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RESEARCH PAPER

Interrelationship between temperature index and South-West monsoon rainfall: Historical analysis and future projections

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Abstract: The South-West monsoon also known as Indian Summer Monsoon (ISM), which is part of the South Asian monsoon system, is one of the largest global phenomena of the general circulation that has its impacts on the global weather and climate. In this study the spatial and temporal correlations were analysed with a Rainfall and Temperature based Index namely, T_Index. This index is developed by taking the product of the Near Surface Air Temperature, Latent Heat Flux and Mean Sea Level Pressure, to understand the inter-annual variability of the ISM rainfall for both the historical (1991-2020) and projected (2021-2050) periods. The monthly data were downloaded from Copernicus website, Coupled Model Inter Comparison Project Phase 6 (CMIP6) with a resolution of 0.5º x 0.5º. The data were processed by using the FERRET and CDO software in the LINUX platform. The results showed that in the historical period (1991-2020), there was a highly positive correlation between T_Index and rainfall throughout India except during 1991 to 2000 period in central and eastern parts of India. For the projected period (2021-2050), there likely to be positive correlation between the T_Index and rainfall throughout India except for north-eastern regions of India.

Key words: Rainfall, South west monsoon, T_Index, Temperature

Introduction

The Indian Summer Monsoon (ISM) is a major component of the South Asian monsoon system, which has a significant impact on global weather and climate, as well as the lives of millions of people in India. The stability, variability, and extremes of summer monsoon rainfall have a profound influence on India's agriculture, economy, and overall well-being. Any deviations in the Indian Summer Monsoon Rainfall (ISMR) from the long-term average can have substantial effects on agricultural productivity and the country's Gross Domestic Product (GDP). Therefore, studying the long-term trends and changes in the temporal and spatial patterns of monsoon rainfall is crucial for water resource management and policy decisions.

The monthly rainfall pattern reveals the maximum amount of rainfall occur in monsoon months that is from June to September (Panda and Sahu, 2019). The Indian Summer Monsoon occurs from June to September (JJAS) and contributes about 80% to the country's annual rainfall (Prasanna, 2014).

Climate change is having a big impact on monsoon rain,this is because the Earth is getting hotter from the pollution and greenhouse gas emissions into the air from automobiles and industries. As it gets hotter, some places lose water faster, which can cause drought. On the other side, warmer oceans can make the monsoon rains stronger leading to erosion and flooding and less predictable which affects our preparedness. Also, because of climate change, the oceans are getting warmer too. When they get warmer, they expand and take up more space, which makes sea levels to go up. This rising sea level can flood coastal areas, causing damage to residence, nature, and infrastructure. The increase in surface air and dew point temperatures significantly influence the frequency and intensity of rainfall events in urban areas (Ali and Mishra, 2017). It can even wash away the land slowly. To stop these problems, one needs to reduce the pollution causing climate change and come up with plans to deal with extreme events and rising sea levels.

The impact of Indonesian through Flow (ITF) on the inter-annual and intra-seasonal variabilities of the Indian Summer Monsoon Rainfall (ISMR) is significant. The ITF refers to a warm ocean current that flows from the western Pacific Ocean to the Indian Ocean. This current carries warm water, which reaches the southern Indian Ocean and subsequently influences the South-West Monsoon currents. As a warm ocean current, the ITF plays a crucial role in regulating the temperature dynamics within the monsoon currents. An increase in Sea Surface Temperature (SST) due to the ITF leads to elevated air temperature, resulting in enhanced evaporation from the ocean surface and evapotranspiration from the land surface. This increased evaporation contributes to higher concentrations of atmospheric water vapour, which in turn affects overall precipitation patterns. Furthermore, the presence of large-scale ocean-atmospheric phenomena like El Niño and La Niña contributes to inter-seasonal and intra-seasonal variations in rainfall from year to year.

The inter-annual fluctuations in monthly and seasonal rainfall have a direct impact on the sustainability of crop production. Consequently, managing sustainable cropping systems requires the implementation of various strategies, including varietal selections, farm management programs, and pest management approaches. These strategies aim to reduce input costs, minimize losses, and maximize yields and profits.

