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Characteristics of Monthly Climate Extremes in High Fire Frequency Biogeographic Zones of India

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Abstract

Forest fires are significantly influenced by climatic extremes, with variability in temperature and precipitation creating conducive conditions. India's diverse biogeographic zones, from tropical deciduous to montane ecosystems, display distinct fire regimes shaped by ecological, topographical, and climatic factors. This study investigates monthly climate indices across India's biogeographic zones experiencing extremely high forest fire frequencies (2003-2022). Four biogeographical provinces, representing subdivisions of larger biogeographical zones: North East Hill, North West Himalaya, Western Ghats, and Eastern Highlands were analysed using standardized indices recommended by the Expert Team on Climate Change Detection and Indices ETCCDI: Monthly Maximum Temperature (TXx), Monthly Minimum Temperature (TNx), Consecutive Wet Days (CWD), and Consecutive Dry Days (CDD). Results indicate distinct climatic patterns between February and June. The North East Hill region shows moderate dry conditions peaking in March, decreasing sharply due to pre-monsoon rainfall, with temperatures peaking (32-33 °C) in April. North West Himalaya experiences consistent dry periods (13-14 days), maximum temperatures in May (35-37 °C), and notable night-time warming. The Western Ghats experience extended dry spells and peak temperatures (45-47 °C in April), transitioning quickly with monsoon onset in June. The Eastern Highlands exhibit peak dryness in March and temperature extremes (43 °C) in April. These climatic transitions from dry-hot conditions to monsoon-driven rainfall significantly modulate seasonal forest fire risks. Understanding these patterns is crucial for developing adaptive, region-specific fire management strategies.

1. Introduction

Forest fire, a significant ecological disturbance has an extensive impact on biodiversity, climate, ecosystem services, and human society. Their occurrence and severity are profoundly influenced by various interacting factors, particularly climate extremes such as prolonged droughts, intense heatwaves, and erratic rainfall patterns. India, with its rich ecological diversity and varying climate conditions, presents a unique context to examine these dynamics, as it encompasses a wide spectrum of ecosystems from tropical deciduous forests to temperate montane landscapes (Singh & Chaturvedi, 2017), each exhibiting distinct fire behaviour. India's biogeographic zones are broadly defined by ecological, topographical, and climatic gradients (Rodgers & Panwar, 1988). Notably, these zones vary extensively in their vegetation types, fuel characteristics, climatic patterns, and anthropogenic influences, factors which directly or indirectly influence fire frequency, intensity, and seasonal timing. The country's forested landscapes frequently experience seasonal forest fires, particularly during dry and pre-monsoon periods and post monsoon periods (Benali et al., 2017; Bar et al., 2021). These fires not only alter the composition and structure of ecosystems but also affect regional air quality, carbon storage, and climate stability through emissions of greenhouse gases and aerosols (Voulgarakis & Field, 2015; Pellegrini et al., 2021; Murmu et al., 2022; Sharma & Kumar, 2025). The relationships between climate and forest fires are complex and region-specific (Jones et al., 2022). In India, climatic extremes, particularly elevated temperatures and extended dry periods, substantially increase fire susceptibility (Jain et al., 2022; Barik & Roy, 2023). For instance, increased daytime temperatures accelerate evapotranspiration, intensifying drought stress, and consequently elevating fire risk. Similarly, prolonged dry spells reduce fuel moisture content, increasing flammability and combustion potential. Conversely, adequate rainfall, especially consecutive wet days, mitigates fire risks by increasing fuel moisture, reducing ignition probability, and limiting fire spread (Ellis et al., 2022). These contrasting conditions underscore the significance of examining climate variables not merely in isolation but as integral components influencing the seasonal and spatial distribution of fires.

