MAUSAM, **75**, 3 (July 2024), 769-782

MAUSAM

DOI : https://doi.org/10.54302/mausam.v75i3.6283
Homepage: https://mausamjournal.imd.gov.in/index.php/MAUSAM

UDC No. 551.553.21 : 551.509.313.4

Triple-dip La Niña (2020-2022) and its influence on Indian Summer Monsoon Rainfall: Insight from the monsoon mission coupled forecasting system

MADHURI MUSALE, TANU SHARMA*, SATYABAN B RATNA, C. T. SABEERALI, P. ROHINI, ARTI BANDGAR, O. P. SREEJITH and K. S. HOSALIKAR

Climate Research and Services, India Meteorological Department, Pune – 411 005, India

**Department of Atmospheric and Space Sciences, Savitribai Phule Pune University, Pune – 411 007, India*

(*Received 13 June 2023, Accepted 8 April 2024*)

e mail :satyaban.ratna@imd.gov.in

सार – अल नीनो-दक्षिणी दोलन (ENSO) को अखिल भारतीय ग्रीष्मकालीन मॉनसून वर्षा (ISMR) में अंतर-वार्षिक परिवर्तनशीलता का प्राथमिक चालक माना जाता है। हाल ही में, लगातार तीन वर्षों (2020-2022) के दौरान ला नीना स्थितियों का अनुभव किया गया, जिसे व्यापक रूप से 'ट्रिपल-डिप' ला नीना एपिसोड के रूप में जाना जाता है आर्द्र इन सभी तीन वर्षों के दौरान ISMR सामान्य से अधिक सामान्य तकथा। इस अध्ययन में 1950 के बाद देखे गए ट्रिपल-डिप ला नीना एपिसोड के दौरान भारत में ला नीना के विकास आर्द्र संबंधित ग्रीष्मकालीन मॉनसून वर्षा वितरण पर चर्चा की गई 1951-2023 की अवधि के दौरान, ट्रिपल-डिप ला नीना (1954-1956) (1973-1975, 1998-2000, आर्द्र 2020-2022) के चार उदाहरण थे। यह अध्ययन हालिया ट्रिपल-डिप ला नीना इवेंट (2020-2022) के दौरान ला नीना आर्द्र ISMR में इसकी संबंधित परिवर्तनशीलता का पूर्वानुमान करने में मॉनसून मिशन जलवायु पूर्वानुमान प्रणाली (MMCFS) मॉडल की क्षमता का भी मूल्यांकन करता है। परिणामों से संकेत मिलता है कि मॉडल अप्रैल आर्द्र मई की शुरूवाती स्थितियों में मॉनसून ऋतु के दौरान ला नीना की तीव्रता आर्द्र पैटर्न का सफलतापूर्वक पूर्वानुमान लगाने में सक्षम था। मॉडल ने भारत के कई क्षेत्रों में सामान्य से अधिक वर्षाका भी सटीक पूर्वानुमान लगाया। हालाँकि, यह इन तीनों वर्षों के लिए मध्य-पूर्व भारत-गांगेय के मैदानी इलाकों आर्द्र उत्तर-पूर्व भारत में सामान्य से कम वर्षा का सही अनुमान नहीं लगा सका। जबकि जलवायु मॉडल आम तौर पर ENSO से जुड़े ISMR के पूर्वानुमान करने में कौशल प्रदर्शित करते हैं, परभारत में स्थानिक वर्षा परिवर्तिता का सटीक पूर्वानुमान करना एक चुनौती बनी हुई है।

ABSTRACT. The El Niño-Southern Oscillation (ENSO) is considered as the primary driver of interannual variability in the all India summer monsoon rainfall (ISMR). Recently, La Niña conditions were experienced during three consecutive years (2020-2022), which is widely known as the 'triple-dip' La Niña episodes and ISMR during all these three years was normal to above normal. This study discusses the evolution of the La Nina and associated summer monsoon rainfall distribution over India during triple-dip La Niña episodes observed since 1950. During the period 1951-2023, there were four instances of triple-dip La Niña (1954-1956, 1973-1975, 1998-2000, and 2020-2022). This study also evaluates the ability of the Monsoon Mission Climate Forecasting System (MMCFS) model in forecasting La Niña and its associated variability in ISMR during the recent triple-dip La Niña event (2020-2022). The results indicate that the model was able to successfully forecast the strength and patterns of La Niña during the monsoon season when initialized with April and May initial conditions. The model also forecasted the above-normal rainfall observed over many regions of India accurately. However, it could not correctly forecast the observed below-normal rainfall over the central-east Indo-Gangetic plains and northeast India for all these three years. While climate models generally exhibit skill in forecasting ENSO-associated ISMR, accurately predicting the spatial rainfall variability over India remains a challenge.

Keywords– Triple-dip La Niña, El Niño-southern oscillation, Indian summer monsoon rainfall, MMCFS model, Sea surface temperature.

1. Introduction

The El Niño Southern Oscillation (ENSO) is amajor climate phenomenon having a quasi-periodic nature, characterized by significant changes in the sea surface temperatures (SSTs)over the tropical Pacific Ocean and associated ocean-atmospheric interactions (Philander, 1983; Zebiak and Cane, 1987). Generally, the life cycle of

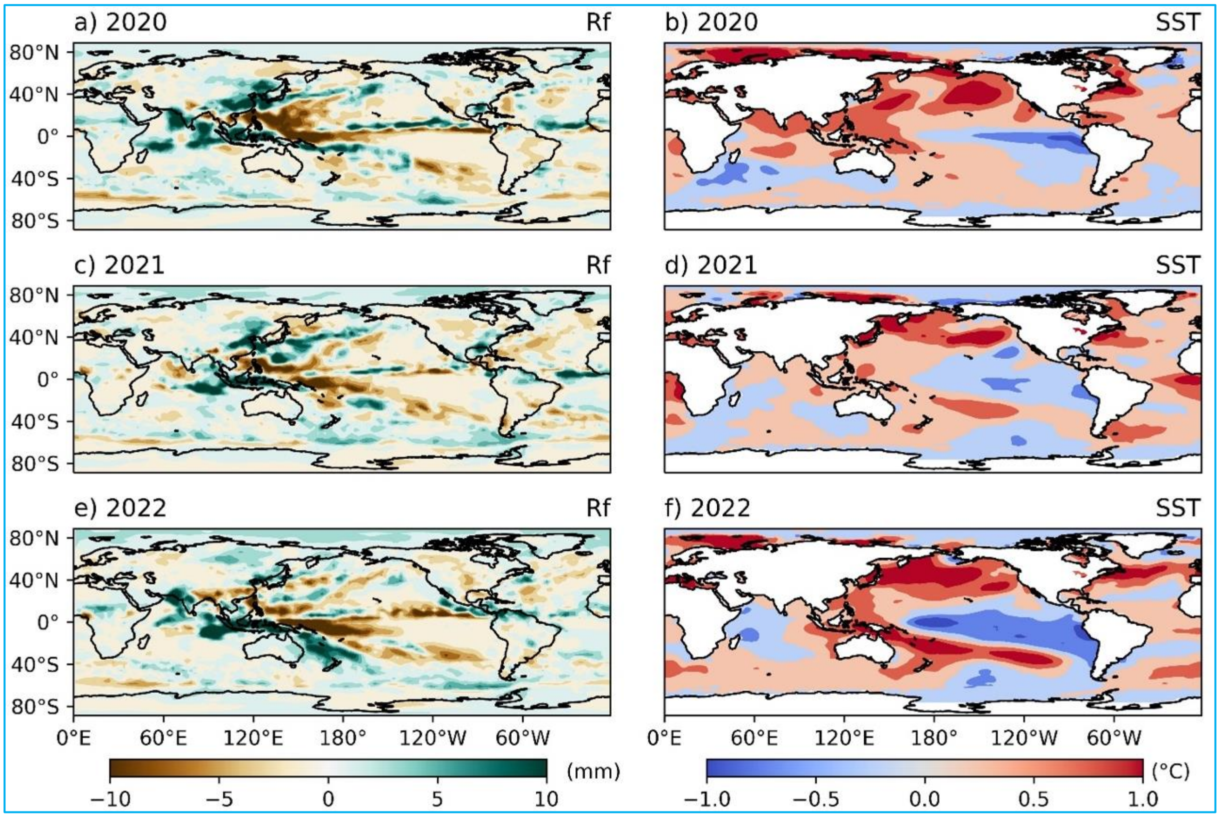

Fig 1. (a) Rainfall anomaly (Rf, in mm) and (b) sea surface temperature (SST, in °C) anomaly during the JJAS season for the year 2020. (c), (d) and (e), (f) are the same as a) and b) but for the years 2021 and 2022 respectively.

ENSO consists of its growth in the boreal spring, peak in winter, and finally decay in the next spring (Jin *et al*., 1994; Iwakiri and Watanabe, 2021). ENSO significantly impacts interannual climate variations worldwide (Bell and Halpert, 1998), including the Indian summer monsoon rainfall (ISMR) (Shukla, 1987; Kucharski and Abid, 2017). Almost 29% of the total interannual variability of ISMR is explained by ENSO forcing (Chakraborty and Singhai, 2021). The positive (negative) phase of ENSO, known as El Niño (La Niña), is typically associated with weaker (stronger) ISMR (Sikka and Gadgil, 1980; Webster and Yang, 1992; Pai, 2004). Generally, the El Niño phase ends quickly whereas the La Niña phase lasts longer known as multi-year La Niña (Cole, 2002).

