Viability of a dynamical climate prediction system for the Kharif rice production in Indian states.

A thesis submitted during 2015-2022 to the University of Hyderabad in partial fulfilment of the award of a PhD degree in Earth and Space Sciences

By

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CERTIFICATE

This is to certify that the thesis entitled **"Viability of a dynamical climate prediction system for the Kharif rice production in Indian states"** submitted by **Hemadri Bhusan Amat** bearing Reg. No. **15ESPE02**, in partial fulfilment of the requirements for the award of Doctor of Philosophy in **Earth & Space Sciences**, is a bonafide work carried out by him under my supervision and guidance.

This thesis has not been submitted previously in part or in full to this or any other University or Institution for the award of any degree or diploma.

Karumuri Ashok 06 April, 2022

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This thesis is free from plagiarism and has not been submitted previously in the part of in full to this or any other University or Institution for the award of any degree or diploma.

Further, the student has the following publications before submission of the thesis monograph for adjudication and has produced evidence for the same in the form of acceptance letter or the reprint in the relevant area of this research: (Note: at least one publication in a refereed journal is required)

1. Amat, H. B., & Ashok, K. (2018). Relevance of Indian Summer Monsoon and its Tropical Indo-Pacific Climate Drivers for the Kharif Crop Production. Pure and Applied Geophysics, 175(6), 2307–2322. https://doi.org/10.1007/s00024-017-1758-9
   This publication appears in Chapter 3 of this dissertation.

2. Amat, H. B., Pradhan, M., Tejavath, C. T., Dey, A., Rao, S. A., Sahai, A. K., & Ashok, K. (2021). Value addition to forecasting: towards Kharif rice crop predictability through local climate variations associated with Indo-Pacific climate drivers. Theoretical and Applied Climatology, 144(3–4), 917–929. https://doi.org/10.1007/s00704-021-03572-6
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and has made presentations at the following conferences:

1. Presented a Poster Presentation on the title *" Relevance of Indian Summer Monsoon and its Indo-Pacific Climate drivers for the Kharif crop production."*; at **TROPMET-2016, National Symposium on Tropical Meteorology: Climate Change and Coastal Vulnerability**, organised by IMS Bhubaneswar chapter and Siksha 'O' Anusandhan University, Bhubaneswar, India. Dated: **18 - 21 December 2016**

2. Delivered an oral presentation on *"Relevance of Indian Summer Monsoon and its Indo-Pacific Climate drivers for the Kharif crop production."* at **International Conference on Global Water Crisis: Agriculture and Food Security in the Era of Climate Change**, organised by Dept. of Geography, Aligarh Muslim University, Aligarh, India. Dated: **1 – 3 December 2018**

3. Delivered an oral presentation on the topic *"Value addition to climate forecasting: predictability of the Kharif Rice crop association with various Indo-pacific climate drivers."* at **TROPMET-2020, Virtual Symposium on Weather and Climate Services over Mountainous Region**, jointly organised by IMS Shillong Chapter and North East Space Application Centre, Shillong, India. Dated: **14 - 17 December 2020.**

Further, the student has passed the following course towards fulfilment of coursework requirement for PhD / was exempted from doing coursework (recommended by Doctoral Committee) based on the following courses during his PhD program.

Course Code	Name	Credits	Pass/Fail
ES 801	Earth System Sciences	4	Pass
ES 805	Research Methodology	3	Pass
ES 806	Mathematics for Earth Sciences	4	Pass
ES 807	Interdisciplinary Course	3	Pass
ES 811-830	Special paper on a specified Research Topic	2	Pass

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DECLARATION

I, Hemadri Bhusan Amat, hereby declare that this thesis entitled "**Viability of a dynamical climate prediction system for the Kharif rice production in Indian states**", submitted by me under the guidance and supervision of Prof. Karumuri Ashok, Centre for Earth, Ocean and Atmospheric Sciences, School of Physics, University of Hyderabad, is bonafide research work.

I also declare that it has not been submitted previously in part or in full to this University or any other University or Institution for the award of any degree or diploma.

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Place: Hyderabad Regd. No. 15ESPE02

Coursework Report

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31|5|17

UNIVERSITY OF HYDERABAD
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Month & Year: April'2017
Semester -II

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1	13ESPE01	KONETI SUNITHA	Pass	Pass	Pass	Pass	Pass
2	13ESPE03	DEBASHRI GARAI	Pass	Pass	Pass	Exempted	Pass
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4	15ESPE02	HEMADRI BHUSHAN AMAT	Pass	Pass	Pass	Fail	Pass
5	15ESPE03	K. MALLESH	Pass	Pass	Pass	Exempted	Pass
6	15ESPE04	CHENNU RAMU	Pass	Pass	Pass	Pass	Pass
7	15ESPE05	GOVARDHAN DANDU	Pass	Pass	Pass	Pass	Pass
8	15ESPE07	BOYAJ ALUGULA	Pass	Pass	Pass	Pass	Pass
9	15ESPE09	TEJAVATH CHARAN TEJA	Pass	Pass	Pass	Pass	Pass
10	15ESPE10	BILLINGI TARUN KUMAR	Pass	NA	Pass	NA	Pass
11	16ESPE01	RESHMA M.R.	Pass	NA	Pass	Exempted	Pass
12	16ESPE02	SEEDABATTULA V BALAJI MANASA RAO	Pass	NA	Pass	NA	Pass
13	16ESPE04	SUNIT MOHANTY	Pass	NA	Pass	NA	Pass
14	16ESPE05	TARUN THOMAS T.	Pass	NA	Pass	NA	Pass

Course No.	Title of the Course
ES 801	Earth system sciences -4
ES 805	Research Mehtodology -3
ES 806	Mathematics for Earth Sciences -4
ES 807	Interdisciplinary course -3
ES 811-830	Special Paper on Spectified Research Topic -2

NA - NOT APPEARED

Dated: 29.05.2017

Controller of Examination 30-5-17

To

Head, Centre for Earth and Space Sciences
Dean School of Physics

07-06-2017

Coursework Report

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University of Hyderabad

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ES801	Earth System Sciences	4.00
ES807	Interdisciplinary Course (Data Mining)	3.00
ES806	Mathematics for Earth Sciences	4.00

N.B. 11.09.2018

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Dedicated to my family

CONTENTS

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Thank you all,

Hemadri Bhusan Amat

LIST OF JOURNAL PUBLICATIONS

1. Amat, H. B., & Ashok, K. (2018). Relevance of Indian Summer Monsoon and its Tropical Indo-Pacific Climate Drivers for the Kharif Crop Production. Pure and Applied Geophysics, 175(6), 2307–2322. https://doi.org/10.1007/s00024-017-1758-9

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CONFERENCE & WORKSHOP PROCEEDINGS

1. Participated in the **training course on *"Indian Ocean Dynamics: From the Large-Scale Circulation to Small-Scale Eddies and Fronts"*** during the November 16-27, 2015, organised at the INCOIS, Hyderabad, India.
2. Attended a **Workshop on *"Extreme Weather and Climate Variability: Observation, Understanding and Prediction"*** from 23-31 December 2016 at IIT Bhubaneswar, Odisha conducted by GIAN.
3. Attended the ***TROPMET-2016, National Symposium on Tropical Meteorology: Climate Change and Coastal Vulnerability*** and Also, delivered a Poster Presentation on the *title " Relevance of Indian Summer Monsoon and its Indo-Pacific Climate drivers for the Kharif crop production."*; organised by IMS Bhubaneswar chapter and Siksha 'O' Anusandhan University, Bhubaneswar, India. Dated: 18 - 21 December 2016.
4. Attended the two-day **workshop on *"Measuring and Forecasting Atmospheric Constituents" with the theme: IoT and Big Data***, on 29.09.2018 & 30.09.2018, organised by IEEE CIS/GRSS Jt. Chapter and IEEE/EDS Jt. Chapter Hyderabad Section and Centre for Advanced Studies in Electronics Sciences and Technology (CASEST), at the University of Hyderabad, India.
5. Attended the ***International Conference on Global Water Crisis: Agriculture and Food Security in the Era of Climate Change***, organised by Dept. of Geography, Aligarh Muslim University, Aligarh(INDIA). Also, delivered an oral presentation on *"Relevance of Indian Summer Monsoon and its Indo-Pacific Climate drivers for the Kharif crop production."* Dated: 1 – 3 December 2018
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List of Abbreviations

ISM	: Indian Summer Monsoon
ISMR	: Indian Summer Monsoon Rainfall
MISO	: Monsoon Intra-seasonal Oscillation
SST	: Sea Surface Temperature
ENSO	: El Niño Southern Oscillation
IOD	: Indian Ocean Dipole
IODMI	: Indian Ocean Dipole Mode Index
EMI	: ENSO Modoki Index
JJAS	: June, July, August, September
IMD	: India Meteorological Departments
IITM-CFSv2	: Indian Institute of Tropical Meteorology-Climate Forecast System Version 2
ERP	: Extended Range Prediction
DSSAT	: Decision Support System for Agro-technology Transfer
KCP	: Kharif Crop Production
KRP	: Kharif Rice Production
KRY	: Kharif Rice Yield
ITCZ	: Inter-tropical convergence zone
NCAR	: National Centre for Atmospheric Research
NCEP	: National Centres for Environmental Prediction
SLP	: Sea level pressure
SWJ	: Subtropical Westerly Jet
TEJ	: Tropical Easterly Jet

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Abstract

The Indian agriculture sector contributes a significant part of India's *Gross Domestic Product (GDP),* and the Indian agriculture sector is dependent mainly on the Indian Summer Monsoon Rainfall (ISMR). On the other hand, the ISMR interannual variability is primarily influenced by the tropical Indo-Pacific climate drivers, namely *El Niño Southern Oscillation (ENSO), El Niño Modoki* and *Indian Ocean Dipole (IOD).* Despite the earlier dependency of Indian agriculture on the ISMR, a multifold increase in irrigation and storage facilities raises the question of whether the ISMR is still relevant. We revisit this question using the latest observational climate datasets and the crop production data and find that the ISMR is still relevant for the Kharif crop production (KCP), specifically Kharif rice. In addition, in the recent changes in the tropical Indo-Pacific driver evolutions and frequency, particularly more frequent occurrence of the ENSO Modokis in place of the canonical ENSOs, we carry out a correlation analysis to estimate the impact of the various Indo-Pacific climate drivers on the rainfall of individual Indian states for the period 1998-2013, for which crop production data for the most productive Indian states, namely, *West Bengal, Odisha, United Andhra Pradesh (UAP), Haryana, Punjab, Karnataka, Kerala, Madhya Pradesh, Bihar, Uttar Pradesh* are available. The results suggest that the KCP of the respective states are significantly correlated with the summer monsoon rainfall at 95%~99% confidence levels. Importantly, we find that the NINO 3.4 & ENSO Modoki indices have a statistically significant correlation with the KCP of most Indian states, particularly in states such as *UAP* & *Karnataka*, through induction of anomalous local convergence/divergence, well beyond the equatorial Indian Ocean. The KCP of districts in UAP also has a significant response to all the climate drivers, having implications for predicting local crop yield.

In addition, to improve the ISMR early forecast, the *Indian Institute of Tropical Meteorology (IITM)* has generated seasonal and extended range hindcast products for 1981–2008 and 2003–2016, respectively, using the IITM-Climate Forecast System (IITM-CFS) coupled model at various resolutions and configurations. Notably, our observational analysis suggests that for the 1981–2008 period, the tropical Indo-Pacific drivers, namely, the canonical ENSO, ENSO Modoki, and IOD, are significantly associated with the observed Kharif rice production (KRP) of various rice-growing Indian states. We used the available hindcasts datasets to evaluate whether these state-of-the-art retrospective forecasts capture the relationship of the KRP of multiple states with the local rainfall as well as the tropical Indo-Pacific drivers, namely, the canonical ENSO, ENSO Modoki, and the IOD. Using anomaly correlation, partial correlation, and pattern correlation techniques, we surmise that the IITM-CFS successfully simulates the observed association of the tropical Indo-Pacific drivers with the local rainfall of many states during the summer monsoon. Significantly, the observed relationship of the local KRP with various climate drivers is predicted well for several Indian states such as United Andhra Pradesh, Karnataka, Odisha, and Bihar. The basis seems to be the model's ability to capture the teleconnections from the tropical Indo-Pacific drivers such as the IOD, canonical and Modoki ENSOs to the local climate and, consequently, the Kharif rice production. Additionally, we attempted to harness the CFSv2 extended-range hindcast skills for crop yield forecast using a state-of-the-art crop growth model named *Decision Support System for Agrotechnology Transfer (DSSAT).* The DSSAT simulations suggest that week-01 (W01) lead skills can significantly stimulate the corresponding rice yield with the least 16% deviation.

Chapter- 1

Introduction

The earliest studies of weather events can be traced back to ancient Greece, documented by Aristotle in his famous *Meteorologica* in 340 BC (Frisinger H. Howard, 1973). However, the various aspects of weather and climate sciences as it is currently known to us were not there until the modern age in the nineteenth century. This thesis aims to extend the understanding of the relevance of the Indian Summer Monsoon and its tropical Indo-Pacific climate drivers towards Kharif rice crop yields.

1.1 The Indian Summer Monsoon

The word "monsoon" is originally derived from the Arabic word "mausim", which means "season." Hence, the monsoon is the seasonal reversal of wind accompanied by a significant amount of precipitation. For centuries, sailors and traders navigated through the Arabian Sea with a better understanding of the monsoon wind system (Rawlinson, 1916). The Indian summer monsoon (ISM) is the most notable among the monsoon systems worldwide, predominantly affecting the Indian subcontinent pouring a tremendous amount of rainfall through the mechanism of land-sea pressure difference and temperature difference (Ramage, 1971; Rao, 1976). ISM Rainfall adds up to over 70%-80% of the annual precipitation over India through June to September (JJAS) (Figure 1.1), which is also mentioned by Ashok et al.(2021), and ISMR's contribution towards agricultural usage, drinking water, and energy production make it the lifesaver for the total population of the vast subcontinent.

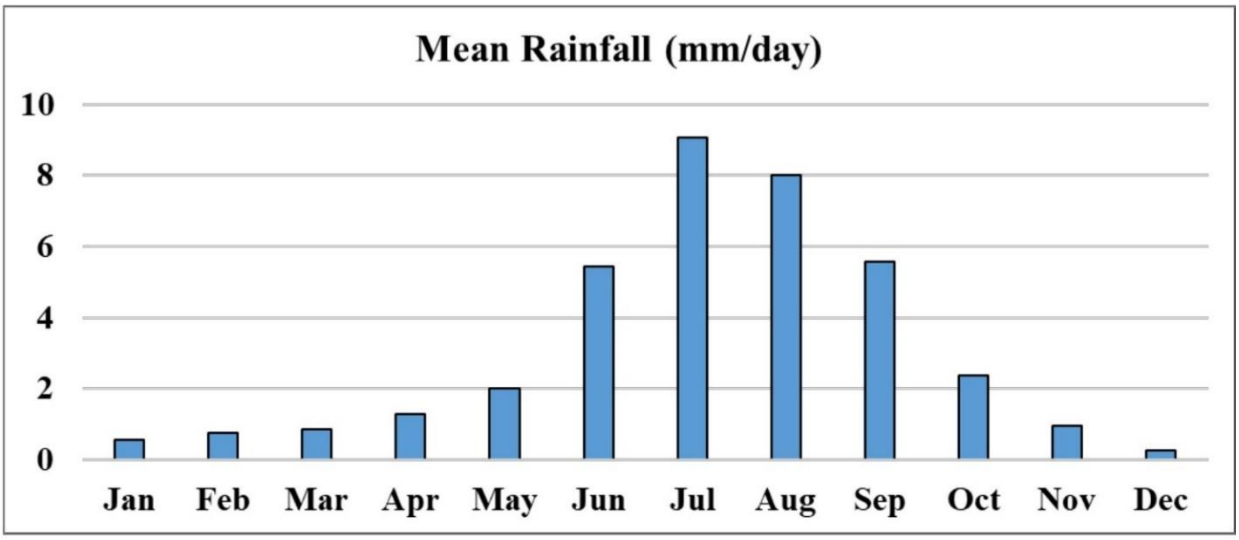

Figure 1.1: Monthly means of All India rainfall using IMD gridded 0.25°×0.25° rainfall dataset available from 1901 to 2019.

Figure 1.1 suggests that India receives maximum rainfall in July and followed August, September and June. The summer monsoon has two branches: the Arabian Sea and the Bay of Bengal. During the pre-monsoon time frame, a pressure gradient induced cross-equatorial flow around the Mascarene Islands of the Southern Indian ocean. The flow is directed from the Mascarene high to a low-pressure system over the Indian subcontinent. This low pressure over India is caused due to the significant thermal gradient between land and sea. Subsequently, the south equatorial easterly trade winds bend towards the Somali coast, becoming westerlies heading towards India. When these south-westerlies reach India, they are called the southwest monsoon winds.

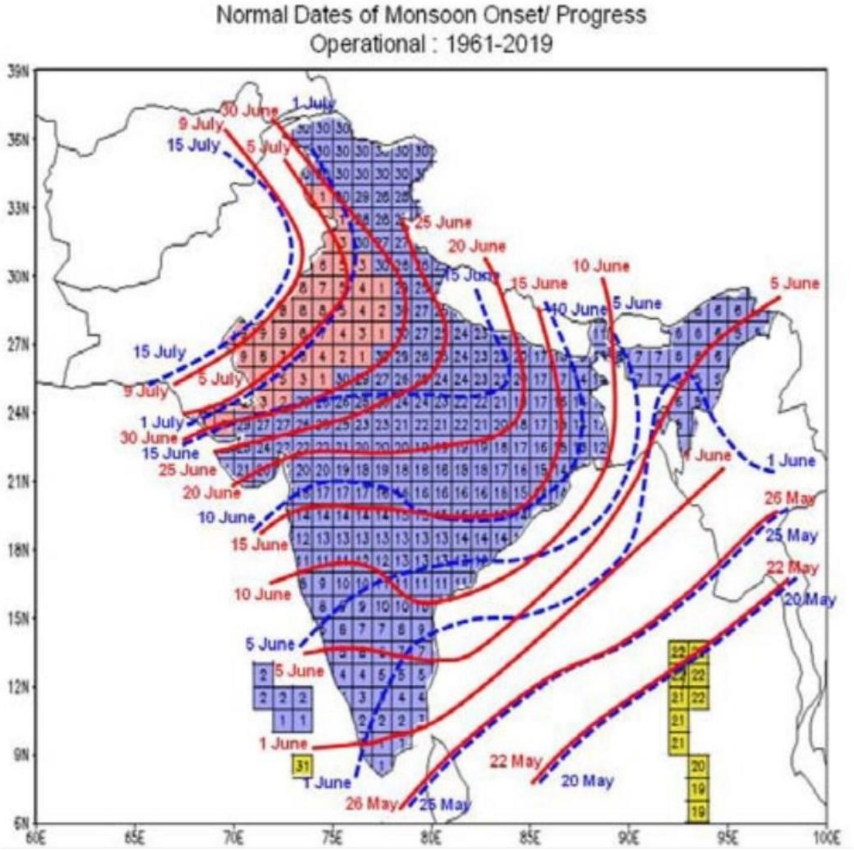

Figure 1.2: A schematic Indian map for the onset dates of the Indian Summer Monsoon adopted from Pai et al.(2020). It shows a clear picture of ISM's movement over the various parts of the Indian subcontinent. This schematic map has been made using the recorded onset dates from 1901 to the present. This map has two types of lines, one is solid red, and another is dotted blue. The dotted-blue isochrones are the old ones, and solid red is the updated ones. The different colourful grids inside the map have been shaded with colours based on the months, for example, Yellow for May, Blue for June, and Peach for July.

The monsoon winds usually hit the west coast of India (Kerala coast) on 1st June, and sometimes the onset date varies up to a week to 9 days (IMD, 1943; Joseph et al., 1994) and hence starting a four-extended month of the wet season, enduring till September. Further, these winds last till the end of September, blowing over the different parts of India.

