

RESEARCH ARTICLE

Evidence of asymmetric change in diurnal temperature range in recent decades over different agro-climatic zones of India

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Abstract

Diurnal temperature range (DTR) is an important indicator of climatic change and a critical thermal metric to assess the impact on agriculture and human health. This study investigates the seasonal, annual and decadal changes in the spatio-temporal trend in DTR and air temperatures (maximum: T_{\max} and minimum: T_{\min}) during 1951–2016 and solar radiation (Srad) during 1984–2016 over 14 different agro-climatic zones (ACZs) in India. The changes in the DTR trend between two time periods: 1951–2016 and 1991–2016 (recent period) are also assessed. The results indicate an overall increasing trend in DTR ($0.038^{\circ}\text{C}/\text{decade}$), T_{\max} ($0.078^{\circ}\text{C}/\text{decade}$, significant), T_{\min} ($0.049^{\circ}\text{C}/\text{decade}$) during 1951–2016 and Srad ($0.10 \text{ MJ}/\text{m}^2/\text{day}/\text{decade}$) during 1984–2016. However, a decreasing trend in DTR ($-0.02^{\circ}\text{C}/\text{decade}$) and a significant increasing trend in T_{\min} ($0.210^{\circ}\text{C}/\text{decade}$) was noted during 1991–2016. The decadal changes showed an evident decline in DTR during the recent period since 1991. The relative increase in T_{\min} ($0.21^{\circ}\text{C}/\text{decade}$, significant) compared to T_{\max} ($0.18^{\circ}\text{C}/\text{decade}$) resulted in a decreasing DTR trend. This was evident across the 5 out of the 14 agro-climatic zones for the 1991–2016 period. The seasonal analysis showed a significant (95%) increasing trend in DTR during pre-monsoon and monsoon (1951–2016), and a negative trend for the post-monsoon and monsoon since 1991. There were also interesting spatial differences found with the ACZs in the north-west, parts of Gangetic plain, north-east, and central India exhibiting negative DTR trends. The effect of Srad is larger on T_{\max} than T_{\min} ; therefore, the decrease in Srad in parts of Gangetic plain likely contributed to a smaller increase in T_{\max} relative to T_{\min} and led to a decreasing trend in DTR. At the same time, the west coast, east coast, and southern region show positive trends. The observational analysis finds a distinct increase in the T_{\min} and also highlights the need for future assessments to continue investigate the causes of these spatio-temporal changes found in this study.

KEYWORDS

agro-climatic zones, decadal changes, diurnal temperature range

1 | INTRODUCTION

Across parts of the world, the minimum temperature (T_{\min}) is increasing at a much faster rate than maximum temperature (T_{\max}) and hence causing diurnal temperature range (DTR) to decrease (Karl *et al.*, 1991, 1993; Braganza *et al.*, 2004; He *et al.*, 2015). Past studies related to DTR changes reported a global decrease of -0.07°C per decade during 1950–1980 (Vose *et al.*, 2005). In another study, a significant decreasing trend in global DTR (-0.036°C decade $^{-1}$) was reported with a relatively smaller increase in the T_{\max} as compared to the T_{\min} (1.1°C vs. 1.6°C) between 1901 and 2014 (Sun *et al.*, 2018). Despite these global conclusions, the DTR trend is highly heterogeneous with variable trends found for parts of northern Eurasia, western North America, Australia, and the Indian subcontinent (Kumar *et al.*, 1994).

Although DTR has become an important factor for climate change, few studies have discussed its spatio-temporal changes and trends. As the changes in T_{\max} and T_{\min} are not uniform, an asymmetry between T_{\max} and T_{\min} can cause an increase/decrease in the DTR (Karl *et al.*, 1991, 1993; Dai *et al.*, 1999; Zhou *et al.*, 2008). Importantly, any changes in DTR would lead to an increase in the risks of drought and heat stress Braganza *et al.* (2004) that in turn may add up to cause crop failure (Mueller and Seneviratne, 2012; Bhatt *et al.*, 2019), increase morbidity in humans Hirschi *et al.* (2011) and mortality rate (Yang *et al.*, 2018). The DTR characteristics strongly influence public health (He *et al.*, 2015; Yang *et al.*, 2018; Singh *et al.*, 2020a). Failure to adjust to the DTR variation might cause increased blood pressure, heart rate, and oxygen requirement (Lim *et al.*, 2012). A study conducted for 308 cities in 10 countries showed an increase in attributable risk fraction to DTR increased from 2.4% (2.1–2.7%) to 2.7% (2.4–2.9%) between 1972 and 2013 (Lee *et al.*, 2017). A decreasing trend in DTR and a negative association with mortality was evident in a study from India (Singh *et al.*, 2019). The health and agronomic impacts are often regional, and additional studies have been sought (Lee *et al.*, 2017; Mall *et al.*, 2017; Tyagi *et al.*, 2019; Singh *et al.*, 2020b; Singh *et al.*, 2021).

A change (lowering) in DTR (often due to high nighttime temperatures) was found to cause an overall adverse effect on vegetative growth in maize in the form of a decrease in total sugars (linear) as well as non-reducing sugars, plant height, total leaf area, and total biomass accumulation (Mall *et al.*, 2006; Sunoj *et al.*, 2016). The negative response of high day and night time temperature on physiological and biochemical processes has been studied for many crops. Examples exist for wheat-Triticumaestivum (Prasad *et al.*, 2011), soybean *Glycine max* (Mall *et al.*, 2006; Djanaguiraman *et al.*, 2013), sorghum, and rice *Oryza sativa* (Aggarwal and

Mall, 2002; Lobell and Ortiz-Monasterio, 2007). There are mixed results about the possibility of future projections and yields. Lobell *et al.* (2017) study considered DTR changes from 11 models (2046–2065) and found an increase in DTR in wheat-growing areas and a decrease in rice-growing areas. The negative effect of DTR has reduced the U.S. maize and India rice yields. On the other hand, an increase/decrease in DTR is known to have a beneficial impact on crops where grain filling and development rates are more sensitive to T_{\min} than T_{\max} (Wilkins and Singh, 2001; Singh *et al.*, 2016; Mall *et al.*, 2018; Sonkar *et al.*, 2019) and where chilling temperatures can cause crop injury or death (Lobell *et al.*, 2006). There are several additional mechanisms through which DTR can influence crop development and yield, but the current understanding is limited.

Recognizing the heterogeneity in the trends for DTR around the globe, a better understanding is required to study the impact of regional DTR on crop and human health. The diurnal asymmetry of temperature over India, with its active monsoon pattern, is quite different from the other parts of the world. Studies have reported an overall increase in DTR with a significant increase in T_{\max} relative to the 1901–2003 period (Rai *et al.*, 2012). For the same period, Kothawale and Rupa (2005) also reported an increase in annual Tmean (0.05°C decade $^{-1}$). Kumar *et al.* (1994) studied the DTR changes from 1960 to 1987, while Rai *et al.* (2012) and Qu *et al.* (2014) analysed the same from 1901 to 2003, and the studies report an increase in DTR annually and seasonally. The seasonal analysis of DTR showed the highest increase in winter and lowest in the post-monsoon period.