The combinations of several atmospheric parameters have been tested in order to develop an Index such as the product of

Near-surface air temperature, sea level pressure, TOA Outgoing long wave radiation and the product of near-surface air temperature, sea level pressure, surface upward latent heat flux, *etc*., but all of these showed negative correlation with rainfall. Finally, an Index is developed namely, the T_Index, by taking the product of near-surface air temperature, surface upward latent heat flux and the mean sea level pressure and it showed a positive and strong correlation with rainfall. Product of near-surface air temperature, surface upward latent heat flux and the mean sea level pressure showed positive and strong correlation with rainfall, hence, these parameters were used to develop T_Index.

Through this research it was focussed to develop a Temperature based Index by taking the product of the near surface air temperature, surface upward latent heat Flux and the Mean Sea Level Pressure. This Index was used to analyse the inter annual variability of the Indian Summer Monsoon,for both the historical and projected climatic scenarios. There are various climatic indices for the prediction of Indian Summer Monsoon and its distribution. Some research works have been conducted to find the relative roles of individual parameters *viz.,* Sea Surface Temperature (SST), Sea Level Pressure (SLP), Wind Velocity, Surface Pressure (SP) and Outgoing Long wave Radiation (OLR) on the inter annual and intra seasonal variability of Indian Summer Monsoon.

The Temperature based Index was developed by taking the product of Near Surface Air Temperature, Surface upward Latent Heat Flux and the Mean Sea Level Pressure.

T_Index was developed as follows,

T_Index = (TS)*(SLP)*(HFLS)

Where, TS is the Near Surface Air Temperature (°K), SLP is the Mean Sea Level Pressure (Pa) and HFLS is the Surface upward Latent Heat Flux (W/m^2). Hence the unit for the T_Index is (**°KPa.W/m^2**).

The objective of the study was to understand the inter relationship between the T_Index and the Indian Summer Monsoon Rainfall, and to find out the spatial and temporal correlation for the index with the Summer Monsoon Rainfall.

Near-Surface Air Temperature is the Temperature of air at 2 m above the surface of land, sea or inland waters. Increase in air temperature can lead to more intense heat waves.

Due to concentrations of greenhouse gases heat-trapping, is increasing in the Earth's atmosphere. As average temperatures of the Earth's surface rise, more evaporation occurs, which in turn increases the overall precipitation with intensity. Trends and variability of Surface Temperature and precipitation are positively correlated. Many studies have shown that temperature and precipitation have positive correlations (Trenberth and Shea, 2005; Wu *et al.,* 2012 and Zhang *et al.,* 2013). However, some researchers have also observed both positive and negative trends in different locations (Trenberth and Shea, 2005 and Saavedra *et al.,* 2020). For example, Trenberth and Shea (2005) showed that precipitation has reduced downward shortwave radiation reaching the Earth's surface, resulting in surface cooling which may contribute to a negative correlation between precipitation and temperature. It is expressed in degree kelvin (°K).

Latent Heat is defined as the energy absorbed or released by a substance during a change in its physical state (phase) that occurs without changing its temperature. Surface upward latent heat flux is defined as the flux per unit area of heat between the surface and the air on account of evaporation including sublimation. The amount of energy is moving from the surface to the air due to evaporation (positive values) or from the air to the land due to condensation (negative values). Latent Heat Flux is one parameter for better understanding of the monsoons and varies with different global phenomena like El Niño and La Niña. Latent heat shows very strong correlation with precipitation (Huang *et al.*, 2018). It is expressed in Watts per meter square (W/m^2).

The Mean Sea Level Pressure (MSLP) is the surface air pressure over the sea level. MSLP has got significant influence over the monsoon rainfall occurring in India. The frequency of the high MSLP days over India is highly negatively correlated with the Indian summer monsoon rainfall (Patil *et al.,* 2011). MSLP is related to precipitation with the opposite sign *i.e.*, higher values of sea surface pressure is accompanied by a decrease in precipitation and it is expressed in Pascal (Pa).

Material and methods

India enjoys a wide range of climates from tropical monsoon in the South to temperate in the North and dry desert like in the North-West. Four homogeneous regions of India namely, North West India (NWI), North East India (NEI), Central India (CI) and South Peninsular India (SPI) were chosen for the study area, which are classified based on the rainfall patterns. These regions exhibit similar climatic conditions and receive varying amounts of rainfall throughout the year.

