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Trends in the Indian summer monsoon after the late seventies

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सार–1970 के दशक के उत्तरार्ध में देखे गए प्रमुख जलवायु परिवर्तन के बाद भारतीय वर्षा के पैटर्न और उनके दूरसंचार में महत्वपूर्ण परिवर्तन हुए हैं। भारतीय ग्रीष्मकालीन (जून से सितंबर) मानसून वर्षा के प्रवृत्ति विश्लेषण ने सत्तर के दशक के उत्तरार्ध के बाद पश्चिमी/पूर्वीभारत में सांख्यिकीय रूप से महत्वपूर्ण वृद्धि/कमी की प्रवृत्ति का अनुसरण किया है। पूर्वोत्तर यूरोप में सतह के तापमान में वृद्धि आर्कटिक प्रवर्धन, उत्तरी अटलांटिक से गर्म तापमान संवहन, बढ़ी हुई सौरविकिरण और क्षेत्र के सूखने का प्रकटीकरण है, जिसके कारण अवतलन और क्षोभमंडलीय दबाव में वृद्धि हुई है। पूर्वोत्तर यूरोप में मध्य-क्षोभमंडलीय अवतलन और सतह के गर्म होने ने इसे यूरेशियन क्षेत्र की ओर रॉस्बीतरंग के अनुकरण/प्रसार के लिए एक सक्रिय क्रिया केंद्र बना दिया है,उष्णकटिबंधीय हिंदमहासागर के पिछले दशकों में बढ़ते तापमान ने उष्णकटिबंधीय पश्चिमी हिंदमहासागर और सोमालिया पर निम्न दबाव पैदा कर दिया है, जिससे अरबसागर की ओर भूमध्यरेखीय प्रवाह बढ़ जाता है और उत्तरी भारत की ओर घट जाता है। इससे पश्चिमी भारत की ओर नमी का प्रवाह/अभिसरण बढ़ जाता है और उत्तरी भारत की ओर नमी कम हो जाती है। भारतीय भूभाग में ऊपरी क्षोभमंडलीय गहरा ईसेप्रवेशितगर्त के साथ नमी से युक्त भूमध्यरेखीय प्रवाह की परस्पर क्रिया से पश्चिमी भारत में भारी वर्षा होती है, जिससे मानसून पश्चिम की ओर स्थानांतरित हो जाता है।

ABSTRACT. Indian rainfall patterns and their teleconnections have exhibited significant changes following the major climatic shift observed in the late 1970s. The trend analyses of the Indian summer (June through September) monsoon rainfall have followed a statistically significant increasing/decreasing trend in western/eastern India after the late seventies. The increase in surface temperature over northeast Europe is a manifestation of Arctic amplification, warm temperature advection from the North Atlantic, increased solar insolation, and drying of the region, which has led to increased subsidence and tropospheric pressure. The mid-tropospheric subsidence and surface warming over northeast Europe have made it an active centre-of-action for the emulation/propagation of the Rossby wave towards the Eurasian region, having a trough east over the Caspian Sea, followed by massive ridges over east Asia. The penetration of this trough towards the Indian landmass favours deep convection. The recent decades of warming of the tropical Indian Ocean have produced low pressure over the tropical western Indian Ocean and Somalia, which increases the cross-equatorial flow towards the Arabian Sea and decreases towards northern India. This increases moisture flow/convergence towards western India and decreases moisture towards northern India. The interaction of the moisture-embedded cross-equatorial flow with the upper-tropospheric deeply penetrated trough through the Indian landmass breaks out to heavy rainfall over western India, which causes a shift of the monsoon westward.

Key words– Trend analysis, Indian summer monsoon rainfall, Eurasian Rossby wave, Upper-troposphere trough, Cross-equatorial flow, Arctic amplification.

1. Introduction

The global climate shift/change observed during the late-seventies along with the global warming of the atmosphere and tropical oceans has altered the regular spatio-tempera l distribution of precipitation (Trenberth *et al.*, 2003, Giorgi *et al.*, 2011, Madakumbura *et al.*, 2019). The Indian rainfall during different seasons has observed such abrupt, substantial and persistent shifts/changes around late-seventies (Yadav 2025, Yadav *et al.*,2020, Yadav and Roxy 2019, Yadav 2013, Yadav 2012, Yadav *et al.*, 2010, Yadav *et al.*, 2009a, Yadav 2009a, Yadav 2009b). Due to this major climate shift/change, the tropical climate system has undergone significant secular changes on the long-term interannual timescale. A significant increase in the tropical central and eastern Pacific, Indo-Pacific warm-pool and Indian Ocean sea surface temperature (SST) was found, which were associated with enhanced tropical convective activities (Nitta and Yamada, 1989, Wang, 1995, Yadav 2025), changed the large-scale circulation and the teleconnections patterns. Following this climate shift in the tropical Pacific, many properties of El-Niño-Southern Oscillation (ENSO), such as frequency, intensity and the direction of propagation, have changed (Trenberth, 1990; Wang, 1995). The Indo-Pacific warm-pool has been also warming since the late-seventies (Yadav 2025) and has been expanding by 2.3×10^5 km^2 per year from 1900 to 2018 and at an accelerated average rate of 4×10^5 km^2 per year from 1981 to 2018 (Roxy *et al.*, 2019).

The Indian rainfall has shown changes/shifts in the seasonal rainfall patterns during different seasons in the late-seventies (Yadav 2009 a,b, 2012, 2013, Yadav *et al.*, 2007, 2009a,b, 2010, 2020). The global teleconnections have changed, the old predictors had lost their significance, and the new predictors had emerged after the late-seventies (Webster and Palmer 1997; Krishna Kumar *et al.*, 1999; Chang *et al.*, 2001; Kripalani *et al.*, 2001, etc.). The India Meteorological Department (IMD) had to upgrade its seasonal empirical/statistical forecast models for all seasons. Out of all the seasons, Indian summer monsoon rainfall (ISMR) is the most important. Because, the annual Indian rainfall peaks during the summer months of June through September (JJAS), when it gets about more than 80% rainfall in most parts of India. For South Asian meteorologists, the JJAS is famous for the Indian summer monsoon (ISM) season. The ISM is so huge that it is an integral part of the global climate system that affects the weather and climate worldwide by modulating the general circulation pattern. The ISMR is the main source of irrigation for the Kharif crops sown during the season. It also maintains the soil moisture for the Rabi crops sown during the coming successive winter season. Therefore, the crop yields of Kharif, as well as Rabi crops of India are highly sensitive to the ISMR variability. What this means is that ISMR has a huge impact on food-grain production, affecting the agrarian economy and the Gross Domestic Product. Thus, infecting the hydroclimatic conditions of the huge population living in India (Gadgil and Gadgil, 2006). Therefore, a slight change/shift in ISMR has severe implications and plays an essential role in human societies. In the current global warming scenarios, studying the recent trends in the ISMR has become very important for designing management strategies for water resources and agricultural policies. On that account, it becomes crucial that the ISMR trends should be minutely studied.