In different agro-ecological zones that witness wide diurnal temperature variation, a small relative change in temperature can have a notable impact plausibly negative. A study by Vinnarasi *et al.* (2017) over different climate zones in India reported an overall $0.36 (^{\circ}\text{C})$ increase in mean DTR till 1980 and a decline further. They reported a positive trend in the west coast and subtropical forest in the north-east and a sound change in DTR in winter and post-monsoon in the arid desert and warm-temperate grasslands. Notably, a decrease in DTR by up to 2°C was observed, in places where the increase in the rate of T_{\min} was higher than the T_{\max} was observed. The changes in DTR were heterogeneous and highly dependent on the local climatic zone.

We found there has been no study on the decadal changes in DTR that could show a much clear picture of the advent of recent warming. Also, it is important from the context of regional agro-climatic adaptation approaches to analyse the rate of increase in two different periods, one that shows the background rate of change and the other that shows warming in recent times. As discussed, the local climate zone can change the rate of change through its

diverse characteristics. Accordingly, in this study, the changes in DTR over different agro-climatic zones across India are considered. Keeping the existing research gap and need, the core of the study seeks to assess the annual seasonal and decadal trends in air temperature (maximum and minimum) and DTR over 14 different agro-climatic zones in India for 66 years (1951–2016). The spatio-temporal trends in DTR and air temperatures for two different periods, that is, the entire period of 66 years (1951–2016) and the recent period (1991–2016) are also undertaken.

2 | MATERIAL AND METHODS

2.1 | Study area

India covers an area of about 3.28 million sq. km. between the latitude of $8^{\circ}4'$ to $37^{\circ}6'N$ and longitude of $68^{\circ}7'$ to $97^{\circ}25'E$. India possesses great diversity over landforms from deep valleys, extensive plains to high mountains, plateau and coastal Ghats, islands and the desert. Therefore, the analysis of DTR changes over 14 agro-climatic zones of India is undertaken. Figure 1

shows these agro-climatic zones that have been developed based on soil, climate and cropping patterns (Alagh, 1990). Note that one additional zone lies outside the mainland and is not considered. The 14 agro-climatic zones are referred to as Western Himalayan (WH), Eastern Himalayan (EH), Lower Gangetic Plain (LGP), Middle Gangetic Plain (MGP), Upper Gangetic Plain (UGP), Trans Gangetic Plain (TGP), Eastern Plateaus & Hills (EPH), Central Plateau Hills Region (CPH), Western Plateau Hills (WPH), Southern Plateau Hills Region (SPH), East Coast Plains (ECP), West Coast Plains (WCP), Gujarat Plain Hills (GPH), Western Dry (WD) regions.

2.2 | Data and methodology

The observed daily minimum and maximum air temperature data of the past 66 years (1951–2016) is acquired from India Meteorological Department (IMD) for the study area and analysed for 1,167 grid boxes at $0.5^{\circ} \times 0.5^{\circ}$ resolution. Initially, the daily air temperature data for the period of 1951–1979 was available at $1^{\circ} \times 1^{\circ}$ resolution, while the

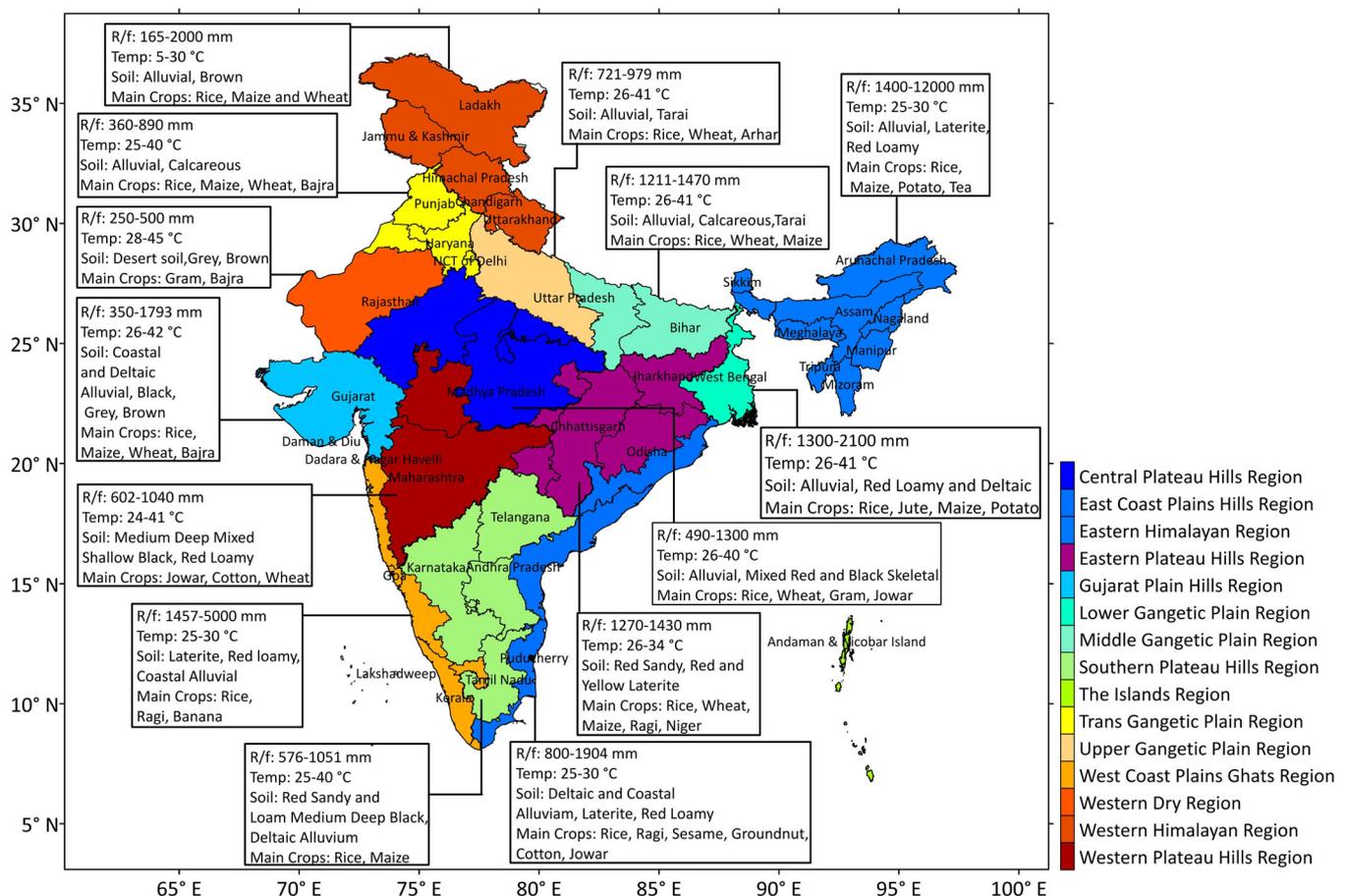


FIGURE 1 Different agro-climatic zones of India [Colour figure can be viewed at wileyonlinelibrary.com]