To systematically capture these extremes, standardized indices established by the Expert Team on Climate Change Detection and Indices (ETCCDI) such as Monthly Maximum Temperature (TXx), Monthly Minimum Temperature (TNx), Consecutive Wet Days (CWD), and Consecutive Dry Days (CDD), are used to quantify and interpreting climatic variability and extremes. These indices have been extensively applied worldwide to monitor changes in climate extremes and to assess their ecological impacts, including fire regimes. Employing these standardized indices allows to quantify critical climate parameters that directly influence fire occurrence and behaviour, facilitating comparability across different ecological and geographic contexts. Previous studies in India have broadly identified correlations between climate variability and fire occurrences. However, few have systematically addressed how monthly variations in climate extremes specifically influence fire regimes within distinct biogeographic regions (Kale et al., 2017; Ahmad & Goparaju, 2019). Considering India's ecological heterogeneity, it is imperative to understand regional climate-fire dynamics rather than generalizing findings at national scales.

This study focuses on four ecologically significant biogeographic provinces- North East Hill, North West Himalaya, Western Ghats, and the Eastern Highlands of the Deccan Peninsula which represent finer subdivisions of broader biogeographic zones.

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These provinces are characterised by distinct climatic regimes and consistently exhibit high frequencies of forest fire events (Kodandapani et al., 2004; Prasad et al., 2008; Kittur et al., 2014; Reddy et al., 2019; Ray et al., 2023). The North East Hill region experiences humid subtropical climates characterized by moderate temperatures and distinct pre-monsoon dry spells, which elevate fire susceptibility. This predisposition to fire is further intensified by the extensive practice of shifting cultivation within North East India (Das et al., 2022). Contrastingly, the North West Himalaya, dominated by Chir pine forests experiences colder temperatures and pronounced seasonal variation, with intense dry periods and significant temperature extremes, particularly during spring and early summer (Kumar & Kumar, 2022; Singh et al., 2024; Kumari et al., 2025). The Western Ghats, renowned for high biodiversity and endemism, experience stark contrasts between dry, hot pre-monsoon months and intense monsoon rainfall, creating sharp seasonal fire transitions. The Eastern Highlands of the Deccan Peninsula exhibit dry tropical climates, characterised by prolonged droughts interspersed with intense heatwaves, strongly influencing fire frequency and severity (Giriraj et al., 2010; Kale et al., 2017; Niyogi et al., 2025). These contrasting climates exemplify how region-specific climatic extremes drive distinct fire dynamics.

Against this background, the present study aims to characterize monthly patterns of climate extremes across these high fire-frequency zones over two decades (2003-2022), explicitly focusing on the pre-monsoon period (February-June), during which forest fire incidents peak. Through detailed analysis of ETCCDI-recommended indices - TXx, TNx, CWD, and CDD. This investigation elucidates regional variations and trends in climate conditions conducive to forest fires. The outcomes of this research are intended to provide critical insights into how climate extremes modulate forest fire occurrences within India's biogeographic diversity. Such insights are vital not only for advancing scientific understanding but also for informing practical fire management policies and adaptive strategies tailored to each ecological context.

2. Study area

India's biogeographic classification comprises distinct ecological zones characterized by unique vegetation, climatic patterns, and topographical features. This study specifically focuses on four biogeographic provinces known for experiencing extremely high forest fire frequencies: these are North East Hill, North West Himalaya, Western Ghats, and Eastern Highlands. The North East Hill zone features subtropical broadleaf forests and experiences humid subtropical climates with pronounced dry spells before the monsoon, significantly influencing its fire regime. The North West Himalaya, characterized by temperate coniferous and mixed forests, exhibits substantial seasonal variation with prolonged dry periods and marked temperature extremes, particularly from late winter to early summer, enhancing fire susceptibility. The Western Ghats, a biodiversity hotspot with tropical moist deciduous and evergreen forests, demonstrate intense contrasts between the hot, dry pre-monsoon period and the subsequent monsoon season, causing abrupt seasonal shifts in fire dynamics. Finally, the Eastern Highlands of the Deccan Peninsula, dominated by dry deciduous forests and grasslands, exhibit tropical dry climates with pronounced droughts and intense heatwaves, conditions highly conducive to recurrent fires. Together, these zones represent diverse ecological conditions, providing an ideal context for analysing how distinct climatic extremes shape forest fire frequency and distribution in India's varied landscapes.