In view of the above, precise prediction of ENSO and its associated impacts are of utmost importance for the seasonal forecast of rainfall in India. The ability to forecast seasonal climate variations around the globe, particularly for ENSO, has significantly improved from the early 1980s to the late 1990s (Luo *et al*., 2008; Guilyardi *et al*., 2009; Barnston *et al*., 2012, 2015). However, the ENSO predictability has not witnessed substantial advancement and has reached a limit since the 1990s (Barnston *et al*., 2012), despite improvement in prediction systems and observations. This stagnation can be due to the weakening of ENSO intensity and the prevalence of non-canonical ENSO episodes in recent years (Hu *et al*., 2013; Wang and Ren, 2017). Additionally, many commonly used operational forecasting systems have exhibited limitations in adequately representing the ENSO variability and its associated teleconnections (Jin *et al*., 2008; Ren *et al*., 2017). Consequently, accurate forecasting of ENSO and its impacts continues to pose significant challenges, even at moderate lead times.

The Monsoon Mission Coupled Forecasting System (MMCFS) is a coupled ocean-atmosphere-land-sea ice forecast system and it has been developed as part of the National Monsoon Mission (NMM) project of the Government of India (Rao *et al*., 2019). India Meteorological Department (IMD) utilizes this model for operational seasonal forecasting of the ENSO and the monsoon (Sreejith *et al*., 2022). The basic modeling framework of MMCFS was initially the National Centers for Environmental Prediction (NCEP) Coupled Forecast System version 2 (CFSv2; Saha *et al*., 2014). The Indian

Institute of Tropical Meteorology (IITM) modified this model to meet the specific requirements of forecasting the ISMR. More details on this model are provided in some previous studies (Benke *et al*., 2019; Pradhan *et al*., 2021; Rohini *et al*., 2022). Several studies have reported the strengths and weaknesses of the CFS model in predicting ENSO events and its associated teleconnection with ISMR (Pokhrel *et al*., 2012; Ramu *et al*., 2016; George *et al*., 2016; Chattopadhyay *et al*., 2016; Pillai *et al*., 2017; Liu and Ren, 2017; Sabeerali *et al*., 2019). Overall, the NCEP CFS has a good skill for predicting ENSO events. However, further research is still required to improve its accuracy.

A triple-dip La Niña is a rare and unusual event that describes the consecutive presence of La Niña conditions for three years in a row. Recently, a triple-dip La Niña was observed during the 2020 to 2022 period. In addition to the observed normal to above-normal ISMR during these three years, this prolonged triple-dip La Niña event had significant impacts on worldwide weather patterns, such as the occurrence of floods in eastern Australia during 2022, droughts in the United States and East Africa (Jones, 2022), heatwaves in the Yangtze River Valley (Tang *et al*., 2023). The spatial distribution of rainfall and SST anomaly in different parts of the globe for the most recent triple-dip La Niña episode (2020, 2021 and 2022) is shown in Fig. 1. Positive rainfall anomalies can be seen over the East Asia, Maritime continent, and parts of Australia as well as India. However, negative rainfall were observed over the parts of north and south America. Although all were La Niña years, the difference in the magnitude as well as the spatial distribution of the negative SST anomaly can be seen over the Pacific Ocean as well as over other Ocean basins.

Although there were previous instances of triple-dip La Niña events, there are limited studies available on the evolution of triple-dip La Niña episodes & the associated observed variability in ISMR. The present study aims to address this research gap by analyzing historical triple-dip La Niña episodes since 1951 and then investigating the performance of the MMCFS in forecasting the evolution of the recent triple-dip La Niña event (2020-2022) and the associated variability in ISMR. The paper is designed as follows. Section 2 discusses the details of the MMCFS model, datasets used in this study and Methodology. Main findings and results are discussed in Section 3. Concluding remarks are provided in Section 4.

2. Data and methodology

2.1. *Model and data*

Since 2017, IMD has been using the MMCFS model for operational forecasting of the ENSO and the Indian monsoon. In this study, MMCFS simulations of SST and rainfall for the 32 years (1991-2022) were utilized. The ocean and atmosphere initial conditions for the MMCFS model runs were obtained from the Indian National Centre for Ocean Information Services (INCOIS), and the National Centre for Medium Range Weather Forecasting (NCMRWF) respectively. The hindcast ensemble members were generated by following the lagged-ensemble technique (Pradhan *et al*., 2021).

IMD uses MMCFS forecasts based on April and May initial conditions to prepare the operational forecasts of south-west monsoon seasonal rainfall over India. Hence, for this study, the model initialized in April and May was utilized, and all the analyses are based on an ensemble mean of 10 members. The MMCFS is a coupled ocean-atmosphere-land model with advanced physics and increased resolution (T382). The initial framework of MMCFS was developed by the National Centers for Environmental Prediction (NCEP), USA, known as the Coupled Forecast System version 2 (CFSv2; Saha *et al*. 2014). The atmospheric component of MMCFS is the Global Forecast System (GFS), a spectral atmospheric model with a horizontal resolution of T382 (~38 km) and there are 64 hybrid vertical levels (Moorthi *et al*., 2001). The ocean component of MMCFS consists of the Geophysical Fluid Dynamics Laboratory (GFDL) Flexible Modeling System (FMS) and Modular Ocean Model version 4p0d (MOM4) which is having a horizontal resolution of 0.25° near the equator, 0.5° in the subtropics and 40 vertical levels (Griffies *et al*., 2004).

In this study, the model output is bias-corrected using the z-score bias correction method (Pan and Van Den Dool, 1998). Before making the forecast, a standardization method is implemented for both the model and the observations. This technique adjusts the systematic model errors by correcting both the bias in the variance and mean. By standardizing the data, the magnitudes of the ensemble mean and observations are brought into a certain range, ensuring that the bias is nearly zero. Further information about this methodology can be obtained from previous studies (Pan and Van Den Dool, 1998; Acharya *et al*., 2013).

For the analysis of sea surface temperature (SST) variations, the National Oceanic and Atmospheric Administration (NOAA) Extended Reanalysis SST version 5 (ERSSTv5: Huang *et al*., 2017) data (https://psl.noaa.gov/data/gridded/data.noaa.ersst.v5.html) for the period 1984-2022 were used as observed data. To generate the anomalies, a climatological period of 1991-2020 is utilized. For the rainfall analysis in this study, India Meteorological Department (IMD)'s high-resolution (0.25° × 0.25°) daily gridded rainfall data over the Indian

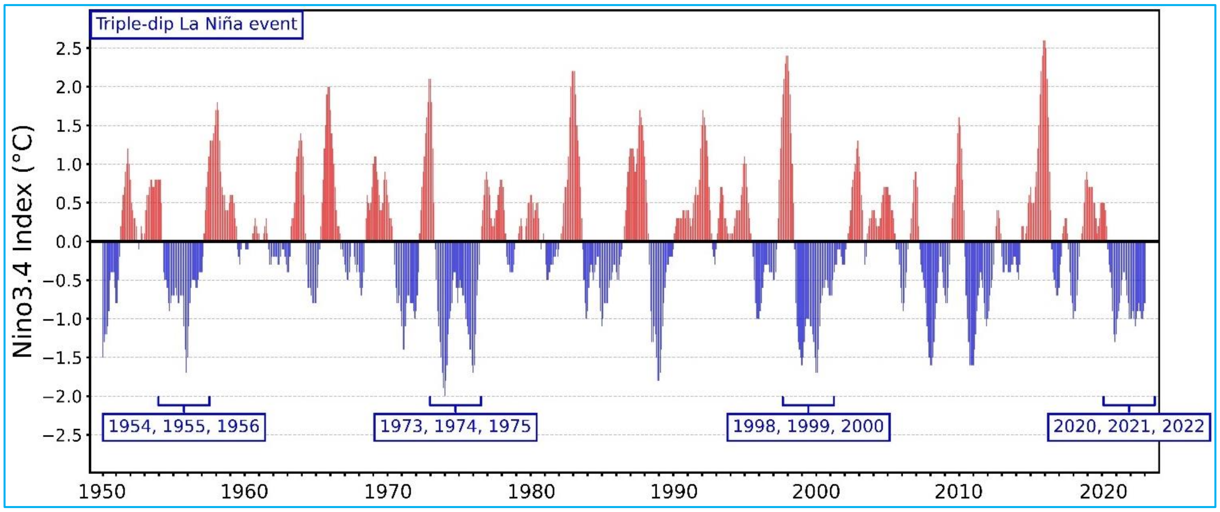

Fig 2. The monthly SST anomalies (°C) from 1950 to 2022, in the Niño 3.4 region. The triple-dip La Niña events are marked in the figure.

land region (Pai *et al.*, 2014) was used. Global precipitation climatology project (GPCP) monthly data with a spatial resolution of 2.5° × 2.5° global grid from 1979 to the present (Adler *et al*., 2003) is downloaded from the NOAA Physical Sciences Laboratory (PSL), Boulder, Colorado, USA, from their website (https://psl.noaa.gov/data/gridded/data.gpcp.html). The Madden-Julian Oscillation (MJO) index from 1975 was obtained from the Bureau of Meteorology (BoM) (http://www.bom.gov.au/climate/mjo/graphics/rmm.74toRealtime.txt).

2.2. *Methodology*

For this study, ISMR is defined as the average rainfall over India during the June to September (JJAS) season. We have calculated the percentage rainfall anomaly for all India and four homogenous regions of India (north-west India, north-east India, central India and south peninsular India) except Fig. 1, where rainfall anomaly is calculated instead of percentage rainfall anomaly. The year is identified as AN: above-normal (BN: below-normal) if the percentage rainfall anomaly is greater (less) than 10% (-10%) with respect to the long-period average (LPA: 1991-2020). The rest of the years are identified as N: normal rainfall years.