data from 1980 to 2016 was available at $0.5^\circ \times 0.5^\circ$. To obtain a homogeneous, high-resolution temperature dataset for the entire study period (1951–2016), the $1^\circ \times 1^\circ$ resolution was re-gridded to 0.5° using a bilinear interpolation method. Additionally, to understand the possible reasons for the changes in the temperature patterns, the daily surface Srad data was obtained from the NASA POWER (Prediction of Worldwide Energy Resources- power.larc.nasa.gov). This data was at 1° resolution for the period 1984–2016. The data has been screened, taking into account the problem of missing data by discarding the years with monthly records of less than 6 months or excluded grids where data were missing substantially. Ultimately, data from 1,099 grids were used in this analysis. The dataset was divided into four seasons; winter (January–February), pre-monsoon (March–May), monsoon (June–September) and post-monsoon (October–December) according to IMD. The DTR was calculated by subtracting the daily T_{\min} from the T_{\max} at each grid box ($DTR = T_{\max} - T_{\min}$).

These daily DTR, T_{\max} , T_{\min} and Srad values were then averaged on a seasonal and annual basis for further analysis, including the annual and seasonal trends in the DTR, T_{\max} , T_{\min} and Srad. The trend was also calculated to assess the spatial variation among different agro-climatic zones for the two study periods, that is, 1951–2016 (1984–2016 for Srad) and 1991–2016. The trend was obtained by the ordinary linear least-square method to calculate the linear trend between time (1951–2016) and temperature ($^\circ\text{C}$) and Srad ($\text{MJ m}^{-2}\text{day}^{-1}$). Moreover, the decadal analysis of DTR seasonally and annually was also calculated to cover the decadal variation in DTR. The trend for the recent past (1991–2016) was then calculated to review the changes in DTR. The 1990 threshold corresponds to when rapid urbanization and economic liberalization saw regional changes post-1990s in India. The modified Mann-Kendall test (Hamed and Rao, 1998) using (Kendall's tau and Sen's slope) were used to detect the change in trend at 95% confidence level ($p < .05$). The modified Mann-Kendall test takes into account the problem of autocorrelation, and thus, the tau and slope value are free of autocorrelation and data normalization. Pearson's correlation coefficient (r) was calculated to estimate the strength of the correlation between DTR and T_{\max} , T_{\min} , and Srad. Values at $p < .05$ were considered significant.

3 | RESULT AND DISCUSSION

3.1 | Correlation analysis

Figure S1a–c shows the relation between the annual DTR with T_{\max} , T_{\min} , and Srad. DTR is positively correlated

with T_{\max} ($r = .6$, significant) and Srad ($r = .2$) and negatively correlated with T_{\min} ($r = -0.3$, significant). Similar relationships were found for the upper Second Songhua River Basin (Wang *et al.*, 2014), Northeast India (Jhajharia and Singh, 2011), and in lower-elevation sites in the Swiss Alps (Rebetez and Beniston, 1998). The effect of Srad is thus more on T_{\max} than T_{\min} due to its presence only during the day (Wang *et al.*, 2014). Thus an increase in Srad may cause an increase in T_{\max} and thus a subsequent increase in DTR.

3.2 | Annual and seasonal trends in air temperature, Srad, and DTR over India

Figure 2 shows the annual and seasonal variations for DTR, T_{\max} , and T_{\min} over India covering the entire period of 66 years (1951–2016), the recent period of 26 years (1991–2016) and Srad (1984–2016). The non-parametric MK trend indicated an overall increase in DTR by 0.25°C for the 66 years (1951–2016), while the recent 26 years (1991–2016) DTR showed a decrease by -0.05°C (Table 1). Also, the annual linear trend showed that there is an increase in T_{\max} and T_{\min} for both periods and Srad during 1984–2016. However, it also shows a (significantly) larger rate of increase in T_{\min} during the recent period compared to T_{\max} , which attributes to the decline in DTR. Similarly, Vinnarasi *et al.* (2017) found an increase in DTR (0.36°C) over India during 1951–1980 and then a decline during 1981–2010, primarily due to an increase in T_{\min} . Similar findings were noted in the study by Jhajharia and Singh (2011) and Sun *et al.* (2018), highlighting the robustness of the results.

The monsoon and pre-monsoon season show a significant increase of DTR by $0.07^\circ\text{C}/\text{decade}$ and $0.07^\circ\text{C}/\text{decade}$, respectively, and a declining trend in the winter season during 1951–2016 Figure 1. While the recent period of 1991–2016, DTR showed a small declining trend during monsoon season ($-0.01^\circ\text{C}/\text{decade}$) and post-monsoon season ($-0.06^\circ\text{C}/\text{decade}$) and a small increase in winter and pre-monsoon season Figure 2. A relatively high increase in T_{\min} and T_{\max} was noted with a faster increase in T_{\min} during the recent period. The post-monsoon season showed the highest increase in both T_{\max} and T_{\min} during 1951–2016, while during the recent period (1991–2016), T_{\max} and T_{\min} showed more increase during the pre-monsoon season Figure 2. The post-monsoon season witnessed the highest warming in 1951–2016, which is different in the recent period where the pre-monsoon season showed the largest seasonal warming (from 1991 through 2016).

Srad, on the other hand, displayed a mixed effect with a consistently increasing trend for the monsoon period