The increasing ISMR towards northwest India and drying towards Gangetic Plains after the late-seventies has been reported by several studies in the past such as Yadav 2016, 2017a, Yadav and Roxy 2019, Yadav *et al.,* 2020. Studies by Yadav in 2016 and 2017a observed flooding of northwest India ISMR is attributed to the rising surface temperature over Iran. The upper-tropospheric ridge of Eurasian Rossby waves shifts and intensifies the Tibetan High core westward. Also, mass accumulation owing to the upper-troposphere ridge induces subsidence, increasing surface temperature and low-pressure area over Iran. This expedites the mid-tropospheric cyclonic circulation over western India, favouring convection. Although, a decreasing trend in the Gangetic Plains was reported in studies by Yadav and Roxy, 2019 and Yadav *et al.*, 2020. Yadav and Roxy, 2019 argued that the drying of the Gangetic Plains is associated with the eastern equatorial Indian Ocean warming. The warmer SST generates off-equatorial Rossby gyres towards the Indian landmass, consequently elevating the geopotential height owing to tropospheric heating, unfavourable for Gangetic Plains rainfall. One more study by Yadav *et al.*, 2020 notifies that the swapping of the Pacific and Atlantic Niño influences the Gangetic Plains ISMR. ENSO regulates upper-tropospheric winds adjusting the tropospheric wind shear in northern India, varying the convective activities over Gangetic Plains. While, the Atlantic Niño tempers the Eurasian Rossby wave influencing Gangetic Plains ISMR (Yadav *et al.* (2018), Yadav, 2017(a&b)).

The current trend and shift observed in the ISMR after the late seventies (Yadav 2009a,b, 2021 Yadav *et al.*, 2020, 2018) when the major climatic shift (Graham 1994; Trenberth and Hurrell 1994) was noted and identifying its possible reasons is the primary objective of this study. It is vitally important to understand India's monsoon season rainfall spatial trends and shifts in the present study. The most reliable high-resolution state-of-the-art dataset comprising a satellite dataset has been analyzed to understand the recent monsoon shift and linear trend in observations. It has been observed that the rising surface temperature over northeast Europe is the main factor responsible for this shift in monsoon rainfall. The structure of this paper is as follows. Section 2 presents 'materials and methods'. Section 3 describes the 'results'. The summary and discussion are recapitulated in the last section.

2. Data and methodology

The ISMR time series has been constructed from the monthly gridded rainfall record of the IMD at 0.25ºX 0.25º resolution for the period 1940–2024 (Pai *et al.*, 2015). The IMD rainfall record is prepared from more than 2000 daily rain gauge observation stations distributed over India. These records then pass through multistage quality control. After the seventies, the quality of these records is highly reliable and best among other rainfall datasets derived over India to be used for accurate examination of trends to be used for scientific purposes and by policymakers. The higher spatial resolution of the data could provide a comparatively clear visualization of the trend results applied in this study. The other dataset used for sea surface temperature (SST), 2-meter temperature (2mT), mean sea level pressure (MSLP), 200-

hPa geopotential height (GPH), 500-hPa omega, and 850- and 200-hPa U (zonal) and V (meridional) wind for the same period 1940–2024 are obtained from the European Centre for Medium-Range Weather Forecasts ERA5 reanalysis dataset at 0.25º spatial resolution (Hersbach *et al.,*, 2020). The higher spatial resolution of the data could provide a comparatively clear visualization of the trend results applied in this study. The trend of the monsoon rainfall has been studied from 1979, as the major climatic shift/changes took place in the late seventies, which has been excluded in this study, and also a large set of satellite sensors with a global coverage dataset was available from the satellite from 1979, which were included in the production of the reanalysis dataset. This allowed the state of the global atmosphere to be analysed with an accuracy and completeness not previously possible before 1979.

In the paper, simple linear least-squares regression estimates are depicted for all the spatial trends. The representation of the rate of change in the dependent variable for a unit change in the independent variable is calculated by the ‘regression coefficient’. This coefficient is referred to as the slope or trend. This study discusses only the 95% significance level of the trend analysis. The incomplete beta function used as a p-Value calculator for the Student **t**-test (significance level 0.05) is used to check the significance of these trend analyses. A regression analysis of 200-hPa GPH onto northeast Europe surface temperature for the period 1979-2024 has been carried out to explore the northeast Europe warming that generates the Eurasian Rossby wave affecting ISMR.

The Vertically Integrated Moisture Flux Convergence (VIMFC) is calculated by processes represented below in the equations 1, 2 and 3

$$\text{IUQ} = -\frac{1}{g}\cdot\int_{\text{psurf}}^{\text{ptop}}\left(\frac{\partial uq}{\partial x}\right)\cdot dp \quad (1)$$

$$\text{IVQ} = -\frac{1}{g}\cdot\int_{\text{psurf}}^{\text{ptop}}\left(\frac{\partial vq}{\partial y}\right)\cdot dp \quad (2)$$