The SST anomaly is averaged over the Niño 3.4 region: 5° N - 5° S and 120° W - 170° W in the central-eastern Pacific Ocean during the JJAS season. In order to capture the triple-dip La Niña episodes without the influence of global warming, the linear trend is removed from the Niño 3.4 Index. The year during which the Niño 3.4 SST anomaly is less than -0.5 °C, is defined as La Niña year. To find the phase of the Indian Ocean Dipole (IOD), we calculate the Dipole Mode Index (DMI) which is derived from the difference in the monthly SST anomalies between two regions: western equatorial Indian Ocean (WEIO: 50° E - 70° E and 10° S - 10° N) and eastern equatorial Indian Ocean (EEIO: 90° E - 110° E and 10° S - 0°). Positive (Negative) IOD episodes are identified when the DMI, exceeds 0.4 °C (-0.4 °C). All the remaining IOD episodes are considered neutral. According to IMD criteria, the active (break) condition is defined when the daily normalized rainfall anomaly over the monsoon core zone is greater (less) than 1 (-1) for at least three consecutive days during the peak rainfall months of July and August (Rajeevan *et al*., 2010). The Madden Julian Oscillation (MJO) phase (Wheeler and Hendon, 2004) is constructed using the Real-time Multivariate MJO series 1 (RMM1) and 2 (RMM2). These series were generated from the pair of Principle Component (PC) time series using the combined fields of near-equatorially averaged 850 hPa, 200 hPa zonal wind, and outgoing longwave radiation (OLR). The MJO phase is considered active when the amplitude of the RMM Index, *i.e.*, $\sqrt{(\mathrm{RMM1})^2 + (\mathrm{RMM2})^2}$ is equal to or greater than 1.

3. Results and discussions

3.1. *Triple-dip La Niña*

The occurrence of La Niña conditions over the equatorial Pacific for three consecutive years is widely known as the 'triple-dip' La Niña. Since 1950, there were four cases of 'triple-dip' La Niña, especially during the Indian summer monsoon season (June-September: JJAS). These are 1954-56, 1973-1975, 1998-2000 and 2020-22

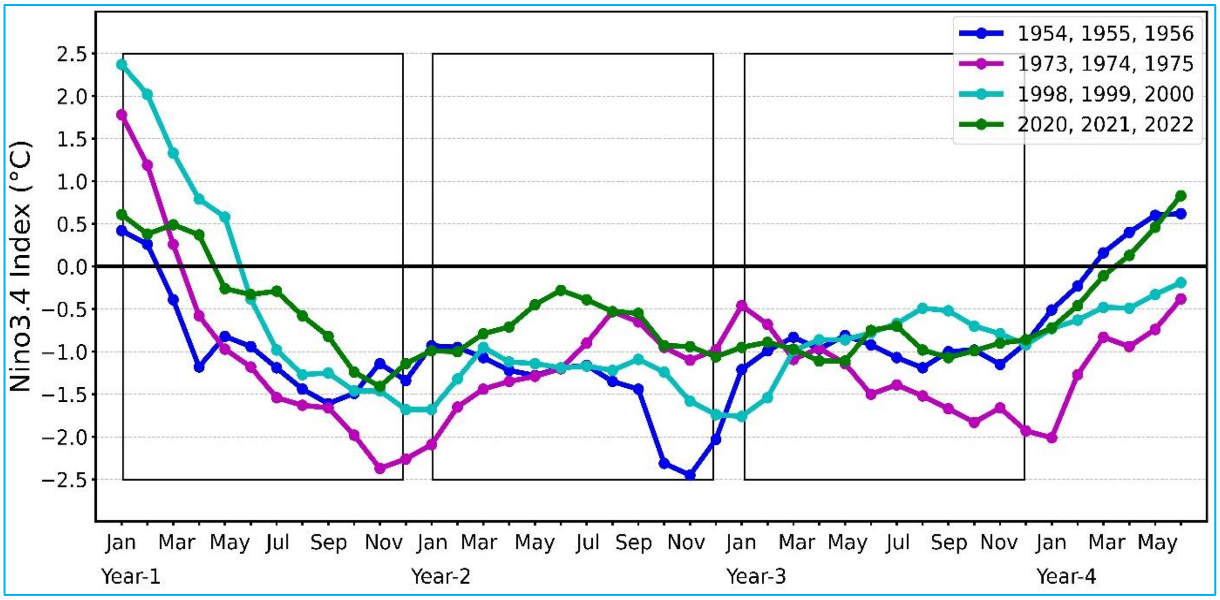

Fig 3. Evolution of the Niño3.4 Index (°C) during four triple-dip La Niña episodes.

(Fig. 2). Notably, the first 'triple-dip' La Niña episode of the 21st century occurred during the 2020-2022 period. A study by Dommenget *et al*. (2013) argued that multi-year La Niña episodes are occurring more frequently in recent decades. However, our analysis shows that all these triple-dip La Niña episodes occurred at an interval of about two decades.

Further analysis focused on the temporal evolution of Niño 3.4 SST anomaly associated with all four triple-dip La Niña episodes (Fig. 3). During the onset of the triple-dip La Niña episode, the transition from positive SST anomaly to negative SST anomaly occurred during the boreal spring season, just like any normal La Niña episode. But, these SST anomalies continued to remain negative for the next two and a half years. Notably, the monthly Niño 3.4 Index crossed a value of -1.5 °C or lower during each triple-dip La Niña period, except for the 2020-2022 events. Previous studies suggest that the probability of occurrence of triple-dip La Niña is high when it is preceded by a strong El Niño episode (Dommenget *et al*., 2013; Iwakiri and Watanabe, 2021). However, we found that out of four triple-dip La Niña episodes, two episodes (1973-1975 and 1998-2000) evolved from a super El Niño (Niño 3.4 Index greater than 1.5 °C: wang and wang, 2021; Ratna *et al*., 2024) condition. The remaining two triple-dip La Niña episodes (1954-1956 and 2020-2022) evolved from mild El Niño (where the Niño 3.4 Index just crossed the threshold value of 0.5 °C) condition, which shows that a triple-dip La Niña episode can also develop even if it is not preceded by a strong El Niño episode. Based on the analysis using the monthly Niño 3.4 Index, it is seen that the recent triple-dip La Niña episode (2020-2022) is the weakest among the four triple-dip La Nina episodes.

The detailed evolution of the recent event 2020-2022, showed a change in the Niño 3.4 Index from positive to negative values around April-May 2020 (Fig. 3). It attained La Niña strength during the boreal summer of 2020 and reached its peak intensity in November 2020. Subsequently, the La Niña strength began to weaken from December 2020 and continued until June 2021. However, in July 2021 it started to intensify again and maintained a La Niña strength until January 2023, albeit with some fluctuation in La Niña strength. At the time of the monsoon season (June-September), it was seen that the intensity of La Niña was strongest in 2022, followed by 2020 and 2021.

Indian Ocean Dipole (IOD: Saji *et al*., 1999) is an ocean-atmospheric coupled phenomenon associated with the interannual variation of the SST anomalies between the western and eastern Indian Ocean. While some studies argue that the IOD is an independent mode of variability (Saji *et al*., 1999; Webster *et al*., 1999), others point out that it is a response of the external ENSO forcing in the Pacific Ocean (Ashok *et al*., 2004; Cherchi *et al*., 2021; Ratna *et al*., 2021). Positive IOD is associated with a meridional tripole pattern of rainfall over India whereas, the response of negative IOD is not exactly symmetric instead it is associated with a zonal dipole pattern of rainfall over Indian landmass (Behera and Ratnam, 2018; Ratna *et al*., 2024).

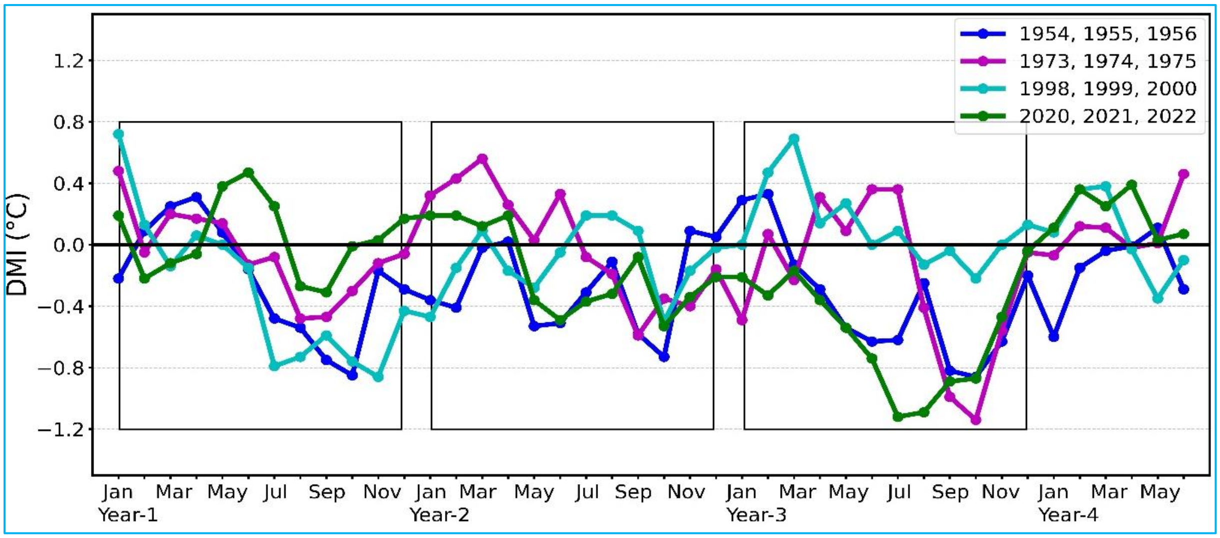

Fig 4. Evolution of the Dipole Mode Index (DMI: in °C) during four triple-dip La Niña episodes.