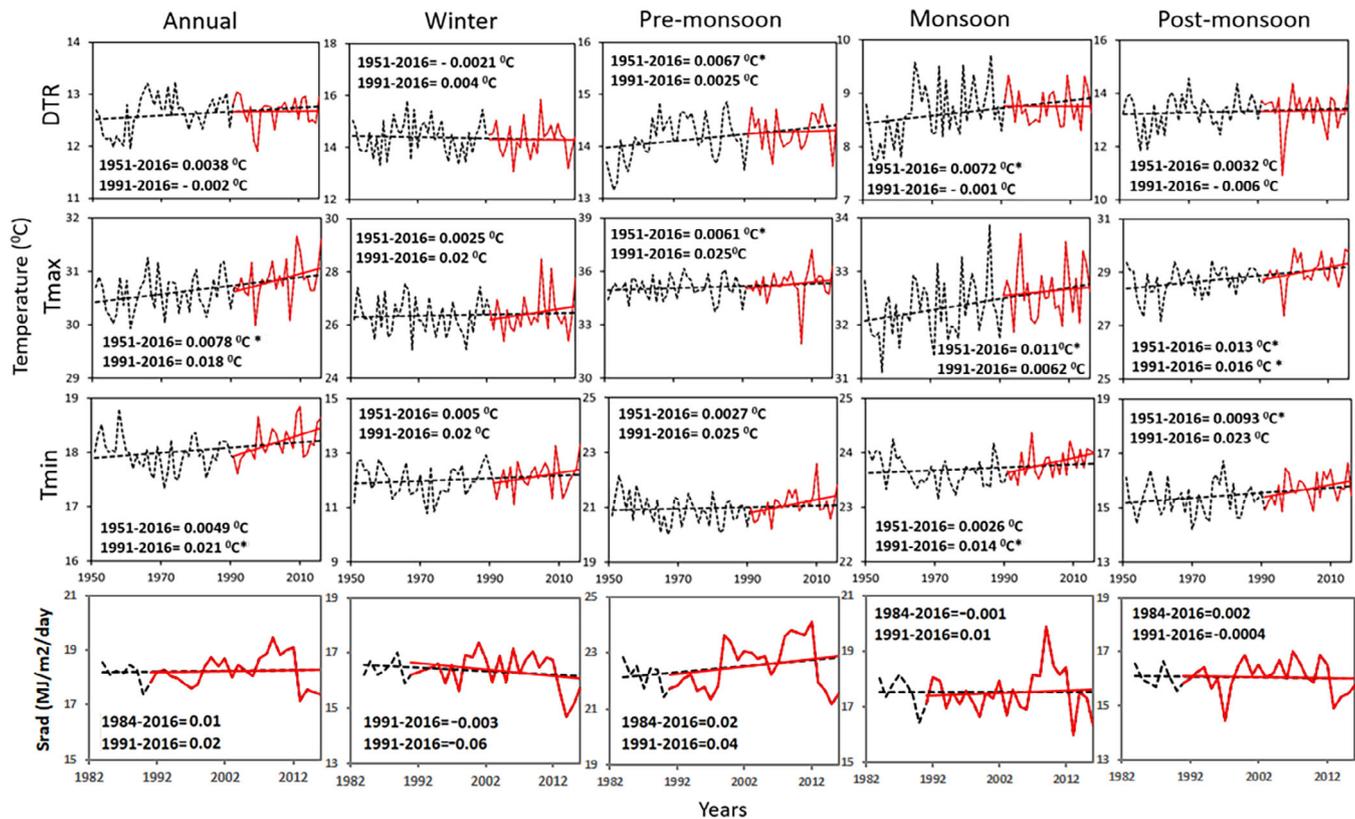


FIGURE 2 Annual and seasonal variation of spatially averaged DTR, T_{\max} , T_{\min} , and Srads over India with linear time trends. The values within the graph show the yearly trend for two time periods of 1951–2016 and 1991–2016 [Colour figure can be viewed at wileyonlinelibrary.com]

TABLE 1 Annual and seasonal long-term temperature values over India for the period of 1951–2016 and 1991–2016 (* denote trends at 95% significance level)

		DTR	Maximum temperature	Minimum temperature
Annual	1951–16	0.25	0.52*	0.32
	1991–16	-0.05	0.47	0.55*
Winter	1951–16	-0.14	0.17	0.33
	1991–16	0.10	0.52	0.52
Pre-monsoon	1951–16	0.44*	0.40*	0.18
	1991–16	0.07	0.65	0.65
Monsoon	1951–16	0.48*	0.73*	0.17
	1991–16	-0.03	0.16	0.36*
Post-monsoon	1951–16	0.21	0.86*	0.61*
	1991–16	-0.16	0.42*	0.60

Abbreviation: DTR, diurnal temperature range.

and a decreasing trend during winter for both the periods (insignificant). However, as the Srads analysis is present only since 1984, the variation in Srads would be much more representative of the recent variation in DTR (and

not since 1951). The increasing trend in Srads during monsoon and the decreasing trend in post-monsoon could lead to a less negative trend in DTR in monsoon and a more decreasing trend in DTR in Post monsoon during 1991–2016. This conclusion is supported by Jhajharia and Singh (2011) analysis over northeast India. The decrease in DTR is supported by the increased loading in atmospheric aerosols that reflect solar radiation and modify cloud properties (e.g., Niyogi *et al.*, 2007; Roy, 2008; Stjern *et al.*, 2020). The findings are consistent with those reported by Sun *et al.* (2018), who reported a 1.5 times higher increase in T_{\min} than T_{\max} , which led to a significant decrease in global DTR between 1901 and 2014 that increased in the first halves of the century and declined later. A similar finding was reported in the work of Rai *et al.* (2012) and Vinnarasi *et al.* (2017) over India (though for a smaller and different period). The analysis by Kothawale *et al.* (2010), Mondal *et al.* (2015), and Jaswal *et al.* (2016) over India considering the seasonal changes in DTR showed significant changes during pre-monsoon, post-monsoon, and winter. Thus the analysis in this study further confirms and extends the broader conclusion emerging regarding the warming in the latter half of the century.

Apart from T_{\max} and T_{\min} , S_{rad} and total cloud cover (TCC) are considered as part of the DTR analysis in the regional and global analysis (Makowski *et al.*, 2008; Stjern *et al.*, 2020). The effect of S_{rad} is positive on DTR because of the apparent effect on daytime T_{\max} relative to T_{\min} due (Wild *et al.*, 2007; Makowski *et al.*, 2008); whereas, clouds can have a negative effect on DTR as they reflect sunlight during the day but enhance downward longwave radiation during the night thus causing a decrease in T_{\max} but increase in T_{\min} (Dai *et al.*, 1999; Zhou *et al.*, 2008; Wang *et al.*, 2014). Other possible factors that influence DTR are surface soil moisture and precipitation (Dai *et al.*, 1999), land surface temperature and land-use changes (Kalnay and Cai, 2003), vegetation and leaf area index (Collatz *et al.*, 2000), and atmospheric aerosols (Wang *et al.*, 2014).

Decreasing DTR has several adverse consequences. For example, a significant reduction in crop yield due to decreased photosynthetic rate, antioxidant scavenging capacity, photochemical efficiency, increased respiration, and carbon loss leading to altered sugar metabolism and lowered biomass accumulation was observed in winter wheat and other crops under low DTR and high T_{\min} exposure (Peng *et al.*, 2004; Lobell *et al.*, 2006; Lobell and Ortiz-Monasterio, 2007; Matsuda *et al.*, 2014). Further, the incremental risk in mortality concomitant with the change in DTR was also reported in different multi-country and multi-community studies (Carreras *et al.*, 2015; Lee *et al.*, 2017; Yang *et al.*, 2018; Singh *et al.*, 2019). In a study by Singh *et al.* (2019), over

Varanasi city, India, a decrease in DTR was noted to correspond to an increased risk of mortality by 0.61% (95% CI: 0.25%,1.01%). In the majority of mortality cases, the leading cause of death is obstructive pulmonary diseases (Song *et al.*, 2008), coronary heart diseases (Cao *et al.*, 2009), or cerebrovascular diseases (Smolensky *et al.*, 2015). It has been suggested that failure to get heat relief, particularly at night after sustained high day temperature, that is low DTR, increases the risk of heat-related mortality (Kovats and Hajat, 2008).