$$\text{VIMFC} = \sqrt{(\text{IUQ})^2 + (\text{IVQ})^2} \quad (3)$$

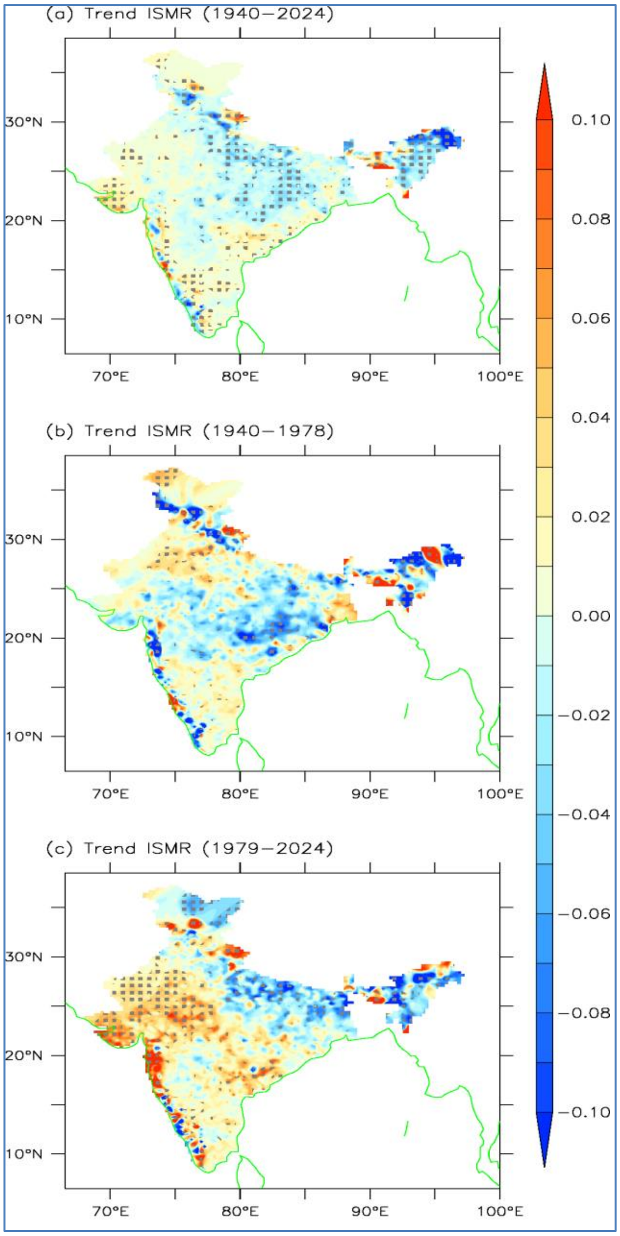
Here, **g** is the acceleration due to gravity, **p** is the pressure, **psurf** is the surface pressure, **ptop** is the pressure at the top of the atmospheric layer, **q** is the specific humidity, and **u** and **v** are the x- and y-components of the wind, respectively. The horizontal moisture flux convergence is calculated using finite centered differences on a lat/lon grid to approximate the term between brackets in Eq. (2&3) over the intervals 1000–300 hPa. The VIMFC values are expressed in 10^{-5} kg m^{-2} s^{-1}units. The trends of VIMFC are calculated in this study.

3. Results and analysis

3.1. *Trend analyses*

The June-July-August-September (JJAS) seasonal linear trend analyses of meteorological parameters related to ISMR are done from 1979-2024 (46-year period) to avoid the major climatic shift observed in the late seventies and also to include satellite datasets, which are available from 1979. With satellite, global coverage datasets were available, which filled the global atmosphere data with an accuracy and completeness not previously possible. The gridded IMD ISMR linear trend analysis (Fig. 1c) broadly shows dipole structure with a significant large patch of flooding in western India and a small patch in the northeast of Peninsular India, and drying in the Gangetic Plain (east of north India) and northeast India. By and large, northwest India gets minimum rainfall during the Indian summer monsoon (ISM) season, constantly increasing towards central India and maximum towards northeast India. Despite that, the ISMR trend analysis dipole pattern proposes a shift of the ISMR towards the west in north India after the late-seventies major climatic shift. A similar trend in the ISMR has also been detected by Yadav 2016, 2017a&b; Yadav and Roxy 2019; Yadav *et al.,* 2020. For comparison, similar trend analyses were computed from the year 1940 to the present, to explain that a similar trend was not present before. The data has been extended back to the year 1940, as the ERA5 reanalysis is also present from 1940. The trend analysis for the full-length data (1940-2024; 85-year data; Fig. 1a) displays decreasing rainfall over the Indo-Gangetic Plains, east and northeast India and increasing trend over the south Himalayas, west and south peninsular India. This trend is more or less similar to the 1979-2024 trend, but with lower values. The trend analysis computed pre-1979 major climatic shift period 1940-1978 (39-year period; Fig. 1b) shows a different trend than the post-1978 major climatic shift period 1979-2024. In the pre-1979 period (Fig. 1b), an increasing trend is observed over comparatively less area towards the north of northwest India, and a decreasing trend over central east, Western Ghats and most parts of northeast India. This clearly differentiates the spatial trend analysis for the pre- and post-late-seventies patterns.

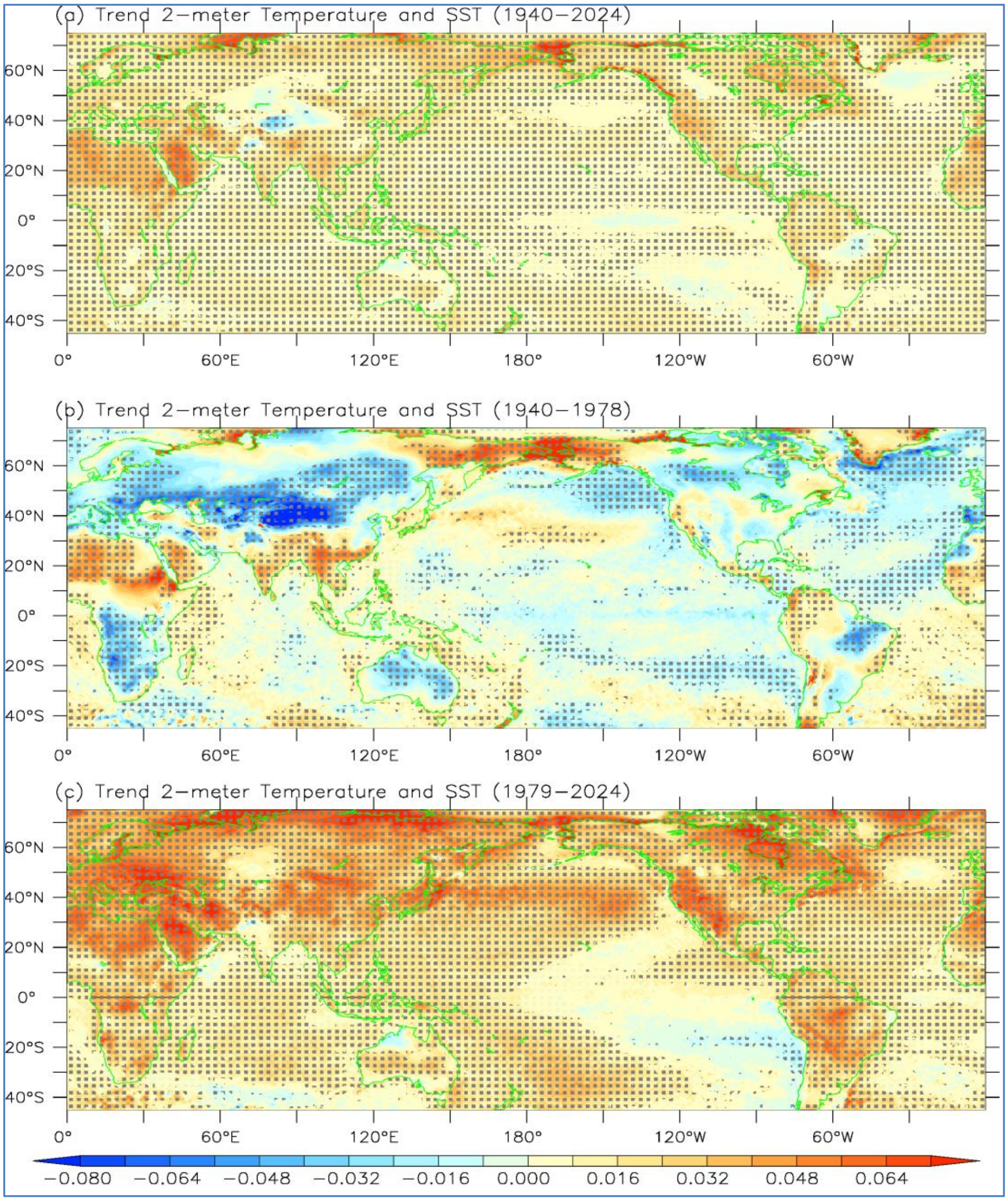
Trend analysis of SST over the ocean and 2mT over land for the full-length period 1940-2024 (Fig. 2a) show a warming trend almost everywhere except the Tibetan Plateau. The trend analysis for the pre - 1979, period from