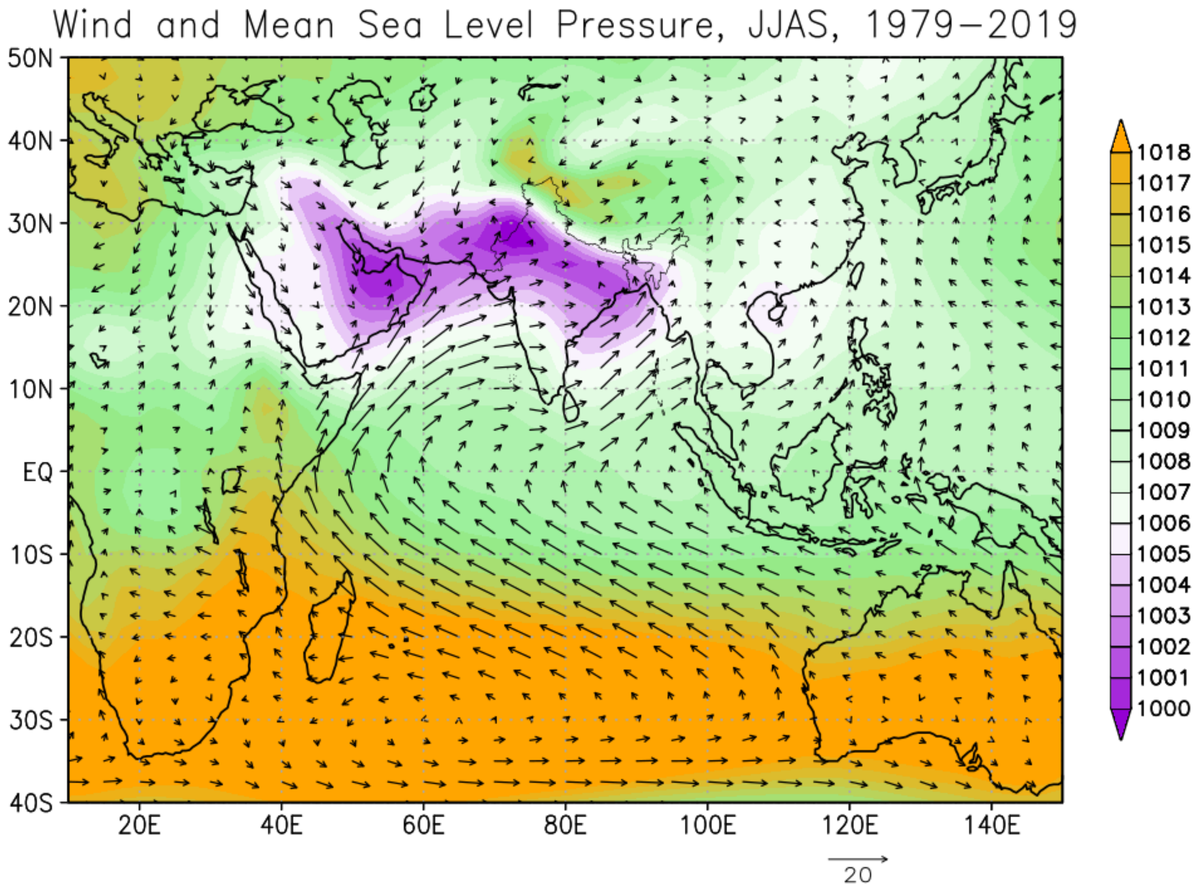

Figure 1.3: The climatological mean monsoon wind vector & magnitude (m/s) and the mean sea level pressure (mb) during JJAS using the NCEP Reanalysis dataset from 1979-2019.

Once the onset occurs, the ISM takes around 20-25 days to cover most of the part of India. Also, the monsoon system needs to be fuelled up timely to sustain until September end. Therefore, the moisture-containing monsoon winds maintain their flow by the land-sea pressure gradient and the latent heat released. At the same time, the Inter-Tropical Convergence Zone (ITCZ) shifts towards 20°-25° N latitude in July. The ITCZ remains most of the time over the Indo-Gangetic Plain. That part of ITCZ is called the "Monsoon Trough" (Riehl, 1954) (Figure 1.3). The ISM precipitation distribution is not uniform over the Indian landmass, showing significant spatial variability (Figure 1.4).

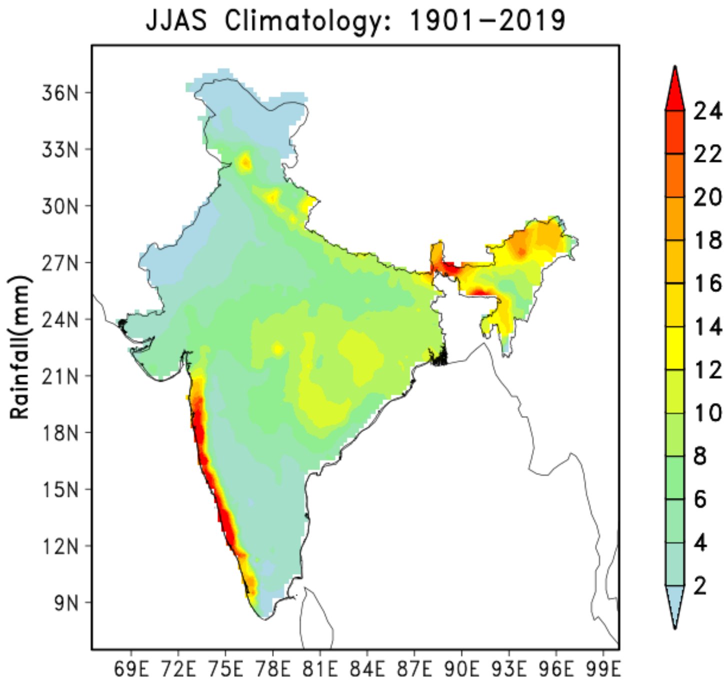

Figure 1.4: Climatology of monsoon rainfall (mm/day) over India from June to September (JJAS) using IMD gridded 0.25°×0.25° rainfall dataset for 1901-2019.

The progression of monsoon winds brings a substantial amount of rainfall over the central part of India (Figure 1.4), termed as the core Monsoon Zone (Sikka and Gadgil, 1980). Northeast India and the west coast of India eventually receive anomalous surplus rainfall. The monsoon trough plays a significant role in monsoon rainfall distribution here. A substitute theory recommends that the ISM be an ITCZ appearance (Charney, 1969; Gadgil., 2018), which shifts northward or southward depending upon the season. Furthermore, Goswami and Chakravorty (2017) suggested the importance of adiabatic processes that excels more than the differential pressure between land and sea. Even though the ISM is a complex ocean-atmospheric coupled system, monsoon researchers over time have identified six semi-permanent features as the driving force behind this coupled system, namely (i) Monsoon Trough, (ii) Mascarene High, (iii) Heat Low, (iv) Low-Level Jet, (v) Tibetan high and (vi) Tropical Easterly Jet.

(i) The **Monsoon Trough** is nothing but a cross-section of the ITCZ situated over the heated Indian landmass during the hot summer. The axial position of this trough receives significantly more rainfall than the rest of the mainland. The monsoon trough's northward and southward movements help determine the distribution of monsoon activity.

(ii) As the name suggests, **Mascarene high** is the high-pressure zone near the Mascarene Islands of the Southern Indian Ocean (figure 1.3) and pressure gradient induced cross-equatorial flow helps accelerate the monsoon winds. Ananthakrishnan et al. (1968) suggest that the mean pressure level at this zone is 1025 hPa.

(iii) The monsoon winds discharge most of their moisture on the southern part of the mighty Himalayas primarily because of the higher orography. Then, the continuity of the monsoon winds fails to cover up the northwestern part of India, causing a shallow low-pressure zone at an altitude of 1.5 km, termed as the **Heat Low.**

(iv) Findlater (1969) suggested a narrow and fast-moving Low-Level Jet over the coast of Somalia during the monsoon season, named after him as **Findlater Jet or Somali Jet.** It joins the pressure-induced cross-equatorial flow from the Mascarene high to carryforwards.

(v) Located at an altitude of 4500 metres above sea level, the **Tibetan High** is part of the Tibetan plateau becomes active during the summer monsoon season (Murakami., 1987). The Tibetan plateau is very important as an orographic obstacle to deny the monsoon winds beyond the Indian subcontinent. Also, because of its high altitude, it receives a lot of heat through direct solar insolation, forming an anticyclone constantly pushing the monsoon winds at the mid-troposphere, nearly 4 km atmospheric height.

(vi) Rooting to the Tibetian High anticyclone zone, a solid fast-moving band of easterly winds blows at the upper atmosphere heading towards the Atlantic ocean, called the Tropical Easterly Jet (TEJ, Koteswaram, 1958). TEJ mainly sets over south India during the ISM between 12º and 15ºN. TEJ helps intensify the summer monsoon winds. Earlier studies suggest that the intensity of TEJ is directly proportional to the ISMR’s interannual variability (Chen and Yen 1991; Chen and Van Loon 1987; Kobayashi 1974).

In short, all these features are firmly connected to the summer monsoon rainfall's spatial and temporal distribution and affect the intra-seasonal to interannual variability of the summer monsoon rainfall. A more comprehensive detail about all these aspects of ISM has been well documented by Rao (1976), Pant and Kumar (1997), and also in the Monsoon Monographs by Tyagi et al.(2012). Moreover, the Indian economy and its lifeline have been significantly influenced by the intraseasonal, interannual variabilities of the ISM (Webster et al., 1998; Krishnamurthy and Goswami, 2000; Gadgil and Gadgil, 2006; Goswami et al. 2006a). A 10% standard deviation is described as the interannual variability of ISM by Parthasarathy et al. (1994); Gadgil (2003); Kothawale and Rajeevan (2017). In addition, the ISM's interannual variability is mainly driven by the tropical Pacific's El Niño Southern Oscillation (ENSO) events, which accounts for ISMR's annual fluctuation (Sikka, 1980; Keshavamurty, 1982; Shukla and Paolina, 1983; Rasmussen and Carpenter, 1983). Apart from ENSO, there are two other Indo-Pacific climate drivers, namely the Indian Ocean Dipole (IOD) (Webster et al., 1999; Saji et al., 1999; Murtugudde et al., 2000) and the ENSO Modoki (Ashok et al. 2007; Kao and Yu 2009; Kug et al. 2010; Marathe et al. 2015; Jadhav et al. 2015, Marathe and Ashok, 2021).

1.2 The Indo-Pacific Climate Drivers:

Large-scale atmospheric circulations like the monsoons are mainly regulated by the oceanic climate drivers, for example, the ENSO, ENSO Modoki, and Indian Ocean Dipole (IOD). Depending upon the different seasons (summer or winter) in both the hemispheres, the oceans receive a tremendous amount of heat energy and create temperature differences over the oceans. These sea surface temperature (SST) anomalies hugely affect the global monsoon systems. The three critical drivers, namely the ENSO, ENSO Modoki, and IOD, significantly impact the Indian Monsoon System.

1.2.1 El Niño Southern Oscillation (ENSO):

The El Niño-Southern Oscillation (ENSO) is a reiterating climate pattern that involves the change in the sea surface temperature over the tropical Pacific. In the 1920s, Sir Gilbert Walker, a mathematician and working as the Director-General of the meteorological observatories of the British colonies, was located in India. He worked on the problem of India's monsoon forecast, following the frequent droughts situations affecting the country's economy, which led him to discover the southern oscillation, the atmospheric component of the ENSO phenomena (Walker 1924). ENSO is a quasiperiodic ocean-atmospheric coupled phenomenon. The ENSO periodicity ranges from 2 to 7 years (Philander, 1990; Ashok et al., 2003; Sarachik and Cane, 2010). A sophisticated explanation of southern oscillation by Bjerknes (1969) and phrased "Walker Circulation" says the large-scale atmospheric flow comprising of sinking air in the eastern Pacific and rising in western Pacific by means of feedback exchange between the surface winds and sea surface temperatures. Usually, the Sea Level Pressure (SLP) over the south-central Pacific (Tahiti) is relatively higher than in the northern part of Australia (Darwin), resulting in the surface trade winds blowing from east to west at the low latitudes. However, the SLP difference between Tahiti and Darwin weakens every few years of periodicity, which further affects the net transport of equatorial trade winds. This SLP difference between Tahiti and Darwin has been coined as the "Southern Oscillation Index" by Bjerknes (1969). Hence, the pressure gradient, abnormal sea surface heating, and trade winds' subsequent transport trigger the ENSO phenomenon.

This ENSO event has two phases: *El Niño* (Warm or positive phase) and *La Niña* (Cold or negative phase). The ***El Niño*** is an abnormal warming of the tropical eastern Pacific (Figure 1.1). El Niño variability is often described by the Niño3 index (SST anomaly averaged within 150°–90°W, 5°S–5°N) or Niño3.4 index (170°–120°W, 5°S–5°N). A warmer ocean makes the surface air rise carrying moisture, becoming anomalously convective and prompting thunderstorms. During *El Niño,* the trade winds weaken, the coastal upwelling off Peru coast diminishes, and eventually, the thermocline becomes deeper (Gill, 1980; Lindzen and Nigam, 1987). ***La Niña*** is opposite of El Niño, associated with the anomalous cooling of the eastern Pacific, strengthening of the easterly trade winds, and more upwelling over the South American coast.

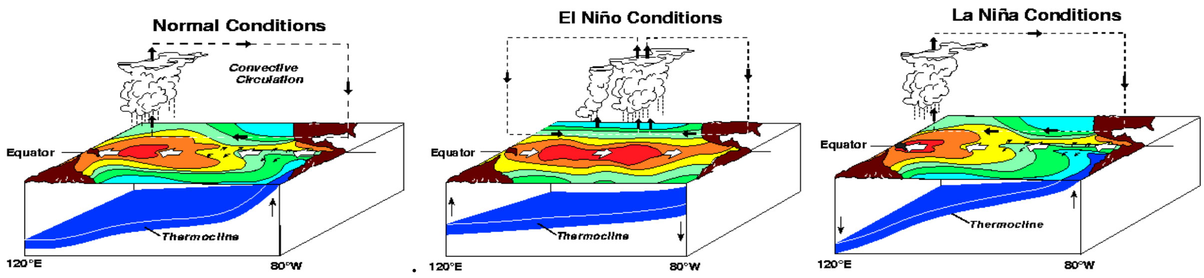

Figure 1.5: Schematic of the ENSO conditions over the Tropical Pacific Ocean (Source: NOAA, PMEL)

As displayed in the schematic, the Walker circulation shifts eastward during El Niño and westward during La Niña (Figure 1.5). The thermocline becomes shallower in the western Pacific during El Niño with minimal steepness. In contrast, the thermocline becomes deeper during La Niña. The conventional way is to explain the ENSO mechanism is that it is either a stochastic driven by various forcing such as westerly wind burst (Lian et al., 2014; Che et al.,2015), Madden-Julian Oscillation (Tang Y and Yu B, 2008), tropical instability waves (Zhang, 2014), monsoon activity (Li C, 1990; Xu J and Chan, 2001; Zheng et al.,2014); or a self-sustained naturally occurring ocean-atmospheric coupled oscillation driven by their feedback mechanism (Bjerknes, 1969). The Bjerknes (1969) feedback suggests that positive (negative) feedback fuelled up the ENSO process, which comprises positive (negative) sea surface temperature (SST) anomaly over the eastern equatorial Pacific associated with the westerly (easterly) winds and weakens (strengthens) Walker Circulation. The anomalous wind stress near the equator deepens the thermocline and shows an anomalously significant rise in the SST. At the same time, the twin off-equatorial cyclones raise the thermocline, due to which the SST decreases and the SLP increases, which leads to upwelling and cooling in the western Pacific. Picaut et al.(1997) emphasize the importance of the central Pacific for the coupled air-sea interaction and the eastward propagating equatorial Kelvin waves, which reflect from the eastern boundary of the Pacific.

The ENSO plays a significant role in impacting the large-scale global ocean-atmospheric circulations. The ENSO impact on North American precipitation and temperature has been studied by Ropelewski and Halpert (1986). They suggested that ENSO brings cooler weather conditions and more precipitation to the southern part of North America. ENSO impacts on agriculture production in various regions (e.g. Adams et al.,1999), including India (Selvaraju, 2003), have been studied. Adams et al.(1999) assessed the impact of ENSO on the United States (US) agro-economic sector. They found an estimated $1.5 to $1.7 billion loss during El Niño as well as $2.2 to $6.5 billion loss due to La Niña.

Furthermore, El Niño causes significantly less precipitation developing drought conditions over the Indian and Australian monsoon regions simultaneously (Sikka, 1980; Rasmusson and Carpenter,1982; Shukla and Paolino,1983; Ropelewski and Halpert,1986). ENSO also affects the tropical cyclone activity (TCA) in various basins. For example, Kim et al.(2009) suggest that TCA is weak during El Niños and more active during La Niña events. However, the frequency of TCA has been significantly increased over the Atlantic. This TCA is associated with El Niño events, with most of the landfalls being along the Gulf of Mexico and the central part of the US. However, the priority of our study is the Indian region. Hence, a separate sub-section concerning the ENSO impact on the Indian summer monsoon has been added below.

1.2.1.1 ENSO impacts

Earlier studies suggest that many El Niño events have caused drought conditions in the Indian region. Usually, an El Niño is associated with a deficit in ISMR, and La Niña with a surplus. Various aspects of ISM and ENSO relationships have been studied extensively by many earlier studies, such as Sikka, 1980; Keshavamurty, 1982; Shukla and Paolina, 1983; Rasmussen and Carpenter, 1983; Palmer et al.,1992; Webster and Yang, 1992; Navarra et al.,1999; Nigam, 1994, Ju and Slingo, 1995; Yang, 1996; Zhang et al., 1996; Soman and Slingo, 1997; Kawamura, 1998; Navarra et at.,1999; Slingo and Annamalai, 2000; Dai and Wigley, 2000; Lau and Nath, 2000; Ashok et al., 2004, Ashok and Saji, 2007; Ashok et al., 2019, and Hrudya et al., 2021.

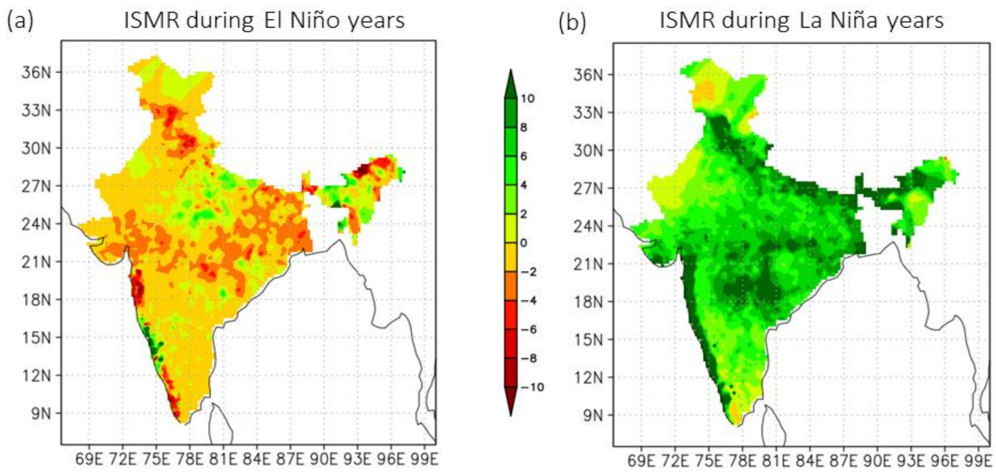

Figure 1.6: The composites of anomalous ISMR (in mm/day) during El Niño and La Niña years. The figures have been plotted using IMD gridded 0.25°×0.25° rainfall dataset, which suggests the associated deficit rainfall during El Niño years. In contrast, La Niña years show a surplus rainfall over the Indian subcontinent.