3.3 | DTR trend over diverse agro-climatic zones

To further understand the temporal evolution of different temperature metrics and S_{rad} of annual and seasonal (explained in a subsequent section), the analysis was repeated and analysed for the 14 different agro-climatic zones of India Table S1.

3.3.1 | The annual variation

A consistent increasing trend (except for WH, MGP, UGP, and TGP) was observed for T_{\max} and T_{\min} , which results in variation in DTR trend from the increase of 0.4°C per decade (ECP, WCP, and SPH) to decrease to -0.2°C per decade (TGP, UGP, and CPH) across the zones (1951–2016; Figure 3).

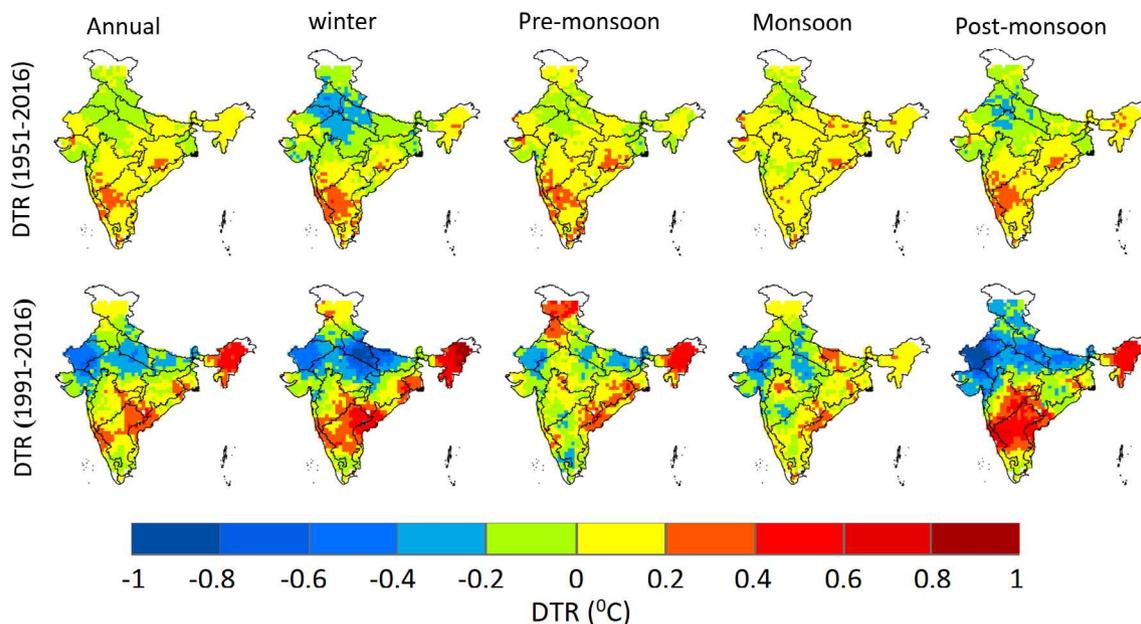


FIGURE 3 Decadal trends of diurnal temperature range over the different agro-climatic zones of India during 1951–2016 and 1991–2016 [Colour figure can be viewed at wileyonlinelibrary.com]

During the later period of 1991–2016, a quantitative increase in a negative trend of DTR in major parts of northern and western India ($0\text{--}0.6^\circ\text{C}/\text{decade}$) was visible, attributed mainly to the large increase in T_{\min} relative to T_{\max} Figures 4 and 5. However, an increasing trend in DTR was also noted in most parts of EH and parts of south India. The significance of trends is assessed at a 5% significance level, and the zones showing the significant

trends for all variables are shown in Figures S2 and S3 and Table S1. Analysis of T_{\max} reveals an increasing trend over most parts of India in both periods. However, a larger increase in trend was noted for the EH region ($0.4\text{--}0.8^\circ\text{C}/\text{decade}$) and the peninsular (WPH and SPH) and south-west coast region ($0.2\text{--}0.4^\circ\text{C}/\text{decade}$) for the recent period (1991–2016; Figure 4). Unlike T_{\max} , a large increase in the T_{\min} trend at a rate of $0\text{--}0.8^\circ\text{C}/\text{decade}$

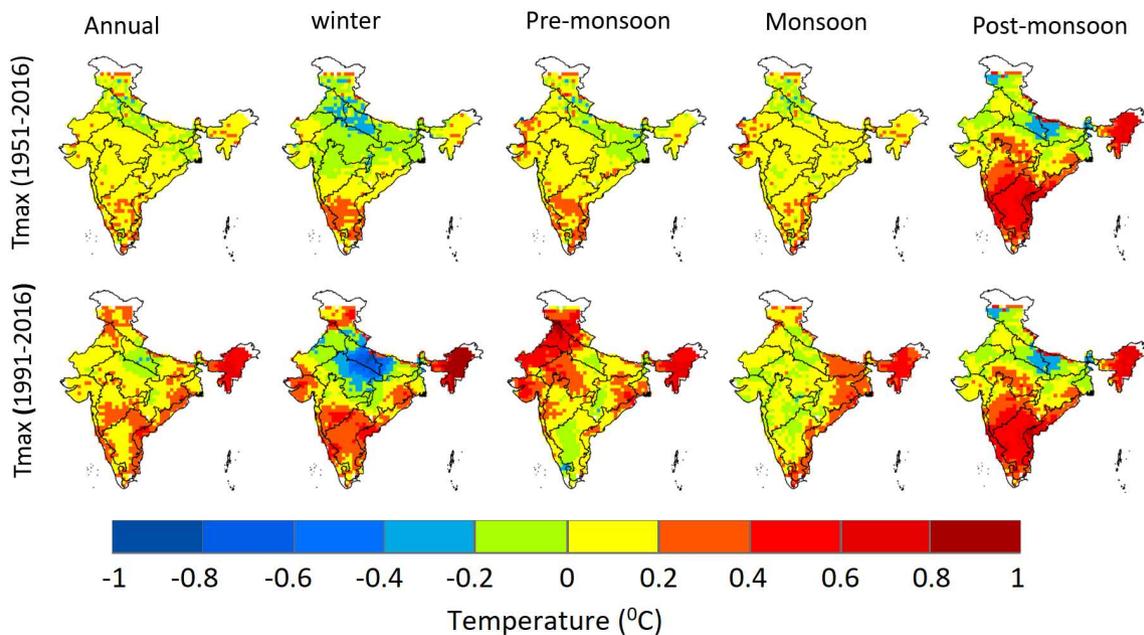


FIGURE 4 Decadal trends of T_{\max} over the different agro-climatic zones of India during 1951–2016 and 1991–2016 [Colour figure can be viewed at wileyonlinelibrary.com]