Figs. 1(a-c). Trend analysis of Indian rainfall for JJAS season for the period (a) 1940-2024, (b) 1940-1978, and (c) 1979-2024. The shaded areas, represented by tiny grey dots, indicate a 95% significance level

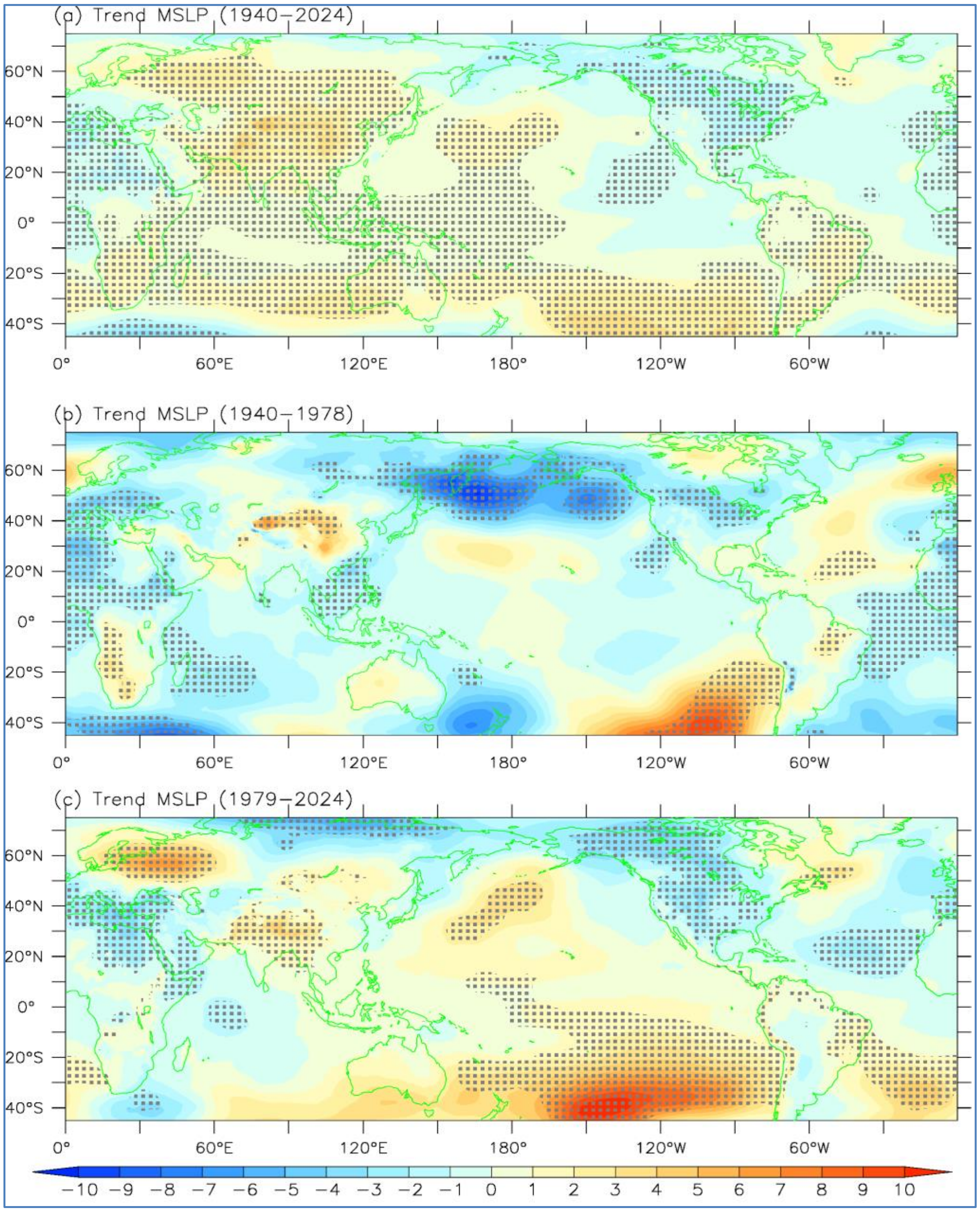
1940-1978 (Fig. 2b), shows a decreasing trend over north and central Asia, tropical and north Atlantic, tropical Pacific and south Africa, and an increasing trend over south Asia, north Africa and Alaska. For the post-1978 period, 1979-2024 (Fig. 2c) shows significant warming SST over the Indo-Pacific warm-pool region, the tropical Indian Ocean and the Mediterranean Sea and significant rising 2mT over east Asia, north Africa, the Middle-East and eastern Europe landmass. The rising surface temperatures over eastern Europe, northwest of India, east Asia and west United States of America (USA) are the centre of action, constituting the circum-global teleconnection (CGT) pattern. The westward active ISM is correlated with the CGT pattern, Yadav, 2009(a&b). The warming trend over northeastern Europe is the revelation of the Arctic Amplification, warm temperature advection from the north Atlantic and drying of the region. The warming trend appearing over north Africa stands in for the monsoon-desert relationship. Arctic amplification isthe phenomenon where the Arctic region warms at a significantly faster rate than the global average, with the Arctic warming three to four times faster than the rest of the planet in recent decades.This accelerated warming is driven by feedback loops, most notably the ice-albedo feedback, where melting ice reveals darker ocean water that absorbs more solar radiation, leading to further warming and melting. The warming of the Arctic region owing to the Arctic Amplification has decreased the horizontal temperature gradient between the extra-tropics and the polar region. Consequently, there is a decrease in storm activity over northeast Europe. The decreased storms reduced the precipitation, raising the surface temperature, as the precipitation decreases the surface temperature and vice versa. The warmer temperature advection from the heated north Atlantic and Arctic has been warming northeastern Europe in recent decades. Also, the drying of the region with fewer storms associated with subsidence, clear skies and increased solar insolation magnifies the adiabatic heating, warming the surface of northeastern Europe. The monsoon-desert mechanismis a remote teleconnection where intense convection from the ISM generates enormous tropospheric heating due to latent heat release, which induces strong atmospheric descent over the Sahara (north Africa). The large-scale atmospheric descent had led to dry conditions, contributing to the formation of the Sahara desert.