Sikka (1980) carried out his study considering five good and five bad monsoon seasons over India. The composite analysis indicates that the anomalous fluctuation in the ISMR coincides with the anomalous SST distribution in the equatorial Pacific. Keshavamurthy (1982) showed the impacts of SST anomalies in the equatorial Pacific during boreal summer (JJAS), showing unfavourable conditions for a good monsoon over the Indian subcontinent. The study suggested an anomalous low-level anticyclonic flow over the Indian region associated with the adiabatic heating anomalies over the central equatorial Pacific and western equatorial Pacific, which influences the monsoon circulation. Shukla and Paolina (1983) studied the relationship between ISMR and the pressure anomalies over Darwin for the period 1901-1981 and suggested that the tendency of Darwin's pressure anomalies is a good indicator or a potential predictor of the Indian monsoon rainfall anomaly. Rasmussen and Carpenter (1983) carried out their study using the monthly mean precipitation data collected over 35 observatories from India and Sri Lanka from 1875 to 1979, which was used to determine the relationship between the equatorial Pacific warm episodes and the interannual variability of summer monsoon rainfall over India and Sri Lanka, which suggests that a lower Southern Oscillation Index (SOI), i.e. negative pressure anomalies over the equatorial southeast Pacific and positive anomalies over the equatorial Indian Ocean is associated with weaker southwest monsoon over the Arabian sea as well as a below-normal monsoon over India and Sri Lanka. Palmer et al.(1992) used the ECMWF NWP model to simulate the monsoon circulation of 1987 and 1988 due to their contrasting behaviour of rainfall fluctuation associated with the El Niño event. The model simulations show an anomalous divergence at 200 mb during 1987 (drought year) and an anomalous convergence during 1988 (normal monsoon) over the eastern Pacific. The upper atmospheric anomalous divergence during 1987 extends across the Atlantic, while there is an anomalous convergence over Indonesia and Southeast Asia. The influence of ENSO on the ISMR has been addressed through the modulation of zonal circulation cells studied by many earlier studies such as Keshavamurty (1982); Palmer et al. (1992); Shukla and Wallace (1983); Navarra et al. (1999); Ju and Slingo (1995); Soman and Slingo (1997); Dai and Wigley (2000) and Ashok et al. (2004). The Walker Circulation shifts to the equatorial Indian Ocean during El Niño s. At the same time, there is a westward shift of the Walker Circulation with the amplification of equatorial convergence over the equatorial Indian Ocean. This anomalous equatorial convergence is also responsible for the cross-equatorial meridional circulations and further divergence over India, which causes dry conditions over India. There are SST induced indices, for example, the NINO3 or NINO3.4, used to determine ENSO events' variability and its association with the ISMR fluctuations. Many ENSO teleconnection studies have been done already by Kumar et al. (1999), Gadgil et al. (2004), Ashok et al. (2012), Roy et al. (2018), Bódai et al. (2021) and Marathe et al. (2021), etc. Among which, the weakened ENSO-ISMR relationship has been over the last two decades has been mentioned by Kumar et al. (1999); Chang et al. (2001); Krishnamurthy and Kirtman (2003); Ashok et al. (2001); Kawamura et al. (2005) and Horii et al. 2012 and Yeh et al. (2021). The weakening ENSO-ISMR relationship can also be addressed based on the recent changes in circulation patterns due to global warming. Also, this weakening relationship helps increase the frequency of co-occurring IOD events in the equatorial Indian Ocean (Ashok et al.,2001, 2004; Ashok and Saji, 2007).

1.2.2 ENSO Modoki:

El Niño Modoki is different from the canonical El Niño. The associated anomalous warming in the equatorial central Pacific and anomalous cooling in the adjacent equatorial western and eastern Pacific characterizes El Niño Modoki. This variant of El Niño was identified many decades ago (Congbin et al.,1986). This El Niño type has been referred to as El Niño Modoki by Ashok et al.(2007) and as Warm Pool El Niño by Kug et al.(2009). Trenberth and Stepaniak (2001) identified the contrasting SST anomalies between the eastern and central Pacific. They proposed having two flavours of El Niño events by adding a Trans-Niño Index (TNI) of SST anomalies along the equatorial Pacific. Larkin and Harrison (2005) demonstrated that the composite precipitation and temperature anomalies are different from the canonical El Niño events. Primarily, Yu and Kao (2007) postulated the possibility that different physical mechanisms might modulate the interannual SST variability between the central and eastern Pacific. Further, they demonstrated the distinctive SST variability between the two parts of the equatorial Pacific using the empirical orthogonal function (EOF) analysis (Yu and Kao, 2009). The evolution and teleconnections of El Niño Modoki have been studied by Ashok et al.(2007), Lee and McPhaden (2010), Yu et al.(2010) (2012), Marathe et al.(2015), Marathe and Ashok (2021). They suggest the abnormal heating in the central Pacific continues to last for more than three consecutive seasons once an El Niño Modoki event thrives. Moreover, the recent increase in the frequency of El Niño Modoki is mainly caused by the wind-induced thermocline variations along the tropical Pacific (Ashok et al.,2007). Subsequently, the equatorial Kelvin wave from the central Pacific gets trapped within the eastern Pacific boundary (Xiang et al.,2013).

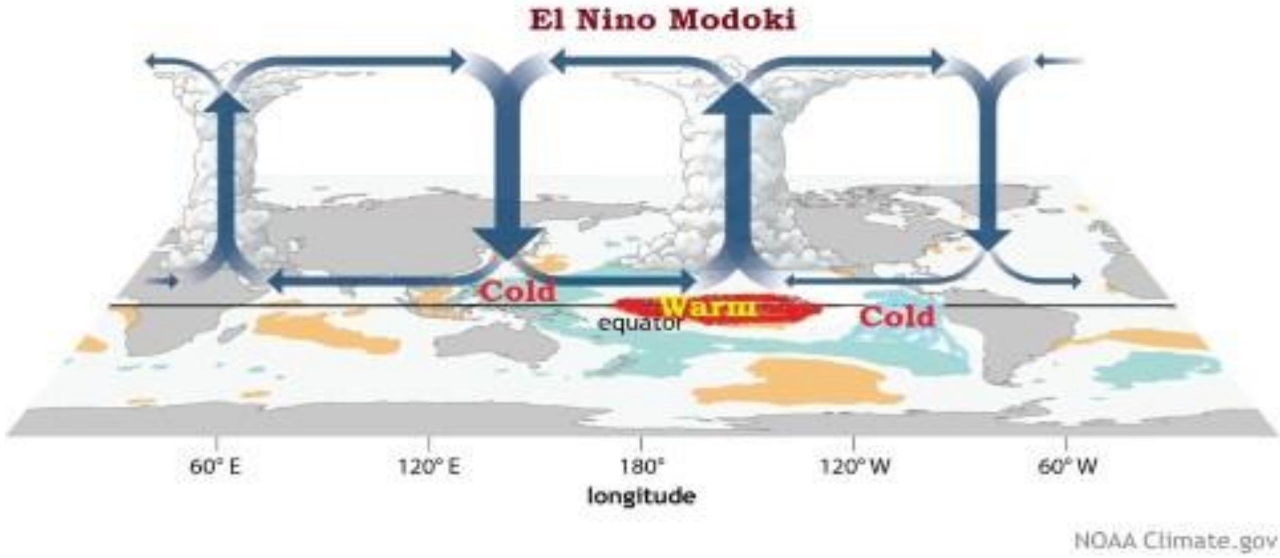

Figure 1.7: Schematic of the El Niño Modoki over the Pacific Ocean (Source: NOAA, PMEL)

In addition, Kug et al.(2009,2010) suggested that the discharge process of condensational heating is prolonged during El Niño Modoki compared to the canonical El Niño. Also, several previous studies, including McPhaden (2012), Jadhav et al. (2015), and Behera and Yamagata(2010), suggested the distinct background and various processes, both dynamical and thermodynamical, that helps in the occurrence of different El Niño types. Among these, Jadhav et al.(2015) conducted sensitive experiments through the ocean general circulation model (OGCM). They suggested that the occurring El Niño types are dependent on the strength of anomalous westerlies and background conditioning. In addition, Marathe et al. (2015) suggested that the dynamical coupling process, which combines the strengths of air-sea coupling, wind-thermocline coupling and thermocline-subsurface temperature coupling, is more dominant during the canonical El Niños than the El Niño Modoki events.

1.2.2.1 ENSO Modoki Impacts:

Yeh et al. (2009) suggested that the frequency of occurrence of this El Niño variant is likely more to experience under the global warming scenario. Due to the significant changes in the tropical Pacific's interannual variability, we have experienced more of these El Niño Modoki events in the recent period

(Kug and Kang, 2006; Ashok et al., 2007; Yeh et al., 2014). These affect typhoons also distinctly (Pradhan et al., 2011).

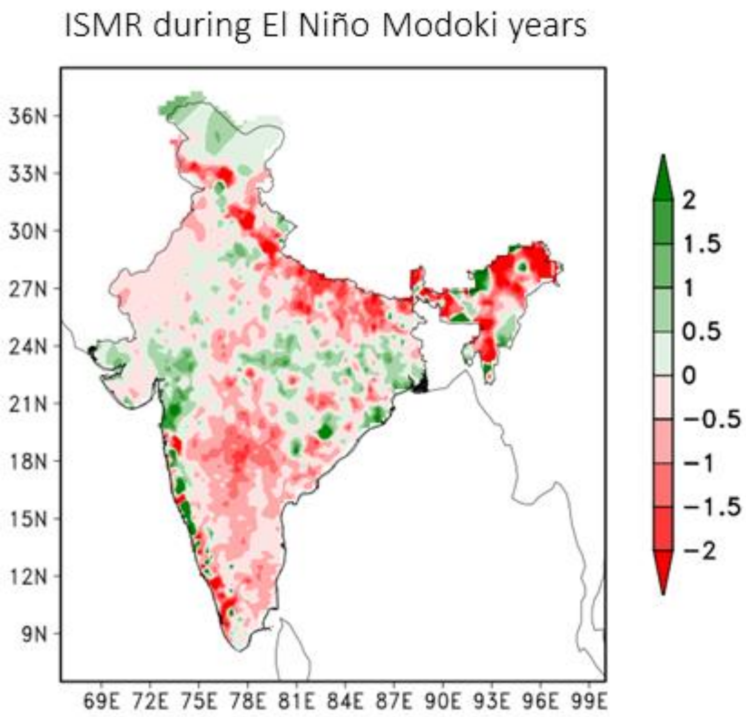

Figure 1.8: The ISMR composites (mm/day) during El Niño Modoki years using IMD gridded 0.25°×0.25° rainfall dataset, which suggests the associated deficit rainfall over India during El Niño Modoki years.

Moreover, the influence of El Niño Modoki on tropical cyclone activity is more robust during the pre-monsoon time, between February to April. Marathe and Ashok (2021) have shown that north western Canada receives below-average precipitation during El Niño Modoki events. They also suggested that during El Niño Modoki events, significantly anomalous surplus precipitation has been observed in the region extending from the southern part of Columbia to Ecuador and northern Peru. El Niño Modoki events are also associated with anomalously surplus rainfall west of the Caspian Sea and mainland Spain. Preeti et al.(2015) suggested that the Sahel region is sensitive to anomalously deficit rainfall, which is more associated with the El Niño Modoki events. Similar to the canonical El Niño events, these El Niño Modoki events are associated with below-average monsoon rainfall over the peninsula of India and a surplus rainfall along the monsoon trough region (Ashok et al., 2007,2019; Shamal and Ashok, 2021).

1.2.3 Indian Ocean Dipole:

Until the end of the 20th century, it was believed that there is no existence of any climate mode in the tropical Indian ocean independent of ENSO, unlike the earlier discoveries in the tropical Pacific (Bjerknes, 1969) and in the Atlantic Ocean (Hisard, 1980; Zebiak, 1993). It was believed that any kind of interannual variability in SST or precipitation in the Indian ocean surrounding was mostly driven by a branch of the tropical Pacific's ENSO events (Weare, 1979; Lau and Nath, 1996, Wallace et al., 1998). In comparison, the relationship between the Pacific's El Niño and the Indian monsoon has been studied and well documented. India received a good amount of monsoon rainfall during 1997 in the middle of an El Niño event, failing the monsoon forecast. In early 1999, studies by Behera et al.(1999) and Vinayachandran et al.(1999) identified a climate variability pattern in the tropical Indian ocean during 1994, accompanied by a comparatively weaker eastward Wyrtki jet (Reppin et al., 1999). Unusual warming in the equatorial western and central Indian ocean and cooling in the eastern Indian ocean was found (Vinayachandran, 1999). Further research led researchers to discover the Indian Ocean Dipole (IOD, Saji et al., 1999; Webster et al., 1999; Murtugudde et al., 2000). As the name suggests, "Dipole" means two areas with opposite polarities. In this case, the poles are the western and eastern parts of the tropical Indian ocean.

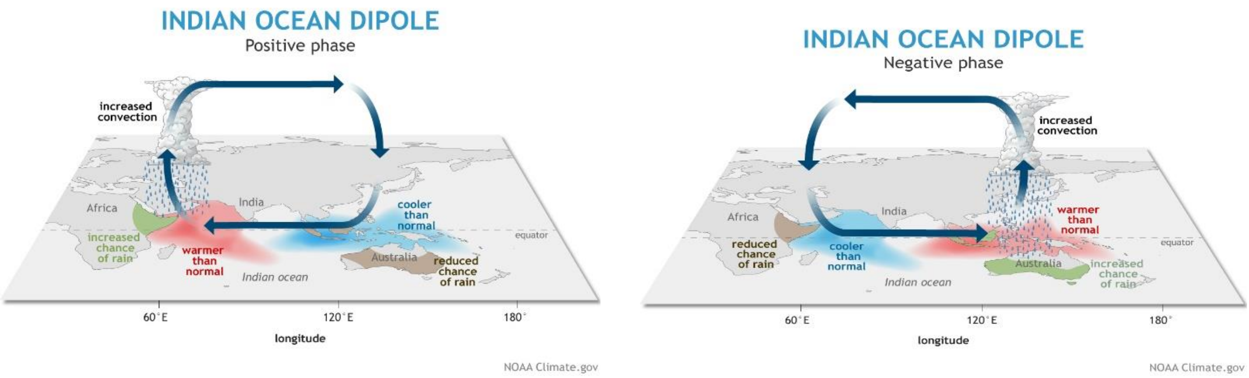

Figure 1.9: Schematic of the Indian Ocean dipole, positive and negative phase (Source: NOAA, PMEL)

The IOD is an irregular pattern of interannual SST anomalies in the tropical Indian ocean, accompanied by wind and precipitation anomalies (Saji et al.,1999). It has two phases, namely positive and negative. During the positive phase, the western Indian ocean is abnormally warmer than the eastern Indian ocean. Similarly, the eastern Indian Ocean is warmer than the western Indian ocean during the negative phase. It is an ocean-atmospheric coupled phenomenon that starts sometime between April to May, reaches its peak during September to November (SON), and then dissipates (Saji et al., 1999). The positive IOD phase prevails stronger south easterlies from the coast of Sumatra cause cooler SST and subsequent coastal upwelling off the eastern tropical Indian Ocean (Vinayachandran et al., 1999, 2002; Murtugudde et al., 1999). The equatorial winds eventually reverse their direction from westerlies to easterlies as the IOD thrives to its peak, which helps create a dipole pattern of contrasting SST anomalies. This air-sea interaction phenomenon is similar to the one earlier proposed by Bjerknes (1969). Rao et al.(2002) suggested that the growth of IOD is modulated by the coupled Kelvin and Rossby wave propagation similar to the ENSO. Also, it occurred to the researchers that many positive IOD events have co-occurred with the ENSO. Yamagata et al.(2004) suggested the seasonal phase-locking of the Pacific's ENSO and IOD of the Indian Ocean due to the co-occurrence of both events. The IOD and ENSOs inter-basin connectivity manifested through the process of an atmospheric bridge (e.g., Ashok et al., 2003; Saji et al., 2018; Izumo et al., 2013; Marathe et al., 2021). The ENSO induces descending motion along the off Java coast to produce cold anomalies by prevailing stronger south easterlies (Yu and Lau, 2005), termed the cold pole of a positive IOD. By October, the easterlies reverse their direction, and the cold pole weakens itself by warming up, and the IOD gets a stronghold during this month (Schott et al., 2009). Usually, the western Indian Ocean operates with a shallower thermocline. However, the thermocline gets deeper through a westward propagating Rossby wave during positive IOD, which causes more warming in the western Indian Ocean, is considered the warm pole of a positive IOD (Xie et al.,2002 and Yu and Lau, 2005). Moreover, the positive Bjerknes feedback gets triggered, and that facilitates the growth of IOD. Apart from this, the equatorial Indian Ocean oscillation (EQUINOO), the atmospheric component of the IOD, was proposed by Gadgil (2003) and Francis and Gadgil (2013). EQUINOO is characterized as an oscillation of enhanced (suppressed) convection process over the tropical western (eastern) Indian Ocean during the positive phase and vice-versa during the negative phase.

1.2.3.1 Indian Ocean Dipole Impacts:

The impacts of IOD can be found globally. The Indonesian throughflow (ITF) is one of the significant characteristics of the Indian Ocean that allows the Pacific water influx to the Indian Ocean. Hence the ITF plays a significant role in global ocean circulation (Hirst and Godfrey, 1994; Schiller et al., 1998) and atmospheric circulation (Schneider, 1998). During IOD events, stronger wind anomalies at the equator modulate the ITF (Meyers, 1996; Sprintall et al., 2009) and cause a lower sea level along the coastal boundary of the eastern Indian Ocean. That triggers a pressure head between the two basins of the Pacific and Indian oceans, allowing more transport via ITF (Wyrtki, 1987; Masumoto and Yamagata, 1996; Meyers, 1996; Wijffels and Meyers, 2004). Another implication of the IOD is the impact on the primary productivity of the Indian ocean through the coastal and offshore upwelling, which helps in increasing productivity (Ghofar, 2005, Amri, 2012; Lumban-Gaol et al.,2015). Saji and Yamagata (2003a, Saji 2018, Kucharski et al., 2020) discuss the global impacts of the IOD. Positive IOD brings above-normal precipitation over the eastern African regions (Saji and Yamagata, 2003a; Behera et al., 2005) while it co-occurred with ENSO, bringing flood situations impacting various socio-economic aspects of that region (Conway, 2002, 2005). The influences of IOD on the Australian winter climate were established by Ashok et al.(2003, 2007b, 2009). While it is noted that co-occurrence of a negative IOD and La Lina brings significantly good monsoon rainfall over Australia, the opposite happened when Positive IOD occurred with El Niño (Risbey et al., 2009). Studies by Ashok et al. (2007b) and Ummenhofer et al.(2009a) demonstrated that IOD plays a primary driver over ENSO, responsible for the drought conditions over south-eastern Australia.

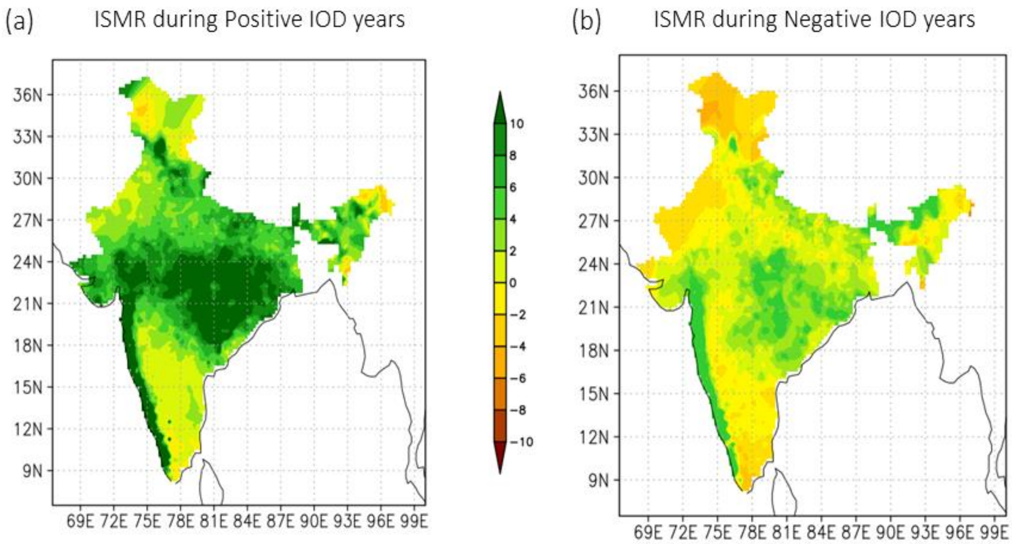

Figure 1.10: The composites of anomalous ISMR (in mm/day) during the positive and negative IOD years. The figures have been plotted using the IMD gridded 0.25°×0.25° rainfall dataset, suggesting the associated deficit rainfall during negative IOD years. In contrast, positive IOD years show a relatively surplus rainfall over the Indian subcontinent.

In addition to that, the wheat yield has been decreased significantly during positive IOD years than the negative years (Yuan and Yamagata, 2015). Interestingly, Saji et al.(1999) speculated that the IOD impact over India is insignificant. Later, Ashok et al.(2001,2004), Ashok and Saji (2007), and Krishnaswamy et al.(2014) proposed that co-occurrence of a positive IOD and an El Niño enhances the monsoon rainfall, which used to be suppressed by El Niño's atmospheric teleconnections. They also showed that IOD is strongly correlated with Indian summer monsoon rainfall during decades of weak ENSO variability. Boyaj (2021) showed that the IOD events had increased the extremity of rainfall events in several parts of India.

1.3 Monsoon Forecast in India

Based on the prediction, an early and skilful prediction of the Indian Monsoon is crucial for the farmers, government organisations, and policymakers to prepare themselves for a good monsoon season or an upcoming drought season. For the last decade, the India Meteorological Department (IMD) has actively given predictions with improved skill on different meteorological time scales, such as the nowcasting, the extended range, and the seasonal forecast.