The data were downloaded for 30 years historical (1991-2020) and for 30 years projected climatic scenarios (2021-2050), so total of 60 years were downloaded from Copernicus website (https://cds.climate.copernicus.eu), Coupled Model Inter Comparison Project Phase 6 (CMIP6) with resolution of 0.5 x 0.5degree. The model was run by the Indian Institute of Tropical Meteorology (IITM), the data downloaded was a global NetCDF (gridded) data in single levels and the study area was set from Equator to 40°N and 60°E to 100°E. The data were processed by using the FERRET and CDO software in the LINUX platform. The TIMCOR function was used to obtain the spatial correlations among the T_Index and Rainfall. The correlation coefficient is a quantity that gives the least squares fitting to the original data. This operator correlates each grid point of two fields over all time steps.

The Pearson correlation co-efficient, is a statistical tool employed to represent the degree of linear association between two sets of data. In this research work it is used for the interpretation of spatial correlation between two parameters. The coefficient of correlation 'r' lies between -1 and +1. The value showing +1.00 is noticed as perfect positive correlation,

+0.75 to +1.00 as high degree of positive correlation, +0.50 to +0.75 as moderate degree of positive correlation, up to +0.50 is classified as low degree of positive correlation and -1.00 as perfect negative correlation, -0.75 to -1.00 as high degree of negative correlation, -0.50 to -0.75 as moderate degree of negative correlation, up to -0.50 classified as low degree of negative correlation and 0 as no correlation.

Results and discussion

Correlation between T_Index and ISMR for historical period (1991-2020) for four homogeneous regions of India

Table 1 shows the numerical representation of the correlation between the T_Index and rainfall for pentadal years over four homogeneous regions of India for the 30-years historical period (1991-2020). Fig 1 shows the graphical representation of pentadal variation of correlation between T_Index and ISMR for historical period (1991-2020) for four homogeneous regions of India, and Fig 3 shows the spatial maps of correlation among T_Index and rainfall across India.

In the historical period, positive correlations were evident between the T_Index and rainfall across all regions, with varying degrees of correlation. Remarkably, North West India displays the high degree of positive correlation during 2006-2010 (0.7531), closely followed by North East India during the same period (0.7001). However, North East India exhibited a low degree of positive correlation during 2001-2005 (0.0392) and during 2016-2020 (0.0455). The spatial correlations had a consistently high degree of positive correlation across the country, except for specific parts of the Eastern, Central, and North-Eastern regions. During 1991-1995, Northern, Western, Eastern, and Southern India showed substantial positive correlation (0.80 to 1.00), Specific areas of Western, Eastern, and North Eastern India showed moderate positive correlation (0.50 to 0.75), Certain regions in Central and Eastern India showed high negative correlation (-0.75 to -1.00) and Himalayan regions, Central, and North Eastern India showed moderate negative correlation (-0.50 to -0.75). During 1996-2000, certain areas of Northern India showed significant positive correlation (0.80 to 1.00), majority of Western, Southern, and Eastern regions of India showed significant positive correlation (0.80 to 1.00), specific regions of Southern and Eastern India showed moderate positive correlation (0.50 to 0.75), certain parts of North Eastern India showed High negative correlation (-0.75 to -1.00) and most parts of Eastern and North Eastern India showed moderate negative correlation (-0.50 to -0.75). During 2001-2005, most parts of Northern and Western India showed notable positive correlation (0.80 to 1.00), certain regions of Southern and Eastern India showed notable positive