3. Datasets and methodology

3.1 Climate indices

This study employed indices from the ETCCDI, which are standard tools for analysing climatic changes (http://etccdi.pacificclimate.org/indices.shtml). These indices effectively used to study extreme events, such as droughts and heat waves, by capturing variations in their frequency, intensity, and absolute values (Panda et al., 2016; Dunn et al., 2024). Comprising both temperature and precipitation metrics, ETCCDI indices facilitate the detection and monitoring of long-term climate trends. For this study, precipitation indices were calculated using daily precipitation data from the Climate Hazards Center InfraRed Precipitation with Station Data (CHIRPS), Version 2.0 Final (Funk et al., 2015). Temperature indices were computed utilising daily Land Surface Temperature (LST) data acquired from MODIS sensors on board the AQUA and TERRA satellites, the MYD11A1.061 and MOD11A1.061 datasets respectively. These datasets offer daily global LST data at a spatial resolution of 1 km. The analysis was conducted at a spatial resolution of 10 km × 10 km for all forested grid cells within the study area, with indices evaluated at monthly scales. To handle data gaps in the daily time series, a temporal imputation method was applied, calculating missing values from the average of preceding and succeeding observations or from the long-term mean of the corresponding day across all years. To ensure the integrity and accuracy of the results, grid cells with insufficient data or persistent gaps were systematically excluded from the final analysis.

Code	Definitions	Units
TXx	Monthly maximum value of daily maximum temperature	°C
TNx	Monthly maximum value of daily minimum temperature	°C
CDD	Maximum number of consecutive days when precipitation <1 mm	day
CWD	Maximum number of consecutive days when precipitation ≥1 mm	day

Table 1: List of climate indices adopted

4. Results

4.1 Forest Fire Frequency Analysis in India

For this study, forest fire frequency was defined as the number of years a given grid cell recorded at least one fire event within the 20-year period from 2003 to 2022. Based on this metric, four frequency classes were established: low (1-5 years), medium (5-10 years), high (10-15 years) and extremely high (15-20 years). Spatial analysis of fire recurrence across India's biogeographic zones (BGZs) in figure 1 revealed that the highest number of grids classified within the extremely high-frequency category are located in the North East Hills (934) and the Eastern Ghats (414). These regions were thus identified as critical hotspots. Consequently, the subsequent calculation and analysis of monthly climate indices were exclusively conducted for these forested grids exhibiting extremely high fire frequency.

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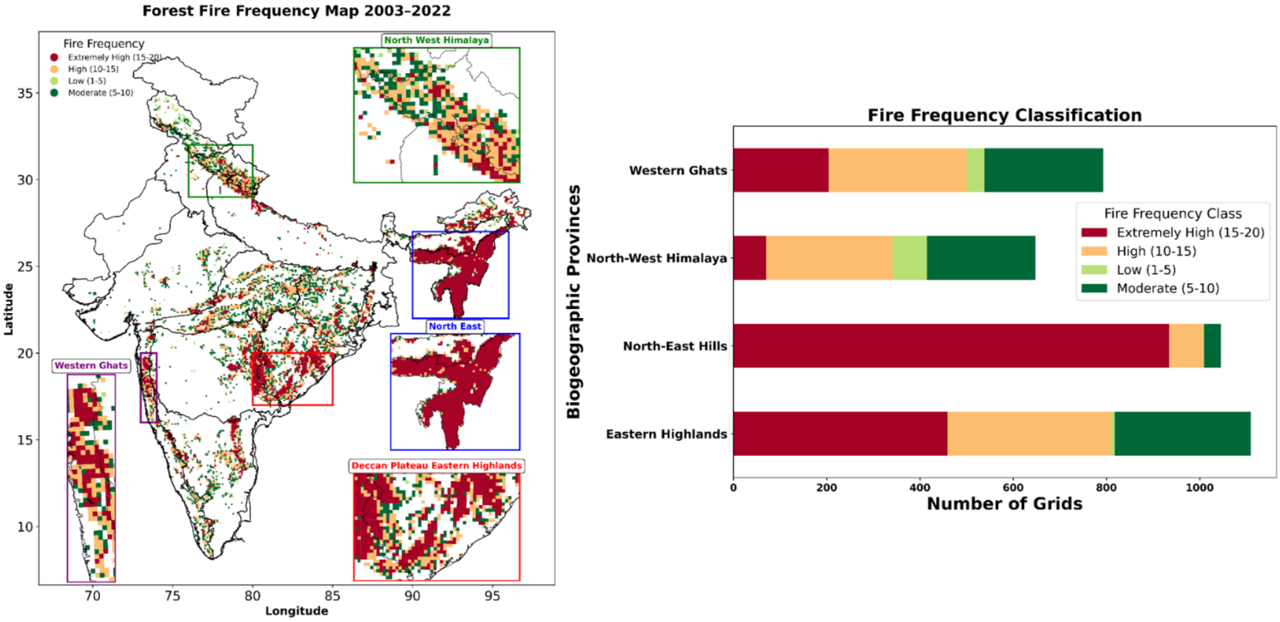