Forecasting the Indian monsoon rainfall can be traced back to the 1880s-1920s, when Himalayan snowfall (Branford, 1884), the atmospheric pressure over South America, and pre-monsoon snow cover over the Himalayas during spring were explored to forecast summer monsoon (Walker, 1923, 1924). Over decades of observational analysis, Jagannathan (1960) suggested that the regression model only works with 65% of the sample and fails to associate with other surface and upper-air parameters. Banerjee et al. (1978) indicated the importance of the position of the 500 hPa subtropical ridge. Parthasarathy and Mooley (1978), based on the 1866-1970 observations, showed that the ISMR is normally distributed, with a dominant biennial signal of variations. Meanwhile, many parameters such as the SOI, meridional winds at 200 hPa, subtropical ridge's position at 500 hPa etc., affecting the ISMR have been suggested by Joseph et al. (1981), Pant & Parthasarathy (1981), Thapliyal (1982), and Shukla and Paolino (1983). They suggested monitoring the ENSO event for long-range seasonal monsoon forecast. Many linear and non-linear models have been proposed and failed significantly with the least skills (Gowariker et al.,1989,1991; Thapliyal and Kulshrestha, 1992; Thapliyal, 1997; Delsole and Shukla, 2002). The latter models with limited predictors (e.g. Rajeevan et al. (2000, 2001), Thapliyal et al.(2003) were reasonably accurate and trained using the dataset from 1989 to 2000. IMD used those models for some years. However, those years used for model training were average monsoon years, so only successful for such years (Guhathakurta, 2006). Sahai et al.(2003)'s forecast with SST-based indices showed good skills with 105 years of data. Still, it was not that skilful for an independent verification over another 22 years, particularly the monsoons during 2002 & 2004 (Gadgil et al., 2005). Gadgil et al. (2004) proposed to use ENSO and an index of the atmospheric component of the Indian Ocean Dipole as potential predictors. IMD developed a two-phased statistical model with six predictors. One phase used the predictors' datasets until March, and another used the dataset until May (Rajeevan et al., 2005). Rajeevan et al.(2007) achieved a significant forecast skill while using the ensembles of multiple linear regressions. Using Artificial Neural Network (ANN), Ashok Kumar et al.(2012) tried to improve the ISMR forecast skill three at different initial conditions starting from April, June and July. The ANN model's output is suggested to be significantly skilful for all the three initial conditions. Further, Joseph et al.(2013) firmly unfolded the tropical Pacific linkage to the ISMR deficit. Wang et al.(2014) suggested adding more predictors to the list, such as the El Niño Modoki, rapid deepening of the Asians low and strengthening of south-north Pacific highs during boreal spring. The dynamical models ruled over the statistical models to better understand governing ocean-atmospheric systems. So, the dynamical predictions of the ISMR with climate models (both atmospheric and coupled Ocean-Atmosphere models) are based on the understanding of the science of the Ocean-Atmospheric fluid properties and the remarkable developments in high-performance computers. This multitude of discoveries laid the way for checking out the Ocean-Atmospheric coupled models for improved prediction skills of ISMR by focusing on each of the individual models and the multi-model ensemble (MME) (Rajeevan, 2012). Recent studies by Preethi et al. (2010), Delsole and Shukla (2012), and Nanjundiah (2013) have shown improved predictive skills of ISMR.

Efforts towards improved predictions skills of monsoon rainfall beyond weather have been carried out, focusing on the extended-range and seasonal timescales. However, successful dynamical prediction of ISM on these time scales has not been possible till a decade back. The poor-skilled prediction was due to the limitations in model fidelity in simulating the intraseasonal and interannual variability due to coarse model resolution and lack of observational data for the much-needed data assimilation. The Ministry of Earth Sciences (MoES), Government of India initiated the Monsoon Mission Project in 2012 to develop dynamic models referring to the seasonal prediction of the ISMR

(Rao et al., 2019). The state-of-the-art Ocean-Atmospheric coupled model Climate Forecast System version 2 (CFSv2, Saha et al., 2014), from The National Centers for Environmental Prediction (NCEP), has been chosen as the primary model on which scientists in India as well as abroad have worked relentlessly to improve the ISM extended-range and seasonal predictions. The efforts have been successful, and the retrospective forecasts have been skilful on both the extended-range and seasonal time scales.

1.4 Agriculture Practices in India

The Indian economy is largely agriculture-based. Agriculture has been practised over here for thousands of years. According to the survey by the National Sample Survey Organization (NSSO) and Federation of Indian Chambers of Commerce & Industry (FICCI) (2015), the agriculture and allied fields contribute around 17% of the total Gross Domestic Product (GDP) of India. The Economic Survey (2021-22) suggests that around 40% of the Indian workforce has been employed in agriculture and allied fields. Timmer (2009) described how the agriculture sector had been reformed recently, followed by the migration of rural workers and a rapid rise of the service sector. There have been many developments in new advanced technologies, cultivation methods, and modern equipment. But there are still many farmers who live in remote areas across the subcontinent and still follow the old traditional methods of agriculture. This is because of a few reasons; for example- (i) the lack of communication to the locations and (ii) lack of education and resources. Therefore, the government of India and the state governments have introduced many schemes related to agriculture and farmers in recent times, for example, the National Mission for Sustainable Agriculture (NMSA) in the year 2014/15, Pradhan Mantri Fasal Bima Yojana (PMFBY) in 2016/2017 for the Kharif rice, Pradhan Mantri Krishi Sinchayee Yojana (PMKSY) in 2015/2016 for the coverage of irrigation and others. Also, the success and prosperity, or the lack thereof of India's agriculture sector, has a significant impact on the country's other industrial and societal sectors because agriculture is a part of life for many, affecting their lifestyle in many different ways.

India has two cropping seasons, namely (i) Kharif Cropping Season (KCS) and (ii) Rabi Cropping Season (RCS). The KCS requires more water. So, the crops such as Rice, Maize, Jowar, etc., are sown on the arrival of the Summer Monsoon to the Indian subcontinent. India is a major rice producer globally and mainly harvests rice during October-November, the Kharif Cropping Season. On the other hand, the RCS requires moderate water for the crops such as Wheat, Barley, and Grams to grow. The harvesting period mostly begins in the summer.

According to the report by the *Directorate of Economics and Statistics (DES), Ministry of Agriculture Government of India* (Agricultural Statistics at a glance, 2015), the area under rice crop used to be 30.81 million/ha during 1950-51, which further has increased to 43.86 million hectares by 2014-15. That is almost 142% higher. The rice production was 20.58 million tonnes during 1950-51. But it was 104.86 million tonnes in 2014-15, which is five times more. In addition, the yield increased from 668 kg/ha during 1950-51 to 2390 kg/ha in 2014-15, a lot of which can be attributed to new technology. The KCS contributes majorly to the total production. Until the late 1960s, when the *Green Revolution* started and high-quality seeds were introduced to amplify the agriculture boost. After that, India became self-sufficient in this sector, and they began exporting the surplus production to other countries. Nevertheless, while Indians have been practising agriculture for thousands of years, productivity is still insufficient to fulfil the demands. In reality, India's agriculture sector is still dependent on the Indian Summer Monsoon Rainfall (ISMR), as shown in chapter 3.

1.4.1 Agriculture in Telangana State

Agriculture plays a crucial role in the economy of the state of Telangana, which was the northwest part of the erstwhile Andhra Pradesh state. According to the report by the planning department, Government of Telangana (Socio-Economic Outlook-2017), the agriculture and allied sector has shown significant growth of 12.1 % in 2016-17, as against an average of 6.3 % observed from 2011 to 2015. Out of that high growth rate, the crop sector contributed around 19% of the growth because of the significantly good monsoon rainfall and various development policies by the government of

Telangana. Since the Green Revolution during the 1970s, Telangana started focusing on rice production. Telangana is probably one of the largest rice producers in India.

Nonetheless, Telangana is considered to be a semi-arid state receiving significantly less amount of rainfall annually. Also, due to the recent climatic impact on precipitation, the area under agriculture has been significantly decreased. This is also true that the central and the local government have introduced multiple schemes, including massive irrigation projects. In recent years, this led to significant changes in the state's agricultural infrastructure and execution in the agrarian economy. Telangana state is enriched with many assets having great soils, diversified cropping patterns, and excellent irrigation systems supported by the rivers like Godavari and Krishna. Agriculture is a part of life, a custom that has moulded the cultural and economic existence of the people of Telangana. In this manner, it will continue to be the epicentre for all the futuristic strategies planned for the state's socio-economic development. While irrigation schemes facilitate an increase in paddy output, predicting the summer monsoon rainfall and the potential paddy yield due to such rainfall will be still useful, given that irrigation also depends on the variability of monsoon rainfall and demand for the limited river water for drinking and non-agricultural industrial use is also increasing.

1.5 Application of DSSAT crop growth model

The decision support system for agrotechnology transfer known as DSSAT (Jones et al.,2003) is a widely popular computerized program to simulate the various stages of crop growth and yield of crops over 30 different crop varieties, including rice. DSSAT is developed by International Benchmark Systems Network for Agrotechnology Transfer (IBSNAT), which has multiple crop modules, including CERES-Rice. The CERES-Rice model helps to simulate the various aspects of rice plant in terms of their growth and yield, forcing the effects of the environment, weather conditions, genetics, soil properties and management practices (Ritchie et al., 1998). These modules can be used to increase the yield efficiency of a particular crop by adjusting the water and nitrogen intake (Timsina et al., 1995). Pickering et al.(1994) suggested how to generate the daily weather data for model usage. Thornton et al.(1995) focused on the experimental simulations of the model with an output to be represented via the tabular and graphical form. In the beginning, Singh et al.(1995) assessed the future of maize production concerning the gap between the strengths and weaknesses of India's maize market. Sood (2013) added a Graphical User Interface (GUI) to better view and experienced the model simulations. DSSAT model has been a handy tool for the study of climatic change assessments and impacts studies on the rice crop yields (Lal et al.,1998; Amien et al.,1999; Geethalakshmi et al.,2011; Subash and Ram Mohan, 2012; Bemal et al.,2013; Bhubaneswari et al.,2014; Dias et al.,2015; Rauff et al.,2015; Mehraj et al.,2017; Ray et al.,2018; Lanie,2020). Apart from that, Basak et al.(2010,2012) assessed the impact of future climate change scenarios on the Boro rice variety (BR3, BR14) with possible yield gaps during 2030, 2050 and 2070 for Bangladesh. Also, Stella et al.(2020) attempted to simulate rice yield under future climate change scenarios for Kerala state. Dhekale et al.(2017) used the disaggregated extended range rainfall forecasts (ERRF) and attempted to predict the Kharif rice crop yield in real-time for the Kharagpur region using the CERES-rice of DSSAT. They suggested that the rice yields can be predicted well in advance using the extended-range rainfall forecasts. Similarly, Akhter et al.(2021) utilised the IITM-CFSv2 extended range hindcast dataset to simulate the rice crop yield over the Gangetic plane using DSSAT. The importance of the temperature parameter for model simulations has been shown by Sastri et al.(1995), White et al.(2005), and Shams & Ahmed (2021). The successful evaluation of DSSAT rice yield simulations has been done by many earlier studies, such as Swain et al.(2007); Anchal et al.(2012); Sudharsan et al.(2013); Amiri et al.(2014); Vijayalaxmi et al. (2016); Kant et al.(2018); Satpute et al.(2018), Ankit et al.(2019); Akhter et al.(2021). In addition, Shrivastava et al.(2018) demonstrated the use of DSSAT to simulate the soil moisture and evapotranspiration during drought years over central India, particularly Madhya Pradesh during the period 1990-2011. The application and evaluation of irrigation water system management have been comprehensively studied using the DSSAT model (Dharmarathna et al., 2011; Amiri et al.,2014; Sailaja et al., 2014; Jeong et al.,2014; Tian et al.,2020). Hence, DSSAT has been used for various studies such as Climate Change Impact

Assessment, Irrigation Management, Fertilizer Management, Crop Improvement, Gene-based Modelling, Pest and Disease Management, Spatial Analysis, Tillage Simulation and Crop Rotations etc. However, in this study, our primary goal using the DSSAT is to simulate the seasonal Kharif Rice Production (KRP) using the retrospective IITM-CFSv2 extended-range hindcast datasets. The DSSAT model requires crop growth and management data, daily weather data, and soil data to simulate the rice yield. Further details about the DSSAT model have been mentioned in chapter 2 and Chapter 5.

1.6 Gaps, Objectives and Scope of the study

My above literature survey essentially covered the importance of ISMR, the tropical Indo-pacific climate drivers, the monsoon forecast in India (IITM-CFSv2), and the agriculture sector in India. Earlier, many studies addressed the ISMR variability and association with that of various, using both observational and model outputs. However, only a few studies have so far been carried out to study the importance of climate drivers and agriculture yields; it is worth documenting the MoES operational model skills in predicting the local rainfall at the seasonal and extended range, as such skills can potentially be used in estimating agriculture yields, particularly the Kharif rice yield. The seasonal and extended predictions of the IITM-CFSv2 model have been used for various forecast applications such as ISM onset, Monsoon Intraseasonal Oscillation, monsoon active-break cycle, cold and heatwaves; which are crucial factors for farmers for agricultural scheduling and crop preservation. However, the implications for the climate at the state level or district level are not available. Therefore, this thesis work focuses on evaluating the potential importance of applying the IITM-CFSv2 seasonal and extended hindcast skills in estimating agriculture crop yields, in particular the Kharif rice productions of notable Kharif productive states in India such as West Bengal (WB), Haryana, Kerala, Bihar, Punjab, Uttar Pradesh (UP), Madhya Pradesh(MP), [1]United Andhra Pradesh (UAP), Karnataka, and Odisha.

[1] The erstwhile undivided Andhra Pradesh has been divided into two states, namely Andhra Pradesh (AP) and Telangana in 2014. The result shown here is for the Undivided Andhra Pradesh (UAP).

Furthermore, I attempt to explore the predictive skills of the DSSAT agriculture growth model for rice crop (MTU-1010 rice variety) by using the available IITM-CFSv2 extended-range dataset for Warangal, a district of Telangana state, as an example.

Based on my literature review and discussions, I propose the following objectives to be addressed in my thesis:

1. ***Understanding the relevance of various tropical Indo-pacific climate drivers to the state-wise Kharif rice yield across India.***
2. ***Evaluating the capability of the IITM-CFSv2 extended and seasonal scale hindcast products in reproducing the association of state-wise Kharif rice yield with the tropical Indo-pacific climate drivers and that with the local climate.***
3. ***Exploring the viability of Kharif rice yield prediction in an Indian state using the IITM-CFSv2 hindcast products and a state-of-the-art crop yield model.***

Chapter- 2

Data, Methodology, And Models

In this chapter, I have briefly discussed various observational, reanalysis, and IITM CFS V2 seasonal and extended hindcast datasets used in the study. I also describe the statistical methods that have been used, along with brief descriptions of the DSSAT crop model. The chapter also describes the IITM-CFSv2 hindcast methodology.

In this study, I use various observational and reanalysis datasets for various parameters such as rainfall, sea surface temperature, specific humidity, wind components (zonal, meridional), and Kharif rice production/yield. As shown in chapter 3, my analysis of observations shows that the state-wise Kharif rice production in India is still significantly dependent on the monsoon rainfall, as also is associated with the variability of various tropical Indo-Pacific climate drivers. To generate the indices of the variability of the Indo-Pacific climate drivers, we use the sea surface temperature(SST). Understandably, the large-scale atmospheric circulations can also directly or indirectly affect the Kharif rice production, i.e. through moisture/rainfall/temperature. The remote drivers such as the ENSO can affect the crops in India through circulation and their impacts on rainfall or/and temperature. The wind components and the moisture parameter are used to illustrate the association of interannual variations in large circulations during the summer monsoon season. At the heart of my study, we focus on the application of IITM-CFSv2 seasonal and extended-range hindcast products towards the state-wise Kharif rice production. We use the predicted rainfall and sea surface temperature (SST) data from the IITM-CFSv2 hindcasts at both the seasonal and extended-range time-scale to study how successfully the hindcasts reproduce the local climate. The reproducibility of the relationship between the Kharif Rice Yield with local rainfall is also explored. We use the DSSAT crop model to forecast the Kharif rice production based on local rainfall observations and then explore the potential usability of the IITM-CFS2 extended range hindcasts. For the DSSAT simulation, we use the weather data (daily rainfall, daily temperature, maximum and minimum temperature, solar radiation), soil properties data, crop management, experiment conditions, and crop genotype information.

A detailed description of all the datasets has given in Section 2.1. All the statistical techniques s used in this thesis have been described in Section 2.2. A brief description of the IITM-CFSv2 coupled model and DSSAT crop model has been given in Section 2.3.

2.1 Observational, reanalysis and model datasets

2.1.1 Rainfall datasets

The daily gridded observed rainfall datasets collected and provided by India Meteorological Department (IMD) have been used, available from 1901 to 2019 (Pai et al., 2014), with a spatial resolution of 0.25°×0.25°. This dataset has been collected from 6955 rain-gauges installed at many stations all over India. These datasets are generated after meeting all the standard measures and quality controls for all the rain-gauges installed across India (Pai et al., 2014).

We use the IITM-CFSv2 seasonal hindcast Rainfall, available at the ~38 km (T382) horizontal atmospheric resolution from 1981 to 2008 (Ramu et al., 2016). These datasets as well as the extended range hindcasts discussed later, were generated at the Indian Institute of Tropical Meteorology (IITM) under the monsoon mission project. The datasets comprise seasonal hindcast simulations for the March, April and May initial conditions with 12 ensemble members during this period. The IITM-CFSv2 retrospective seasonal forecasts are a set of 9-month long hindcasts initiated on every 5th day of the month, four times per day (i.e., 00, 06, 12, 18 GMT), starting from 1st, since 1981-2008. The necessary initial conditions have been taken from the NCEP Climate Forecast System Reanalysis (CFSR) (Saha et al., 2010).

The extended-range rainfall hindcasts used in this study were generated at two horizontal resolutions, specifically, 1°X1° (T126) and 38 km (T382) for the 2003- 2016 period. Note that the hindcast datasets for the monsoon season of the year 2010 were not generated due to technical issues. For a better understanding, the Week one lead forecast is denoted as W01, and is prepared by averaging the daily hindcasts for each day of week 1. For example, the initial conditions (IC) of 31 May generates the week 1 forecast for 1st to 7th June. Again, the 7th June IC generates a week 1 forecast for 8th to 14th June data, and so on. Following a similar procedure, the hindcasts for Weeks 2, Week 3 and week 4 (denoted as W02, W03 and W04, respectively, up to W18) have been generated. More details on the generation of these hindcasts can be obtained from Abhilash et al. (2014). These extended-range data are actually meant to provide a forecast up to a 4-week lead and then evaluate the weekly skill. These model simulations have been carried out operationally for 18 weeks from 01 June to 04 October. However, our goal is to harness the predictive skills of this hindcast dataset towards the Kharif rice yield, which is a seasonal activity. Therefore, we choose to reconstruct the suitable variant of these weekly hindcasts to monthly scales. We also reconstructed the seasonal data from these individual week forecasts (W01, W02, W03, W04) for June through September (JJAS), as briefly described in the following. We calculate for each year from 2003 through 2016 (or, more specific, each summer monsoon) the weekly mean of the SST hindcast for each of the 18 weeks from all W01, W02, W03 & W04 leads. For example, the lead W-1 forecasts, available at the intervals of a week, over the 18 months starting 31 May, we have a week-1 lead seasonal forecast from 01 June till 07 June. Note that this particular concatenated product has no real-time applicability unless the month-lead hindcasts can be generated using the 4-week extended range hindcasts. However, a comparison of the seasonal week lead forecasts with a regular seasonal lead hindcast will give an idea of any deterioration of lead skills over a period beyond a week or more.

