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On the increasing length of the southwest monsoon season over India

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सार– दक्षिण -पश्चिम मॉनसूनी वर्षा का भारत में कृषि प्रथाओं और जल संसाधन प्रबंधन पर एक सर्वोपरि प्रभाव पड़ता है। यह अध्ययन 1971 से 2020 की अवधि के लिए भारत में दक्षिण-पश्चिम मॉनसून अवधि के दौरान दीर्घकालिक बदलावों की जांच करता है। देश भर में दक्षिण-पश्चिम मॉनसून ऋतु की अवधि 1971-2020 के दौरान 1.6 दिन प्रति दशक की दर से वृद्धि दिखाती है। दक्षिण-पश्चिम मॉनसून अवधि में वृद्धि की दर इस अवधि के दौरान मॉनसून की वापसी के दिनों में देरी की दर के साथ मेल खाती है। यद्यपि केरल (MOK) पर मॉनसून उद्भव की तारीख उल्लेखनीय अंतर-परिवर्तनशीलता दिखाती है, लेकिन यह पिछले 50 वर्षों के दौरान सांख्यिकीय रूप से महत्वपूर्ण परिवर्तन नहीं दिखाता। आमतौर पर दक्षिण-पश्चिम मॉनसून वर्षा विश्लेषण के लिए 01 जून और 30 सितंबर (JJAS) के बीच की वर्षा को मानक माना जाता है। यह अध्ययन MOK और वापसी की तारीखों (MOK2WDRL के रूप में कहा जाता है), और 1971-2020 के लिए JJAS वर्षा के बीच वर्षा में अंतर की जांच करता है, एक वर्षामापी आधारित ग्रिडेड वर्षा डेटासेट का उपयोग करता है। JJAS वर्षा पूरे भारत की वार्षिक वर्षा का 75% है, जबकि यह MOK2WDRL वर्षा द्वारा 79% है। पूरे भारत की मॉनसून वर्षा की अंतर-परिवर्तिता को भी MOK2WDRL और JJAS वर्षा के अनुमानों से कई वर्षों तक अलग दिखाया गया है। NINO 3.4 इंडेक्स पूरे भारत की रबी फसल की उपज और रेपसीड और सरसों की उपज के साथ सहसंबंध गुणांक देश में JJAS वर्षा की तुलना में MOK2WDRL वर्षा के साथ अधिक दिखाया गया है।

ABSTRACT. The southwest monsoon rainfall has a paramount impact on agricultural practices and water resources management across India. This study investigates long-term changes in the southwest monsoon length over India for the period from 1971 to 2020. The length of the southwest monsoon season across the country shows an increase at the rate of 1.6 days per decade during 1971-2020. The rate of increase in the southwest monsoon length coincides with the rate of delay in the monsoon withdrawal dates during this period. Although the monsoon onset date over Kerala (MOK) shows notable interannual variability, it does not show significant change during the last 50 years. Rainfall between 01 June and 30 September (JJAS) is typically considered for the southwest monsoon rainfall analyses. This study investigates the difference in rainfall between MOK and withdrawal dates (termed as MOK2WDRL), and JJAS rainfall for 1971-2020 using a rain gauge-based gridded rainfall dataset. JJAS rainfall contributes 75% to all-India annual rainfall, whereas it is 79% by MOK2WDRL rainfall. The interannual variability of all-India monsoon rainfall is also shown to be different for several years from MOK2WDRL and JJAS rainfall estimates. The correlation coefficients with Nino 3.4 index, all-India *Rabi* crop yield, and all-India rapeseed & mustard yield are shown to be higher with MOK2WDRL rainfall than JJAS rainfall over the country.

Key words– Rainfall, Southwest monsoon season, Monsoon onset and withdrawal, Interannual variability, Crop yield.

1. Introduction

The southwest monsoon rainfall contributes to about three-fourth of the annual rainfall across India and has a substantial impact on agricultural-dominated economy of the country. The monsoon onset over Kerala (MOK) is considered as the beginning of the southwest monsoon or summer monsoon rainy season for the country. The India Meteorological Department (IMD) was using criteria for declaring MOK operationally based on daily rainfall of seven observatory stations over Kerala and adjoining areas namely, Colombo, Minicoy, Trivandrum, Alleppey, Cochin, Kozhikode, and Mangalore till 2005 (Ananthakrishnan *et al*., 1967). Several meteorological variables such as rainfall, wind fields, relative humidity, vertically integrated zonal moisture transport and convective activity through outgoing longwave radiation (OLR) composites have been analyzed to examine their evolution during the onset phase of the Indian summer monsoon (Soman and Krishna Kumar, 1993). This study revealed sudden rise in rainfall over the peninsular India except east coast stations, weakening and poleward shift of upper-tropospheric subtropical westerlies as well as strengthening of the tropical easterlies with the onset of the summer monsoon. The relative humidity, vertically integrated zonal moisture transport and convective activity also showed sharp increase over the south peninsular India and adjoining oceanic areas during this period.