Figure 1: Fire frequency over selected Biogeographic provinces of India (2003-2022)

4.2 Monthly Climate Variability Across High Fire Frequency Biogeographic Zones

In regions experiencing extremely high fire frequency, distinct monthly climate patterns were observed across biogeographic zones from February to June. The figure 2 indicates the monthly variability of climate indices of the four biogeographic provinces. North-East Hills zone exhibited a clear transition into the pre-monsoon season. CDD rose from approximately 13.6 days in February to a peak of 15.6 days in March before declining sharply to 9.1 days in April and under 5 days by June. Mirroring this, CWD increased from 1.6 days in February to 7.3 days in June. TXx peaked in April at 32.9 °C, while TNx climbed steadily from 15.9 °C in February to 21.5 °C in May. The North-Western Himalayan region showed a more prolonged dry period. CDD remained relatively constant at 13-14 days from February through June. CWD varied between 2-3 days monthly, with a minor increase to 3.4 days in June. A significant warming trend was evident, with TXx rising from 22.7 °C in February to 36.2 °C in May. Similarly, TNx increased substantially from 10.0 °C to 20.6 °C over the same period.

The Western Ghats were characterised by an extreme early dry season followed by a rapid monsoon onset. CDD was very high in February-March (25-26 days), dropping to 18.5 days in April and then falling sharply to 8.2 days by June. Consequently, CWD was minimal (<1 day) until April, after which it increased to 5.6 days in June. Temperatures were extreme, with TXx peaking at a notable 46.5 °C in April. TNx followed a similar pattern, rising from 21.2 °C to a peak of 25.0 °C in April-May. In the Eastern Highlands of the Deccan Peninsula, CDD peaked in March at 18.5 days and subsequently declined to 4.4 days by June. Inversely, CWD was lowest in March (1.5 days) and rose steadily to a high of 8.8 days in June. TXx increased from 36.0 °C in February to a maximum of 43.5 °C in April, while TNx climbed to a peak of 27.6 °C in May.

4.3 Temporal Trends of Seasonal Climate Indices

The inter-annual variability and long-term trends of key climate indices during the February-June fire season for highly fire-frequented areas in the Western Ghats are presented for the period 2003-2022 in the figure 3 (a) showed a moderate trend towards cooler and less contiguously dry conditions during the fire season. The seasonal CDD exhibited a decreasing trend over the 20-year period, declining at a rate of approximately 0.126 days per year. Substantial inter-annual variability was observed, with values fluctuating between a maximum of 21.5 days in 2011 and a minimum of around 17 days in 2018. A slight positive trend was observed for CWD, increasing at a rate of 0.012 days per year. However, this trend is not statistically significant, as indicated by a very low coefficient of determination ($R^2 = 0.022$). The index is characterized by high year-to-year fluctuations, with notable peaks in 2007 and 2018. TXx, which decreased at a rate of 0.125 °C per year.