2.1.2 Sea surface temperature datasets

The Hadley Centre Sea Ice and Sea Surface Temperature (HadISST) monthly gridded datasets have been used in this study, which is available at 1°×1° spatial resolution (Rayner et al., 2003), to generate the indices of respective tropical Indo-Pacific climate drivers. The Hadley Centre for Climate Prediction and Research, The U. K. Met Office, has developed and distributed these datasets. The data distribution was initiated as the Global Sea Ice and Sea Surface Temperature (GISST) datasets, now renamed as HadlSST and available for 1870-present. The Met Office Marine Data Bank (MDB) has been improving HadISST datasets by improving the data assimilation techniques and observed data collected from many in-situ ocean observations, including the SST data, available from 1982 onwards. This data is received from the Global Telecommunications System (GTS). Earlier, this SST data was used to be distributed as

International Comprehensive Ocean-Atmosphere Data Set (ICOADS) from 1850 to 2014, which are supplemented by drifting buoy observations generated using "E.U. Copernicus Marine Service Information" from Copernicus Marine Environment Monitoring Service (CME

We use the IITM-CFSv2 seasonal SST hindcast data at ~38 km (T382) horizontal atmospheric resolution, generated for 1981- 2008 (Ramu et al., 2016). The dataset comprises of seasonal hindcasts for various lead months such as March, April and May initial conditions with 12 ensemble members during that period. The necessary initial conditions have been taken from the NCEP Climate Forecast System Reanalysis (CFSR) (Saha et al., 2010).

2.1.2 Wind components, Specific humidity datasets

The monthly mean \specific humidity and monthly mean wind (u, v) datasets from the National Centers for Environmental Prediction/National Centers for Atmospheric Research (NCEP/NCAR), in this study available from 1950 to 2019 (Kalnay et al., 1996), have been used. The dataset has 2.5°×2.5° a horizontal resolution having 144x73 global grids, and 17 vertical pressure levels from the surface. I used these datasets to diagnose the large-scale wind convergence/divergence and moisture convergence during the JJAS, associated with different ENSO and IOD events.

2.1.3 Crop production datasets and inputs for the DSSAT model

The datasets for total agriculture production, total area used for agriculture, Kharif rice production and the area under irrigations have been provided by the Directorate of Economics and Statistics (DES), Ministry of Agriculture, Government of India from the website https://www.indiastat.com/. The datasets are available from 1990 to 2016.

2.1.4 Maximum & Minimum temperature

The DSSAT model requires the daily maximum and minimum temperature to simulate the crop yield, among other input parameters. These are essential weather parameters concerning the growth of any plant. Here we use the India Meteorological Department (IMD) maximum and minimum temperature at $0.25°\times0.25°$ horizontal resolutions for the 2004-2010 period. Also, the IITM-CFSv2 extended-range maximum and minimum temperature hindcast at 100 km resolution have been used for the period 2004-2010.

2.1.5 Solar Radiation

Solar radiation is one of the necessary weather parameters required to simulate crop growth, as it is the primary driver for plant photosynthesis. For my study, I used the daily solar radiation dataset acquired from NASA's Prediction of Worldwide Energy Resources (POWER) project (https://power.larc.nasa.gov/#:~:text=The%20Prediction%20Of%20Worldwide%20Energy,%2C%20and%20(3)%20Agroclimatology), which was initiated in 2003. The solar radiation dataset in POWER's latest release is based on satellite observations with subsequent inversion to surface solar insolation by NASA's Global Energy and Water Exchange Project (GEWEX) /Surface Radiation Budget (SRB) Release 3 and NASA's CERES Fast Longwave And Shortwave Radiative project (FLASHFlux) at $1°\times1°$ horizontal resolution.

2.1.6 Soil properties dataset

The DSSAT requires input information on the water holding capacity of different soil layers. It needs a root weighting factor that accommodates the impact of many adverse soil factors on root growth in different soil layers, such as soil pH, soil impedance, and salinity. Additionally, the soil parameters are needed for computing surface runoff, evaporation from the soil surface, and drainage. Initial values of Nitrogen, Organic matter and ammonium are required as well. All these soil properties data has been taken for Warrangal district, adopted from the earlier study by V.Rajagopal (2009).

2.1.7 Crop management and experimental conditions

The DSSAT requires crop management information such as the planting dates, planting depth, row spacing, fertilization and irrigation. The planting dates have been determined according to the onset of the summer monsoon for Telangana, which is usually 08 June, according to the Weather and Climatology of Telangana, the document released by Telangana State Development Planning Society (TSDPS)/Directorate of Economics & Statistics (DES). We assumed the amount of rainfall required for the initial field preparation and estimated the possible plantation dates according to the crop calendar. The planting depth, row spacing and fertilizer information have been taken from the Rice Knowledge Bank (http://www.knowledgebank.irri.org/). DSSAT simulations are done without using irrigation to estimate the utility of rainfall forecasts, and also that the irrigation timings may be stochastic. I, however, plan to explore the relevance of the impact of irrigation information in improving the forecast skills of Kf Rice Yield in my future work.

2.1.8 Crop variety and crop genotype information

DSSAT requires the genotype information of a particular crop variety. Each crop variety has its own specific genotype coefficients, which are determined by nursey growth experiments done for the respective crop type. I used the MTU-1010 rice variety, one of the rice varieties used in Telangana, in my study. The various genotype coefficients of the MTU-1010 required as inputs for the DSSAT simulations have been adopted from Vijayalaxmi et al. (2016) and are shown in Table 1.

Table no.1: Genetic Coefficients of MTU-1010 rice variety used for DSSAT simulations, adopted from Vijayalaxmi et al.(2016).

Sl. No.	Description of coefficients	Value
1	**P_1:** Time period (expressed as growing degree days (GDD) in ^{o}C above a base temperature of 9^{0}C) from seedling emergence during which the rice plant is not responsive to changes in photoperiod. This period is also referred to as the basic vegetative phase of the plant.	450
2	**$P_2$0:** Critical photoperiod or the longest day length (in hours) a which the development occurs at a maximum rate. At values higher than P20 developmental rate is slowed; hence there is a delay due to longer day lengths.	12
3	**P_2R:** Extent to which phasic development leading to panicle initiation is delayed (expressed as ^{0}C) for each hour increase in photoperiod above P20.	160
4	**P5:** Time period in GDD (^{o}C) from the beginning of grain filling (3 to 4 days after flowering) to physiological maturity with a base temperature of 9^{o}c.	350
5	**G1:** Potential spikelet number co-efficient as estimated from the number of spikelets per g of main culm dry weight (fewer leaf blades and sheaths plus spikes) at anthesis. A typical value is 55.	55
6	**G2**: Single grain weight (g) under ideal growing conditions, i.e. non-limiting light, water, nutrients and absence of pests and diseases.	0.025 0
7	**G3**: Tillering coefficients (scalar value) relative to IR64 cultivar under ideal conditions. A higher tillering cultivar would have a coefficient greater than 1.0.	1
8	**G4**: Temperature tolerance co-efficient. Usually 1.0 for varieties grown in typical environments. G4 for japonica type rice growing in a warmer environment would be 1.0 or greater. Likewise, the G4 value for Indica type rice is very cool environments or season would be less than 1.0	1

2.2 Methodology

2.2.1 Statistical techniques

I used the well-known linear correlation technique. Linear correlation is defined as the measure of association between a series of two random variables, for example, the association between the interannual variability of ISM and an Indo-Pacific climate index such as the NINO3 index. The standard equation of the linear correlation is

$$r_{x,y} = \frac{\sum_{i=1}^{n}(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{(\sum_{i=1}^{n}(x_i - \bar{x})^2)\,(\sum_{i=1}^{n}(y_i - \bar{y})^2)}} \qquad (2.1)$$

Where x, y are two random variables and $\bar{x}$, $\bar{y}$ are their respective means. "n" is the time steps over which the evaluation is carried out. The value of r lies between -1 and 1.

Next, I have used the partial correlation (Wilks, 1995; Nicholls, 1983; Ashok et al., 2001) to measure the individual impact of the co-occurring Indo-Pacific climate drivers on ISMR and the seasonal Kharif rice production (KRP). A standard form of the partial correlation has been given below.

$$r_{xy,z} = \frac{r_{xy} - r_{xz} r_{yz}}{\sqrt{(1 - r_{xz}^2)(1 - r_{yz}^2)}} \qquad (2.2)$$

Where '$r_{xy,z}$' is the partial correlation between variables x & y after removing the simultaneous impact of z. 'r_{xy}' is the correlation between x & y, 'r_{yz}' is a correlation between y & z, and 'r_{xz}' is the correlation between x & z. The partial correlation method has been used in many earlier studies, which aims to portray the individual teleconnections and impacts of the tropical Indo-Pacific drivers such as the ENSO and IOD from each other (e.g. Nicholls, 1983; Ashok et al., 2001, 2003a, 2003b, 2007a, b; Guan et al., 2003a; Saji and Yamagata, 2003) Rao et al., 2003; Behera et al., 2005). Such a technique of linear delineation is necessary because of the evolutions of ENSO and

IOD, which are seasonally phase-locked through boreal summer. Most of the time, they co-occur together (Yamagata et al., 2004), and their impacts get smeared up.

To determine the statistical significance of correlations, we used the Student's t-test with the degrees of freedom is considered as n-1 for the one-tailed and (n-2) for the two-tailed test (Wilks, 2011), where n is the number of sample sizes. A standard form of the t-test has been given below.

$$t = r_{x,y}\frac{\sqrt{(n-2)}}{\sqrt{(1-r_{x,y}^2)}} \qquad (2.3)$$

Where '$r_{x,y}$' is the correlation coefficient and 'n' is the independent sample size.

2.2.2 Dynamical analysis

We calculate the velocity potential fields (850 hPa) derived from the NCEP data sets, which are incidentally, an updated reanalysis (1979-Present) as compared to those used in many earlier ENSO-Monsoon teleconnection studies (e.g. Guan et al., 2003a; Ashok et al., 2004, Guan and Yamagata, 2003b etc.). The composite analysis for the divergence of wind anomalies & velocity potential during major El Niño & El Niño Modoki events has been carried out over the period 1976-2013. Following Marathe et al. (2015) and Preethi et al. (2015), for the composite analysis, we choose two major El Niño years, both 1982 & 1997, and four significant El Niño Modoki years, such as 1991, 1994, 2002 and 2004. Another relevant statistic that is also used in this study is moisture convergence. As known, the moisture Flux Convergence comprises contributions from both an advection and convergence terms (Banacos et al., 2005). Briefly, the constituent moisture advection term represents the vertical transport of moisture, while the constituent moisture convergence term deals with the horizontal transport of moisture, referred to as moisture convergence (MC) in literature (e.g. Guan et al., 2003a; Ashok et al., 2003, 2004, etc.). We use the MC, defined in equation (2.4), at the 850 hPa as a diagnostic to ascertain that ENSO-related dynamics play a role in the inter-annual variability of the local moisture convergence, which is critical for the crop production at district and state levels.

$$MC = -qV(u,v).\nabla = \frac{d(-uq)}{dx} + \frac{d(-qv)}{dy} = -q\left(\frac{du}{dx} + \frac{dv}{dy}\right) = -q.\nabla V(u,v) \qquad (2.4)$$

Here q, u and v represent the specific humidity, zonal wind and meridional wind component, respectively.

2.3 NCEP-CFSv2 model description:

The National Centre for Environmental Prediction- Climate Forecast System version 2 (NCEP-CFSv2) (Saha et al. 2013) is a state-of-the-art ocean-atmospheric-land coupled climate model developed by the NCEP, USA. It has been implemented on the Prithvi High-Performance Computer (HPC) at Indian Institute of Tropical Meteorology (IITM), Pune, as a part of the Monsoon Mission Project, supported by the Ministry of Earth Science, Govt. of India. The atmospheric component of the IITM-CFSv2 is the Global Forecast System (GFS) with a horizontal spectral resolution of T126, i.e. about 110 km, and has 64 hybrid vertical levels (Moorthi et al. 2001; Yang et al. 2006). The ocean component of CFSv2 is the Geophysical Fluid Dynamics Laboratory (GFDL) Flexible Modeling System (FMS) Modular Ocean Model version 4 (MOM4) (Griffies et al. 2004). The simplified Arakawa-Schubert convection has been used as the convective parameterization with momentum mixing. The model also executes the orographic gravity wave drag based on the earlier Kim and Arakawa (1995) approach and the sub-grid scale mountain blocking by Lott and Miller (1997). The Rapid radiative transfer model shortwave radiation has been integrated with the maximum random cloud overlap according to Iacono et al. (2000) and Clough et al. (2005). Additionally, a four-layer NOAH land surface model (Ek et al. 2003) and a two-layer dynamical sea-ice model (Wu et al. 1997; Winton 2000) has been added.

All these components have been coupled together with the Atmosphere and Ocean components in Earth System Modeling Framework (ESMF). Further details of the model can be sourced from Ramu et al.(2016).

The IITM-CFSv2 generates the seasonal hindcast simulations from March, April and May initial conditions with 12 ensemble members during this period. The initial conditions have been obtained from the NCEP Climate Forecast System Reanalysis (CFSR) (Saha et al., 2010). Another variant of the IITM-CFSv2 has been used to generate the extended range hindcast datasets (Borah et al., 2013) at the resolutions of T382 & T126 (~38 km and ~110 km, respectively), mainly for the summer monsoon seasons of the period 2003 to 2015. The atmospheric and oceanic initial conditions have been obtained from the National Data Centres NOAA Operational Model Archive and Distribution System online model data server (http://nomads.ncep.noaa.gov). The Ensemble Prediction System (EPS) developed for Extended Range Predictions produces 11 member ensemble forecasts for 25 days lead time at every 5-day interval starting from 16 May to 28th (16 May, 21 May, 26 May,...., 23 September, 28 September) September over the 2003-2015 period, at both T126 and T382 resolutions.

2.3 DSSAT-CERES Rice model description:

The Decision Support System for Agrotechnology Transfer, known as DSSAT, is a computer-based program. It has the Cropping System Model (CSM)-Crop Environment Resource Synthesis (CERES)-Rice model. This model can simulate the growth, development, and crop yield depending upon the various inputs(Jones et al. 2003) such as the soil properties, water availability, crop management data, and from our context, weather conditions that we shall provide from the IITM-CFS2 hindcasts.

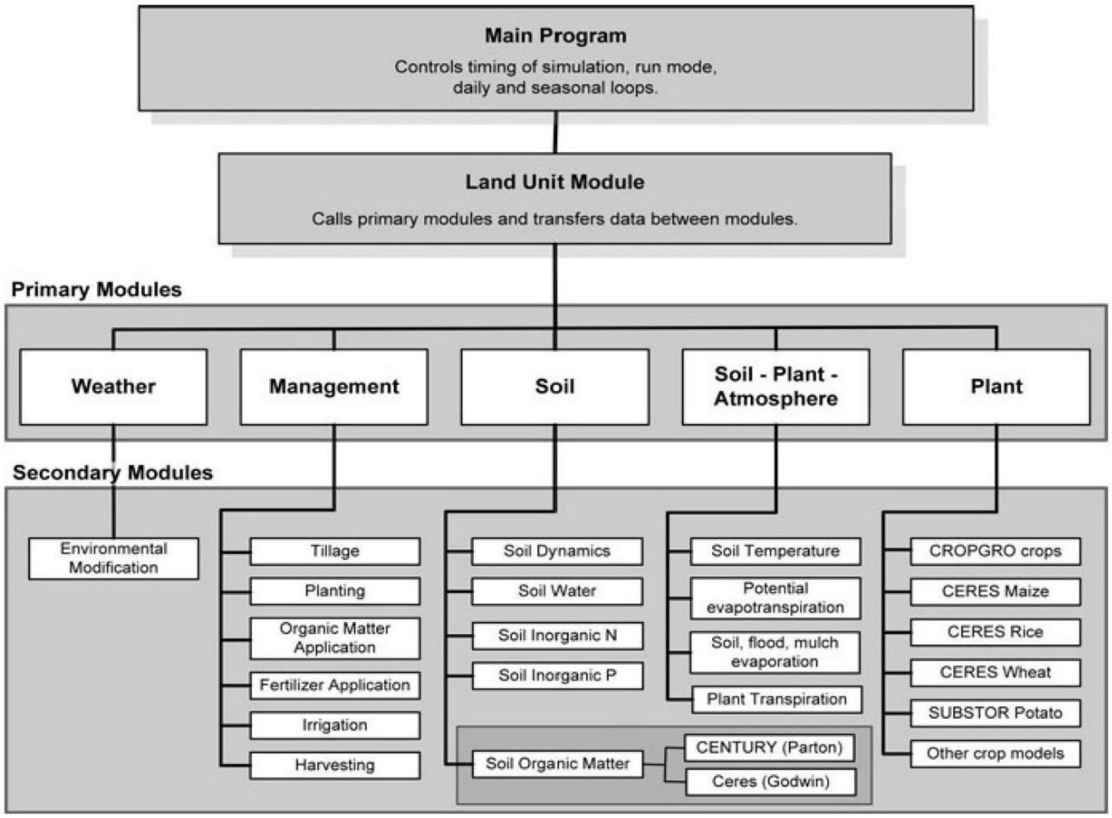

Figure 2.1 DSSAT-CSM Cropping System Model schematic (Source: Porter et al.,2009)

The model is also used in understanding the environmental stress factors (water and nitrogen), which affect the growth of a crop. The CERES-Rice model significantly estimates the phenology, biomass, and yield of a crop. It has been used for various studies such as assessing the impacts of climate change on rice production (Timsina & Humphreys,2006; Stella et al.,2021), the yield gap analysis of various crops (Nyang'au et al. 2014; Singh et al. 2015; Balderama et al. 2016; Daret al. 2017), and also, to improve the production through nutrient management (Singh et al. 2015; Vilayvong et al. 2015). These studies have shown how beneficial the increased CO_2 emissions and increased temperature could be for increasing crop production. Also, the limitation of exceeding the optimum levels and its impacts on rice production has been well reported by Azdawiyah Hariz & Fairuz (2015).

Chapter- 3

Relevance of various tropical Indo-Pacific climate drivers for the state-wise Kharif rice production in India

This chapter focuses on the relevance of Indian Summer Monsoon Rainfall and its tropical climate drivers for the state-wise Kharif rice productions, using the observed IMD rainfall and NCEP datasets. [2]

[2] All the results of this chapter have been published during the course of PhD as ***Amat and Ashok, (2018)***.

3.1 Introduction

The *Gross Domestic Product (GDP)* of India depends primarily on agriculture. The agriculture sector generally relies on the Indian Summer Monsoon Rainfall (ISMR), which occurs from June to September (JJAS). India has two cropping seasons, the Kharif and Rabi. The Kharif season crops grow during the summer monsoon period and are harvested in the consecutive late fall/or early winter months of October and November. The Rabi crops are grown during the month of October-March months and reaped in the straight spring (April-May). The ISMR is deemed a significant contributor to both the cropping seasons through the direct supply of water for the Kharif crops and the provision of soil moisture content and irrigated water for the Rabi crops. Of course, most of the Kharif crops, such as rice, mainly require more water than the Rabi crops. However, several other issues are also crucial for crop production in India. An official report published in 2014 by the *Directorate of Economics And Statistics (DES), Ministry Of Agriculture Government Of India,* suggests that the total crop production of India for the period 1966-2013 has an average value of 163.73 Million Tonnes/year. However, the corresponding time series shows (Figure 3.1a) a strong increasing trend, with the total production increasing from 74.23 Million Tonnes in 1966-67 to 257.13 Million Tonnes in 2012-13. The agriculture output in 2012-13 is 54.66% more than the 1966-67 period. However, this increasing trend in productivity is not associated with any such increasing trend in the ISMR (e.g. Krishnan et al., 2012). Studies by Goswami et al. (2006), Guhathakurta and Rajeevan (2007), Dash et al. (2007), Rajendran et al. (2012) and Krishnan et al. (2012) show that the ISMR has a weak to moderately decreasing trend. Interestingly, the DES-2014 report shows that an annual average of 123.83 Million Hectares of the area is being used for agriculture from 1966 to 2013 (Figure 3.1b). Also, India's agriculture area has only increased by approximately 6.9%. The increasing crop yield per acre trend also attests that the increased production is not primarily due to an increase in the area under agriculture.