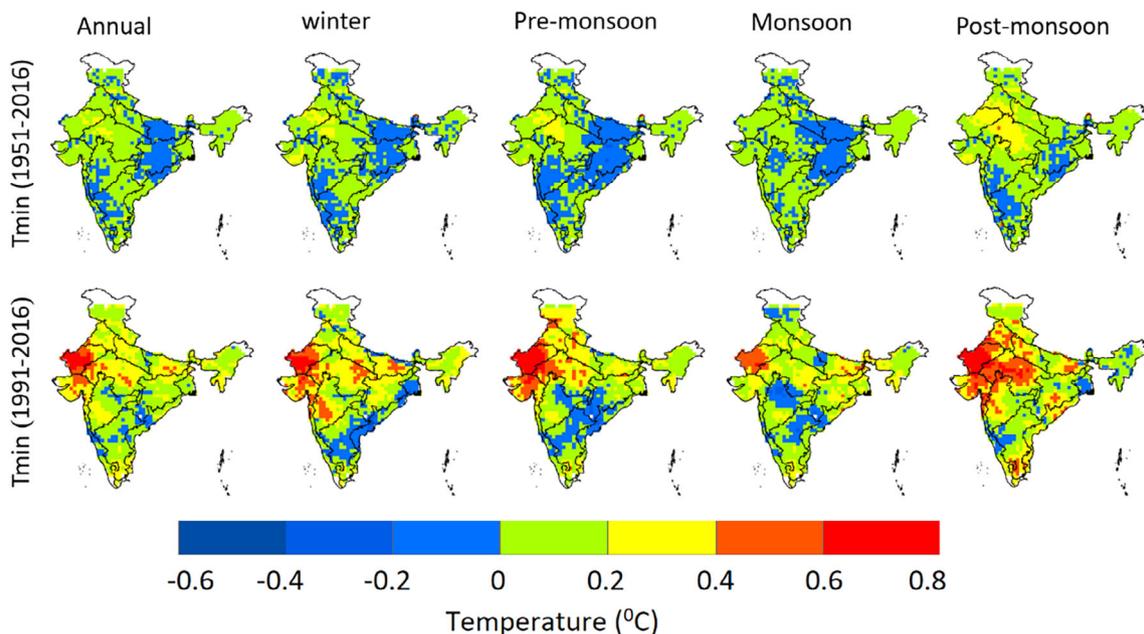


FIGURE 5 Decadal trends of T_{\min} over the different agro-climatic zones of India during 1951–2016 and 1991–2016 [Colour figure can be viewed at wileyonlinelibrary.com]

(a significant increase of $0.3^{\circ}\text{C}/\text{decade}$ into Gangetic plain region) was observed for the recent decades (1991–2016; Figure 5). A gradual increase in Srad (up to $+0.6 \text{ MJ m}^{-2}/\text{decade}$ from 1951 to 2016 to $1.0 \text{ MJ m}^{-2}/\text{decade}$ during 1991–2016) was also observed for most parts of India except Himalayan and Gangetic plain where a declining trend was observed (Figure 6). This explains the decrease in DTR for the recent warming period (1991–2016) in which a larger increase in T_{\min} over the Himalayan region and Gangetic plain was observed. Our results are in line with the findings of Sonkar *et al.* (2019), who reported an overall increasing trend in T_{\max} ($0.02\text{--}0.29^{\circ}\text{C}/\text{decade}$ highest over the southern region) and T_{\min} ($0.16\text{--}0.29^{\circ}\text{C}/\text{decade}$) and Srad ($0.013\text{--}0.027 \text{ MJ m}^{-2} \text{ day}^{-1}/\text{decade}$) with a notable increase in T_{\min} over northern India. The persistent warming over the southern and north-western region likely coincides with the presence of anthropogenic brown haze that usually absorbs the short-wave solar radiation (Kulkarni *et al.*, 2012; Ross *et al.*, 2018).

The surface net radiation is also influenced by land surface changes, which are rapidly underway across India (Niyogi *et al.*, 2018). The landuse/land cover change (LULC) primarily modifies the surface albedo which in turn alters the surface radiative properties and the surface temperatures (Wen-Jian and Hai-Shan, 2013). An overview of the pathways causing the DTR change due to LULC is outlined in Pielke *et al.* (2011). The change in land surface alters the surface energy balance, which in turn modifies the daytime maximum temperature as well

as the nocturnal radiative cooling which can alter the T_{\min} (Niyogi, 2019). LULC influences regional and spatial differences in the trend of DTR as shown by Gallo *et al.* (1996) for the U.S. Historical Climate Network data, and by Mohan and Kandya (2015) for Indian airshed as an example. LULC changes could lead to a decrease in DTR, which is mainly caused by the reduction in daily maximum temperature (Wen-Jian and Hai-Shan, 2013). In general, the LUCC significantly controls the DTR change through the changes in land evaporation and vegetation transpiration, which is altered as the land surface characteristics change. In the context of Indian region, agroclimatic-based LULC- DTR has also been noted for few locales (e.g., Majumder *et al.*, 2020), and a more comprehensive analysis is pending.

3.3.2 | The seasonal variation

In the seasonal analysis, the post-monsoon and winter season showed a negative trend in DTR primarily over the northern agro-climatic zones (EH, WD, TGP, UGP, MGP, and TGP) with values typically varying from -0.1 to -0.4°C per decade (Figure 3) and a positive trend in other regions during 1951–2016. The spatial extent of the negative trend increased during 1991–2016, and in fact, a more robust trend was noted with a decrease of almost 1.6°C ($-0.6^{\circ}\text{C}/\text{decade}$ for winter) in UGP and 2°C (-0.83°C per decade; post-monsoon) in WD region (Figure 3). Moreover, the increasing trend in DTR

