–32 °C and $T_{\text{min}}$ as 22 °C–24 °C, while for the northwest, it is 34 °C–36 °C and 24 °C–26 °C respectively.

Repeating the analysis on three different decadal time windows, as mentioned earlier, clearly indicate the decrease of cold joint extremes and an increase of $T_{\text{min}}$ during summers (see Panel ‘a’ in figures S4–S6). A clear indication of the shifting of both $T_{\text{max}}$ and $T_{\text{min}}$ towards hot joint extremes are visible overall. The analysis emphasises that the magnitude and density of probability shifts toward the joint higher extremes (i.e. $T_{\text{max}}$ and $T_{\text{min}}$) over decades, especially with higher intensity for $T_{\text{max}}$ and $T_{\text{min}}$ at 30 °C–35 °C and 20 °C–25 °C, respectively. Further analysis with an increment of 2 °C, reveals that these intensifications occurred mostly over the whole Central and Northeast India. This raises the alarm about human comfort, and productivity during the humid summer days (Dash and Kjellstrom 2011).

3.2. Changes in the GS

The impact of the shift from winter to summer days is investigated to understand the potential for changes in the GS characteristics, using the indices mentioned in table S1. The long-term average onset and length ($O_{\text{GS}}$ and $L_{\text{GS}}$) for 60 years (1951–2010) is shown in figures 3(a) and (b), which reveals that from south to north $O_{\text{GS}}$ has delayed and $L_{\text{GS}}$ has decreased. Moreover, in southern India, the temperature remains within the thresholds defined for GS all through the year (see panels a and b in figure 3). Further, $L_{\text{GS}}$ is found to exhibit a linear relation with $O_{\text{GS}}$ (see panel c in figure 3), i.e. early the onset, more the growing period, which is in agreement with the previous study (Xia et al 2013). More interestingly, onset has advanced, and length has increased in the last decade, which is clearly demonstrated by the marginal plots. For instance, the maximum probability of $O_{\text{GS}}$ and $L_{\text{GS}}$ in the first decade is for the 67th day and 248.5 days respectively, while in the last decade, corresponding values are 64th day and 254.8 days—2 days advancement in the onset and 6 day increase in length from first to last decade time window. The spatial variation of these indices (figures S7(a) and (b)) reveal that these changes are more apparent in northwest and northeast, while the Indo-Gangetic plains also exhibit an earlier onset.

The evolution of $O_{\text{GS}}$ and $L_{\text{GS}}$ over decades demonstrated through the EEMD trend are shown in figures 3(d) and (e) respectively. In the first period, 1951–1980, overall a positive trend with a range of 0.8–3.3 days/decade, i.e. a delay in the onset is visible in major parts of India, except a few grids in southern
India. However, over the decades, the spatial extent of positive trend in the OGS gradually diminishes and the recent decade has seen a reversal of trends, with the advancement of onset (−7.5 to −0.8 days/decade) in majority of grids. On the contrary, the dominant negative trend in LGS has gradually declined, giving rise to the intensification in extent and magnitude of the significant positive trend, which further emphasizes the apparent lengthening of GS over India in the recent decades, along with the advancement of onset. Especially, a significant positive trend is observed in upper west-coast (3.3–5.8 days/decade) and northwest (1.3–3.33 days/decade). Recently Xia et al (2013) analyzed the GSL for 1960–1999 using the EEMD approach over the globe except tropical regions, in which they observed a 1.66 day/decade increment in GS with an advancement of a 0.89 day/decade in onset, especially in the extra-tropical region of India (upper part of northern India) and 1.5–2 day/decade increment in GS which is almost in agreement with our study. Moreover, Qian et al (2009) also adopted the same approach for Stockholm and observed lengthening of GS with the advancement of onset.