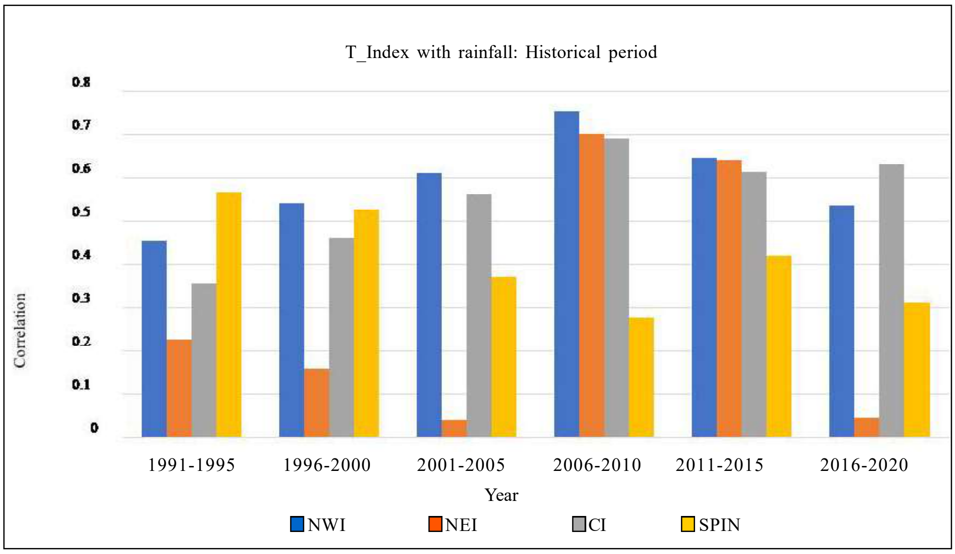


Fig1. Graphical representation of pentadal variation of correlation between T_Index and ISMR for historical period (1991-2020) for four homogeneous regions of India

Table 1. Correlation of pentadal T_Index with ISMR during historic period (1991-2020) for four homogeneous regions of India

Year	NWI			NEI			CI			SPI		
	T_Index (*10⁶)	ISMR	Correlation	T_Index (*10⁶)	ISMR	Correlation	T_Index (*10⁶)	ISMR	Correlation	T_Index (*10⁶)	ISMR	Correlation
1991-1995	1396	101.86	0.4526	2424.0	221.54	0.2253	2164.2	158.92	0.3553	2588.2	136.55	0.5660
1996-2000	1306	97.59	0.5402	2453.2	226.76	0.1589	1993.8	127.89	0.4608	2476.4	95.66	0.5251
2001-2005	1277	79.71	0.6099	2438.6	231.75	0.0392	1915.4	116.65	0.5606	2449.0	110.48	0.3700
2006-2010	2822	94.95	0.7531	2367.0	196.11	0.7001	2111.8	156.39	0.6916	2596.8	132.16	0.2743
2011-2015	2883	94.06	0.6467	2352.6	229.08	0.6407	1951.4	140.26	0.6139	2476.0	118.12	0.4182
2016-2020	1279	80.90	0.5357	2272.4	216.71	0.0455	1840.6	106.19	0.6313	2447.4	107.33	0.3094

NWI=North-western India, NEI=North-eastern India, CI=Central India, SPI=South Peninsular India, ISMR= Indian Summer Monsoon Rainfall.12

correlation (0.80 to 1.00) whereas,specific areas of Southern and Eastern India showed moderate positive correlation (0.50 to 0.75) certain parts of North Eastern India showed high negative correlation (-0.75 to -1.00) and Himalayan regions and North Eastern India showed moderate negative correlation (-0.50 to -0.75). During 2006-2010, there was a widespread high positive correlation throughout India (0.80 to 1.00), certain regions in Central and North Eastern India showed moderate positive correlation (0.50 to 0.75) and specific parts of Central and North Eastern India showed high negative correlation (-0.75 to -1.00). During 2011-2015, all parts of India showed High positive correlation (0.80 to 1.00), certain regions in Southern, Eastern, and North Eastern India showed Moderate positive correlation (0.50 to 0.75), but specific areas of Central and North Eastern India showed High negative correlation (-0.75 to -1.00). North East India is one big cluster having highly decreasing trend whereas North West part of India showed increasing trend since last two decades (Mohapatra *et al., 2018*). During 2016-2020, majorityof the Northern, Western, Central, and Southern India showed high positive correlation (0.80 to 1.00), certain areas of Central and Eastern India showed moderate positive correlation (0.50 to 0.75). The strongest positive correlations (0.75 to 1) were recorded between 1991 and 2000, particularly in Northern, Western, and Southern India. Moderate positive correlations (0.5 to 0.75) were noted in certain areas of these regions, while Central and Eastern India displayed moderate to high degree of negative correlation (-0.5 to -1). Positive correlation suggests high rainfall with increasing T_Index values and negative correlations depicts high rainfall with low T_Index values. The fluctuations in surface temperature significantly affect the intensity and duration of monsoon rainfall in India, which underscores the critical impact of temperature changes on monsoon behaviour, highlighting the importance of monitoring these variables for effective climate adaptation strategies (Sharma and Sinha, 2021). These correlations provide insight into the relationships between different regions in India during these time periods, likely related to various environmental, economic, or socio-political factors.