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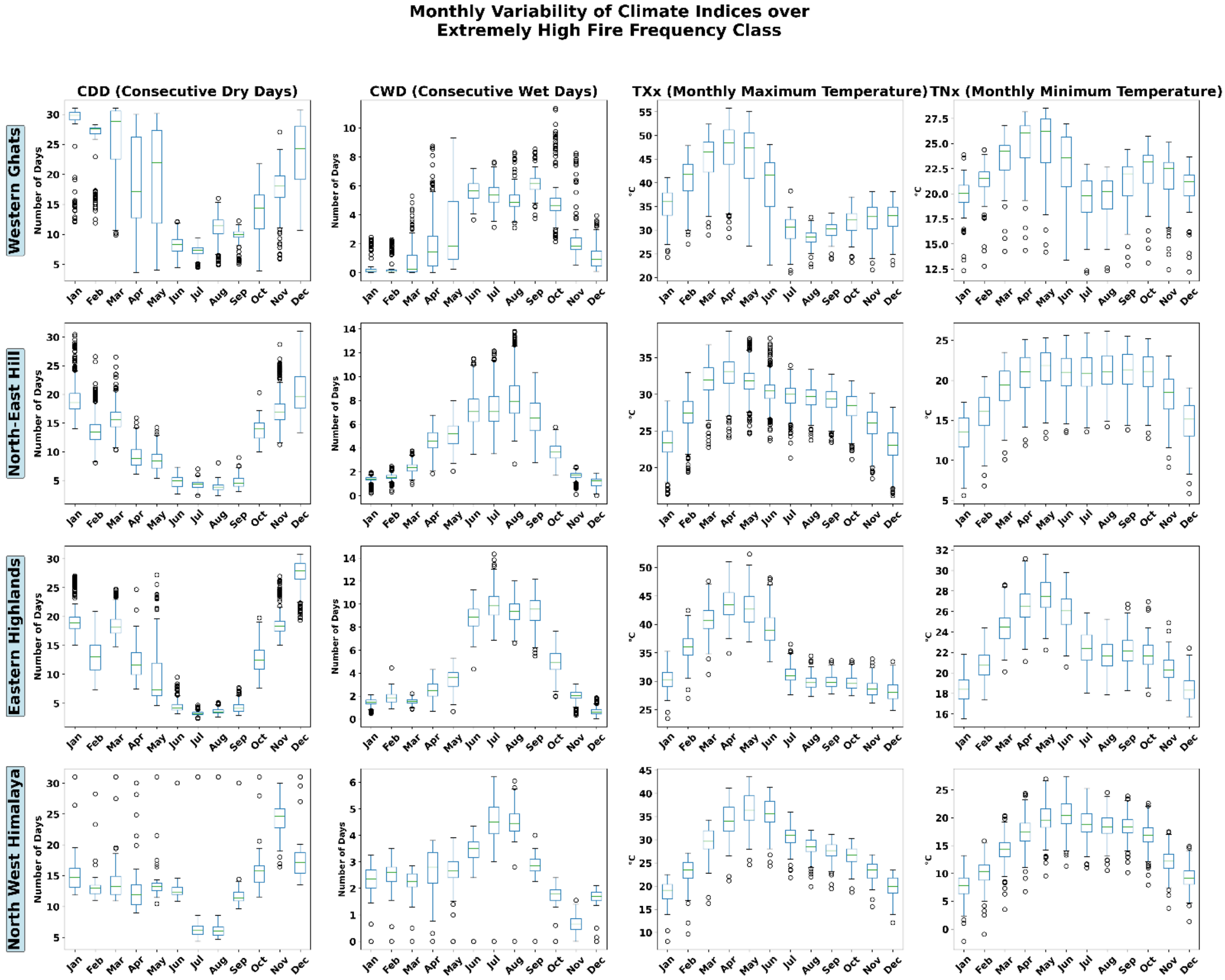