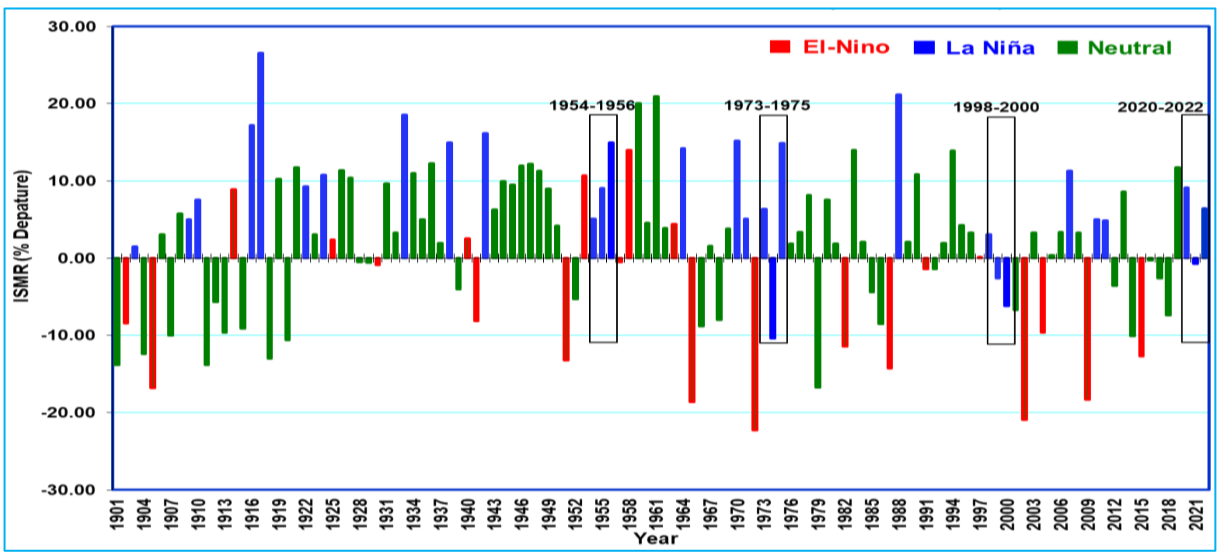

Fig 5. All India averaged percentage rainfall anomaly for the JJAS season for the period 1901-2022 (1971-2020 climatology). The years with El Niño, La Niña and Neutral years are highlighted with red, blue and green colors respectively.

To understand the role of SST over the Indian Ocean during the triple-dip La Niña episode, we analyzed the monthly evolution of the Dipole Mode Index (DMI) for these episodes (Fig. 4). During September-October-November of the first year of triple-dip La Niña, negative IOD (DMI less than -0.4 °C) occurred in all triple-dip La Niña episodes except 2020. During the second year, IOD remain neutral or slightly negative for all the triple-dip La Niña episodes. During the third year, of all triple-dip La Niña episodes, the Indian Ocean showed strong negative IOD conditions during September-October-November, except for the year 2000. After third year, DMI gradually turns neutral for all the triple-dip La Niña episodes (Fig. 4).

3.2. *ISMR Variability during the Triple-dip La Niña Years*

The interannual variation of the observed ISMR, which is the all-India rainfall during the south-west monsoon season (June-September) for the period 1901-2022 is given in Fig. 5. Interestingly, no triple-dip La Niña episode occurred between 1901-1953 period. It was seen that during the triple-dip La Niña years, the observed

TABLE 1

Observed Rainfall Characteristics for the Indian Summer Monsoon during four triple-dip La Niña episodes. Rainfall categories are N (Normal), AN (Above-Normal), BN (Below-Normal). The number of Low-pressure system/depressions (LPS/D) during the season is also listed.

S. No.	Year	Season Total Rainfall (in mm)	% departure*	Category+	Break Days (Jul+Aug)	Actives Days (Jul+Aug)	Number of LPS/D**
	1954	912	5.1	N	11	4	9
1	1955	948	9.1	N	3	3	6
	1956	999	15.0	AN	5	17	8
	1973	924	6.4	N	3	15	8
2	1974	778	-10.4	BN	5	4	5
	1975	998	14.9	AN	0	13	9
	1998	896	3.1	N	13	3	4
3	1999	846	-2.6	N	13	0	4
	2000	815	-6.2	N	8	7	2
	2020	959	9.0	AN	0	16	1
4	2021	872	-1.0	N	11	0	3
	2022	925	6.5	N	7	18	6

rainfall over India was mostly normal or above-normal. During the 1954-1956 triple-dipLa Niña episode, the ISMR was normal and above-normal for all these three years. In the subsequent triple-dipLa Niña episode of 1973-1975, the ISMR was normal and above-normal in 1973 and 1975 respectively, but below-normal in 1974. During 1974, weak La Niña conditions over the tropical Pacific Ocean (Fig. 3) and neutral DMI over the Indian Ocean prevailed (Fig. 4). A study by Abbi *et al*. (1975), discusses that in 1974, the first half of the south-west monsoon period was deficient due to the absence of monsoon depression systems, the later half with some weak low-pressure systems helped in the slight revival of the monsoon however, for the season as a whole, it was a below-normal monsoon year. Moving on to the 1998-2020 episode, ISMR was normal for all three years. For the case of the recent 2020-2022 episode, the ISMR was above-normal in 2020 and normal in 2021 and 2022. The observed rainfall behavior of the ISMR during these triple-dip La Niña episodes has been analyzed. The rainfall characteristics for these four episodes are given in Table 1.

During the summer monsoon season, a substantial portion of the rainfall variability over India comes from fluctuation on the intraseasonal scale. These fluctuations involve alternating periods of active spells with above-normal rainfall and breaks or weak spells with below-normal rainfall over the core monsoon zone region (Rajeevan *et al*., 2010). By comparing the active and break days of monsoon during the latest triple-dip La Niña episode, it was noticed that the strength of the total seasonal rainfall aligns with the number of active monsoon days. In 2020, there were a higher number of active days and no break days, which led to higher seasonal rainfall compared to 2021 and 2022. Conversely, a lesser number of active days and a higher number of break days in 2021 contributed to less seasonal rainfall compared to 2020 and 2022 (Table 1). However, in the year 1954 and the triple-dip La Niña episode 1998-2000, the monsoon was normal despite more (less) no. of break (active) phase. This shows the complex dynamic behavior of monsoons and may be contributing from the influence of other local synoptic features as well as the meridionally propagating monsoon intraseasonal oscillations (MISO) (Dey *et al*., 2022).

Some past studies discuss that Madden Julian Oscillation (MJO) can affect other modes of climate variability even if they are present at time scales other than intraseasonal, including the ENSO and IOD (McPhaden, 1999; Rao and Yamagata, 2004). While few other studies found that the strength and propagation of MJO can be influenced by ENSO through ocean-atmospheric interactions, connecting the equatorial Pacific and Indian Oceans (Hendon *et al*., 2007; Marshall *et al*., 2016). The MJO is identified as one of the prominent factors influencing the ISMR variability at intraseasonal timescale (Pai *et al*., 2011).So, in order to understand the role of MJO and its association with the ISMR, in the

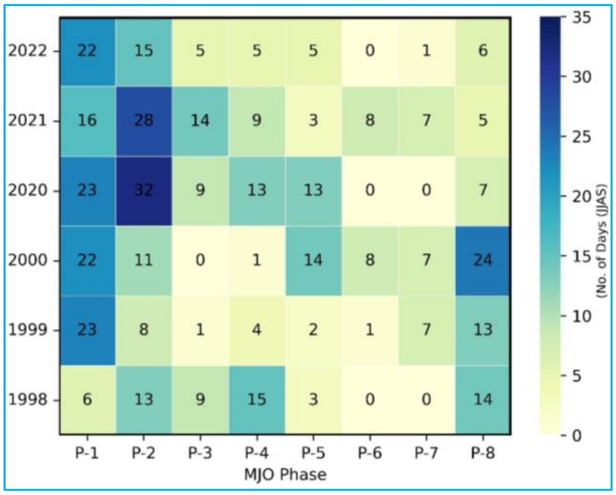

Fig 6. Heatmap representing the number of MJO days in each phase during the JJAS season of two recent triple-dip La Nina episodes (1998-2000, 2020-2022).

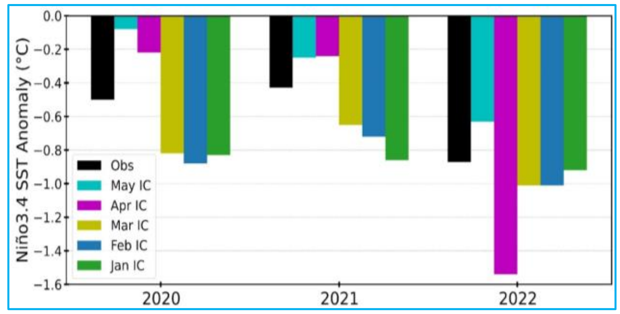

Fig 7. Comparison of observed and different lead times of model forecasted Niño 3.4 Index for the season June to September (JJAS) of 2020, 2021 and 2022.

presence of triple-dip La Niña condition, we analyzed the eastward propagation of the MJO activity during the JJAS season of two recent triple-dip La Niña episodes: 1998-2000 and 2020-2022, based on the availability of MJO data (Fig. 6). The days during which the amplitude of the RMM index is found to be greater than 1 is considered as an ‘active’ MJO day. During the triple-dip La Niña episode 1998-2000, the MJO was found active mainly over phase 1, phase 2 and phase 8 (western Hemisphere, west-central equatorial Indian Ocean, and Africa region), however, during the triple-dip La Niña episode 2020-2022, the MJO activity was found prominent over phase 1 and phase 2 (western and west-central equatorial Indian Ocean).