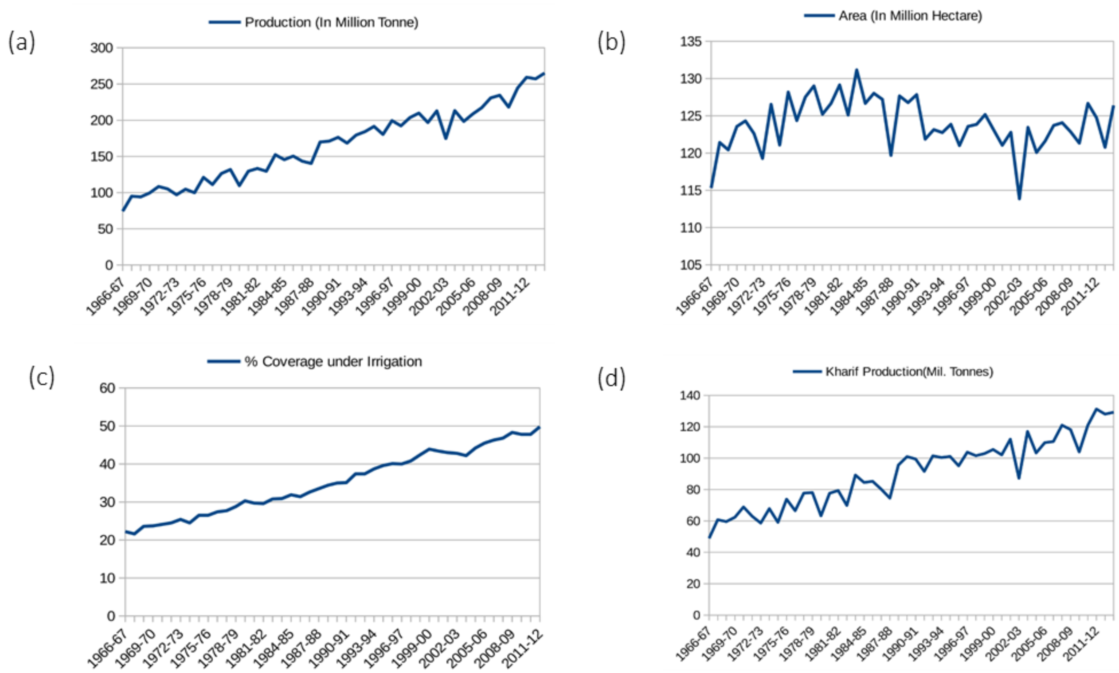

Figure 3.1 Interannual variation of (a) total annual agricultural production (in Million Tonnes) and (b) Area used for agriculture (in Million Hectare) (c) Percentage of the area under irrigation (d) Kharif rice production (in Million Tonnes) during the 1966–2013 period.

In this background, it is apt to attribute such an increase in total production, among other things, the increasing use of fertilizers and modern agricultural practices. However, as per the DES-2014 report, we see that irrigation activity has also played a significant role in increasing crop productivity. We see a noticeable increasing trend in the agricultural area under irrigation (Figure 3.1c). Increasing irrigation is a crucial factor that helps increase crop productivity. An average of 35.22 % of aggregate land used for agriculture has been irrigated annually from 1966 to 2012. The irrigated area is 36.97% less than the sample's mean during 1966–1967. During the financial year

2011–2012, it has increased by 41.37% of the mean (Figure. 3.1c). Independent of irrigation, the Kharif rice production has also increased significantly over the years, mainly rainfed rice.

Thus, we generally observe that many factors in addition to rainfall, such as irrigation, crop variety, fertilizers, pesticides, cropping patterns, and various modern technological advancements, have contributed to the increasing crop production growth in recent decades. Mainly, with increasing irrigation facilities, one is apt to ask whether the Indian summer monsoon rainfall is still an essential factor for crop production. There has been a noteworthy increase in crop production since the green revolution during the 1960s; also, India as a country has been confronted with numerous drought conditions in between, which has affected crop production. For example, a less than average summer monsoon rainfall in years such as 1987, 2002, 2004, and 2009 (Ashok et al., 2004, 2012; Nanjundiah et al.,2013) is also associated with decreased crop productivity (Figure 3.1a), suggesting that vagaries in monsoon rainfall, particularly the extreme years, may still be significant for crop production. The surface "monsoon trough", extending from Rajasthan in northwest India through the head bay of Bengal, is the most distinct stationary feature of the Indian summer monsoon. This is a manifestation of a land-sea thermal gradient, starting sometime in April (Rao, 1976). Associated with this is the well known low-level monsoon circulation. The summer monsoon rainfall in most regions along the monsoon trough and significant extent in peninsular India is associated with the day-to-day variability in monsoon trough location and its intensity. Orography also plays an important role. The regions in western peninsular India located west of western ghats and those in northeast India receive a lot of summer monsoon rainfall due to orographic influence. East coastal peninsular India also gets a significant portion of the summer monsoon rainfall from transient disturbances (Godbole, 1977; Ashok et al., 2000; Prajeesh et al., 2013).

The El Niño-Southern Oscillation (ENSO) is one of the most important drivers of the Indian summer monsoon rainfall variability (e.g. Sikka 1980; Rasmusson and Carpenter 1983; Ashok et al. 2007). Strong El Niños are associated with a drier than average summer monsoon condition over the Indian region. Interestingly, since the late 1970s, we see an increasing frequency in the El Niño Modokis, also referred to as central Pacific El Niños as against the canonical El niños (Ashok et al., 2007; Yu and Kao, 2009; Kug et al., 2009; Marathe et al., 2015; Freund et al., 2020). The El Niño Modokis are distinguished by a warmer than average central tropical Pacific flanked on both sides by cooler than typical anomalies. While both types of El Niños cause drier than normal rainfall conditions during summer monsoons, the Modoki events have a distinct substantial impact from a linear perspective (e.g. Kumar et al., 2006; Ashok et al., 2007; Ashok et al., 2020). There is, of course, some non-linearity in the relation between the rainfall-crop yield links. For example, the impact of deficit rainfall on GDP & grain production is more effective than the impact of surplus rainfall (Gadgil et al., 2006). In addition, the crop yield is relatively more in La Niña years than in the fall in El Niño years (Kumar and Barbosa, 2012). In addition, studies suggest that climate drivers other than ENSOs, such as the Indian Ocean Dipole events (IOD; Saji et al., 1999; Webster et al., 1999; Murtugudde et al., 2000) also influence the Indian summer monsoon (Ashok et al., 2004; Ashok and Saji, 2007). A strong positive IOD co-occurring with an El Niño can reduce the negative influence of the El Niño (Ashok et al., 2001). A recent study by Krishnaswamy et al. (2015) suggests a relatively dominating effect of the IOD events compared to the ENSOs in the recent period.

The current chapter explains the relevance of the interannual variability of summer monsoon rainfall (SMR) and the tropical Indo-Pacific climate drivers for that of crop production in various states of India during the Kharif season.

3.2 State-wise response of SMR & its climate drivers to that of the KRP

This section evaluates the relevance of the summer monsoon rainfall (SMR) on the Kharif crop production in various states that grow crops in the Kharif season through a correlation analysis. As per the DES report, the Kharif rice-producing major states are Undivided Andhra Pradesh (UAP), Odisha, West Bengal (WB) , Haryana, Punjab, Karnataka, Kerala, Madhya Pradesh (MP), Bihar, and Uttar Pradesh (UP). Linear correlations between state-wise SMR and KRP have been calculated to check their linkage. Table 3.1 shows the correlations between the state-wise KRP in each of these states with the area-averaged SMR (Parthasarathy, 1993).

Table 3.1 presents the correlations between the state-wise Kharif crop production with the state-wise SMR for the 2001-2013 period. Correlations with a magnitude above 0.47 are statistically significant at 95% from a one-tailed t-test and are shown in bold.

States	Correlation Cofficients (*r*)
WB	-0.17
Haryana	-0.26
Kerala	**-0.47**
Bihar	0.34
Punjab	-0.04
Uttar Pradesh	0.44
Madhya Pradesh	**0.76**
UAP	**0.74**
Karnataka	**0.81**
Odisha	**0.50**

Table 3.1 demonstrates that in most states that practice Kharif farming, crop production during the season in most states depends on the SMR. Andhra Pradesh, Karnataka, Madhya Pradesh, Odisha & Uttar Pradesh show a strong positive correlation between state-wise SMR and the state-wise KRP. However, the crop production of Uttar Pradesh is y weakly correlated with the state-wise SMR as compared to the other states. All this implies a strong influence of regional monsoon rainfall on the KRP of most states. An exception is the state of Kerala, whose crop production is negatively correlated with the SMR. Also, Earlier studies by Kumar et al.(2006) and Lal et al.(2020) suggest that in excessive rain, paddy crop dies. This must be the reason for the negative correlations.

We now present the partial correlations of the SMR in various states with various indices of tropical Indo-Pacific drivers, which can be interpreted as an estimate of the association of local state-wise SMR with the tropical Indo-Pacific climate drivers. Further, Table 3.2 suggests that the various Indo-Pacific climate drivers indeed influence the local SMR across the Kharif states. Primarily, the El Niño, as well as the El Niño Modoki, exhibit significant impacts on the states such as WB, Haryana, Kerala, Bihar, UAP and Karnataka.

In tune with Table 3.1, the rainfall in various states is negatively correlated with El Niño & El Niño Modoki indices. The IOD only influences the rainfall in relatively fewer states events. The local SMR of the states such as WB & Bihar along the monsoon trough show some statistically significant positive association with the IODMI, in agreement with earlier studies such as Ashok and Saji (2007).

Table 3.2 presents the partial correlations between the state-wise SMR with the Indo-Pacific climate driver indices during the 2001-2013 period. Correlations with magnitudes above 0.38 &

0.47 are statistically significant at 90% & 95%, respectively, from a one-tailed t-test and are shown in bold.

States	Partial Correlation of El Niño & SMR adjusted for IOD	Partial Correlation of IOD & SMR adjusted for El Niño	Partial Correlation of EMI & SMR adjusted for IOD	Partial Correlation of IOD & SMR ajusted for EMI
WB	**-0.51**	**0.60**	0.05	**0.45**
Haryana	**-0.40**	-0.34	**-0.58**	**-0.62**
Kerala	**-0.59**	0.16	-0.20	-0.10
Bihar	**-0.55**	**0.71**	-0.10	**0.53**
Punjab	-0.13	0.06	**-0.58**	-0.27
UP	-0.32	0.18	**-0.40**	-0.09
MP	-0.22	0.09	-0.19	-0.05
UAP	**-0.75**	0.27	**-0.50**	-0.23
Karnataka	**-0.47**	0.03	**-0.43**	-0.28
Odisha	-0.11	0.36	-0.11	0.28

Next, we examine the association of the Kharif rice production with the inter-annual variability of the tropical Indo-Pacific climate drivers (ENSO, IOD & ENSO Modoki) during the concurrent season of JJAS. We use partial correlations to find the associations between KRP with NINO3 index, EMI, IODMI and NINO 3.4 index. Table 3.3 shows several states whose KRP demonstrates a noteworthy response to one or several climate drivers listed indices. In particular, the SST variability in the NINO 3.4 index & ENSO Modoki region has a tremendous influence over the KRP for most Indian states, as seen by the significant negative correlations. From Weng et al. (2007), we know that the NINO 3.4 index mixes up signals from both flavours of ENSO.

Table 3.3 presents the partial correlations between the state-wise KCP and the Indo-Pacific climate driver indices during 2001-2013. Correlations with magnitude above 0.38 & 0.47 are statistically significant at 90% & 95% confidence levels, respectively, from a one-tailed t-test and are shown in bold.

States	Partial Correlation of NINO3 & KCP adjusted for IOD	Partial Correlation of IOD & KCP adjusted for NINO3	Partial Correlation of EMI & KCP adjusted for IOD	Partial Correlation of IOD & KCP adjusted for EMI	Partial Correlation of NINO3.4 & KCP adjusted for IOD	Partial Correlation of IOD & KCP adjusted for NINO3.4
WB	**0.38**	-0.07	0.22	0.13	**0.42**	0.03
Haryana	**-0.38**	**0.48**	**-0.56**	0.17	**-0.54**	**0.46**
Kerala	**0.42**	**-0.54**	**0.58**	-0.24	**0.56**	**-0.52**
Bihar	-0.11	**0.68**	-0.30	**0.60**	-0.21	**0.69**
Punjab	-0.01	0.23	**-0.52**	-0.01	-0.22	0.24
UP	**-0.39**	**0.48**	**-0.49**	0.19	**-0.50**	**0.44**
MP	-0.17	0.24	-0.14	0.13	-0.17	0.21
UAP	**-0.68**	**0.66**	**-0.60**	0.23	**-0.77**	**0.62**
Karnataka	**-0.43**	-0.07	**-0.68**	**-0.53**	**-0.63**	-0.22
Odisha	-0.30	0.13	-0.31	-0.09	-0.36	0.06

This, coupled with the relatively weak correlations of the regional KRP with the NINO3 index, suggests a reasonably dominant impact of the Modoki events on crop production in a linear sense. It may also be noted that the KRP of a couple of states has other signs of correlations with different ENSO types. A composite analysis of rainfall deficit associated with strong El Niño events by Ashok et al.(2020) indicates a widespread anomalously deficit rainfall across the country. This is in conformation with studies such as those by Ashok et al. (2007, 2019), which show that the negative impacts of various El Niño types differ in magnitude in the sub-regions of India. For example, the EMI has a strong negative correlation with the summer monsoon rainfall in peninsular India and a moderately positive correlation in north India (Figure 9(b) of Ashok et al., 2007). This type of regional distinction in the ENSO impacts on India is because the Indian region is well outside the Walker circulation footprint in the tropical Pacific, which is the direct impact region of the ENSO. The type and level of impact depending on the flavour and strength of the individual ENSOs (Kumar et al., 1999).

Interestingly, an earlier study by Selvaraju (2003) suggests a non-linearity of the impacts between ENSOs phases on all India annual crop production (inclusive of both Kharif and Rabi) production. Specifically, during the warm phase of El Niños, there is a significant reduction of 1% in the probability of above-average production relative to that during the neutral ENSO phase; on the other hand, the probability of above-average food grain production increases for the La Niña events by 5% relative to the neutral ENSO phase. This can be easily explained by the fact that the ENSO impacts on the rainfall in India change based on the background circulation, which is strongly phase-locked to the seasons. To be more explicit, while El Niños cause below-average rainfall in India during summer monsoons, they cause either above-average rainfall in the regions of Tamilnadu and Andhra Pradesh (e.g. Boyaj et al.,2018), and no significant impacts elsewhere during the northeast monsoons that occur during October-December, owing to the change of direction in mean circulation from summer (e.g. Yadav et al., 2012; Prakash et al., 2013).

3.3. Response of the dynamical aspects of the atmosphere with respect to the Indo-Pacific climate Drivers.

3.3.1 Response of Moisture Convergence to the Indo-Pacific climate drivers

Our correlation analysis between the 850 hPa moisture convergence and indices of various tropical Indo-Pacific drivers suggests that the El Niño Modokis are associated with a statistically significant anomalous reduction in the MC over the east coast of India, including the UAP (Fig. 3.2a). This is also supported by the zone of anomalous divergence in the region, seen from the composite analysis of 850 hPa velocity potential (Fig. 3.3a). This anomalous divergence is apparently due to the manifestation of its north-east zone of anomalous convergence, which extends southwest through the Philippines to the equatorial central tropical Pacific, in agreement with earlier studies such as Chen and Tam (2010) and Pradhan et al. (2011).

These studies show that such a convergence is associated with a low-level cyclonic circulation over the northwest tropical Pacific as a Rossby response to the central tropical Pacific. When combined with the results from Table 3.3, these findings show that the Modoki event indeed modifies the moisture convergence over India and affects crop production in many states.

Figures 3.2a, 3.2b, 3.3a and 3.3b, while qualitatively agreeing with the results from tables, suggest that the impact of the canonical ENSOs on the moisture content in the subcontinent during boreal summer is relatively weak. This is quite reasonable, given the fact that the canonical ENSO events have been relatively few during 1976-2010 as compared to the Modoki events, and also that their impacts are deemed to be relatively weaker (e.g. Kumar et al.,2005; Ashok et al., 2007; Marathe and Ashok, 2021).

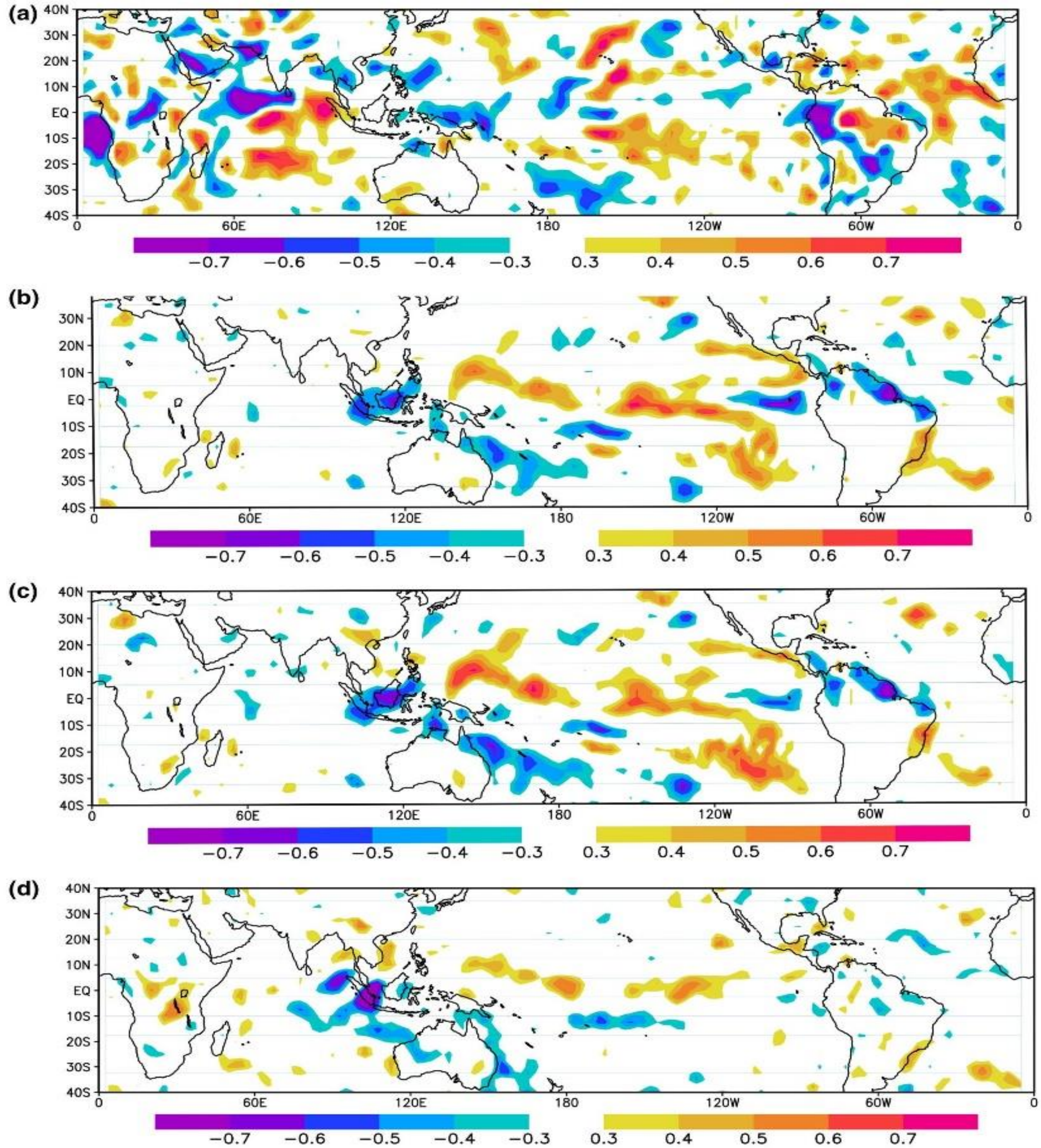

Figure 3.2: The correlation of Moisture Convergence and indices of (a) EMI (b) NINO3 (c) NINO 3.4, and (d) IODMI over the tropical region during June through September at 850 mb for the period (1978–2013).

Furthermore, the IODMI also shows some positive association with the moisture convergence over the Indian region, such as the Coastal Andhra Pradesh & Odisha (Fig. 3d), suggesting the relevance of the strong IOD events for the Kharif rice production.

3.3.2 Composite analysis of divergence of wind anomalies & the velocity potential for the El Niño & El Niño Modoki years for the period of 1978-2013.

Figure 3.3 demonstrates a strong divergence zone over the Indian region during the El Niño years. Which further helps in triggering a dry condition over the area. Subsequently, there could be a significant impact on agriculture production.

Also, it has been stated that during the warm phase of ENSO, there is a significant reduction of 1% in the probability of the above-average output over the neutral ENSO phase (Selvaraju, 2003). So the divergence characteristics of the wind at 850 hPa over the Indian region implies the weakening of the monsoon and associated consequences on agriculture production. While the composite plot figure 3.3c for Modokis makes a difference compared to that of the El Niño years. It suggests a significant divergence over the southwest Indian region, close to the monsoon core region. While there is also a comparatively less diverged wind zone, mainly near the eastern coast (Odisha, Andhra Pradesh & West Bengal) of the Indian sub-continent. As a result, the coastal region of the Bay of Bengal may get adequate rainfall due to the convergence of anomalous wind. Also, in section 3.2, I have demonstrated that the impact of El Niño Modoki over the KRP in the region is significantly higher compared to the other Indo-Pacific climate drivers. In particular, we have demonstrated that the district-wise KRP of UAP is well associated with the El Niño Modoki region. So this is because of the convergence zone over the east coast of India that shows significant production during the El Niño Modoki occurrence.