Similarly, trend analysis for MSLP, for the full-length period 1940-2024 (Fig. 3a) shows an increasing trend over central, east and south Asia, the Indian ocean, west and south Pacific and Brazil, and a decreasing trend over Africa, north America and tropical northeast Pacific. The trend analysis of MSLP for the pre-1979 period from 1940-1978 (Fig. 3b), shows a decreasing trend over the extra-tropical Pacific, tropical Atlantic, north Africa, southeast Indian ocean and northwest Pacific, and an increasing trend over east Asia and south Africa. For the post-1978 period, 1979-2024 (Fig. 3c) shows a significant rise in MSLP over north India, Pakistan, Tibet and the Himalayan region, and northeast Europe, and a significant drop in MSLP over north Africa, the Mediterranean Sea, Saudi Arabia, Somalia and the south of the equatorial Indian Ocean. The significant rise in MSLP in northeastern Europe explicates a region of high pressure



Figs. 2(a-c). Trend analysis of 2-meter Temperature (2mT) over land and sea surface temperature (SST) over ocean basins for JJAS season for the period (a) 1940-2024, (b) 1940-1978, and (c) 1979-2024. The shaded areas, represented by tiny grey dots, indicate a 95% significance level

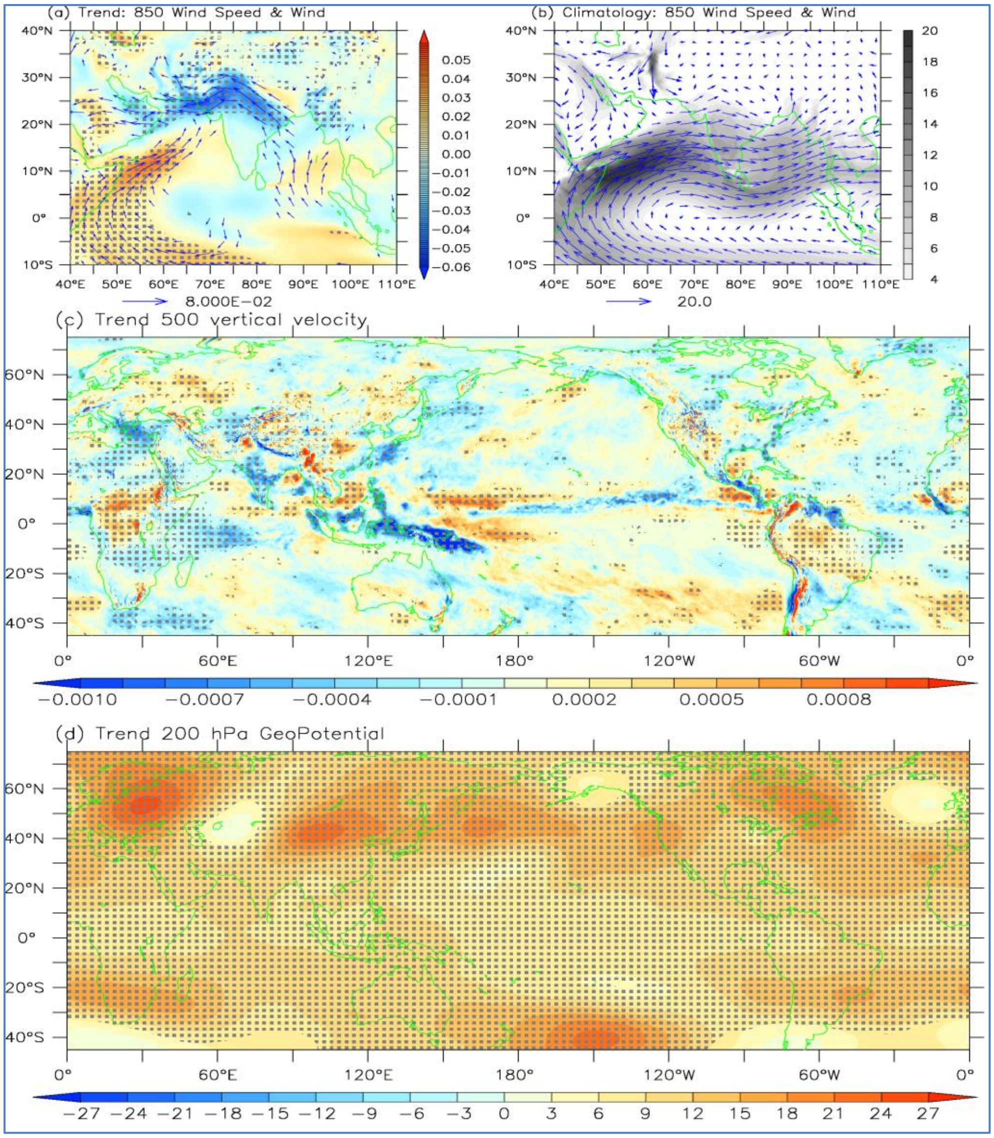
and is the manifestation of fewer storm activities. The drop in MSLP at Somalia and south of the equatorial Indian Ocean and the rise in MSLP over north India decrease the pressure gradient force between north India and the southwest Arabian Sea, which weakens the cross-equatorial monsoon flow towards central and north India. Contrarily, between the northwest Indian Ocean and the southern Indian Ocean (over Mascarene High), the pressure gradient force increases owing to the drop in MSLP trend observed south of the equatorial Indian Ocean and Somalia, intensifying the monsoonal flow towards the southern Indian Ocean and the Arabian Sea. From the spatial pattern of the trend analysis of IMD rainfall over India, surface temperature of land and ocean, and MSLP, it is clear that the trend between the pre-1979, period (1940-1978) and post-1978 for the period (1979-2024) was very distinct. Mostly, the full-length data trend analysis was more dominant by the recent four and a



Figs. 3(a-c). Trend analysis of mean sea level pressure (MSLP) over ocean basins for JJAS season for the period (a) 1940-2024, (b) 1940-1978, and (c) 1979-2024. The shaded areas, represented by tiny grey dots, indicate a 95% significance level

half decades of data from 1979 to 2024, with reduced values Further, the study of trend analysis for different meteorological parameters is done for the 1979-2024 datasets to identify the possible reason for the current trend and shift observed in the ISMR after the major climatic shift of the late seventies.