The EEMD trend of the joint extremes with $T_{\text{max}}$ and $T_{\text{min}}$ above 35°C and 25°C respectively shows that over the northwest the number of days with the joint extreme behaviour is increasing, along with an early occurrence rate (see figures S8(a) and (b)). The grids exhibiting a negative trend in the number of hot extremes are also shrinking in the Central India and Indo-Gangetic Plains. The number of winter days is also found to be decreasing in the Northwestern regions, in recent decades. Hence, though the increase in $L_{\text{GS}}$ is correlated to increase in crop production

![Figure 2. Joint probability of $T_{\text{max}}$ and $T_{\text{min}}$ (a) spatial average of ALC for entire India, (b) for each panel with 5 °C increments, and (c) for each panel with 2 °C increment, which is the expansion of the subpanel of (b) with the spatial variation of $T_{\text{max}}$ 30°C to 35°C and $T_{\text{min}}$ 20°C to 25°C for 60 years (1951–2010). Light grey represents zero probability. Grids with inconsistent data are shown in dark grey colour (in b extreme left, and in c bottom), which is represented as NA (Not Analysed). Here, $T_{\text{n}}$ and $T_{\text{x}}$ denote $T_{\text{min}}$ and $T_{\text{max}}$ respectively.](image-url)
(Mueller et al 2015), with $L_{GS}$ increasing in most of the grids, we cannot conclude that it is favourable for crop production since the extreme temperature is also inevitably increasing rapidly. For instance, wheat cannot grow above $37°C/23°C$ of $T_{max}/T_{min}$ (Peng et al 2004, Nagai and Makino 2009), and the intensified heat stress may reduce the wheat yield even up to 30% (Jain et al 2017). Besides, Singh et al (2013) report that the yield of potato also may reduce up to 13.7% by 2050 at higher temperatures and elevated CO2 levels, if unchecked. However, an earlier sowing date had reportedly increased the wheat yield in the Indo-Gangetic Plains (Bassu et al 2009, Lobell et al 2013, Jain et al 2017).

### 3.3. Changes in the transition period

This study is further extended to analyse the effective growing period of crops and the comfortable period for human (termed as transition period). The length of the transition period from winter to summer ($T_{WS}$) and summer to winter ($T_{SW}$) are extracted using the thresholds defined in table S1, and the trends are plotted in figure 4. Northeast and southern west coast regions have a higher number of average $T_{WS}$ and $T_{SW}$ respectively. However, scatter density plot of these for three different decades reveal that the transition period has decreased in majority of grids in recent decades, especially $T_{SW}$ (for the spatial variation of the temporal average of three chosen decades of $T_{WS}$ and $T_{SW}$—see figure S7(c) and (d)). Furthermore, to understand the evolution of changes in the transition period, we evaluated the spatial EEMD-trend of $T_{WS}$ and $T_{SW}$

![Figure 3. Average of (a) $O_{GS}$ (days) and (b) $L_{GS}$ (days) for 1951–2010, (c) scatter plot of the $O_{GS}$ (days) and $L_{GS}$ (days) for the first (1951–1960), middle (1976–1985) and last (2001–2010) decades along with the respective marginal probability plots. Spatial evolution of ensemble empirical mode decomposition trends of (d) $O_{GS}$ (days) and (e) $L_{GS}$ (days). Each sub-panel has four windows (1) 1951–1980, (2) 1951–1990, (3) 1951–2000 and (4) 1951–2010. Grids with inconsistent data are shown in dark grey colour (extreme left of the colour bar), which is represented as NA (Not Analyzed). Plus (+) sign represents the grids with a statistically significant positive and negative trend. Statistical significance is estimated for 10% significance level using the two-tailed hypothesis test.](image-url)
Here, $T_{WS}$ shows a positive trend in Central India and few grids of northern west-coast during the initial 30 years, which shrinks over the decades. On the contrary, a significant negative trend is observed in few parts of southern India and northeast regions, which gradually extends over the entire southern India and northeast over decades. A similar analysis of $T_{SW}$ reveals a substantial increase in the spatial extent and magnitude of the positive trend in both northwest and northern west-coast, while the remaining region shows a negative trend. The positive trend of $T_{SW}$ in northwest is dominantly due to the decrease in the number of days in winter (see figure S8(c)), while warming winter will severely affect winter crops (Mall et al 2006, Kalra et al 2008), which are extremely sensitive to the changes in the minimum temperature (Bapuji Rao et al 2014).