3.3. *Performance of MMCFS model*

The accuracy of the MMCFS model in forecasting the triple-dip La Niña episode that occurred during the 2020-2022 period, specifically focusing on the Niño 3.4 SST anomaly during the monsoon season (JJAS), was analyzed and compared it with the observation (Fig. 7). The model forecast at various lead times are compared against observations. The observed JJAS Niño 3.4 index for 2020, 2021 and 2022 were -0.5 °C, -0.45 °C and -0.85 °C respectively indicating strongest anomaly in 2022. For all three years, the observed La Niña events, characterized by a negative Niño 3.4 index was forecasted well by the MMCFS model across all lead times (1-5). However, there was a tendency for the model to overestimate the intensity of La Niña from a lead time of 3 to 5 months. Simultaneously, the intensity of the La Niña was under estimated, at lead times of 1 and 2 months, especially for the years 2020 and 2021 La Niña events. Furthermore, the MMCFS forecasted well the stronger magnitude of La Niña in 2022 compared to 2020 and 2021.

The spatial SST anomaly patterns forecasted by MMCFS model with April and May initial conditions during the period of 2020-2022 were compared with observed SST patterns in Fig. 8. During the year 2020 monsoon season, the observed spatial SST anomaly pattern over the Pacific Ocean showed the presence of eastern Pacific (EP) La Niña with colder than normal SSTs over the eastern Pacific Ocean with gradually weakened SSTs extending to the central Pacific. At the same time, warmer than normal SST anomalies over the Indian Ocean, western Pacific Ocean and extra-tropical regions in the north and south [Figs. 8 (a-c)]. The MMCFS model, initialized with initial condition (IC) from April and May, reasonably captured the negative SST anomalies over the eastern and central tropical Pacific Ocean, as well as the positive SST anomalies over the western Pacific Ocean and over the Indian Ocean. However, in comparison to observations both model forecasts underestimated the intensity of SST cooling over the central-eastern tropical Pacific Ocean as well as the SST warming over the Indian Ocean.

During the 2021 JJAS monsoon season, a weak central Pacific (CP) La Niña was observed, with negative SST anomalies prevailing across eastern and central tropical Pacific Ocean, and positive SST anomalies over the western Pacific Ocean [Figs. 8(d-f)]. Over the Indian Ocean, weak positive SST anomalies were observed. The MMCFS model, initialized with April IC correctly captured the negative SST anomalies over the central and easterntropical Pacific Ocean while it slightly overestimated the positive SST anomalies over the Indian Ocean. Similarly, the MMCFS model initialized with May IC also captured below - normal SST anomalies over the

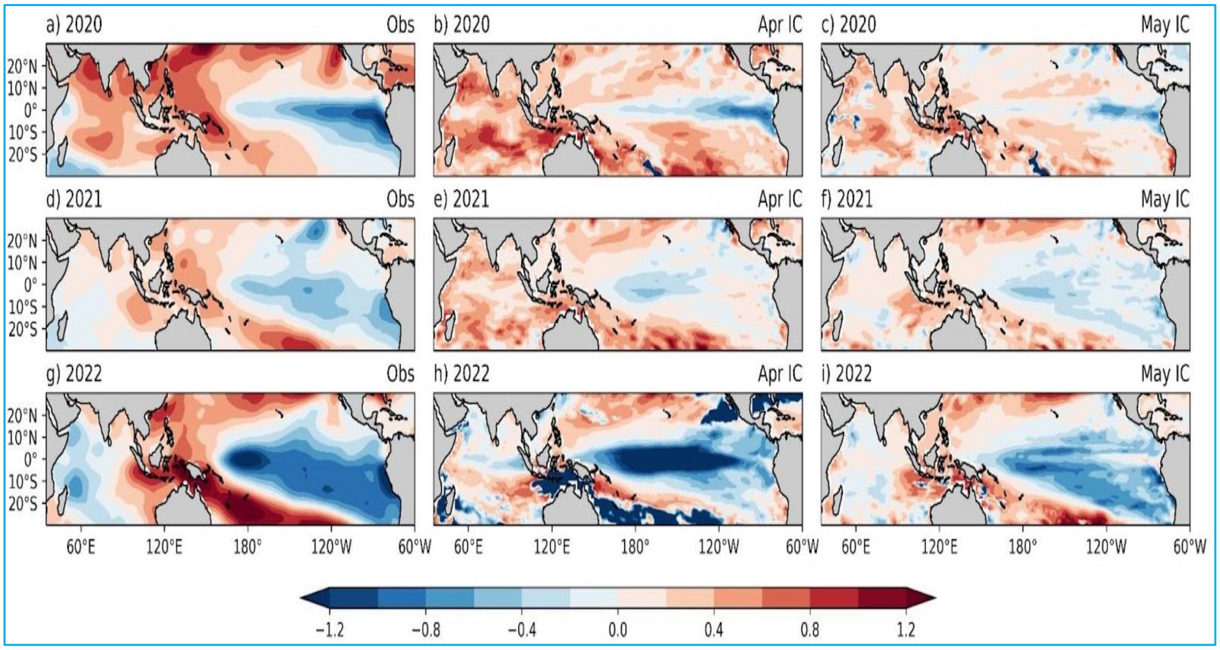

Fig 8. Observed and model comparison of SST anomalies during the June-September season for the years 2020, 2021, and 2022. The panels a), d) and e) are for observed SST anomalies for the years 2020, 2021, and 2022 respectively. Panels b), e), h) and c), f), i) are same as a), d), e) but for model forecasts initialized with April and May initial condition (IC) respectively.

central and eastern tropical Pacific Oceans and above-normal SST anomalies over the western Pacific Ocean. However, in both the model runs, the intensity of negative SST anomalies was underestimated compared to observations.

During the 2022 JJAS monsoon season [Figs. 8(g-i)], the observed SST pattern over the tropical Pacific Ocean clearly showed EP as well as CP La Niña conditions, characterized by below-normal SST anomalies over tropical central-eastern Pacific Ocean extending up to central-western Pacific and above-normal SST anomalies over the western tropical Pacific. The MMCFS forecast, using both April IC and May IC captured the observed negative SST anomaly over the Pacific Ocean. However, the magnitude of this SST anomaly was overestimated in April IC and underestimated in May IC compared to observations. During 2022, a strong negative IOD condition was observed with negative (positive) SST anomalies over the western (eastern) equatorial Indian Ocean but the MMCFS model could not forecast this negative IOD episode.

Generally, the IOD episodes co-occur with the ENSO conditions in the tropical Pacific Ocean. Specifically, positive (negative) IOD episodes are typically accompanied by El Niño (La Niña) episodes (Annamalai *et al*., 2003; Xie *et al*., 2002). Our analysis shows that during all the triple-dip La Niña years, the Indian Ocean observed either neutral or negative IOD conditions. A latest study by Zhang *et al*. (2024) shows that the westward-displaced La Niña episodes produce more pronounced Walker Circulation anomalies, which trigger strong negative IOD episodes (year 2022, Fig. 8(g). However, eastward-displaced La Niña episodes co-occur with insignificant or neutral IOD conditions (Year 2020 and 2021, Figs. 8(a and d).

As the model successfully predicted La Niña a few months in advance, our next objective was to check its ability to forecast associated rainfall variability over the Indian region (Fig. 9). To accomplish this, we compared the summer monsoon (JJAS) mean rainfall over the Indian region with the model predicted seasonal rainfall with April and May IC. The observed monsoon seasonal rainfall in 2020 [Fig. 9(a)] showed that western India and the south peninsula experienced a good amount of rainfall, while most parts of northern, eastern central, and north-eastern India had below-normal rainfall. The spatial distribution of MMCFS seasonal rainfall anomaly forecast (expressed as percentage departure from the LPA) with the April and May ICs for the 2020 JJAS season is shown in Figs. 9(b and c). The MMCFS forecast using April and May IC showed above-normal rainfall over most parts of India. However, the model successfully forecasted the below-normal rainfall in the extreme north and north-eastern regions of India. Simultaneously, the model failed to forecast below-normal rainfall in central-east India.

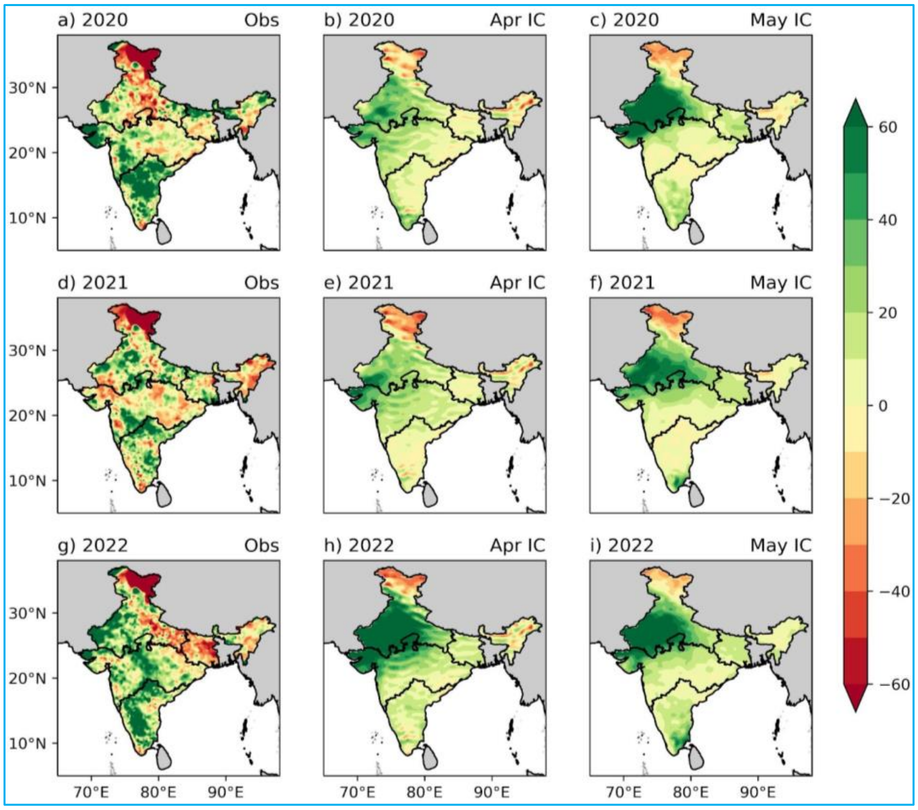

Fig 9. Percentage of rainfall anomaly during the June-September season a) observation, b) MMCFS with April initial condition (IC), and c) MMCFS with May IC for the year 2020. d), e), f) and g), h), i) are same as a), b), c), but for the years 2021 and 2022, respectively.