Few criteria and indices have also been proposed for the onset and withdrawal of the Indian summer monsoon using vertically integrated moisture transport and low-level zonal wind speed over the Arabian Sea instead of rainfall (Fassulo and Webster, 2003; Taniguchi and Koike, 2006; Wang *et al*., 2009). An index namely, hydrologic onset and withdrawal index (HOWI) was proposed by Fasullo and Webster (2003) utilizing vertically integrated moisture transport over the Arabian Sea for determination of onset and withdrawal of the Indian summer monsoon. However, Taniguchi and Koike (2006) showed that onset criterion defined using low-level wind speed over the Arabian Sea presented Indian summer monsoon onset date more adequately than using moisture transport.

Since 2006, IMD declares MOK operationally based on rainfall, wind field and OLR criteria (Joseph *et al*., 2006; Pai and Nair, 2009) and are given by:

(*i*) If at least 8 out of 14 rain gauge stations in Kerala state (namely Minicoy, Amini, Thiruvananthapuram, Punalur, Kollam, Allapuzha, Kottayam, Kochin, Trissur, Kozhikode, Talassery, Cannur, Kasargode and Mangalore) report daily rainfall of 2.5 mm or more for two consecutive days after 10thMay, the MOK may be declared on the second day if following two criteria are also satisfied in concurrence.

(*ii*) Depth of westerlies in the IMD wind analysis or satellite-derived winds should be maintained upto 600 hPa over the area bounded by 0º-10º N latitude and 55º-80º E longitude. In addition, zonal wind speed over the area bounded by 5º-10º N latitude and 70º-80º E longitude should be of the order of 15-20 knots at 925 hPa.

(*iii*) The INSAT derived OLR value should be lower than 200 Wm^{-2} in the area bounded by 5º-10º N latitude and 70º-75º E longitude.

The dates of MOK and the monsoon advances across India play a critical role in agricultural practices and water management. The mean date of MOK is found to be 1st June with a standard deviation of about one week, whereas the southwest monsoon covers the entire country by 8th July climatologically (Tyagi *et al*., 2011; Pai *et al*., 2020). In addition, the dates of MOK show remarkable interannual and decadal variability (Pai and Nair, 2009; Ghanekar *et al.*, 2019).

Since 2006, IMD declares withdrawal of the southwest monsoon from extreme northwest India operationally based on the following major synoptic features (Pai *et al*., 2020):

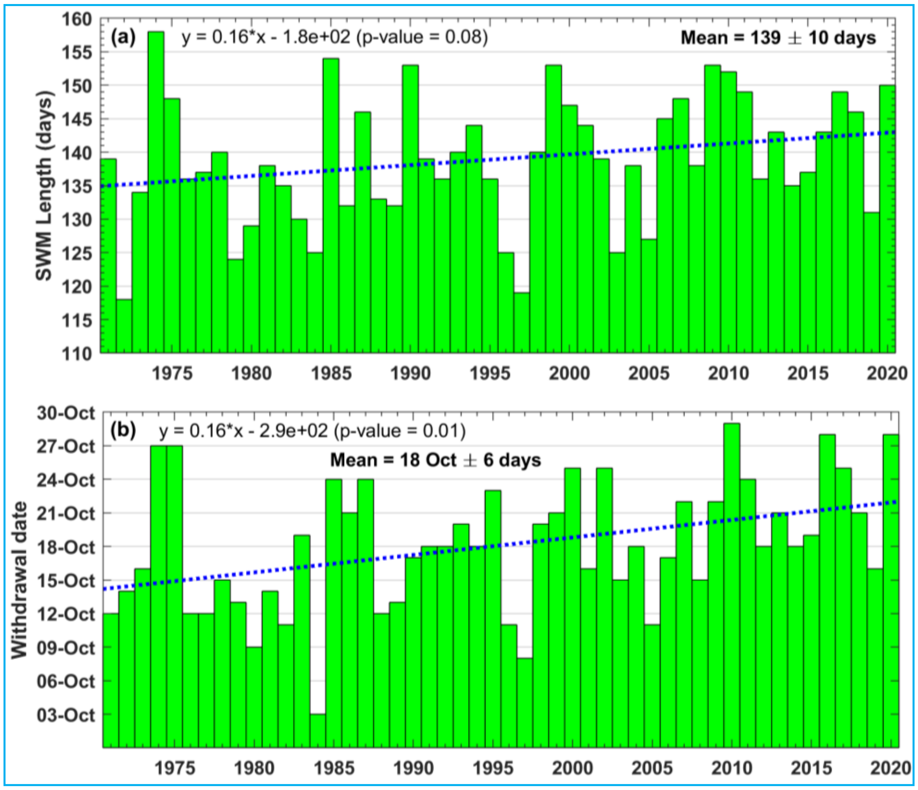
(*i*) Cessation of rainfall activity over the area for continuous 5 days after 1st September.

(*ii*) Establishment of an anticyclone in the lower troposphere of 850 hPa and below.

(*iii*) Considerable reduction in moisture content is seen in satellite water vapour imageries and T-Phi grams.

The dynamic and thermodynamic features and large-scale circulations also show significant changes during the withdrawal of the southwest monsoon (Raju and Bhatla, 2014). Based on a fixed network of 2140 rain gauges-based gridded rainfall dataset at 1º spatial resolution, IMD has revised the dates of normal monsoon onset/progress and withdrawal across the country (Pai *et al*., 2020). The climatological mean monsoon withdrawal date from the country has been found to be 15th October by the IMD. The withdrawal dates of the monsoon also exhibit large interannual variability similar to MOK dates. The variability in duration of the withdrawal phase of the southwest monsoon considerably influences the variability in both southwest and northeast monsoon rainfall over India (Mondal and Chaudhari, 2022).