Correlation between T_Index and ISMR for the projected period (2021-2050) over four homogeneous regions of India

Table 2 shows the numerical representation of the correlation between the T_Index and rainfall for pentadal years over four homogeneous regions of India for the 30-years projected period (2021-2050). Fig 2 shows graphical representation of pentadal variation of Correlation between T_Index and ISMR for projected period (2021-2050) for four homogeneous regions of India, and Fig-4 shows the spatial map of correlation among T_Index and rainfall across India. Because of the 0.5 x 0.5 degree data resolution, values

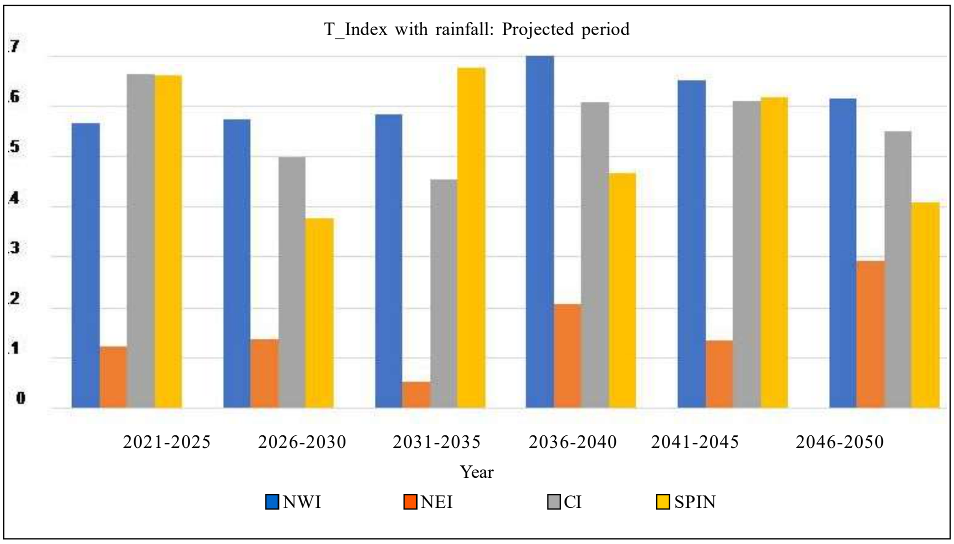


Fig 2. Graphical representation of pentadal variation of correlation between T_Index and ISMR for projected period (2021-2050) for four homogeneous regions of India

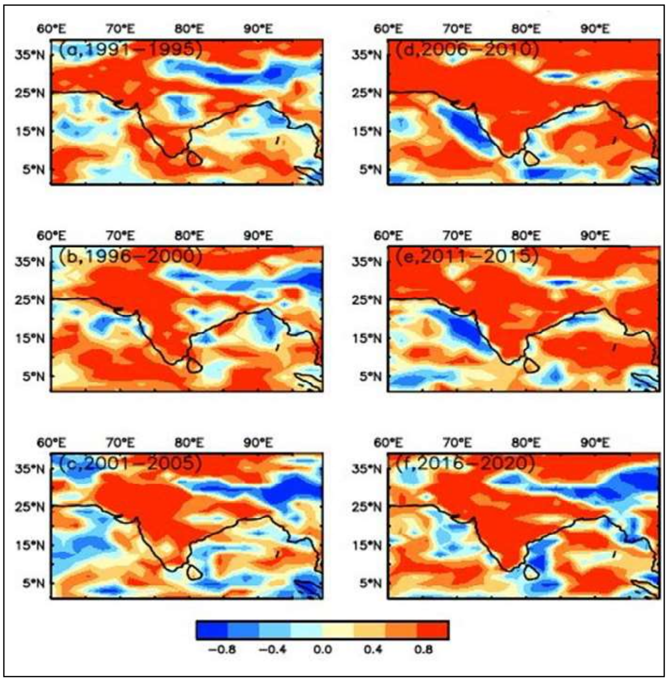
Table 2. Correlation of pentadal T_Index with ISMR during projected period (2021-2050) for four homogeneous regions of India