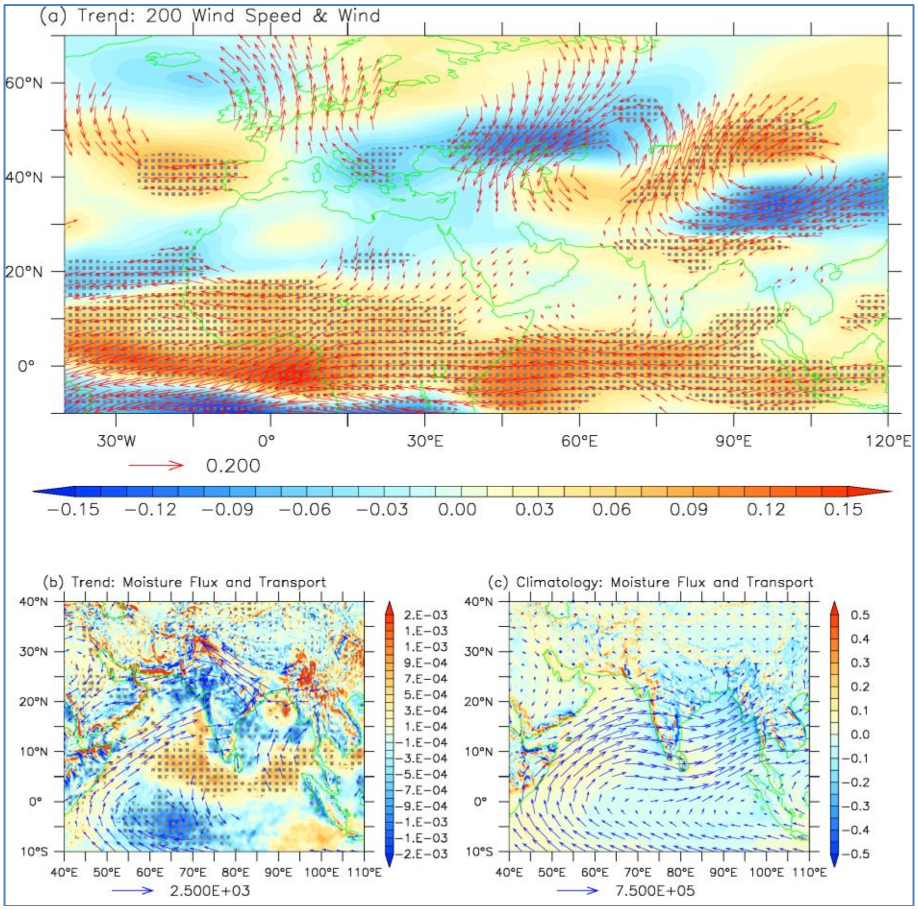
The 850-hPa wind and speed trend analysis (Fig. 4a) shows that the lower-level cross-equatorial flow from the southern Indian Ocean to the central Arabian Sea has increased, while the wind over north India has decreased. The trend winds spotted over north India are against climatological winds (Fig. 4b). This is associated with the increasing surface pressure gradient between the south Indian Ocean and Somalia, intensifying monsoonal winds from the south Indian Ocean to the Arabian Sea. The monsoonal wind decreasing trend in north India results from increasing surface pressure, decreases pressure gradient towards north India. The trends in 500-hPa Omega (Fig. 4c) show significant negative trends over the tropical west Indian Ocean. Omega is a term used in the atmosphere to describe vertical motion in pressure



Figs. 4(a-d). JJAS seasonal trend analysis for (a) 850-hPa wind (u,v; vectors) and wind speed (shade), (c) 500-hPa Omega, (d) 200-hPa Geopotential Height (GPH) for the period 1979-2024. The shaded areas, represented by tiny grey dots, indicate a 95% significance level. (b) JJAS seasonal climatology for 850-hPa wind (u,v; vector) and speed (grey shade)

coordinates. Omega has units of pressure per time and because pressure decreases from the surface towards the height, the positive omega values equate to the downward vertical motion and vice-versa. Here, 500-hPa Omega represents the mid-tropospheric vertical motion. The negative trend in 500-hPa omega at the tropical west Indian Ocean suggests a surge in convection owing to increased SST. The ascending motion trends observed over the northeast of Peninsular and western India and a descending motion trend over northeast India agree with the ISMR trend in Fig. 1(a). Remarkably, northeastern Europe and tropical Africa show significant positive (descending motion) trend patches. The subsidence trend over northeastern Europe is related to the Arctic Amplification, temperature advection and drying of the region, further abetting an increase in surface temperature trend owing to adiabatic warming and increased solar insolation. Since the Arctic Amplification warms the Arctic region, decreasing the horizontal temperature gradient between the extra-tropical and polar regions, decreasing storm activities, and hence subsidence trends are seen in recent decades.

The trends in 200-hPa GPH (Fig. 4d) show a significant increasing trend over northeast Europe and east Asia. The positive MSLP and 200-hPa GPH trend remains at the same positions in northeast Europe, exhibiting an increase of pressure throughout the troposphere, which



Figs. 5(a-c). JJAS seasonal trend analysis for (a) 200-hPa wind (u,v; vectors) and wind speed (shade), (b) vertically integrated moisture transport (iuq,ivq; vector) and flux convergence (vimfc; color shade). (c) JJAS seasonal climatology for vertically integrated moisture transport (iuq,ivq; vector) and flux convergence (vimfc; color shade). The shaded areas, represented by tiny grey dots, indicate a 95% significance level

inhibits the storm activities. This increase in the thickness of the GPH is due to Arctic amplification observed in recent decades. The thickness of GPH has caused an increase in subsidence, which additionally increases the surface temperature due to the adiabatic warming. Moreover, subsidence being cloud-free, increases solar insolation further abetting surface warming. Over and above, melting sea ice owing to Arctic Amplification reduces albedo, also releases greenhouse gases from thawing permafrost and frozen methane from the ocean bottom (Schuur *et al.*, 2015). The above-mentioned processes have increased the surface warming of northeast Europe due to diabatic heating (Fig. 1b), which stimulates the Rossby wave that propagates towards central Asia (Cen *et al.*, 2020, Yadav 2016), known as the 'Silk-Road Pattern (SRP)' (Yadav 2017a). The SRP is also part of the 'circum-global teleconnection (CGT)' (Ding and Wang 2005, Yadav 2009a&b) pattern. The Rossby wave that propagates towards central Asia gives rise to negative and positive upper troposphere pressure anomalies east of the Caspian Sea and east Asia, respectively (Fig. 4d). The positive upper troposphere pressure anomaly intensifies present east Asia blocking high. The blocking High deepens the troughing east of the Caspian Sea. The frequent intrusion of deep high-amplitude troughs towards western India is responsible for intense convection. In recent decades, such types of extreme events are frequently observed, like July 2015 and mid-June 2013 a multi-day of hefty rainfall centred on the north Indian state of Jammu and Kashmir, and Uttarakhand, respectively and the late July 2010 floods in Pakistan.