The Indian southwest or summer monsoon rainfall (ISMR) exhibits large interannual variability leading to the occurrence of floods and droughts intermittently (Gadgil, 2003). The interannual variability of ISMR is shown to be closely associated with major oscillations in the Indian, Pacific and Atlantic Oceans (Mooley and Parthasarathy, 1983; Webster and Yang, 1992; Ju and Slingo, 1995; Gadgil *et al*., 2007; Rajeevan and Pai, 2007; Borah *et al*., 2020; Hrudya *et al*., 2021; Athira *et al.*, 2023). The El Niño Southern Oscillation (ENSO) in the tropical Pacific Ocean is one of the major factors affecting ISMR. Although there is no one-to-one relationship between the strength of ENSO and ISMR, positive phase of ENSO is generally associated with deficient ISMR. The length of the southwest monsoon season also influenced by ENSO through changes in onset and withdrawal dates (Goswami and Xavier, 2005; Xavier *et al.*, 2007). Rain-fed agricultural foodgrain yields across India are largely affected by interannual variations in ISMR. A linear correlation coefficient of 0.71 was found between ISMR



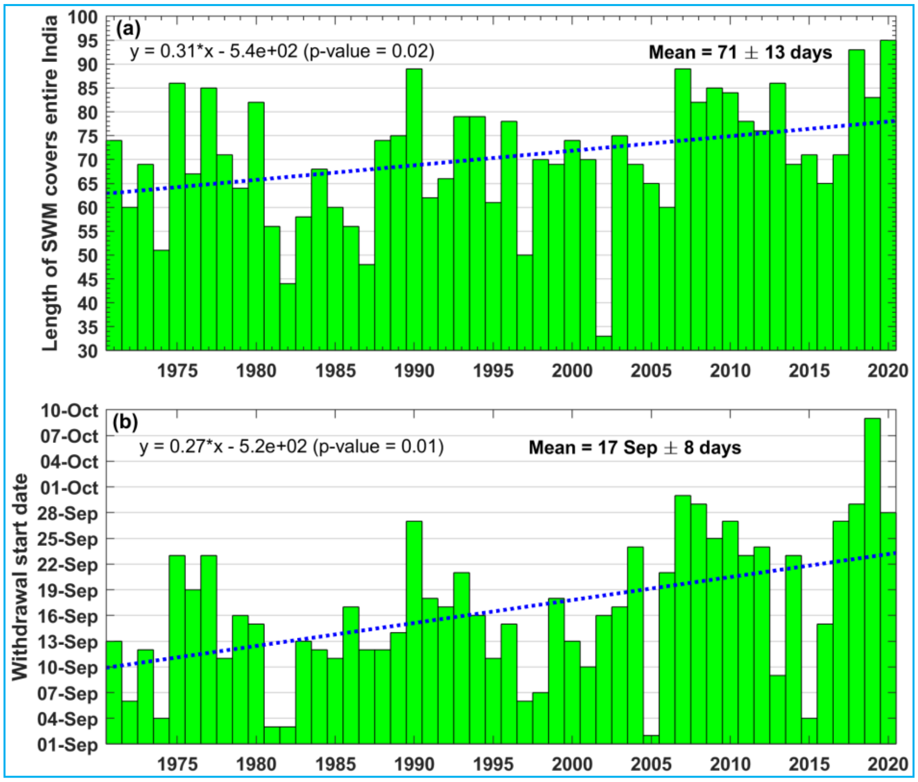
Figs. 1(a&b). Time-series of the southwest monsoon length (period between monsoon onset over Kerala and monsoon withdrawal from India) and (b) monsoon withdrawal dates for the period of 1971-2020.

and all-India Kharif crop yield for the period of 1966-2010 (Prasanna, 2014). Moreover, intraseasonal oscillations in ISMR also play a crucial role in Kharif food grain yield across the country (Preethi and Revadekar, 2013). There is a weak association between ISMR and *Rabi* crop yield over the country because sowing of *Rabi* crops generally starts in the month of October.

For research and operational studies, all-India rainfall between 1st June and 30th September (hereafter JJAS) is typically considered as ISMR. But, actual southwest monsoon rainfall eventually occurs prior to June during early MOK years and also in the month of October until the withdrawal is declared. As dates of MOK and withdrawal of ISMR show considerable interannual variability, length of the southwest monsoon season would also vary year-to-year. The objective of this study is to assess the changes in the southwest monsoon season length (SWML) between 1971 and 2020, and impact of the associated rainfall over India. This analysis would important with the advent of climate change. The 50-year period considered in this study covers more reliable observed data, and is reasonably good period to verify the historical simulations of the global climate models to study future projections of SWML. The changes in SWML and associated rainfall are also crucial for planning improved water management strategies.