Figure 2: Monthly climate indices of biogeographic provinces

This trend accounted for 35.6% of the temporal variance ($R^2 = 0.356$). The highest seasonal TXx was recorded at the beginning of the period (46.5 °C in 2003), with a general decline to a low of approximately 41 °C in 2021. TNx showed a negligible positive trend (slope = +0.007 °C/year). This trend was not statistically significant ($R^2 = 0.012$), and the data displayed considerable variability around the long-term mean of approximately 23.5 °C. In the North Eastern Hills, figure 3 (b) seasonal CDD shows no discernible long-term trend over the 20-year period with year-to-year fluctuations, with values oscillating primarily between 9 and 13 days. In contrast, CWD exhibited a decreasing trend, declining at a rate of approximately 0.058 days per year. The seasonal maximum temperature (TXx) did not show a statistically significant trend. The calculated slope was negligible (-0.009 °C/year), and the extremely low coefficient of determination ($R^2 = 0.004$). The seasonal TNx remained stable over the period. The temporal evolution of the Eastern highlands, in figure 3(c) seasonal climatic indices shows a decreasing trend of CDD at a rate of 0.168 days per year. In contrast, CWD index showed no discernible long-term trend but a high inter-annual variability around a mean of 3.5 days. TXx exhibited a moderate cooling trend, decreasing at a rate of 0.115 °C per year and a temporal variance of $R^2 = 0.210$. In the North West Himalaya region, in figure 3(d) the seasonal CDD index showed a weak and statistically insignificant decreasing trend (slope = -0.082 days/year) and a strong year-to-year fluctuations, with values ranging widely from 11 days to nearly 18 days. The CWD exhibited no significant long-term trend. TXx declined at a rate of 0.077 °C per year. TNx displayed no discernible linear trend.