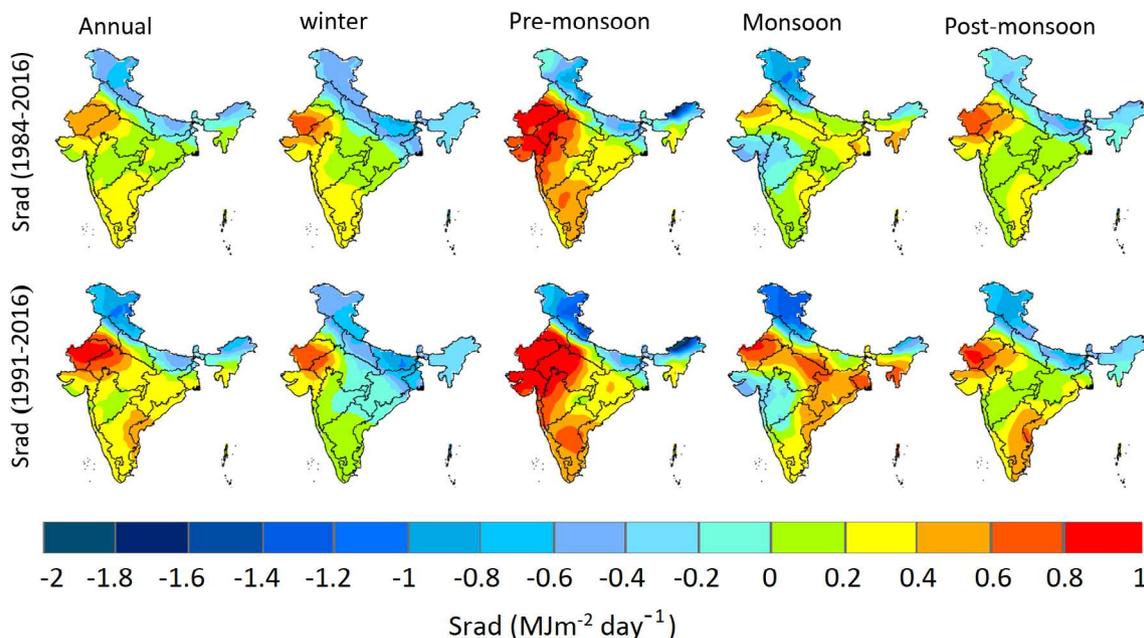


FIGURE 6 Decadal trends of Srad over the different agro-climatic zones of India during 1984–2016 and 1991–2016 [Colour figure can be viewed at wileyonlinelibrary.com]

remained consistent or unchanged for other zones namely: WH and EH, Peninsular India (WCP, ECP, WPH, and SPH) during the pre-monsoon season, and other parts across India have shown unanimous decrease (Figure 3).

Putting the above results in a broader context, Waqas and Athar (2019) reported a decrease in DTR over the Hindukush Karakoram Himalaya region, and Roy and Balling (2005) found no significant trend over different regions of India but mostly declining (-0.30 to 0.14°C ; 1931–2002) trend for the winter season. The increasing trend in DTR during the post-monsoon season was found, as stated earlier, in the work of Jhajharia and Singh (2011) over EH (1976–2000) and by Jamir *et al.* (2016) over North-east (EH) and west coast (1901–2010). The overall seasonal changes in the DTR trend also follow the conclusions discussed in Kumar *et al.* (1994) and Vinnarasi *et al.* (2017). Other seasons like pre-monsoon and monsoon also showed a negative DTR trend for both periods. A quantifiable increase in negative trend was apparent for 1991–2016 for most of the zones, including parts of North-west (WD and GPH), Indo-Gangetic Plain (UGP and MGP), CPH and WPH during pre-monsoon and monsoon season Figure 3.

The variation in seasonal DTR can be attributed based on further understanding of the variation in T_{max} , T_{min} , and Srad (Figures 4–6). The increasing trend in T_{max} was observed for all the seasons during both 1951–2016 (0.01 – $0.8^{\circ}\text{C}/\text{decade}$ in all seasons) and 1991–2016 ($0.78^{\circ}\text{C}/\text{decade}$ in EH during winter). However, the increase in T_{max} was weak or declining over parts of Indo-Gangetic plain (TGP, UGP, and MGP), WD and CPH, particularly in winter, monsoon and post-monsoon season 1991–2016. Similarly, like T_{max} , there has been a significant increase in T_{min} prominently for the WD, over EPH during winter, UGP, CPH, GPH, and WD region during pre-monsoon season and EH, GP, and WD Region during monsoon and post-monsoon season with an increase of up to 2°C (Figure 5). As the warming was intense and apparent for all seasons and that the rate of increase in T_{min} is substantially higher than T_{max} , the end outcome is a decrease in DTR. This decrease is more in recent decades from 1991 to 2016 relative to the 66 years from 1951 to 2016. We found that the unanimous increase in both T_{min} and T_{max} in diverse agro-climatic zones of India has vastly influenced the evolution in DTR, where local and regional factors can further explain the variation at a finer level.

Surface radiation is affected by local variability in cloudiness and aerosols, and large spatial heterogeneity was observed for the trend in Srad Figure 6. A consistent positive trend in all season was reported in different parts of the western and peninsular region in both time

periods, but a declining trend was prominent in Himalayan ($\sim 1 \text{ MJ m}^{-2}/\text{decade}$ in 1991–2016 during monsoon) and Gangetic plain ($0.87 \text{ MJ m}^{-2}/\text{decade}$ in monsoon in Middle Gangetic Plain during 1991–2016). Solar radiation-clouds-aerosols may impact DTR by altering radiative flux, modifications in cloud microphysical properties, the thermal balance of lower atmosphere, and surface insolation. There are reports of the persistence of thick aerosol layer over the Indo-Gangetic Plain (IGP; Kumar *et al.*, 2018), that has been indirectly linked to cloudiness and solar dimming over IGP and rise in T_{min} (Padma Kumari and Goswami, 2010). The consistent decrease in Srad due to a systematic rise in airborne particulate concentration was reported in several other studies (Hu *et al.*, 2017). However, a focused topical investigation is beyond the scope of this study.

3.3.3 | The decadal variation

The spatio-temporal decadal analysis of DTR shows an increase in DTR from 1951–1960 till 1981–1990 and decreased after that Figure 5. There is an increase of about 2°C from 1951–1960 to 2010–2016. The increase was most notable in 1981–1990 and showed a decrease, particularly in terms of spatial extent in later decades. The increase has been consistent and followed the same pattern across the seasons, and the increase was most visible in grids of northern, central, and western India Figure 7. The decrease in DTR in recent decades over a larger part of India and more specific to the north-west (WD and TGP) and CPH, is consistent with the broader regions reported in Zhou *et al.* (2007, 2008) and appears to be part of large-scale climatic changes. Chen and Dirmeyer (2019) recently summarized that the climate forcing from LULC exerts relatively strong impacts on hot extremes and DTR compared with other anthropogenic forcings. A number of studies indicate that LULC alter the energy and water cycles, thus contribute significantly to the changes in the climate variables such as maximum and minimum temperature, evapotranspiration and hence the DTR (Kishtawal *et al.*, 2010; Niyogi *et al.*, 2011; Mohan and Kandya, 2015; Shen *et al.*, 2017). Nayak and Mandal (2019a) studied and shows that even though the LULC contributed towards overall cooling during 1981–2006 over India, it contributed towards warming during 1991–2006. In a study, Nayak and Mandal (2012) highlighted that LULC over Western India contributed to warming by 0.06°C per decade mainly due to the decrease of forests and increase of agricultural lands. In another study, Nayak and Mandal (2019b) find LULC over Eastern India contributed towards the warming at a rate of $\sim 0.2^{\circ}\text{C}$ per decade due