2. Data used

The dates of MOK and monsoon withdrawal for a 50-year period (1971-2020) have been obtained from the IMD, Pune. The dates of MOK prior to 2006 taken from Pai and Nair (2009) have been considered in this study. All other dates such as MOK since 2006, dates for monsoon covered the entire county, withdrawal start dates from the northwest India, and dates of withdrawal of the monsoon from the entire country have been taken from the operationally declared dates by IMD through monsoon reports and archives. As uncertainty in these dates may be greater for the pre-satellite era, we considered data from 1971 in this study. The daily gridded rain gauge-based rainfall dataset available at 0.25º spatial resolution by IMD has also been used in this study. This gridded rain gauge-based rainfall dataset has been developed using an inverse distance weighted interpolation method after rigorous quality checks (Pai *et al*., 2014). This dataset is



Figs. 2(a&b). Time-series of the number of days when the southwest monsoon covers entire India (period between monsoon covers entire India and withdrawal starts from extreme northwest India) and (b) southwest monsoon withdrawal start dates from extreme northwest India for the period of 1971-2020

regularly updated and publicly available from the IMD, Pune website at https://imdpune.gov.in/. The Nino 3.4 sea surface temperature (SST) index is widely used for the study of occurrence and strength of ENSO in the Pacific Ocean and this index is generated using an SST dataset over the area bounded by 5º S - 5º N latitude and 170ºW-120º W longitude. The monthly Nino 3.4 SST index generated from the Met Office Hadley Centre SST (HadISST1) dataset has been obtained from the NOAA Physical Science Laboratory website at https://psl.noaa.gov/gcos_wgsp/Timeseries/Nino34/. All-India rabi yield, and rapeseed & mustard yield datasets for 1971-2021 have been obtained from the Directorate of Economics and Statistics, Ministry of Agriculture and Farmers Welfare, Government of India (https://agricoop.nic.in/).

3. Results and discussion

Fig. 1(a) shows time-series of SWML for the period of 1971-2020. The SWML is defined as the number of days between MOK and withdrawal of the southwest monsoon from the entire country. The SWML is computed for each year of the study period using MOK (Pai and Nair, 2009) and withdrawal dates operationally declared by IMD. The mean SWML for India is found to be 139 days with a standard deviation of 10 days. The smallest SWML of 118 days was during 1972 and the largest SWML of 158 days was during 1974. The SWML shows substantial interannual variation. The time-series of SWML shows an increasing trend at a rate of 1.6 days decade^{-1} during the study period. The linear trend has a p-value of 0.08, which depicts its statistical significance. As MOK dates do not show statistically significant change during this period (Pai and Nair, 2009; Ghanekar *et al.*, 2019), long-term change in the withdrawal dates has been examined. Fig. 1(b) shows time-series of dates of the monsoon withdrawal from the entire country for 1971-2020. The withdrawal dates show a statistically significant increasing trend and the rate of increase is the same, *i.e.*, 1.6 days decade^{-1}, as that for the SWML. Hence, the increase in SWML is primarily due to a delayed withdrawal during the study period. The earliest withdrawal date is found to be 3rd October, 1984 and the most delayed withdrawal date was 29th October, 2010. It is also noticed that mean date of withdrawal of the southwest monsoon from the entire country is 18th October against the normal date of 15th October derived

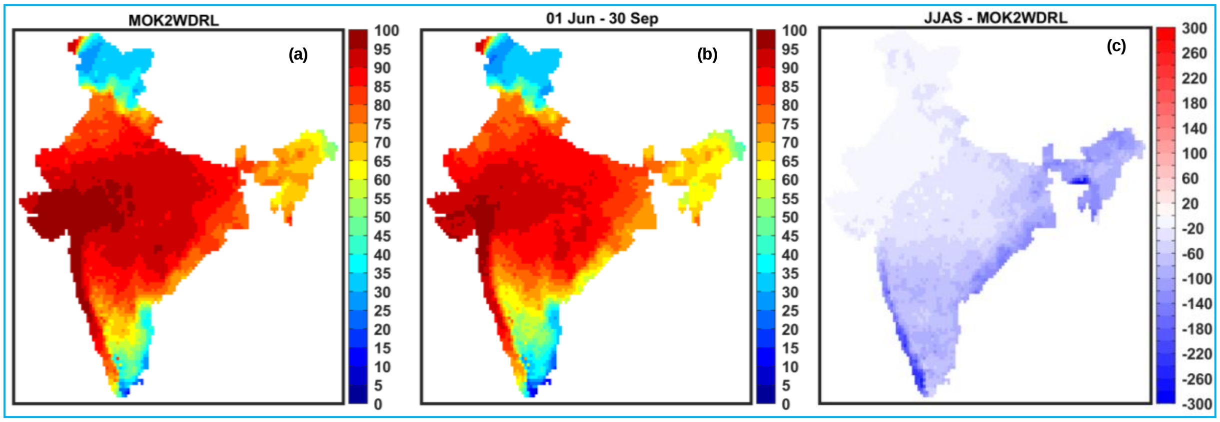


Fig. 3. Percentage contribution of (a) monsoon onset to withdrawal rainfall to annual rainfall, (b) JJAS rainfall to annual rainfall, and (c) difference in rainfall (mm) between JJAS and onset-withdrawal over India for 1971-2020

using 1º rain gauge-based gridded rainfall data for 1971-2019 (Pai *et al*., 2020).