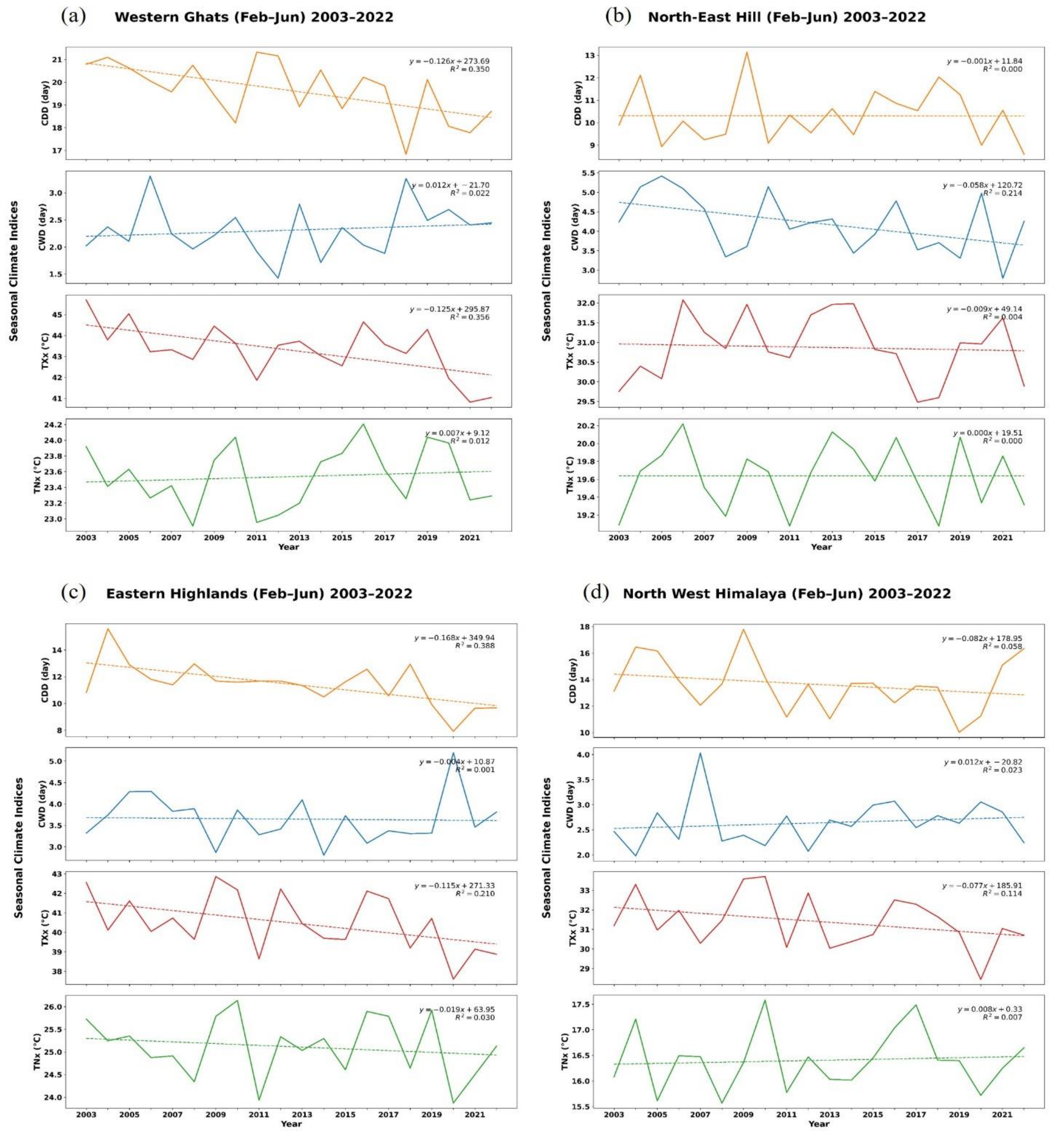

Figure 3: Seasonal climatic indices trend of (a) Western Ghats, (b) North East Hills, (c) Eastern Highlands, (d) North West Himalaya

5. Discussion

This study of climatic conditions during the fire season from 2003 to 2022 reveals distinct regional trends across India's fire-frequented areas. In some regions, a moderate shift towards cooler and wetter conditions was observed (Shawky et al., 2023). For instance, the fire season climate in the Eastern Highlands was principally marked by a significant trend towards shorter, less persistent dry periods, indicated by the CDD index, and moderately cooler daytime maximum temperatures TXx. Conversely, indices related to wet-day duration CWD and night-time minimum temperatures TNx remained stable, with patterns dominated by strong inter-annual fluctuations. Similarly, the Western Ghats experienced a moderate trend towards cooler and less contiguously dry conditions. Significant negative trends in TXx and CDD stood in contrast to the statistically insignificant trends in CWD and TNx, which were also dominated by high inter-annual variability (Rehana et al., 2022). In other regions, however, climatic conditions were characterised primarily by variability rather than strong directional change. In the North West Himalaya, all four indices investigated were dominated by high inter-annual variability, with the calculated linear trends being statistically weak. A comparable pattern was observed in the North-East Hill region, where climate indices were predominantly characterised by high inter-annual variability. Although a statistically weak drying sign was noted in the decreasing trend of CWD, key indicators of drought duration CDD and temperature extremes (TXx, TNx) did not exhibit any significant long-term change (Deka et al., 2016; Vinnarasi & Dhanya, 2016; Choudhury et al., 2019; Benny et al., 2024). Collectively, these distinct climatic indices highlight the interplay between temperature and precipitation that modulates fire risk. The zonal profiles demonstrate that fire-prone zones often combine an early, hot, and dry period (February-April) with a rapid, monsoon-driven increase in moisture from April onward, which alters fire risk as the season progresses.

6. Conclusion

This study assessed climatic characteristics in India's highly fire frequented biogeographic forested zones, highlighting notable regional heterogeneity in seasonal patterns and long-term trends from 2003 to 2022. The analysis identified two primary patterns. First, peninsular regions, notably the Western Ghats and Eastern Highlands, demonstrated a decreasing trends of TXx and CDD during the fire season in the forested areas. This observation challenges conventional assumptions of uniformly hotter and drier conditions across fire prone regions (Collins et al., 2022). Second, Himalayan regions, including the North-West Himalaya and North-East Hills, showed no significant directional trends in key climate indices but were characterised by pronounced inter-annual variability, with extreme climatic fluctuations dominating rather than consistent trends. These divergent climatic trajectories have substantial implications for fire management (Halofsky et al., 2017). In the Western Ghats and Eastern Highlands, management strategies must adapt to evolving moisture regimes rather than solely addressing increased heat. Conversely, Himalayan zones require resilience-building approaches to manage high climatic unpredictability, as fire risk fluctuates significantly from year to year without clear long-term trends. The study utilised a 20-year dataset based on ETCCDI indices; future research should explore longer climatological periods for trend validation. Additionally, incorporating variables like wind speed, population density, roads, topographic features, relative humidity, burned areas and fuel moisture could enhance fire risk assessments (Vadrevu et al., 2010; Mamgain et al., 2023; Kumari et al., 2024). Investigating large-scale climate drivers, such as the El Niño-Southern Oscillation, would further enhance regional climatic dynamics. This research emphasises the necessity of spatially tailored, data-driven fire management strategies to effectively address India's diverse climatic realities.

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