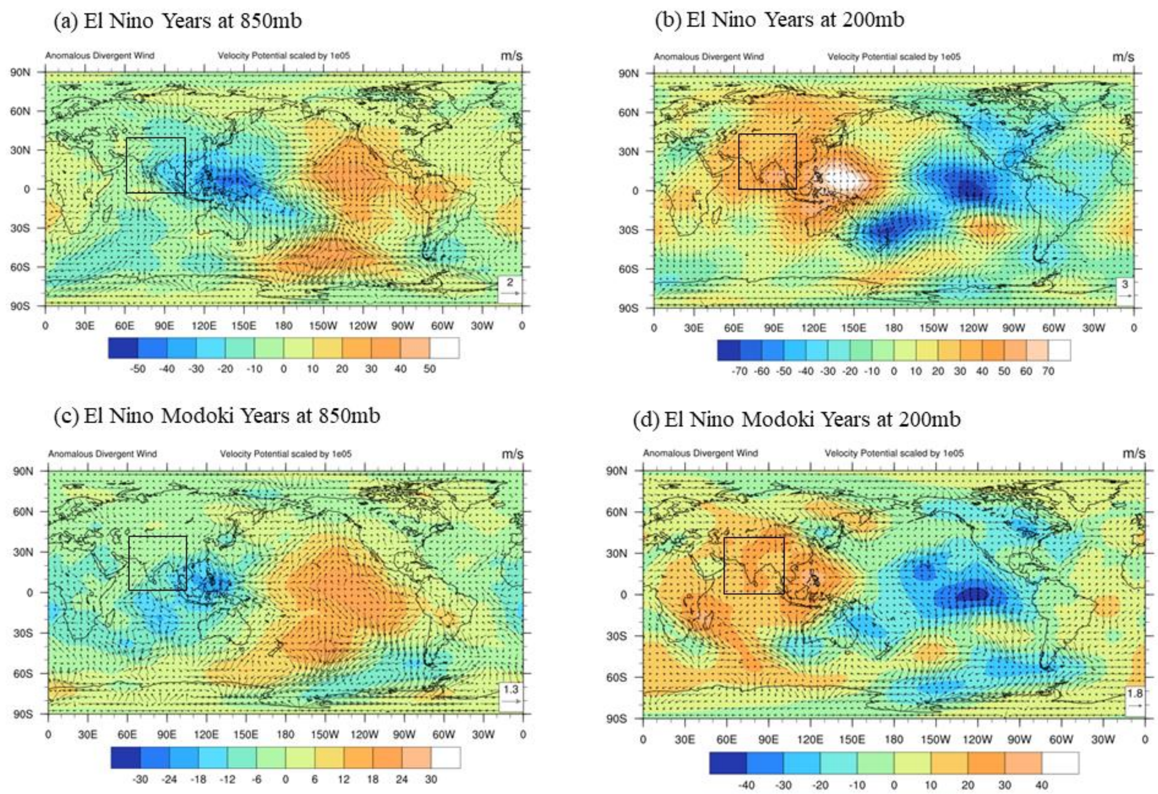

Figure 3.3 The composite plot of the divergence wind anomalies (m/s) and the velocity potential (m2/s) during June through September, during the major El Niño Modokis years (1991, 1994, 2002 and 2004) and El Niño years (1982 and 1997) years for the period of (1978–2013) at 850 mb and 200 mb.

4. Conclusion

Using the NCEP datasets mainly over the 1983-2013 period, we explore the relevance of the Indian summer monsoon rainfall and the tropical Indo-Pacific climate drivers to the Kharif crop production. The results suggest that, despite the improvements in irrigation, technology, availability of fertilizers, etc., the KRP is still significantly dependent on the concurrent rainfall during the summer monsoon season in many states of India. The results suggest that the two ENSO types, particularly the ENSO Modoki, substantially impact the inter-annual variability of the KRPin several states of India. The results also suggest that the two ENSO types, particularly the ENSO Modoki, substantially impact the inter-annual variability of the KRP in several states of India.

Important from the prediction viewpoint, these signatures are prominent even at sub-regional levels, for example, in rice-producing states such as the UAP, Karnataka, etc. In particular, the local KRP of UAP responds quite significantly to the variations in the tropical Pacific, as seen by its strong correlations with the NINO 3.4 & the ENSO Modoki indices. An analysis of the NCEP/NCAR reanalysis datasets shows that the impact of these tropical Pacific is through an abnormal modulation of the Walker circulation. We find that an anomalous divergence over the Indian region during a co-occurring El Niño of any type influences the KRP of most states. We found that the KRP of UAP is well associated with most of the drivers. The results suggest that the central tropical Pacific SST variations can critically influence the KRP over most Indian states under consideration. The relevance of the IOD events is also critical, although not for as many states as in the case of ENSOs.

Chapter- 4

Harnessing the IITM-CFSv2 Seasonal and Extended–range hindcast skills towards Kharif rice predictability through the Indo-Pacific Climate drivers.

The primary goal of this chapter is to focus on the IITM-CFSv2 Seasonal and Extended-range hindcast skills and harness those skills for the local rice production of various Indian states. [3]

[3] All the results of this chapter have been published during the course of PhD as ***Amat et al.(2021)***.

4.1 Introduction

The prominent tropical Indo-Pacific drivers, namely, the El Niño-Southern Oscillation (ENSO), ENSO Modoki, and Indian Ocean Dipole (IOD), not only impact the summer monsoon rainfall and temperatures in India but also have a statistically significant correlation with the Kharif rice production(KRP) of several rice-growing states in India, as discussed in Chapter 3.

Notably, the Indian Institute of Tropical Meteorology (IITM), Pune, India, has generated seasonal and extended range hindcast products for 1981-2008 and 2003-2015 using the IITM-Climate Forecast System version2 (IITM-CFSv2) coupled model at various resolutions and configurations. Briefly, as discussed in Chapter 2, the retrospective hindcasts have been generated using different initial conditions, and the final ensemble forecast is usually used to inform the scientific community as an end product per their requirement. Such uncertainties estimations will add more decision-making capabilities to the user community in a practical sense. For example, The importance of ERP has been used for determining the Monsoon Intraseasonal Oscillations (MISOs) (Sahai et al., 2013a; Sharmila et al., 2013) in terms of active & break spells. Further details are available from Chapter 2.

In this chapter, we explore whether these retrospective-predicted climate local rainfall from these sophisticated retrospective forecasts captures the observed relationship of the KRP of multiple states with the respective state-wise local rainfall and the fidelity of the hindcast indices of the major tropical Indo-Pacific climate drivers. Using methods such as the anomaly correlation, partial correlation, and pattern correlation techniques, we examine whether the IITM-CFSv2 successfully simulates the association of the tropical Indo-Pacific climate drivers with the local rainfall in many states during the summer monsoon.

4.2 Analysis from the CFSv2 T382 seasonal hindcast

4.2.1 Correlations of anomalous observed and model-predicted rainfall

The anomaly correlation coefficients between the observed ISMR and seasonal prediction hindcasts for 1981-2008 (Figure 4.1) are 0.49, 0.48, and 0.43 from March, April, and May initial conditions, respectively. These correlations agree with those reported by Pokhrel et al. (2016). The magnitude values 0.29 and 0.37 are statistically significant at 90% and 95% confidence levels, respectively, from a one-tailed Student t-test. Apparently, these correlations are even statistically significant at a 98% confidence level, which suggests that these seasonal forecasts of ISMR at 1-3 months lead are reasonably good. Figure 4.1 suggests that there is not much spread across the predicted rainfall evolutions of various ensembles, indicating that boundary conditions may have played an important role in constraining the hindcast evolution. Figure 4.1 also suggests that there is not much variation in the simulation at the other months. Further, figure 4.2 shows the anomalous rainfall distribution over India during JJAS, associated with various Indo-Pacific climate drivers.

We present the anomalous summer monsoon rainfall over the Indian region during various El Niño years (e.g. - 1984, 1987, 1988, 1993, 1995, 1997, 2001, 2002, 2004, 2006) , El Niño Modoki years (e.g.- 1981, 1984, 1991, 1992, 1993, 1996, 1998, 1999, 2002, 2004, 2008) and IOD years(1982, 1984, 1986, 1988, 1992, 1994, 1998, 1999, 2004, 2005) using both the observed and model-simulated these from the hindcasts with March April, and May initial conditions. Figure 4.2(a) shows the observed rainfall anomalies, which suggest that during the 1981-2008 period, the canonical El Niño events are associated with an abnormal deficit of rainfall across a significant part of the Indian subcontinent, such as along the monsoon trough, including central India, north India, and the west coast of India (e.g. Ashok et al., 2019). The corresponding model hindcasts with March and April initial conditions (Figures 4.2(d) & Figure 4.2(g), respectively) capture this anomalous signature of ENSO. In contrast, the rainfall anomalies from those with March (May) initial condition are overestimated (underestimates) compared with the observations.

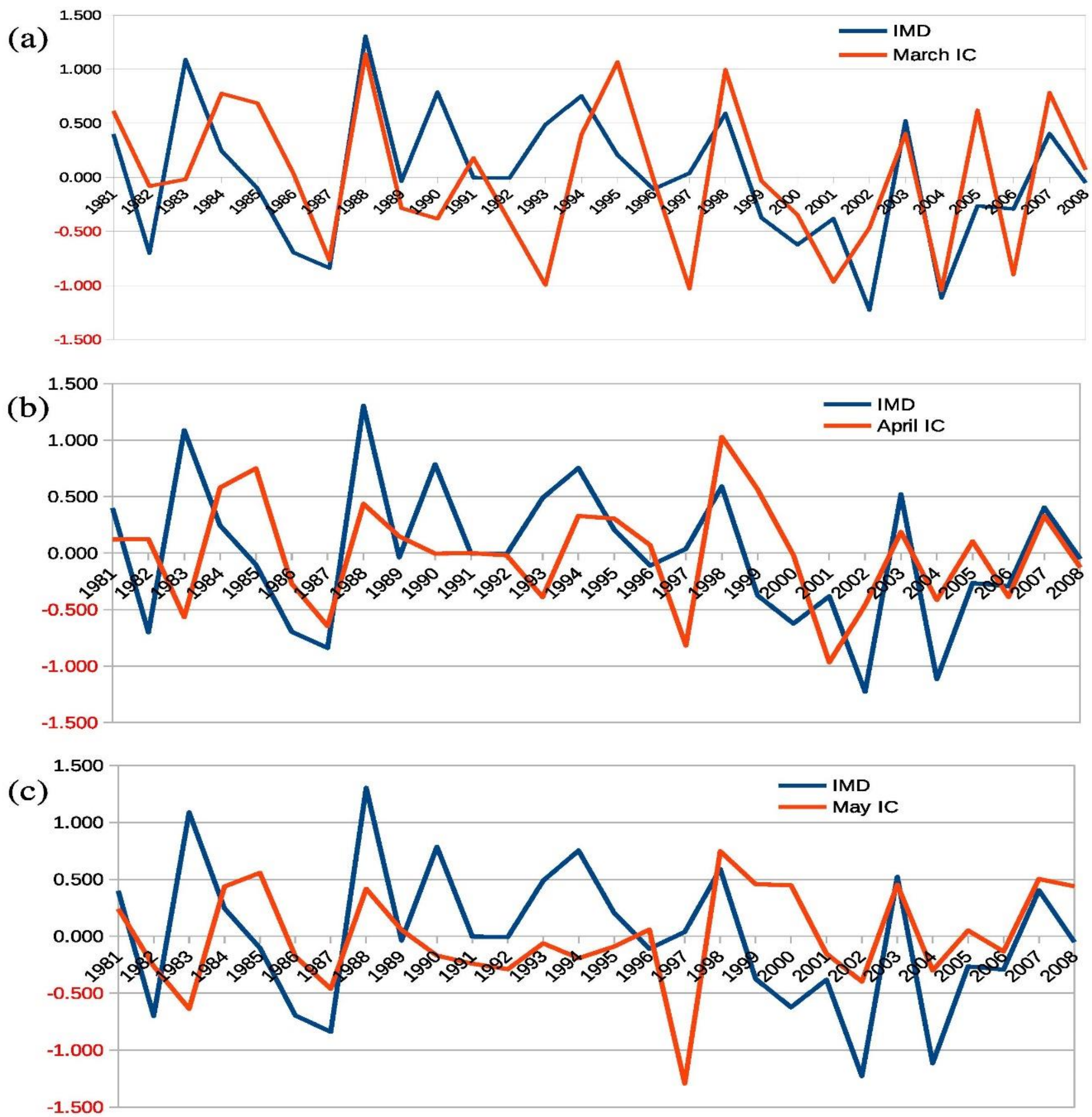

Figure 4.1 Observed(IMD) time series of area-averaged JJAS rainfall anomaly (blue) and the IITM-CFSv2 T382 seasonal hindcast (red) in mm/day, for different initial conditions (a) March, (b) April, and (c) May from 1981 to 2008 respectively.

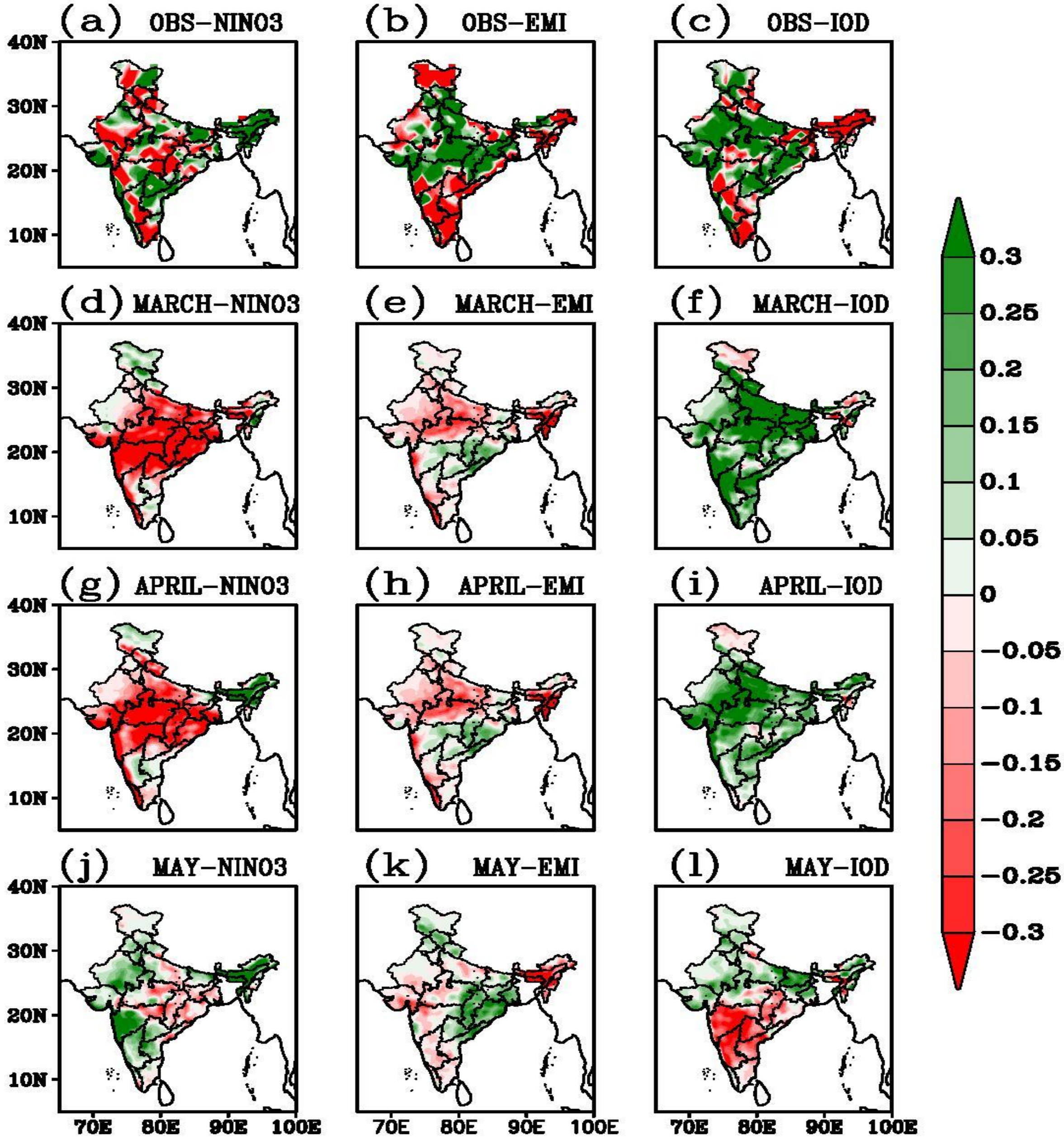

Figure 4.2 Composite of anomalous rainfall during El Niños, El Niño Modokis and IOD events over India, during the period 1981-2008, for the observed (a) to (c) and model simulations (d) to (l).

Figures 4.2(b) shows a strong summer monsoon rainfall reduction over India during the El Niño Modoki events, conformation with the observational studies (e.g., Ashok et al., 2007; 2019). The performance of the hindcasts (Figures 4.2(e), 4.2(h), and 4.2(k)) are relatively good in replicating the El Niño Modoki's impact, just like that of the El Niños. Also, a significant surplus rainfall associated with the IOD events along the monsoon trough is captured by the March and April initial conditions (Figures 4.2(c), 4.2(f) & 4.2(i)).

4.2.2 State-wise SMR (Observed & CFSv2 T382 hindcast) association with the KRP

The seasonal hindcasts give us general guidance for long-term strategic water management planning for agriculture and other public purposes. Using linear correlation analysis, we evaluate the potential importance of summer monsoon rainfall (SMR) for the state-wise KRP from significant Kharif rice-producing states in India through a correlation analysis. We carry out this analysis only for the 1990-2008 periods to match the limited span of the seasonal hindcast data sets. The results are presented in Table 4.1.

Table 4.1 suggests that the correlations between the state-wise KRP with the local rainfall are significant for UAP and WB, at a 90% confidence level from a One-tailed Student's t-test. The correlations are significant for both observed & IITM-CFSv2 hindcast from 1990 to 2008. Qualitatively, similar results have been found earlier, but for the shorter period 2000-2013 (Shown in chapter 2). Interestingly, the correlations for the state of WB are negative for this period. Several studies show that such a relationship can be attributed to the frequent floods/heavy rainfall damaging the crops (Kumar et al., 2004; Lal et al., 2020). A similar negative correlation is seen between the local KRP from Kerala and the local rainfall for a shorter 2001-2013 (Chapter 3).

Table 4.1 shows the correlations between the state-wise Kharif rice production (KRP) with the observed & CFSv2 Seasonal hindcast rainfall of that state for the 1990–2008 period. All bold values are statistically significant at a 90% confidence level of 0.29 from a one-tailed student t-test.

States	Observed	Model
UAP	**0.74**	**0.42**
Bihar	**0.45**	0.26
Haryana	-0.13	-0.14
Karnataka	**0.65**	0.26
Kerala	0.13	**0.34**
MP	**0.56**	0.26
Odisha	**0.7**	-0.18
Punjab	-0.19	-0.2
UP	**0.41**	-0.11
WB	**-0.34**	**-0.39**

The corresponding correlations of the observed state-level KRP with the model-predicted state-level SMR for the UAP, Bihar, Karnataka, Kerala, MP, and WB from Table are qualitatively realistic. However, the skills of the model predictions for some states are statistically insignificant. The negative relationship over the WB is also well-captured. This weak correlation may be because of the dry biases of IITM-CFSv2 over the Indian region.

4. 2.3 Association of the KRP to the tropical Indo-pacific Climate Drivers for the period 1990-2008

As shown in chapter 3, the state-wise KRP of several states such as Karnataka, UAP, Odisha, etc., is significantly associated with the interannual variability of the canonical ENSO, ENSO Modoki, and the IOD. We also showed in the chapter that this is potentially due to the modulation of the local moisture convergence by these drivers.

Given the decadal changes in the ENSO-Monsoon links and the apparently recent decline in the ENSO impacts on monsoons as claimed by Feba et al. (2018), we now compute the partial correlations of the KRP with various indices of various tropical Indo-Pacific drivers over the 1990-2008 period. The results are presented in Table 4.2.