A study using 12 selected Coupled Model Intercomparison Project Phase 5 (CMIP5) models showed shortening of the SWML by 11 days by the end of this century under the Representative Concentration Pathways 8.5 (RCP8.5) scenario due to delayed MOK and early withdrawal dates (Sabeerali and Ajayamohan, 2018). In contrast, CMIP6 model projections showed that duration of the Indian summer monsoon would increase by more than three pentads in the future primarily due to a delayed withdrawal (Ha *et al*., 2020; Moon and Ha, 2020). However, models have rather greater uncertainty in the monsoon rainfall representation. The all-India mean temperature showed a warming trend at the rate of 0.15ºC decade^{-1} during 1986-2015 (Sanjay *et al*., 2020) and likely to exacerbate in the future. Further, the global climate model projections of CMIP6 showed an increase in ISMR at a rate of about 6% per ºC rise in temperature in the future (Moon and Ha, 2020). Hence, further detailed studies are needed to explain the projected change of SWML under the future scenarios. This analysis of 50-year SWML may be considered as a benchmark to verify historical simulations of the global climate models in representation of SWML and its interannual variability.

Based on the new normal dates of monsoon onset, progress and withdrawal, the southwest monsoon covers entire India by 8^{th} July and the withdrawal starts from the extreme northwest India from 17^{th} September (Pai *et al*., 2020). The interannual variations of the period between these two dates for 1971-2020 are shown in Fig. 2(a). On an average, the monsoon covers the entire country for 71 days with a standard deviation of 13 days. Rainfall during these 71 days contributes 49% to all-India annual rainfall. The contribution of these 71 days of rainfall to all-India JJAS rainfall is 66%, and to all-India rainfall between MOK and withdrawal dates (referred as MOK2WDRL hereafter) is 62%. This period also shows a statistically significant increasing trend at a rate of 3.1 days decade^{-1}, which is primarily due to a delayed start of monsoon withdrawal from the extreme northwest India [Fig. 2(b)].

For study of the southwest monsoon rainfall, a period of 122 days spanning from 1^{st} June to 30^{th} September is usually considered. However, it is clear from Fig. 1(a) that the southwest monsoon rainfall occurs over the country generally more than 122 days and it varies year-to-year. Except for years 1972 and 1997, the SWML is more than 122 days. Therefore, differences in all-India JJAS rainfall and MOK2WDRL rainfall are expected, and it becomes imperative to examine their differences and associated implications. Fig. 3 presents the spatial distribution of percentage contributions of MOK2WDRL rainfall and JJAS rainfall to annual rainfall over India for the study period. The contribution of MOK2WDRL rainfall is notably greater than JJAS rainfall over central and western parts of India. The spatial distribution of difference between MOK2WDRL rainfall and JJAS rainfall over the country is also shown in Fig. 3. The southern peninsula, including the west coast, east and northeast India, receives about 100 mm more rainfall from MOK2WDRL than JJAS rainfall. All-India JJAS rainfall contributes 75% to the annual rainfall, whereas MOK2WDRL rainfall contributes 79% to the annual rainfall. A linear correlation of 0.70 between SWML and ISMR for MOK2WDRL was reported using IMD rain gauge-based gridded dataset (Misra *et al.*, 2017). However, the onset and withdrawal dates considered in this study were based on rainfall alone and might be different from the operational dates declared by IMD.