Year	NWI			NEI			CI			SPI		
	T_Index ($*10^6$)	ISMR	Correlation	T_Index ($*10^6$)	ISMR	Correlation	T_Index ($*10^6$)	ISMR	Correlation	T_Index ($*10^6$)	ISMR	Correlation
2021-2025	1283.0	88.38	0.5661	2347.2	204.22	0.1226	2022.8	132.35	0.6617	2462.2	110.49	0.6600
2026-2030	1366.4	100.53	0.5726	2415.4	230.37	0.1370	1980.2	127.48	0.4968	2379.6	90.86	0.3753
2031-2035	1361.4	93.78	0.5815	2454.8	227.95	0.0499	2067.4	145.61	0.4537	2514.0	114.28	0.6751
2036-2040	1353.0	94.35	0.6994	2390.8	216.34	0.2060	1976.8	129.36	0.6075	2496.0	103.53	0.4653
2041-2045	1343.4	94.38	0.6496	2393.6	230.55	0.1330	2049.2	131.27	0.6101	2540.4	124.15	0.6169
2046-2050	1399.6	101.27	0.6154	2432.4	205.98	0.2920	2165.8	148.23	0.5489	2608.6	131.91	0.4076

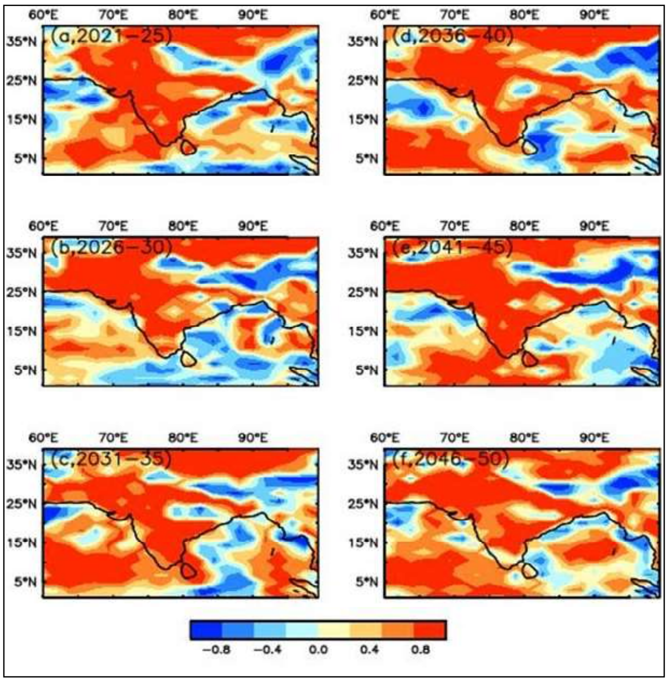
NWI=North-western India, NEI=North-eastern India, CI=Central India, SPI=South Peninsular India, ISMR= Indian Summer Monsoon Rainfall.

were identical. This spatial resolution was the limitation of this study.