Additionally, the model underestimated the above-normal rainfall anomaly over the west coast and peninsular India, while overestimating rainfall in northwest India.

In 2021, the observed monsoon rainfall in Fig. 9(d) showed that the extreme north and northeast parts of India, many regions of central India and the extreme southwest parts of peninsular India received below-normal rainfall. However, most parts of the northwest, peninsular India and Indo-Gangetic plains of India received above-normal rainfall. The spatial pattern of the MMCFS seasonal rainfall anomaly forecast with the April and May ICs for the 2021 JJAS season is shown in Figs. 9(e and f). The model failed to forecast the below-normal rainfall anomaly over central-east and northeast India. However, the model correctly forecast the above-normal rainfall over major parts of India. Moving on to the year 2022 [Fig. 9(g)], the observed rainfall was above-normal for major parts of India, excluding the extreme north, east-central India, northeast, and Indo-Gangetic plains. A positive rainfall anomaly was noticed over most areas of northwest and peninsular India. The spatial pattern of the MMCFS ensemble average seasonal rainfall forecast for the 2022 monsoon season (JJAS), with the April and May ICs is shown in Figs. 9(h&i). The model correctly forecasted the above-normal rainfall over major parts of India, but it failed to correctly forecast the below-normal rainfall over the Indo-Gangetic plains. Additionally, the model overestimated the above-normal rainfall in northwest India and underestimated the below-normal rainfall in extreme north India and northeast India. Furthermore, it underestimated the above-normal rainfall over peninsular India.

In the recent 2020-2022 triple-dip La Niña episode, the observed percentage rainfall anomaly over India was positive. In particular, the rainfall prediction of the model with April IC is tends to be close to observation in 2020 and 2021 compared to the May IC. However, for the year 2022, although both the April and May IC simulations in the model showed a positive rainfall anomaly, they did not closely correspond to the observation. The model overestimated the percentage rainfall anomaly across the entire Indian landmass. This overestimation could be attributed to the MMCFS's ability to simulate the ISMR-ENSO correlation well, but failing to replicate the ISMR-IOD correlation (Ramu *et al*., 2017).

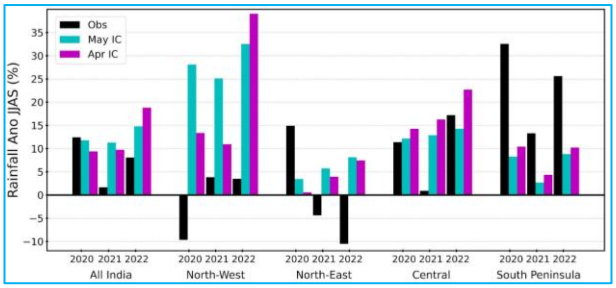

Fig 10. Observed and MMCFS model rainfall anomalies (%) with April initial condition and May initial condition, for all India and four homogeneous regions during the JJAS Season of Triple-dip La Niña years 2020, 2021, and 2022.

Predicting seasonal rainfall at a smaller regional scale is even more challenging than at the national level. In order to analyze whether the percentage rainfall anomaly over the four different homogenous regions of India is predictable during the latest triple-dip La Niña using the MMCFS, we compared the observed anomaly with the MMCFS simulations based on April and May IC (Fig. 10). During 2020, the MMCFS model with April IC as well as May IC, slightly underestimated the ISMR. However, during 2021 and 2022, the ISMR was overestimated in the forecast using both ICs. The overestimation of rainfall by the model may be due to model's inability to accurately capture the Indian Ocean SSTs. A study by Ramu *et al*. (2017) also discussed that the influence of the tropical Indian Ocean on the regional rainfall is still not accurate in the MMCFS model. Among the four homogenous regions, the central Indian region shows the minimum bias. On the other hand, both north-west as well as north-east India showed relatively higher bias compared to central India. Interestingly, all regions showed positive and negative bias with April and May IC, except for south peninsular India. In the case of south peninsular India, the MMCFS simulations using both ICs showed a large negative bias (Fig. 10). The observed rainfall over south peninsular India showed a high correlation with the central Pacific ENSO, but this teleconnection was underestimated in the MMCFS, resulting in a large negative bias over south peninsular India (Ramu *et al*., 2017).

The common characteristics during these three triple-dip La Niña events were below normal rainfall over major parts of the central-east, extreme north India, Indo-Gangetic plains, and northeast India. However, the rainfall was above-normal for most areas of western India and peninsular India. The common feature of the model's performance is that it failed to correctly forecast below-normal rainfall over the plains of Himalayas and central India. Instead, models forecast above-normal rainfall for most parts of India during all three years associated with the triple-dip La Niña. This is again confirming that the MMCFS model has a strong tendency to forecast the La Niña associated above-normal rainfall anomaly over India similar to previous studies (Pillai *et al*., 2018; Pradhan *et al*., 2021).

4. Conclusions

This study discusses the triple-dip La Niña episodes that were observed during the period 1950-2022 and its association with Indian summer monsoon rainfall. Moreover, based on the availability of the model data, this study also analyses the performance of MMCFS model in predicting the recent triple-dip La Niña (2020-2022) and associated ISMR rainfall variability.

There have been four occurrences of triple-dip La Niña since 1950. It can be noteworthy that the prolonged period of colder conditions in the eastern equatorial Pacific Ocean persisted in a warming world with a roughly 20-year interval since the 1950s. The time evolution of the four triple-dip La Niña reveals a consistent pattern. The initial transition from positive Niño 3.4 Index to negative Niño 3.4 Index occurred during the boreal spring season and the colder condition persisted for the following two and a half years. It is also evident that, except for the 2020-2022 event, the Niño 3.4 Index dropped below -1.5 °C during each triple-dip La Niña period. So this observation indicates that the recent event (2020-2022) is the weakest in terms of Niño 3.4 intensity. The ISMR during all these three years of triple-dip La Niña events were normal to above-normal.

Comparing the observed data with the MMCFS model forecasts for the recent trip-dip La Niña event, it was noticed that the model successfully predicted the Niño 3.4 SST anomaly values during these triple-dip La Niña years with a lead time of five months. Furthermore, the comparison of the SST patterns for the three years indicated that the spatial patterns and intensity of SST anomalies over the tropical Pacific, associated with the La Niña event, were well simulated by the model with April IC and May IC. The observed rainfall averaged for the country during the JJAS season of triple-dip La Niña years 2020-2022 was normal to above normal with respect to the LPA. Throughout these three years, the MMCFS model correctly forecasted this above-normal rainfall over major parts of India, and. At the same time, model failed to predict the below-normal rainfall over some parts of the central-east, Indo-Gangetic plains, and northeast India. Also, the model consistently forecasted above-normal rainfall for many regions of India during all three years associated with La Niña. This is similar to previous studies showing that the MMCFS model tends to overestimate the La Niña associated above-normal rainfall anomaly over many parts of India (Ramu *et al*., 2017; Pillai *et al*., 2018; Pradhan *et al*., 2021).

It is important to mention that from 1950 to 2022, we identified four events of triple-dip La Niña. However, our model discussion focused on the recent 2020-2022 event based on the availability of such seasonal forecast data. Therefore, our results are based on a comparative study between the output of the MMCFS model and observations from this particular triple-dip La Niña event. Also, we found a noticeable variation in the emergence, development/continuation, and decay of the negative SST anomaly among the triple-dip La Niña episodes. These variations may be related to the spatio-temporal variability of the ENSO (Capotondi *et al*., 2015) and hence need further investigation. The results of our study show that the model was unable to accurately forecast the negative rainfall anomaly over central-east, Indo-Gangetic plains, and northeast India during the recent triple-dip La Niña event. The reasons behind this discrepancy require a comprehensive understanding and additional research, which falls beyond the scope of our current study.

Despite improvements in prediction systems, accurately forecasting the spatial and temporal variability of ISMR remains a challenging task, even with moderate lead times. This difficulty may arise from the interactions between the ENSO and other large-scale climate modes, such as the IOD (Cherchi *et al*., 2021) and Atlantic Zonal Mode (Sabeerali *et al*., 2019 a, b) and many other factors. To enhance the forecast accuracy of climate models regarding the spatial variation of the ISMR, further research is necessary. It is crucial to gain a deeper understanding of the intricate interactions between ENSO and other climate modes as well as the interaction between intraseasonal and interannual variability (*e.g.* Sikka and Ratna, 2011). Improving the representation of these interactions within the models will likely contribute to enhanced prediction capabilities for the ISMR across different regions.

Acknowledgments

All the authors express their sincere thanks to Dr. M. Mohapatra, Director General of Meteorology (DGM), India Meteorological Department (IMD) Delhi, for his support and guidance in carrying out this work. The authors thank the reviewers for the valuable comments and suggestions which helped in improving the quality of the manuscript. The authors are also thankful to all the officers and staff of the Climate Monitoring and Prediction Group (CMPG) at Climate Research and Services (CRS), IMD Pune for their support. Tanu Sharma acknowledges the research fellowship support from the MRFP (Ministry of Earth Sciences Research Fellowship Program) Project, MoES, Government of India. Computational and graphical analysis for this study have been performed using open-source software Python.

Disclaimer: The contents and views expressed in this study are the views of the authors and do not necessarily reflect the views of the organizations they belong to.

References

Abbi, S. D. S., Nagasubramanian, M. R. and Roy, P. K. D., 1975, "Rainfall and floods in India during 1974 southwest monsoon period", *MAUSAM*, 26, 4, 435-441.