The 200-hPa wind (red arrows) and speed (colour shade) trend analyses (Fig. 5a) show a sequence of upper-troposphere cyclonic and anti-cyclonic circulation from the north Atlantic to east Asia, illustrating the Eurasian Rossby wave. The east of the cyclonic circulation shows a decreasing wind speed trend towards the northeast and an increasing wind speed trend towards the west of the cyclonic circulation north of India. This increasing wind speed produces divergence at the upper troposphere, inducing upward motion as observed in the 500-hPa

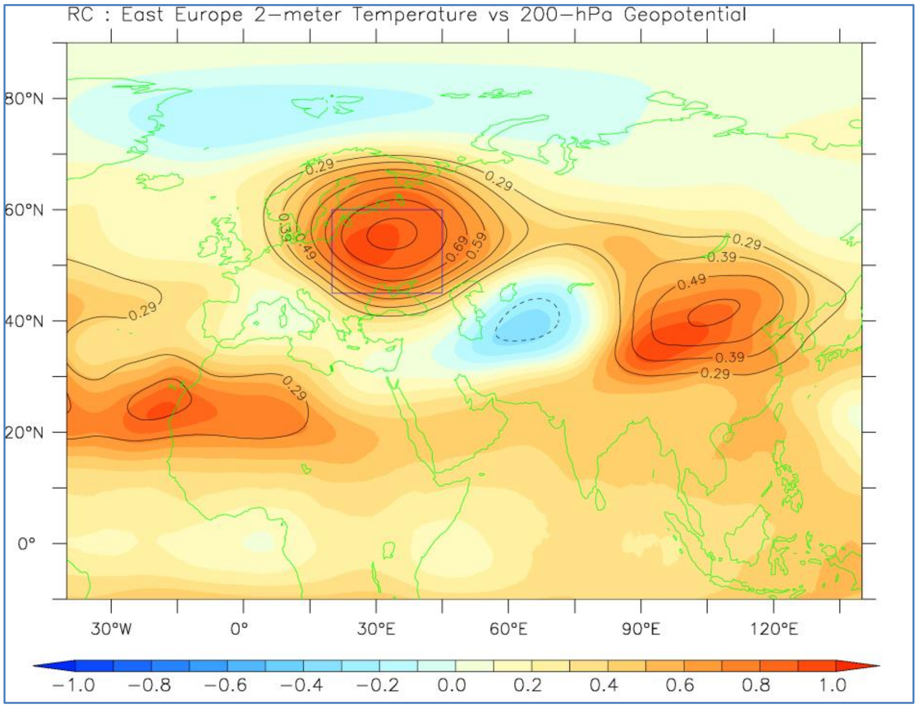


Fig. 6. Contiguous regression of 200-hPa Geopotential (m) onto 2-meter Temperature (K) averaged over 20°-45° E, 45°-60° N (shown by blue box at northeast Europe) (color shade, scaled by 500) for 1979-2024. Black contours show the significance at a 95% confidence level

omega (Fig. 4c), favouring the outbreak of convection over northwest India. The upper-troposphere anti-cyclonic circulation associated with the high GPH trend over east Asia resembles frequent and long duration Blocking highs. Blocking highs effectively block or redirect the migratory mid-latitude westerly disturbances. The troughs embedded in the westerly disturbances deepen and intrude into northwest India. These troughs are high-amplitude and can intrude deep into northwest India, when interacting with the lower-level monsoonal flow, producing hefty rainfall, as recorded in the years 2015, 2013 and 2010.

Vertically integrated moisture flux (color shade) and transport (vectors) trend (Fig. 5b) show more moisture accumulation towards the western India and less moisture accumulation towards Gangetic Plains, consistent with the rainfall trend observed in Fig. 1a. The vertically integrated moisture transport trend depicts transport of moisture from south Indian Ocean through cross-equatorial monsoonal flow towards western India. The vertically integrated moisture transport climatological flow (Fig. 5c) shows westerly moisture transport flow (*i.e*. from the Arabian Sea) towards central India and the south Gangetic Plains. But, the moisture transport trend flow is southeasterly, suggesting weak moisture flow towards the Gangetic Plains. The moisture transport trend is showing cyclonic flow with southwesterly flow from Somalia to Gujarat and northeasterly flow from north of the Arabian Sea to south of the Red Sea. A similar cyclonic circulation trend is also observed at the lower troposphere (850-hPa) wind (Fig. 4a). This cyclonic circulation is the consequence of the upper-troposphere trough observed east Caspian Sea, which induces a surface low in the north Arabian Sea. Eventually, the decrease of moisture transport towards the north India, especially the Gangetic Plains, has decreased the monsoon rainfall there. In contrast, the increase in moisture transport towards western India has increased monsoon rainfall.

In summary, the increasing JJAS rainfall trend over west India and the decreasing trend over the Gangetic Plains and northeast India are due to the Eurasian Rossby waves originating from the warmed northeastern Europe. The Arctic Amplification has led to a descent and drying over northeastern Europe, which has warmed the surface temperature of the region. The upper-troposphere Eurasian Rossby wave emulates and propagates from northeastern Europe as it acts as the centre of action for the effective excitation of the Eurasian Rossby wave towards east Asia *via* central Asia. This reinforces the successive anomalous ridge, trough and ridge over eastern Europe, east of the Caspian Sea and east Asia, respectively, of the Eurasian Rossby wave. The east of the Caspian Sea anomalous trough intrudes/penetrates deep into western India, causing devastating rainfall. Also, a warming trend over the Indian Ocean forms surface low pressure over Somalia and the western tropical Indian Ocean, which builds up an intense pressure gradient between the south Indian Ocean and western tropical Indian Ocean and reduces the pressure gradient towards north India. This strengthens the monsoonal flow towards western India and turns down the monsoonal flow towards northern India, responsible for increasing the JJAS rainfall trend in western India and decreasing the trend towards the Gangetic Plains.