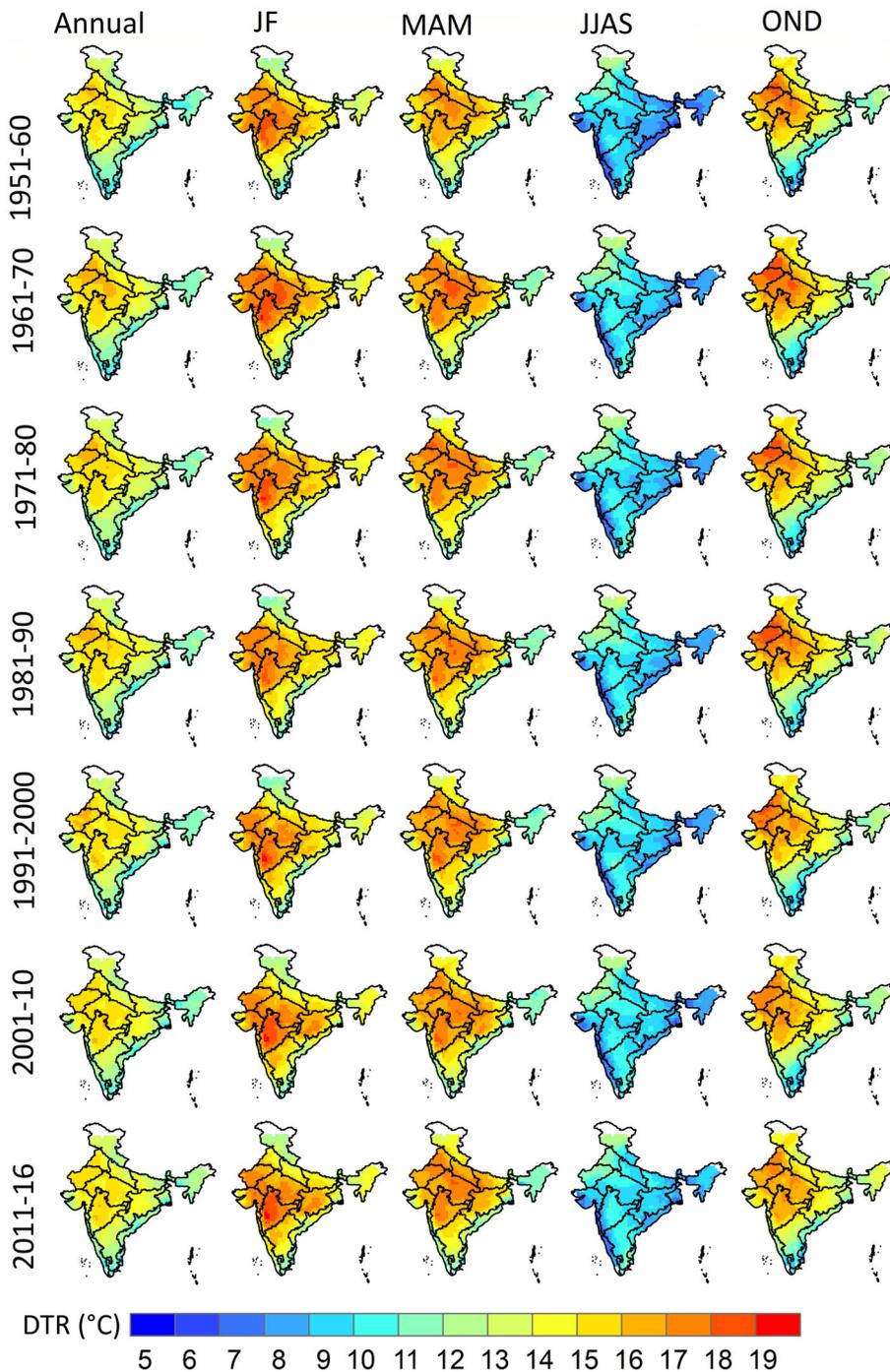


FIGURE 7 Decadal spatial variation for diurnal temperature range during 1951–2016 [Colour figure can be viewed at wileyonlinelibrary.com]

to the conversions of shrubs/agricultural/fallow land into bare land. Thus, there is a clear signal of LULC feedback on the DTR changes, which remains to be systematically extracted in the context of the agroclimatic zones across and will be reported in a follow up study.

Considering the likely projected ($\sim 2.6^{\circ}\text{C}$) rise in global surface temperature in the mid-century (IPCC, 2013), and about 2.9°C (under RCP 4.5, Rao *et al.*, 2016) for India by 2100, there is a widespread challenge to precisely quantify the extent of adverse impact due to change in DTR in several dimensions of

agriculture, water, and health (Krishnan *et al.*, 2020). The above findings indicate that the change in DTR is regionally heterogeneous and necessitates investigations of factors that influence DTR at the regional scale.

4 | CONCLUSIONS

The study found an overall increasing trend of DTR during 1951–2016, and a decreasing trend during the recent period 1991–2016 across the different agro-climatic zones

in India. For recent decades, the decreasing DTR trend is primarily because of the relatively faster increase in T_{\min} relative to the T_{\max} and the Srad.

The results also show distinct spatial and temporal variations in the DTR trends. The monsoon and pre-monsoon seasons show significantly increasing DTR trend during 1951–2016 and decreasing trend during the recent period 1991–2016, while winter season has a decreasing DTR trend during 1951–2016 and increasing trend during the recent period. The DTR over the SPH, WCP, ECP, and EH region showed an increasing trend in all seasons during both the period (1951–2016 and 1991–2016). A significant declining trend in DTR was noted for parts of Gangetic Plain, WD, and CPH. The DTR trends and rates over all other regions differ not just in value but also for the seasonal variations.

The rise in nighttime temperature (T_{\min}) may affect the plant growth and grain formation (Peraudeau *et al.*, 2015; Sonkar *et al.*, 2019), and the decreasing trend of DTR may cause an increase in mortality rate (Lee *et al.*, 2017; Singh *et al.*, 2019). Though the effects from DTR changes may not be evident in the near short term, the higher intensity of change necessitates its consideration in developing sustainable agro-climatic and bioclimatic assessments to help the inhabitants to better adapt to these changes (Mall *et al.*, 2019). Although the analysis of T_{\max} , T_{\min} , and Srad can help to understand DTR trends, it would be interesting to investigate other factors related to temporal and spatial changes.

Atmospheric aerosols may be causing a decrease in DTR and modify cloud properties. Clouds reflect the incoming solar radiation during day time and enhance the downward longwave radiations towards earth at night, thus decreasing T_{\max} in the day and increase T_{\min} at night (Zhou *et al.*, 2007). On the other hand, land surface change also influences surface energy and hydrological balance and, in turn, may cause a decline in DTR (Zhou *et al.*, 2007; Wang *et al.*, 2014; Pielke *et al.*, 2007, 2011; Niyogi, 2019). Future studies need to address these interactions and synthesize the spatiotemporal patterns noted in the DTR trends across the Indian monsoon region.

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CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of this article.

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