Acharya, N., Chattopadhyay, S., Mohanty, U. C., Dash, S. K. and Sahoo, L. N., 2013, "On the bias correction of general circulation model output for Indian summer monsoon", *Meteorological Applications*, **20**, 3, 349-356.

Adler, R. F., Huffman, G. J., Chang, A., Ferraro, R., Xie, P., Janowiak, J., Rudolf, B., Schneider, U., Curtis, S., Bolvin, D., Gruber, A., Susskind, J. and Arkin, P., 2003, "The Version 2 Global Precipitation Climatology Project (GPCP) Monthly Precipitation Analysis (1979-Present)", *Journal of Hydrometeorology*, **4**, 1147-1167.

Annamalai, H., Murtugudde, R., Potemra, J., Xie, S. P., Liu, P. and Wang, B., 2003, "Coupled dynamics over the Indian Ocean: Spring initiation of the zonal mode. *Deep-Sea Research*, **50**, 12-13, 2305-2330. https://doi.org/10.1016/s0967-0645(03) 00058-4.

Ashok, K., Guan, Z., Saji, N. H., Yamagata, T., 2004, "Individual and combined influences of ENSO and the Indian Ocean dipole on the Indian summer monsoon", *Journal of Climatology*, **17**, 16, 3141-3155.

Barnston, A. G., Tippett, M. K., L 'Heureux, M. L., Li, S., DeWitt, D. G., 2012, "Skill of real-time seasonal ENSO model predictions during 2002-11: Is our capability increasing?", *Bulletin of the American Meteorological Society*, **93**, 5, 631-651.

Barnston, A. G., Tippett, M. K., van den Dool, H. M. and Unger, D. A., 2015, "Toward an improved multi-model ENSO prediction", *Journal of Applied Meteorology and Climatology*, **54**, 7, 1579-1595.

Behera, S. K. and Ratnam, J. V., 2018, "Quasi-asymmetric response of the Indian summer monsoon rainfall to opposite phases of the IOD", *Nature Scientific Reports*, **8**, 123. doi : https://doi.org/10. 1038/s41598-017-18396-6.

Bell, G. D. and Halpert, M. S., 1998, "Climate assessment for 1997", *Bulletin of the American Meteorological Society*, **79**, 5s, S1-S50.

Benke, M., Takle, J., Pai, D. S. and Rao, S. A., 2019, "Analysis of Monsoon Mission Coupled Forecasting System (MMCFS) model simulations of sub-division scale temperatures over India for the hot weather season (April-June)", *Journal of Earth System Science*, **128**, 1-22.

Cole, J. E., 2002, "Multiyear La Niña events and persistent drought in the contiguous United States", *Geophysical Research Letters*, **29**, 1-4. doi : https://doi.org/10.1029/2001GL013561.

Capotondi, A., Wittenberg, A., Newman, M., Di L. E., Yu, Jin-Yi, Braconnot, P., Cole, J., Dewitte, B., Giese, B., Guilyardi, E., Jin, Fei-Fei, Karnauskas, K., Kirtman, B., Lee, T., Schneider, Niklas, Xue, Y. and Yeh, Sang-Wook, 2015, "Understanding ENSO diversity", *Bulletin of the American Meteorological Society*, **96**, 921-938. doi : 10.1175/BAMS-D-13-00117.1.

Chakraborty, A. and Singhai, P., 2021, "Asymmetric response of the Indian summer monsoon to positive and negative phases of major tropical climate patterns", *Nature Scientific Reports*, **11**, 22561, 1-13. doi : https://doi.org/10.1038/s41598-021-01758-6.

Chattopadhyay, R., Rao, S. A., Sabeerali, C. T., George, G., Rao, D. N., Dhakate, A. and Salunke, K., 2016, "Large-scale teleconnection patterns of Indian summer monsoon as revealed by CFSv2 retrospective seasonal forecast runs", *International Journal of Climatology*, **36**, 9, 3297-3313.

Cherchi, A., Terray, P., Ratna, S. B., Sankar, S., Sooraj, K. P. and Behera, S., 2021, "Chapter 8 - Indian Ocean Dipole influence on Indian summer monsoon and ENSO: A review, Indian Summer Monsoon Variability", *Elsevier*, *ISBN 9780128224021*, 157-182. https://doi.org/10.1016/B978-0-12-822402-1.00011-9.

Dey, A., Chattopadhyay, R., Joseph, S., Kaur, M., Mandal, R., Phani, R., Sahai, A.K. and Pattanaik, D. R., 2022, "The intraseasonal fluctuation of Indian summer monsoon rainfall and its relation with monsoon intraseasonal oscillation (MISO) and Madden Julian oscillation (MJO)", *Theoretical and Applied Climatology*, **148**, 819-831. doi :https://doi.org/10.1007/s00704-022-03970-4.

Dommenget, D., Bayr, T. and Frauen, C., 2013, "Analysis of the non-linearity in the pattern and time evolution of El Niño southern oscillation", *Climate Dynamics*, **40**, 2825-2847. doi : https://doi.org/10.1007/s00382-012-1475-0.

George, G., Rao, D. N., Sabeerali, C. T. and Srivastava, A. and Rao, S. A., 2016, "Indian summer monsoon prediction and simulation in CFSv2 coupled model", *Atmospheric Science Letters*, **17**, 1, 57-64.

Griffies, S. M., Harrison, M. J., Pacanowski, R. C. and Rosati, A., 2004, "A technical guide to MOM4", *GFDL Ocean Group Technical Report*, **5**, 337, NOAA/GFDL.

Guilyardi, E., Wittenberg, A., Fedorov, A., Collins, M., Wang, C., Capotondi, A., Van Oldenborgh, G. J. and Stockdale, T., 2009, "Understanding El Niño in ocean-atmosphere general circulation models: Progress and challenges", *Bulletin of the American Meteorological Society*, **90**, 3, 325-340.

Hendon, H. H., Wheeler, M. C. and Zhang, C., 2007, "Seasonal dependence of the MJO-ENSO relationship", *Journal of Climatology*, **20**, 531-543. doi : https://doi.org/10.1175/jcli4003.1.

Hu, Z. Z., Kumar, A., Ren, H. L., Wang, H., L' Heureux, M. and Jin, F. F., 2013, "Weakened interannual variability in the tropical Pacific Ocean since 2000", *Journal of Climate*, **26**, 8, 2601-2613.

Huang, B., Peter, W. T., Boyer, T., Chepurin, G., Jay H. Lawrimore, Matthew J. Menne, Thomas M. Smith, Russell S. Voseand Huai-Min Zhang, 2017, "Extended reconstructed sea surface temperature version 5 (ERSSTv5), upgrades, validations, and intercomparisons", *Journal of Climate*. doi : https://doi.org/10.1175/JCLI-D-16-0836.1.

Iwakiri, T. and Watanabe, M., 2021, "Mechanisms linking multi-year La Niña with preceding strong El Niño", *Scientific Reports*, **11**, 17465. doi : https://doi.org/10.1038/s41598-021-96056-6.

Jin, E. K., Kinter, J. L., Wang, B., Park, C. K., Kang, I. S., Kirtman, B. P., Kug, J. S., Kumar, A., Luo, J. J., Schemm, J. and Shukla, J., 2008, "Current status of ENSO prediction skill in coupled ocean-atmosphere models", *Climate Dynamics*, **31**, 6, 647-664.

Jin, F. F., Neelin, J. D. and Ghil, M. E., 1994, "El Niño on the devil's staircase: Annual subharmonic steps to chaos", *Science*, **264**, 70-72. doi : https://www.science.org/doi/10.1126/science.264.5155.70.

Kucharski, F. and Abid, M. A., 2017, "Interannual variability of the Indian monsoon and its link to ENSO", *Oxford Research Encyclopedia of Climate Science*.

Jones, N., 2022, "Rare 'triple' La Niña climate event looks likely-what does the future hold", *Nature*, **607**, 21. doi : https://doi.org/10.1038/d41586-022-01668-1.

Liu, Y. and Ren, H. L., 2017, "Improving ENSO prediction in CFSv2 with ananalogue-based correction method", *International Journal of Climatology*, **37**, 15, 5035-5046.

Luo, J. J., Masson, S., Behera, S. K. and Yamagata, T., 2008, "Extended ENSO predictions using a fully coupled ocean-atmosphere model", *Journal of Climate*, **21**, 1, 84-93.

Marshall, A. G., Hendon and H. H. and Wang, G., 2016, "On the role of anomalous ocean surface temperatures for promoting the record Madden Julian oscillation in March 2015", *Geophysical Research Letters*,**43**, 472-481. doi : https://doi.org/10.1002/2015GL066984.

McPhaden, M. J., 1999, "Genesis and evolution of the 1997-98 El Nino", *Science*, **283**, 950-954.

Moorthi, S., Pan, H. L. and Caplan, P. 2001, "Changes to the 2001 NCEP Operational MRF/AVN Global Analysis/Forecast System", *Department of Commerce, National Oceanic and Atmospheric Administration, National Weather Service, Office of Meteorology, Program and Plans Division.* Technical procedures bulletin. Serial No. 484.

Pai, D. S., 2004, "A possible mechanism for the weakening of El Nino-monsoon relationship during the recent decades", *Meteorology and Atmospheric Physics*, **86**, 143-157. doi : https://doi.org/10.1007/s00703-003-0608-8.

Pai, D. S., Bhate, J., Sreejith, O. P. and Hatwar, H. R., 2011, "Impact of MJO on the intraseasonal variation of summer monsoon rainfall over India", *Climate Dynamics*, **36**, 41-55. doi : https://doi.org/10.1007/s00382-009-0634-4.