3.2. *Regression analysis*

We have seen from the previous sub-sections that the ISMR has decreased over the Gangetic Plain (east of north India) and northeast India and increased over northwest and northeast peninsular India contemporaneously, with the increased tropospheric pressure and surface temperature over northeast Europe. To investigate the role of northeast Europe surface temperature on ISMR, the 200-hPa GPH has been regressed onto the 2mT averaged over a box 20°-45°E, 45°-60°N at the northeast Europe index (Fig. 6). The successive significant positive, negative and positive anomalies over Eurasia represent the Rossby wave pattern. This reveals that the northeast Europe surface temperature is associated with the evolution and propagation of the Eurasian Rossby wave towards the northwest of India to east Asia. The positive pressure anomaly over east Europe is followed by a negative pressure anomaly east of the Caspian Sea and then a positive pressure anomaly in eastern Asia. The eastern Asia positive anomaly acts as a Blocking High. The negative GPH anomaly east of the Caspian Sea represents troughs in westerlies, which deepen and penetrate towards north India. This high-amplitude upper-troposphere trough penetration/intrusion favours strong convection over northwest India. Moreover, the warming of the tropical Indian Ocean is related to a negative surface pressure trend over the western tropical Indian Ocean and Somalia. Also, an increasing surface pressure trend is seen north of India. The positive and negative pressure anomaly over north India and Somalia, respectively, reduces the cross-equatorial monsoon flow towards north India. However, the surface pressure gradient between Mascarene High and Somalia is increased by Somalia's negative anomaly, strengthening the cross-equatorial flow from the Mascarene High towards western India.

4. Conclusions

In this study, a recent four-and-a-half-decade long-term trend analysis of ISMR has been done on the best reliable, state-of-the-art and higher spatial resolution dataset. The trends of ISMR show a significant decreasing trend in the Gangetic Plain (east of north India) and northeast India and an increasing trend in western India and a small patch of northeast peninsular India. The increasing/decreasing trend observed in ISMR is connected to the warming of the south-central equatorial Indian Ocean. The warming of the SST increases convection on the spot and the drops in surface pressure trend over the tropical western Indian Ocean and Somalia. The dropin surface pressure over Somalia has built up a pressure gradient between the south Indian Ocean and Somalia, which amplified the moisture accumulation towards the western Arabian Sea from the south Indian Ocean. This provides sufficient moisture to western India. In contrast, the rise in surface pressure north of India and the dropin surface pressure over the tropical western Indian Ocean has declined the pressure gradient between the tropical western Indian ocean and north India, which had turned down the monsoonal flow towards north India, diminishing the moisture supply, resulting in decreasing ISMR trend towards Gangetic Plains.

Further, the rising surface temperature trend over northeastern Europe is very crucial as it is the centre of action for the effective excitation of the Eurasian Rossby wave. The rising surface temperature over eastern Europe is the manifestation of the Arctic Amplification noted in recent decades. The warming of the Arctic reduces the horizontal temperature gradient between the extra-tropics & polar region, lessening the storm activities over northeast Europe. Consequently, the upper-troposphere ridge is placed over northeast Europe. The extra accumulation of atmospheric masses owing to the upper-troposphere ridge increases the upper-tropospheric GPH over the Arctic Amplification region. Also, the extra accumulation of atmospheric masses increases subsidence. This anomalous subsidence over eastern Europe increases the adiabatic warming. The Eurasian Rossby wave emanating from eastern Europe reinforces anomalous troughs and ridges east of the Caspian Sea and east Asia, respectively. The anomalous ridge in east Asia acts as a Blocking High, which deepens the migratory mid-latitude troughs and redirects to deeply penetrate into northwest India. This creates a conducive condition for intense convection to occur, which increases the ISMR trend towards western India.

We are already familiar that the Arctic is warming almost three times as fast as the global rate due to the unique features in the Arctic climate system. This phenomenon is known as Arctic amplification. Above that, human-caused warming has been driving reductions in Arctic sea ice since the late 1970s. Evidence suggests that rapid warming in the Arctic can also destabilize the stratospheric polar vortex, forcing cold Arctic air to mid-latitude regions such as Europe (Schuur *et al.*, 2015). As described above, the warming of northeastern Europe is the center of action for the effective excitation of the Eurasian Rossby wave. On that account, the role of Eurasian Rossby wave interaction with the monsoonal flow affecting ISMR has increased, which we have observed in recent decades and is going to increase in the future.

Warming of tropical SSTs has been an important driver of climate variability. The tropical SSTs are very close to the threshold temperature of 28 °C. A small increase in tropical SSTs reaches the threshold temperature of 28 °C, inciting deep atmospheric convection consisting of high convective clouds, which can reach an altitude of up to 15 km, and generate much latent heat in the convection process, capable of modulating atmospheric general circulation. Also, an increase in SST near the Equator attracts the intertropical convergence zone (ITCZ). ITCZ is the region of trade wind convergence, accumulating moisture and generating a perpetual series of thunderstorms that heat the troposphere. These act as the tropical heat source modulating the planetary-scale general circulation, affecting the ISM. The warming of the tropical India Ocean induces a surface low-pressure area in the western tropical Indian Ocean, disturbing the climatological pressure gradient between the southern Indian Ocean and north India. This intensifies cross-equatorial monsoonal flow towards the Arabian Sea and inhibits the monsoonal flow towards north India, drying monsoonal rainfall in the Gangetic Plains and flooding in western India.

The Gangetic plain drying trend during monsoon season is a severe concern. Because the rain during the summer monsoon not only affects the Kharif crops sown during the concurrent summer season, but also the Rabi crops sown during the succeeding winter season harvests. Therefore, it provides huge food grain production to feed the Indian population. The Gangetic Plains drying trend puts massive pressure on irrigation infrastructure, resulting in a heavy load on the power supply and maintaining the groundwater table. Despite all efforts, it results in low food grain production which will create serious challenges to India's food security in the coming years. That is why the study of the Indian monsoon system is required with more reliable and high-resolution reanalysis data for a better understanding of the recent trends and shifts in monsoon rainfall prediction. These studies are of utmost necessity to mitigate the long-term impact of changing rainfall trends and patterns in India and will be applicable to policymakers for their future plans.

Data availability

The European Centre for Medium-Range Weather Forecasts ERA5 reanalysis dataset used in this study is available athttps://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-pressure-levels-monthly-means?tab=form. for high-resolution precipitation data and the Indian Meteorological Department (http://www.imd.gov.in/) for the availability of the daily rain gridded data over India.

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Authors' contributions

Ramesh Kumar Yadav: Conceptualization, Methodology, Data collection, Formal analysis and investigation and Writing - original draft preparation. The author has read and approved the final manuscript.

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