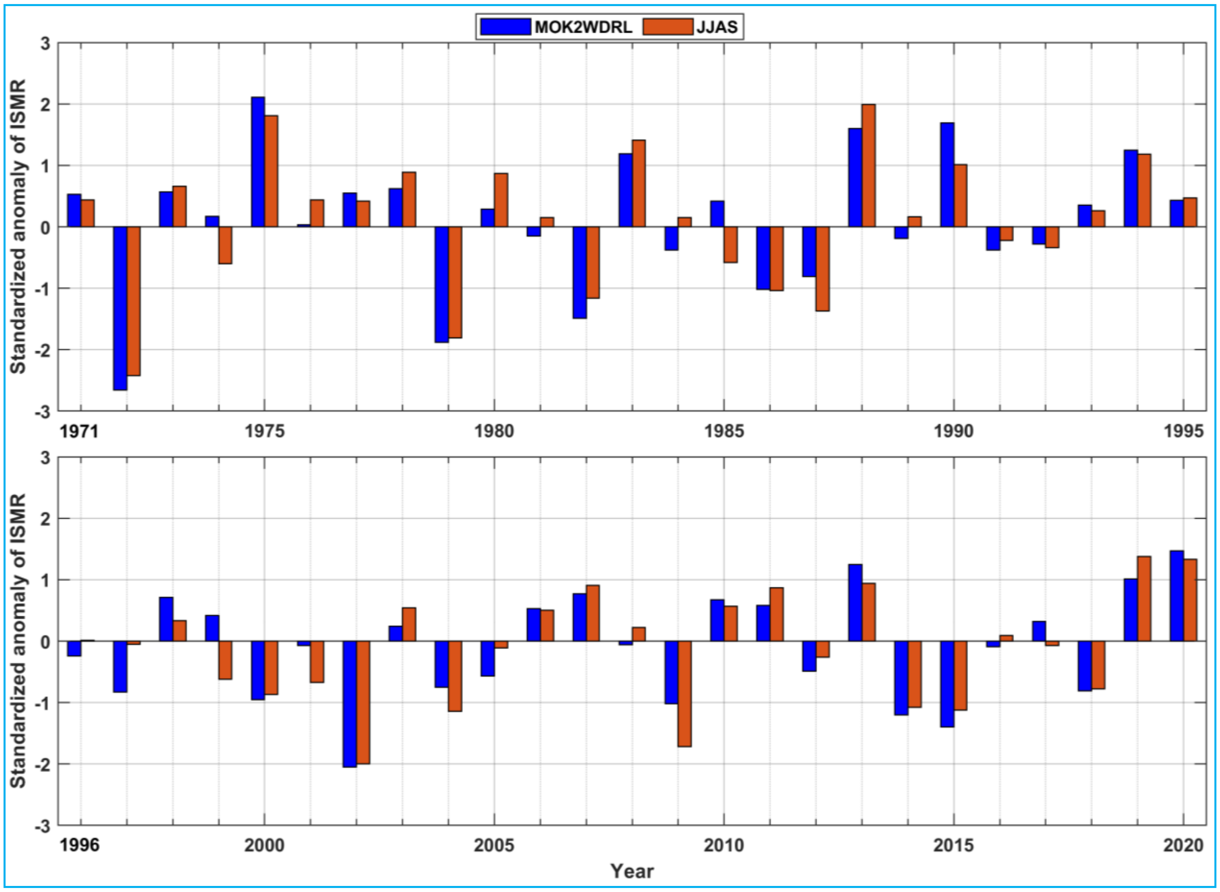


Fig. 4. Standardized anomaly of all-India JJAS rainfall and rainfall between the monsoon onset and withdrawal for 1971-2020

Fig. 4 shows the interannual variations of standardized anomaly of ISMR during JJAS and MOK2WDRL periods for 1971-2020. The standardized anomaly less than–1 corresponds to deficient ISMR year, whereas the standardized anomaly greater than +1 indicates excess ISMR year. ISMR anomalies derived from both JJAS rainfall and MOK2WDRL rainfall show differences during several years. JJAS rainfall indicates deficient ISMR years during 1987 and 2004, which are shown to be normal ISMR years by MOK2WDRL rainfall. JJAS rain anomaly shows normal ISMR year in 2013, but MOK2WDRL anomaly indicates excess ISMR year. In addition, there are 10 years (*e.g.*, 1974, 1981, 1984, 1985, 1989, 1996, 1999, 2008, 2016 and 2017) when ISMR anomalies from both JJAS and MOK2WDRL rainfall showed opposite signs. In addition, ISMR using JJAS shows a marginal decrease of 0.19 mm decade^{-1}, whereas ISMR using MOK2WDRL shows a marginal increase of 0.14 mm decade^{-1}for the 50-year period. However, these long-term trends are not statistically significant. This analysis reveals a considerable difference in ISMR between JJAS and MOKWDRL rainfall estimates in the study of interannual variations of ISMR.

The ENSO in the tropical Pacific Ocean is one of the most important parameters affecting the Indian summer monsoon rainfall. In general, El Niño is linked to deficient Indian monsoon rainfall and La Nina is linked to excess or good Indian monsoon rainfall. However, out of 23 deficient Indian monsoon rainfall years between 1901 and 2015, only 13 years are linked with the occurrence of El Niño (Borah *et al*., 2020). The relationship between ISMR and ENSO were found to be time-varying and exhibits distinct regional variability across the country (Athira *et al*., 2023). In addition, the La Nina condition in the tropical Pacific Ocean has been shown to be associated with delayed monsoon withdrawal over India (Pattanaik *et al*., 2015). The modulation of the Indian monsoon onset and withdrawal dates under the influence of ENSO was also reported by Goswami and Xavier (2005) and Xavier *et al*. (2007). Fig. 5 shows the scatter plots between standardized anomalies of ISMR from both JJAS and