Looking in to the projected period (2021-2050), the trend of positive correlations persists. North West India demonstrated the moderate degree of positive correlation in 2036-2040 (0.6994), while Central India indicates a moderate degree of positive correlation in 2021-2025 (0.6617). In contrast, North East India exhibited a relatively lower degree of positive correlation during 2021-2025 (0.1226) and 2041-2045 (0.1330). Zheng *et al.* (2016) has reported that rainfall rates are primarily stronger (weaker) over NWI, CI, and SPI during strong (weak) monsoons, while rainfall rates over NEI show no remarkable changes between strong and weak monsoons. The combined map illustrates the correlation between T_Index and ISMR for the projected period (2021-2050). During this period, the positive correlation ranging between 0.50 and 1.00 was observed in most parts of the country. However, in a few parts of Central and North Eastern India, negative correlation was observed. During 2021-2025, there was a high degree of positive correlation (0.80 to 1.00) over almost all parts of India, moderate degree of positive correlation (0.50 to 0.75) was observed in Central and North Eastern India and low to high degree of negative correlation (0 to -1.00) is evident over most parts of Central, Eastern, and North Eastern India. During 2026-2030, high degree of positive correlation (0.80 to 1.00) was observed in some parts of Northern, Western, and Central India, as well as a few parts of North Eastern India, moderate degree of positive correlation (0 to 0.75) in some parts of Central, Eastern, and North Eastern India and low to moderate degree of negative correlation (0 to -0.75) was observed over some parts of Central, Eastern, and North Eastern India. During the period 2031-2035, high degree of positive correlation (0.80 to 1.00) was observed over most parts of India. High degree of negative correlation (-0.75 to -1.00) in few parts of North Eastern India and low to moderate degree of negative correlation (0 to -0.75) was evident across most parts of Eastern, Central, and North Eastern India. Period 2036-2040 had high degree of positive correlation (0.80 to 1.00) in most parts of Northern, Western, Eastern, Southern, and North Eastern India. Moderate degree of positive correlation (0 to 0.75) in Central and Eastern parts of India and low to moderate degree of negative correlation (0 to -0.75) in some parts of Eastern and North Eastern India. During 2041-2045, there was a high degree of positive correlation (0.80 to 1.00) in almost all parts of India. Moderate degree of positive correlation (0.50 to 0.75) was noticed over a few parts of Eastern and North Eastern India and moderate to high degree of negative correlation (-0.50 to -1.00) was observed over most parts of Central and North Eastern India. During 2046-2050, high degree of positive correlation (0.80 to 1.00) was observed in most parts of Northern, Western, Central, and Southern India, as well as a few parts of North Eastern India. Moderate degree of positive correlation (0.50 to 0.75) was evident in some parts of Southern, Central, Eastern, and North Eastern India and low to moderate degree of negative correlation (0 to -0.75) in few parts of Central, Eastern, and North Eastern India. In contrast to the historical period, negative correlations were less pronounced in projected



(a-1991_1995, b-1996_2000, c-2001_2005, d-2006_2010, e-2011_2015, f-2016_2020)
Fig 3. Spatial correlation between pentadal T_Index and ISMR for Historical Period (1991-2020)



(a-2021_2025, b-2026_2030, c-2031_2035, d-2036_2040, e-2041_2045, f-2046_2050)
Fig 4. Spatial correlation between pentadal T_Index and ISMR for Projected Period (2021-2050)

period, primarily seen in parts of Central and North-Eastern India. In the initial years of the projected period (2021-2025), this connection is anticipated to strengthen further, but with progress in time, it is likely to gradually weaken. This weakening trend is most noticeable in Central and North-Eastern India. Negative correlations, where lower temperatures result in increased rainfall, are becoming less common, primarily confined to Central and North-Eastern India. This indicates a continued relationship between temperature indices and rainfall patterns over time, underscoring the potential influence of temperature on rainfall trends. Notably, the projected period maintains the positive correlation trend, but with some variations in strength and regional distribution.Understanding the intricacies of seasonal prediction models is crucial for improving the accuracy of Indian summer monsoon rainfall forecasts, which emphasizes on the importance of enhancing predictive capabilities vital for agriculture, water management, and disaster preparedness in the region (Madolli *et al.,* 2022).

Conclusion

It has been observed that the majority of India experiences a positive relationship between temperature and rainfall. This means that when temperatures rise, rainfall tends to increase as well. This relationship has been particularly more in the Northern, Western, and Southern regions of India. However, in certain areas like Central and Eastern India, a unique pattern emerges where, lower temperatures are associated with higher rainfall. Looking ahead to the future, this positive correlation between temperature and rainfall is expected to persist across most parts of India. However, there are some notable changes on the horizon. The calculated T_Index values and their variations across these diverse regions underscore the intricate nature of the Indian Summer Monsoon and its intricate relationship with climatic factors. It's important to recognize that this relationship varies across different regions and may undergo some changes in the years to come. In the North-Eastern regions, the abundance of rainfall is not predominantly dependent on temperature fluctuations; instead, it is primarily due to orographic lifting, leading to an orographic type of rainfall.

This study provides valuable insights into the evolving thermal conditions across various regions of India, with significant implications for climate adaptation and mitigation efforts. The substantial disparities between historical and projected T_Index values emphasize the urgency of addressing climate change and its potential consequences for these regions. It is imperative for policymakers, researchers, and communities to take these findings into account when formulating strategies to mitigate the consequences of rising temperatures and shifting climate patterns in India. Furthermore, research on climate dynamics, including investigations into the correlation between sea surface temperatures (SST) and seasonal rainfall, enhances our comprehension of these temperature trends and their potential effects on India's climate, agriculture, and overall sustainability

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