Pai, D. S., Sridhar, Latha, Rajeevan, M., Sreejith, O. P., Satbhai, N. S. and Mukhopadhyay, B., 2014, "Development of a new high spatial resolution (0.25° × 0.25°) Long period (1901-2010) daily gridded rainfall data set over India and its comparison with existing data sets over the region", *MAUSAM*, **65**, 1, 1-18.

Pan, J. and van den Dool, H., 1998, "Extended-range probability forecasts based on dynamical model output", *Weather and Forecasting*, **13**, 4, 983-996.

Philander, S. G. H., 1983, "El Nino southern oscillation phenomena", *Nature*, **302**, 5906, 295-301.

Pillai, P. A., Rao, S. A., George, G., Rao, D. N., Mahapatra, S., Rajeevan, M., Dhakate, A. and Salunke, K., 2017, "How distinct are the two flavors of El Niño in retrospective forecasts of Climate Forecast System version 2 (CFSv2)?", *Climate Dynamics*, **48**, 11, 3829-3854.

Pillai, P. A., Rao, S. A., Ramu, D. A., Pradhan, M. and George, G., 2018, "Seasonal prediction skill of Indian summer monsoon rainfall in NMME models and monsoon mission CFSv2", *International Journal of Climatology*, **38**, e847-e861. doi : https://doi.org/10.1002/joc.5413.

Pokhrel, S., Chaudhari, H. S., Saha, S. K., Dhakate, A., Yadav, R., Salunke, K., Mahapatra, S. and Rao, S. A., 2012, "ENSO, IOD and Indian Summer Monsoon in NCEP climate forecast system", *Climate Dynamics*, **39**, 9, 2143-2165.

Pradhan, M., Rao, S. A., Doi, T., Pillai, P. A., Srivastava, A. and Behera, S., 2021, "Comparison of MMCFS and SINTEX-F2 for seasonal prediction of Indian summer monsoon rainfall", *International Journal of Climatology*, **41**, 13, 6084-6108.

Rajeevan, M., Gadgil, S. and Bhate, J., 2010, "Active and break spells of the Indian summer monsoon", *Journal of Earth System Science***119**, 229-247. doi : https://doi.org/10.1007/s12040-010-0019-4.

Ramu, D. A., Sabeerali, C. T., Chattopadhyay, R., Rao, D. N., George, G., Dhakate, A. R., Salunke, K., Srivastava, A. and Rao, S. A., 2016, "Indian summer monsoon rainfall simulation and prediction skill in the CFSv2 coupled model: Impact of atmospheric horizontal resolution", *Journal of Geophysical Research: Atmospheres*, **121**, 5, 2205-2221.

Ramu, D. A., Rao, S. A., Pillai, P. A., Pradhan, M., George, G., Rao, D. N., Mahapatra, S., Pai, D. S. and Rajeevan, M., 2017, "Prediction of seasonal summer monsoon rainfall over homogenous regions of India using dynamical prediction system", *Journal of Hydrology*, **546**, 103-112, ISSN 0022-1694. doi : https://doi.org/10.1016/j.jhydrol.2017.01.010.

Rao, S. A. and Yamagata, T., 2004, "Abrupt termination of Indian Ocean dipole events inresponseto intraseasonal disturbances", *Geophysical Research Letters,* **31**, L19306. doi : https://doi.org/10.1029/2004GL020842.

Rao, S. A., Goswami, B. N., Sahai, A. K., Rajagopal, E. N., Mukhopadhyay, P., Rajeevan, M., Nayak, S., Rathore, L. S., Shenoi, SSC, Ramesh, K. J. and Nanjundiah, R. S., 2019, "Monsoon mission: a targeted activity to improve monsoon prediction across scales", *Bulletin of the American Meteorological Society*, **100**, 12, 2509-2532.

Ratna, S. B., Cherchi, A., Osborn, T. J., Joshi, M. and Uppara, U., 2021, "The Extreme positive Indian Ocean Dipole of 2019 and Associated Indian Summer Monsoon Rainfall Response", *Geophysical Research Letters.* doi : https://doi.org/10.1029/2020GL091497.

Ratna, S. B., Sabeerali, C. T., Sharma, T., Pai, D. S. and Mohapatra, M., 2024, "Combined influence of El Niño, IOD and MJO on the Indian Summer Monsoon Rainfall: Case Study for the years 1997 and 2015", *Atmospheric Research*, **299**, 107214. doi : https://doi.org/10.1016/j.atmosres.2023.107214.

Ren, H. L., Jin, F. F., Song, L., Lu, B., Tian, B., Zuo, J., Liu, Y., Wu, J., Zhao, C., Nie, Y. and Zhang, P., 2017, "Prediction of primary climate variability modes at the Beijing Climate Center", *Journal of Meteorological Research*, **31**, 1, 204-223.

Rohini, P., Rajeevan, M., Rao, S. A. and Pillai, P.A., 2022, "Assessment of hot weather seasonal temperatures over India using Monsoon Mission Coupled Forecasting System hindcasts", *International Journal of Climatology*, **42**, 16, 9823-9835.

Sabeerali, C. T., Ajayamohan, R. S. and Rao, S. A., 2019a, "Loss of predictive skill of indian summer monsoon rainfall in NCEP CFSv2 due to misrepresentation of Atlantic zonal mode", *Climate Dynamics*, **52**, 7, 4599-4619.

Sabeerali, C. T., Ajayamohan, R. S., Bangalath, H. K. and Chen, N., 2019b, "Atlantic zonal mode: an emerging source of Indian summer monsoon variability in a warming world", *Geophysical Research Letters*, **46**, 8, 4460-4467.

Saha, S., Moorthi, S., Wu, X., Wang, J., Nadiga, S., Tripp, P., Behringer, D., Hou, Y. T., Chuang, H. Y., Iredell, M. and Ek, M., 2014, "The NCEP climate forecast system version 2", *Journal of climate*, **27**, 6, 2185-2208.

Shukla, J., 1987, "Interannual variability of monsoons", *Monsoons*, **14**, 399-464.

Saji, N.H., Goswami, B.N., Vinayachandran, P. N. and Yamagata, T., 1999, "A dipole mode in the tropical Indian Ocean", *Nature*, **401**, 6751, 360-363.

Sikka, D. R. and Gadgil, S., 1980, "On the maximum cloud zone and the ITCZ over Indian longitudes during the southwest monsoon", *Monthly Weather Review*, **108**, 1840-1853. doi : https://doi.org /10.1175/15200493(1980)108<1840:OTMCZA>2.0.CO;2.

Sikka, D. R. and Ratna S. B., 2011, "On improving the ability of a high resolution atmospheric general circulation model for dynamical seasonal prediction of the extreme seasons of the Indian summer monsoon", *MAUSAM*, **62**, 3, 339-360.

Sreejith, O. P., Surendran, D., Bandgar, A. and Pai, D. S., 2022, "Operational Seasonal Forecasting of the Southwest Monsoon Rainfall", *Springer Nature Singapore, Social and Economic Impact of Earth Sciences*, 31-48.

Tang, S., Qiao, S., Wang, B., Fei Liu, Taichen Feng, Jie Yang, Meng He, Dong Chen, Jianbo Cheng, Guolin Feng and Wenjie Dong, 2023, "Linkages of unprecedented 2022 Yangtze River Valley heatwaves to Pakistan flood and triple-dip La Niña", *Npj Climate and Atmospheric Science*, **6**, 44. doi : https://doi.org/ 10.1038/s41612-023-00386-3.

Wang, R. and Ren, H. L., 2017, "The linkage between two ENSO types/modes and the interdecadal changes of ENSO around the year 2000", *Atmospheric and Oceanic Science Letters*, **10**, 2, 168-174.

Wang, J. W. and Wang, C., 2021, "Joint boost to super El Nino from the Indian and Atlantic oceans", *Journal of Climate*, **34**, 4937-4954. doi : https://doi.org/10.1175/JCLI-D-20-0710.1.

Webster, P. J. and Yang, S., 1992, "Monsoon and ENSO: Selectively interactive systems", *Quarterly Journal of the Royal Meteorological Society*, **118**, 507, 877-926. doi : https://doi.org/ 10.1002/qj.49711850705.

Webster, P. J., Moore, A. M., Loschnigg, J. P. and Leben, R. R., 1999, "Coupled oceanic-atmospheric dynamics in the Indian Ocean during 1997-98", *Nature*, **401**, 6751, 356-360. doi : https://doi .org/10.1038/43848.

Wheeler, M., Hendon, H. H., 2004, "An all-season real-time multivariate MJO index: Development of an index for monitoring and prediction". *Monthly Weather Review*, **132**,1917-1932.

Xie, S. P., Annamalai, H., Schott, F. A. and McCreary, J. P. 2002, "Structure and mechanisms of south Indian Ocean climate variability", *Journal of Climate*, **15**, 8, 867-878. doi : https://doi. org/10.1175/1520-0442(2002)015<0864:SAMOSI>2.0.CO;2.

Zebiak, S. E. and Cane, M. A., 1987, "A model elniño-southern oscillation", *Monthly Weather Review*, **115**, 10, 2262-2278.

Zhang, T., Zhang, W., Jiang, F. and Jin, F. F., 2024, "La Niña's teleconnection to the Indian Ocean Dipole controlled by its longitudinal position", *Geophysical Research Letters*, **51**, e2023GL107119. doi : https://doi.org/10.1029/2023GL107119.

Zheng, F., Wu, B., Wang, L., Jingbei Peng, Yao Yao, Haifeng Zong, Qing Bao, Jiehua Ma, Shuai Hu, Haolan Ren, Tingwei Cao, Renping Lin, Xianghui Fang, Lingjiang Tao, Tianjun Zhou and Jiang Zhu, 2023, "Can Eurasia Experience a Cold Winter under a Third-Year La Niña in 2022/23", *Advanced Atmospheric Science* 40, 541-548. doi : https://doi.org/10. 1007/s00376-022-2331-8.