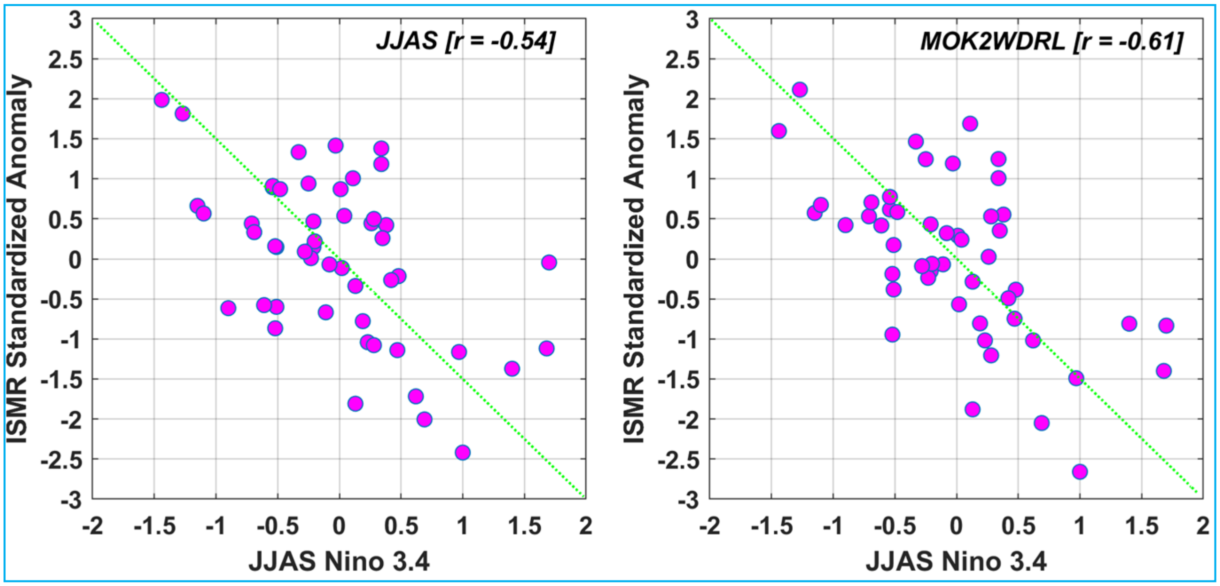


Fig. 5. Scatter plots between Nino 3.4 index and ISMR standardized anomalies for 1971-2020

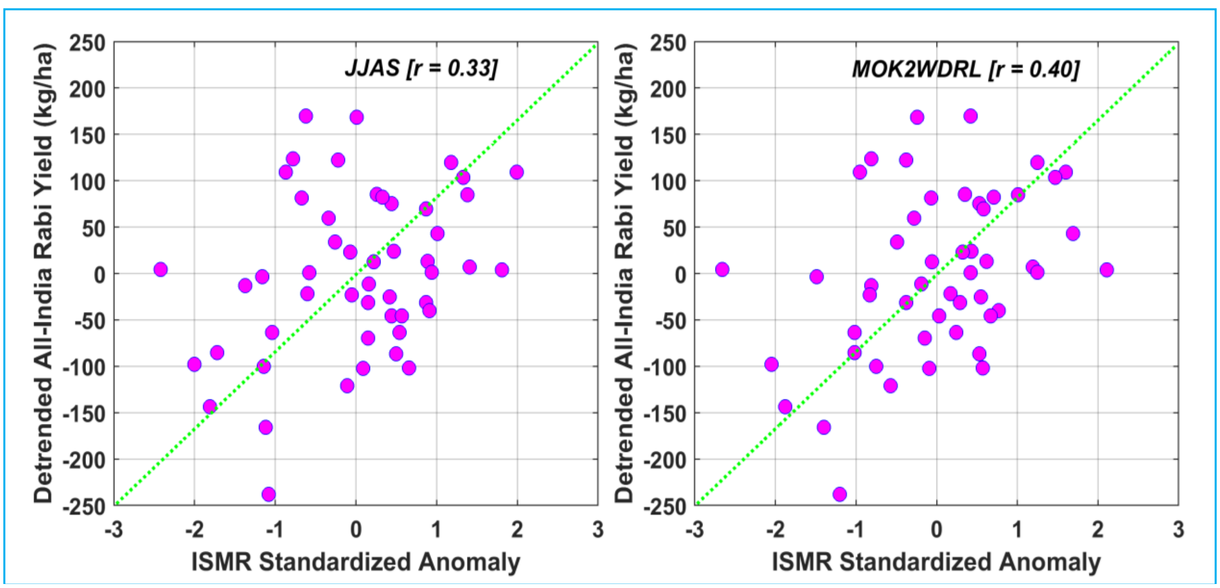


Fig. 6. Scatter plots between detrended all-India *rabi* crop yield and ISMR standardized anomalies for 1971-2020

MOK2WDRL rainfall against Nino 3.4 index for 1971-2020. Standardized anomalies of ISMR using JJAS rainfall show a linear correlation coefficient of –0.54 with the concurrent Nino 3.4 index, whereas the same using MOK2WDRL rainfall shows a correlation of –0.61. Both correlation coefficients are found to be statistically significant at 95% significance level. Hence, ISMR considering MOK2WDRL rainfall shows better association with ENSO than ISMR using JJAS rainfall.

Although JJAS rainfall has a weak relationship with rabi crop yield in India, the delayed withdrawal dates are vital for rabi crop sowing practices. Fig. 6 shows scatter plots between ISMR standardized anomalies using JJAS and MOK2WDRL rainfall estimates against all-India rabi crop yield. The same for the all-India rapeseed & mustard yield is shown in Fig. 7. As the crop yield values are showing significant long-term trends due to technological advancement, they are detrended to remove the linear