Overall, there is a decrease in the comfort periods in recent decades, throughout the country. Especially, the longest duration observed in the southern west coast—a region encompassing the Western Ghats and Kerala, termed as god’s own country, with natural landscapes and comfortable climate shows a drastic reduction of comfortable days in recent decades. Though not this intense, similar changes are also observed in east-coast, central India, northeast and foot-hills of Himalayas, with drastically decreasing comfortable days and nights. This clearly indicates that the summer is encroaching into the transition/comfortable periods. Besides, the gross diminishing of transition periods over the country explains the increased usage of power production, with the continuous usage of air-conditioners during intense summers and heaters during severe winters. Overall, it can be inferred that there is an evident increase in the

![Figure 4](attachment:image.png)

Figure 4. Average of (a) transition period of winter to summer ($T_{WS}$) in days and (b) transition period of summer to winter ($T_{SW}$) in days for 1951–2010, (b) scatter plot of the $T_{WS}$ (days) and $T_{SW}$ (days) for the first (1951–1960), middle (1976–1985) and last (2001–2010) decade along with the respective marginal probability plots. Spatial evolution of the ensemble empirical mode decomposition trend of (d) $T_{WS}$ (days) and (e) $T_{SW}$ (days). Each sub-panel has four windows (1) 1951–1980, (2) 1951–1990, (3) 1951–2000 and (4) 1951–2010. Grids with inconsistent data are shown in dark grey colour (extreme left of the colour bar), which is represented as NA (Not Analyzed). Plus (+) sign represents the grids with a statistically significant positive and negative trend. Statistical significance is estimated for 10% significance level using the two-tailed hypothesis test.
night-time and day-time temperatures, with the variation especially prominent in the day-time temperature of the latter phase (second mode—October to November). To tackle this dynamic weather, it is necessary to adopt adaptation options such as dynamic cropping pattern and flexible human working hours in tropical countries like India.

4. Conclusion

This analysis draws attention to the possibly increasing vulnerability of two productive elements, i.e. crop production and human comfort, due to the intensification/shifting in the annual cycles and the joint behaviour of diurnal temperature extremes. The following conclusions are derived from this study:

i. Higher probability of $T_{\text{max}}$ (30 °C–22 °C) and $T_{\text{min}}$ (22 °C–24 °C) observed in central India and North East shows that hot extremes have intensified, while cold extremes are waning.

ii. There is an evident increase in the night-time and day-time temperatures, especially the intensification is more prominent in the day-time temperature of the latter phase (second mode—October—November).

iii. A refined definition of GSL for the tropical region sounds reasonable, as it agrees with the changes in the crop yield and sowing date reported by the previous studies.

iv. The decline in comfort days and nights in warm humid regions reveals that summer is encroaching into the transition period.

v. Comfort days and nights (transition period) are increasing in semi-arid regions (northwest), an area known for the low and high-temperature extremes. The increase, however insignificant may be, is found to be due to shortened winters, without much relief evident during the summers.

The study highlights the importance of adopting adaptation options such as dynamic cropping pattern, change in crop variants and types, and flexible human working hours in tropical countries like India, to tackle its highly dynamic weather. Also, it provides quantified figures on the onset and the length of GS, grid-wise, which will aid in devising region-wise adaptive and mitigative measures, such as earlier sowing and cultivating crop varieties tolerant to thermal stress. Besides, we emphasise the need for an in-depth study of hourly variation of temperatures to formulate regulations on the maximum limit of the exposure of workers to higher temperatures. Further, it is suggested that the existing international guidelines should also be corroborated using the available facts about the seasonal temperature variations.

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