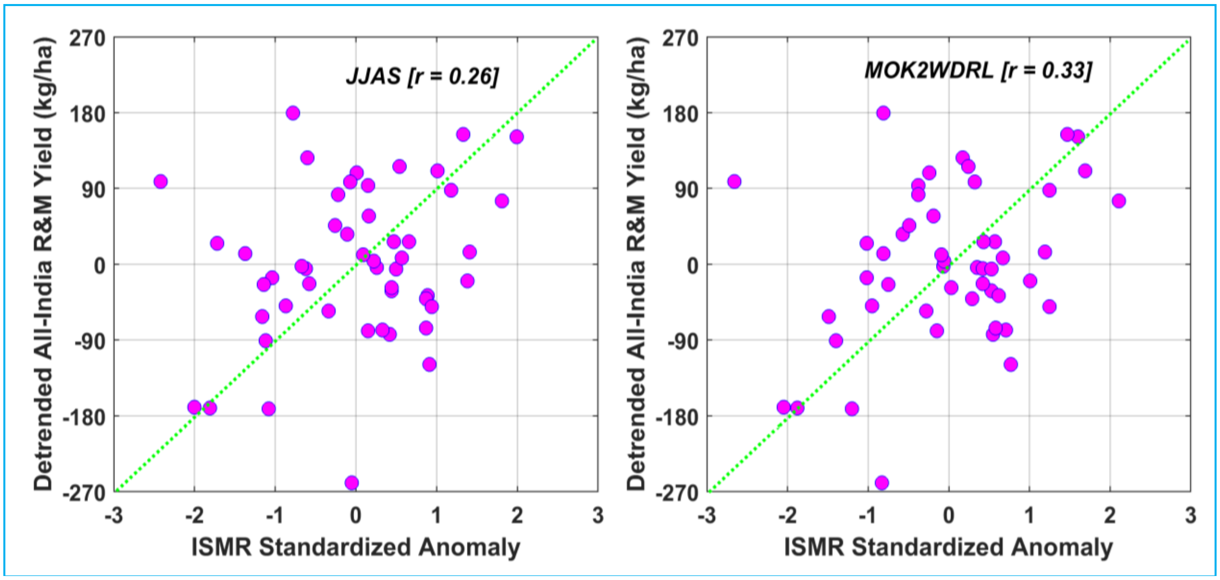


Fig. 7. Scatter plots between detrended all-India rapeseed & mustard yield and ISMR standardized anomalies for 1971-2020

Trend for a fair comparison. Both rabi and rapeseed & mustard crops are sown following the southwest monsoon rainfall, yield of both crops for the next year is compared with ISMR for a given year. For instance, ISMR of 1971 is compared with the yield of both crops for 1971-1972. ISMR anomalies using JJAS rainfall show a linear correlation of 0.33, whereas ISMR anomalies using MOK2WDRL rainfall show a correlation of 0.40 with all-India rabi yield. Both correlation coefficients are found to be statistically significant at 95% significance level. Similarly, all-India rapeseed & mustard yield shows a linear correlation of 0.26 with ISMR anomalies computed using JJAS rainfall, whereas it is 0.33 using MOK2WDRL rainfall. The correlation coefficient between MOK2WDRL rainfall anomalies and rapeseed & mustard yield is statistically significant at 95% significance level, whereas the same with JJAS rainfall anomalies is not statistically significant at 95% significance level. These results show a better association of MOK2WDRL rainfall with all-India rabi, and rapeseed & mustard yield than all-India JJAS rainfall. As May to September rainfall is crucial for kharif crops, there is no difference in correlation coefficients of ISMR using JJAS and MOK2WDRL rainfall with all-India kharif yield.

4. Conclusions

The interannual variations in ISMR are crucial for rain-fed agricultural production and the Indian economy. The MOK, progress of the monsoon and withdrawal are three major steps involved in the southwest monsoon, and they are vital for the computation of ISMR. An analysis of the SWML between 1971 and 2020 showed an increase in SWML at the rate of 1.6 days decade^{-1}, primarily due to a delay in the monsoon withdrawal dates. The number of days in which the monsoon covers the entire India also showed a statistically significant increasing trend at a rate of 3.1 days decade^{-1}, mainly due to the delayed start of the southwest monsoon withdrawal from the extreme northwest India. Generally, JJAS rainfall of 122 days is considered for the southwest monsoon rainfall analysis, which is different from MOK2WDRL rainfall. This study examined the difference in JJAS and MOK2WDRL rainfall for 1971-2020 using IMD rain gauge-based gridded rainfall dataset. JJAS rainfall contributed 75% to all-India annual rainfall, whereas it was 79% by MOK2WDRL rainfall. The interannual variations of ISMR showed a considerable difference between JJAS and MOKWDRL rainfall estimates during several years. Moreover, ISMR considering MOK2WDRL rainfall showed a better association with ENSO than ISMR using JJAS rainfall. Furthermore, larger linear correlation coefficient values between ISMR anomalies and all-India rabi, and rapeseed & mustard yields were found using all-India MOK2WDRL rainfall than JJAS rainfall. The results of this study would be useful for climate modelers and decision makers. Results of this study would also be useful for the verification of historical simulations of SWML, and dates of MOK and withdrawal of the southwest monsoon from different global coupled climate models for reliable future projections. However, further studies using sub-seasonal scale datasets at meteorological sub-division or state level are needed to explore the underlying mechanisms.

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Authors' Contributions

S. Prakash: Conceptualization, analysis, writing and editing.
R. K. Giri: Analysis, review and editing.
S. C. Bhan: Conceptualization and supervision.

Disclaimer: The contents and views presented in this research article/paper are the views of the authors and do not necessarily reflect the views of the organizations they belong to.

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