From table 4.2, we see that the model hindcasts from the April and May initial conditions qualitatively capture the correlations of observed IODMI with the KRP of Odisha, with significant correlations of 0.35 and 0.36, respectively; the observed correlation is 0.32. The partial correlations from the hindcasts are comparable to those from the observations. Also, we see a high negative correlation of -0.54 between the observed NINO3 index and the observed KRP index over UAP. While the corresponding correlations of the KRP with hindcast NINO3 index from all initial conditions (March, April and May) qualitatively capture the negative relationship, the magnitudes are not significant for March and April.

On the other hand, the *hindcast* IODMI exhibits a correlation of -0.35 with observed KRP over Bihar, which is exactly the opposite in sign to that observed. Interestingly, the observed positive association of the IODMI with the KRP is well-captured with the May initial conditions after we remove the association of the NINO3.4 index through partial correlation analysis of (Table 3). The correlations of the IODMI also leads improve when we partial out the EMI impact (Table 4). This is understandable as the NINO3.4 index captures impact from both canonical and Modoki ENSOs (e.g., Weng et al., 2007). The better representation of the NINO3.4 index to isolate the effects over the KRP of Bihar suggests that the summer monsoon rainfall in the region is more sensitive to the temperature variations in the central tropical pacific (e.g., Keshavamurty 1982; Krishna Kumar et al., 2006; Ashok et al., 2007).

Table 4.2 presents the partial correlations between the observed state-wise KRP with the observed Nino3 & IOD for 1990-2008 and those drivers from the model hindcast. The magnitude with 0.29 and 0.37 are statistically significant at 90% and 95% confidence intervals, respectively, from the One-tailed Student t-test and are shown in bold.

States	***NIN03-KRP adjusted for (IOD)***				***IOD-KRP adjusted for (NINO3)***			
	Observed	March	April	May	Observed	March	April	May
Odisha	-00.04	-0.12	0.01	-0.02	**0.32**	0.22	**0.35**	**0.36**
Karnataka	-00.25	-0.16	-0.04	-0.03	-0.01	-0.05	-0.06	-0.26
AP	**-0.54**	-0.22	-0.19	-0.21	0.15	-0.13	-0.20	**-0.31**
MP	00.09	**-0.32**	**-0.52**	**-0.50**	-0.20	0.17	**0.45**	**0.37**
UP	-00.13	-0.12	-0.01	0.07	0.20	**-0.30**	-0.23	-0.10
Punjab	-00.22	0.14	**0.39**	**0.33**	0.27	-0.14	**-0.56**	**-0.30**
Bihar	-00.02	-0.20	**-0.35**	-0.21	**0.35**	**-0.29**	0.14	0.26
Kerala	00.13	-0.02	-0.12	-0.20	0.02	0.26	**0.46**	**0.40**
Haryana	-00.17	0.04	**0.33**	**0.32**	0.28	-0.04	**-0.46**	**-0.29**
WB	00.10	0.24	**0.55**	**0.45**	0.13	0.02	**-0.42**	-0.02

This becomes clearer because the hindcasts with May initial conditions also reasonably reproduce the observed positive correlations between the KRP over Bihar and the IOD (Table 4) once the co-occurring impacts from the EMI are removed. The seasonal hindcasts with April and May excellently recapture the significant negative correlations of Karnataka, AP, Bihar & Haryana between the KRP and the EMI (Table 4.4).

Table 4.3 presents the partial correlations between the observed state-wise KRP with the observed Nino3.4 index& IODMI for 1990-2008 and those drivers from the model hindcast. The magnitude with 0.29 and 0.37 are statistically significant at 90% and 95% confidence intervals, respectively, from the One-tailed Student t-test and are shown in bold.

States	***NIN03.4-KRP adjusted for (IOD)***				***IOD-KRP adjusted for (NINO3.4)***			
	Observed	March	April	May	**Observed**	March	April	May
Odisha	0.01	-0.05	0.01	-0.02	**0.31**	0.18	**0.34**	**0.36**
Karnataka	**-0.40**	-0.14	0.00	-0.13	0.03	-0.06	-0.04	-0.22
AP	**-0.71**	-0.22	0.02	**-0.35**	0.22	-0.12	-0.15	-0.27
MP	0.06	**-0.31**	-0.03	**-0.45**	-0.19	0.17	**0.45**	**0.36**
UP	**-0.41**	-0.23	0.02	-0.11	**0.31**	-0.24	-0.17	-0.04
Punjab	-0.26	0.12	-0.02	0.23	0.28	-0.13	**-0.55**	-0.27
Bihar	-0.27	-0.23	-0.01	**-0.32**	**0.44**	-0.27	0.21	**0.30**
Kerala	0.25	0.06	0.02	-0.03	-0.02	0.22	**0.43**	**0.35**
Haryana	-0.24	-0.01	-0.01	0.20	**0.30**	-0.02	**-0.44**	-0.25
WB	0.19	0.21	-0.03	**0.43**	0.10	0.02	**-0.44**	-0.04

From Table 4.3, we observe a significant negative correlation of the observed KRP in the UAP with the NINO 3.4 index. The model-predicted with the May initial conditions reproduce the observed relationship with the UAP KRP. For Odisha & Bihar, the IODMI from both observations and model hindcasts of April & May initial conditions has a statistically significant positive correlation with the KRP of UAP after removing the impact of NINO3.4 index correlation.

Table 4.4 presents the partial correlations between the observed state-wise KRP with the observed EMI & IOD for 1990-2008 and those drivers from the model hindcast. The magnitude with 0.29 and 0.37 are statistically significant at 90% and 95% confidence intervals, respectively, from the One-tailed Student t-test and are shown in bold.

States	***EMI-KRP adjusted for (IOD)***				***IOD-KRP adjusted for (EMI)***			
	Observed	March	April	May	**Observed**	March	April	May
Odisha	**-0.32**	0.21	-0.06	-0.01	**0.39**	0.03	**0.34**	**0.35**
Karnataka	-0.25	-0.08	**-0.35**	**-0.40**	-0.07	-0.07	0.12	-0.09
AP	-0.26	-0.16	**-0.55**	**-0.63**	-0.04	-0.13	0.07	-0.11
MP	-0.03	-0.23	-0.11	-0.01	-0.17	0.14	**0.33**	0.18
UP	0.09	**-0.56**	**-0.70**	**-0.67**	0.15	-0.02	0.18	**0.29**
Punjab	-0.11	0.02	-0.06	-0.24	0.21	-0.07	**-0.42**	-0.08
Bihar	-0.01	**-0.31**	**-0.49**	**-0.43**	**0.36**	-0.20	**0.33**	**0.38**
Kerala	-0.13	**0.29**	**0.31**	**0.45**	0.10	0.08	**0.29**	0.17
Haryana	**-0.31**	-0.15	-0.17	**-0.33**	**0.29**	0.07	-0.28	-0.04
WB	0.03	0.09	0.25	0.11	0.17	0.07	**-0.36**	0.06

We can thus conjecture that the seasonal hindcasts of the CFSv2 reasonably reproduce the significant impacts of various tropical Indo-Pacific drivers on the KRP of UAP, Odisha, and Bihar with a maximum lead of 2-3 months. The other skills include the reproduction of the observed negative correlations between the EMI and KRP over Haryana (Table 4.4) with the May initial conditions. On the other hand, there are certain false alarms, such as the high correlations of the KRP over the UP with the hindcast EMI, which in reality are very weak.

4. 3 Analysis from the CFSv2 Extended-Range seasonal hindcast:

4.3.1 Correlations of anomalous observed and model-predicted rainfall:

To evaluate the model skills in predicting the fidelity of correlations between observed climate drivers and local KRP in India, we use the observed rainfall data set and CFSv2 (T382 & T126) extended-range hindcast outputs with the initial conditions with 4-week leads (W01, W02, W03, W04), with the week one initial conditions date of 31st May of each year. We calculate the area-averaged anomalous rainfall over the Indian landmass during June through September (JJAS) from 2003 to 2015. For the extended range prediction, correlations with a magnitude of 0.36 and 0.45 are statistically significant at 90% & 95% confidence intervals from a one-tailed *student t-test*. Figure 4.3 suggests that T126 & T382 based predictions for rainfall positively correlate with the observed rainfall with a magnitude varying between 0.64 & 0.68, respectively, which are statistically significant at 95- 98% confidence interval. We observe that the extended range hindcast at both the resolution of ~38km (T382) & ~110km (T126) similar behaviour to the observed rainfall over the Indian region.

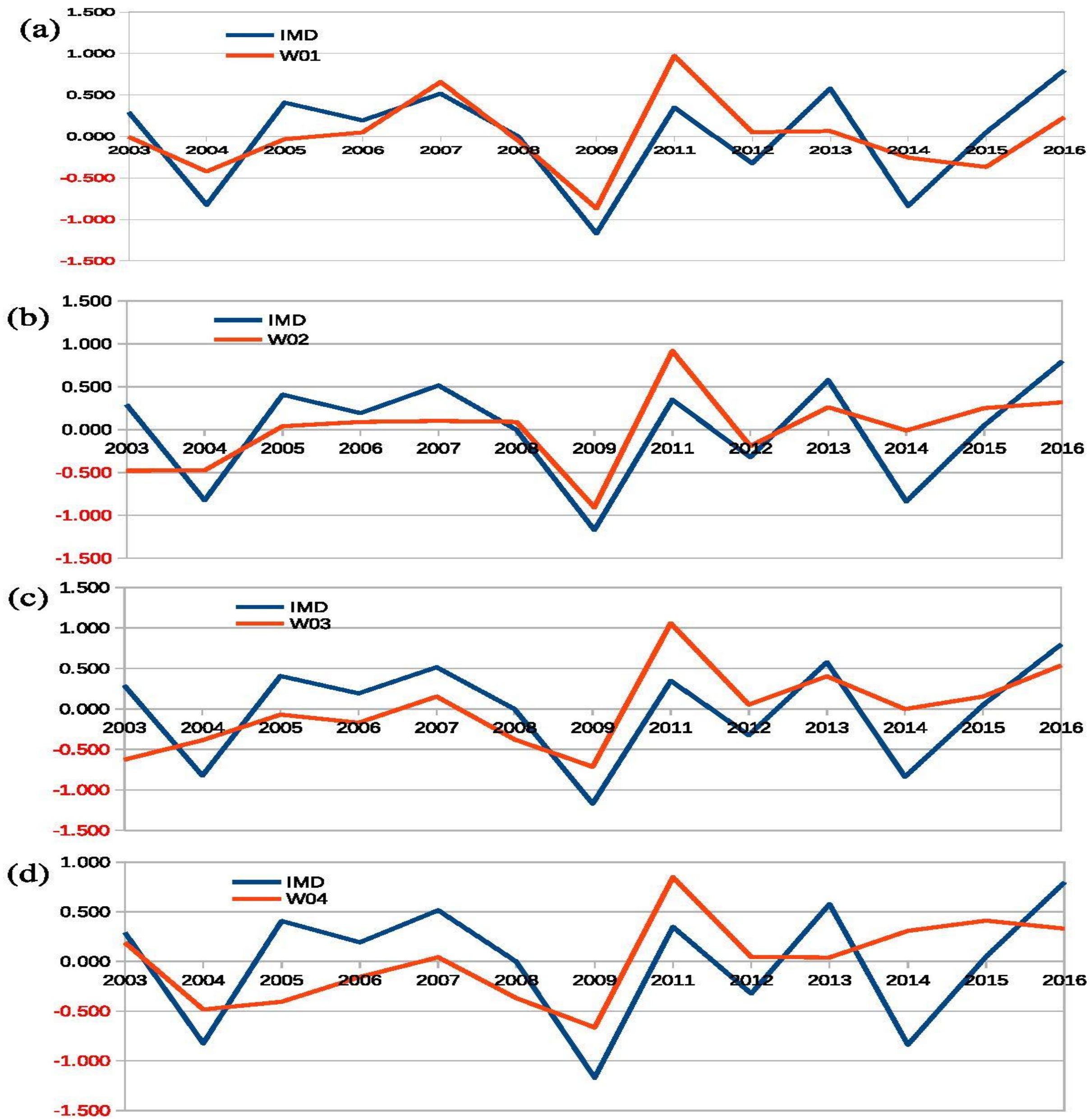

Figure 4.3 Observed(IMD) time series of area-averaged JJAS rainfall anomaly (blue), shown with those from the CFSv2 T126 extended range hindcast (mm/day; red) with different week leads (a) W01, (b) W02, (c) W03 and (d) W04 during 2003 to 2016 respectively.

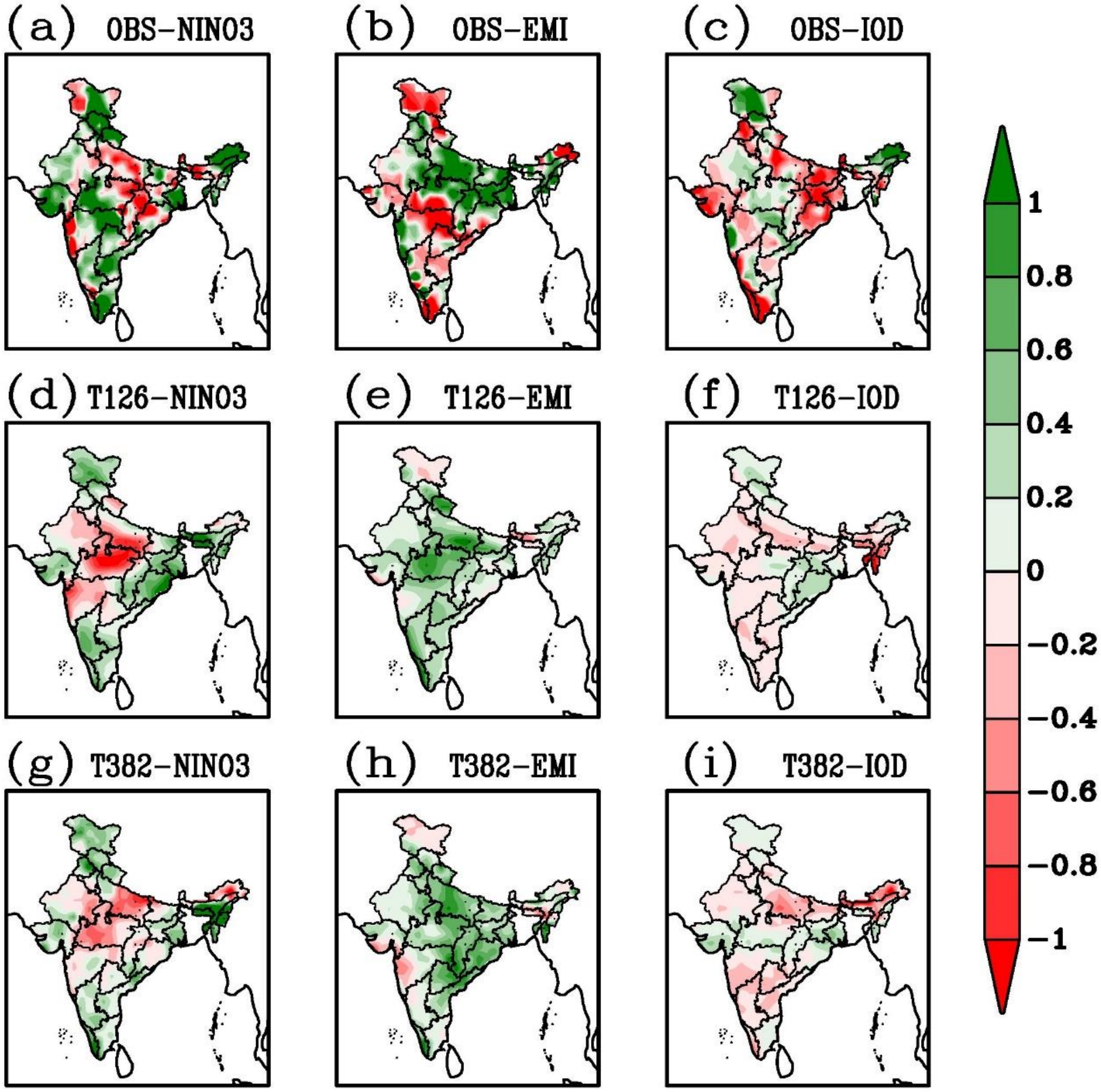

Figure 4.4 Composite of anomalous rainfall during El Nino (El Nino Modoki and IOD) events over India, from 2003 to 2015, for the observed (a) to (c) and extended range model simulations, T126 from (d) to (f) and T382 from (g) to (i).

Figure 4.4 shows the anomalous observed rainfall patterns over India on an extended-range time scale during El Niño years, which is the composite of 2007, 2012 and 2014. The observed IOD events, e.g., 2004, 2005, 2011, 2012, 2013, 2014 and the El Niño Modoki events, e.g., 2004, 2008 and 2010, have been considered. Figures 4.4(a), 4.4(d) & 4.4(g) suggest that the model captures the significant anomalous deficit rainfall during the El Niño summers over central India.

Table 4.5: shows the partial correlations between the state-wise KRP with the NINO3, NINO 3.4 Index & EMI, and removing the impact of IOD for 2003-2015. Correlations with magnitude above 0.36 & 0.45 are statistically significant at 90% & 95% confidence levels, respectively, from a one-tailed t-test and are shown in bold.

States	***Correlation of NINO3& KRP, adjusted for IOD***			***Correlation of NINO 3.4 & KRP, adjusted for IOD***			***Correlation of EMI & KRP, adjusted for IOD***		
	T126	OBS	T382	T126	OBS	T382	T126	OBS	T382
WB	-0.05	**0.38**	0.15	0.25	**0.42**	0.25	**0.46**	0.22	**0.46**
Haryana	0.07	**-0.38**	0.08	-0.29	**-0.54**	-0.29	0.37	**-0.56**	0.37
Kerala	0.02	**0.42**	-0.06	0.14	**0.54**	0.14	**-0.42**	**0.58**	**-0.42**
Bihar	**0.61**	-0.11	0.27	0.27	-0.21	0.27	**-0.44**	**-0.38**	**-0.44**
Punjab	-0.03	-0.01	0.14	0.16	-0.22	0.16	**0.43**	**-0.52**	**0.43**
UP	0.11	**-0.39**	0.04	**0.63**	**-0.50**	**0.63**	0.25	**-0.49**	0.25
MP	0.03	-0.17	0.56	-0.21	-0.17	-0.21	**0.56**	-0.14	**0.56**
UAP	0.01	**-0.68**	-0.2	-0.31	**-0.77**	-0.31	0.18	**-0.60**	0.18
Karnataka	-0.32	**-0.43**	-0.07	0.22	**-0.63**	0.22	**-0.43**	**-0.68**	**-0.43**
Odisha	0.02	-0.30	-0.03	0.00	-0.36	0.00	0.37	-0.31	**0.37**

However, figures 4.4(b), 4.4(e) & 4.4(h) suggest that model simulations are unable to capture the observed negative rainfall anomaly over India during the El Niño Modoki events and indicate an oppositely phased rainfall anomaly. In the extended range simulations, the prediction signal may not be as straightforward as the seasonal hindcast because of the limited data availability from the context of observations, i.e. the issue of sampling.

Table 4.6 presents the partial correlations between the state-wise KRP with the IOD & removing the impact of NINO3, NINO 3.4 Index and EMI for 2003-2015. Correlations with magnitude above 0.36 & 0.45 are statistically significant at 90% & 95% confidence levels, respectively, from a one-tailed t-test and are shown in bold.

States	***Correlation of IOD& KRP, adjusted for NINO3***			***Correlation of IOD& KRP, adjusted for NINO 3.4***			***Correlation of IOD& KRP, adjusted for EMI***		
	T126	OBS	T382	T126	OBS	T382	T126	OBS	T382
WB	-0.05	-0.07	-0.05	-0.07	0.03	-0.02	0.16	0.13	0.07
Haryana	0.07	**0.48**	0.07	0.06	**0.46**	0.09	0.23	0.17	0.16
Kerala	0.02	**-0.54**	0.02	0.05	**-0.52**	0.01	-0.15	-0.24	-0.03
Bihar	**0.61**	**0.68**	**0.61**	**0.66**	**0.69**	**0.66**	**0.62**	**0.60**	**0.95**
Punjab	-0.03	0.23	-0.03	-0.04	0.24	0.02	0.16	-0.01	0.09
UP	0.11	**0.48**	0.11	0.10	**0.44**	0.11	0.21	0.19	0.17
MP	0.03	0.24	0.03	0.15	0.21	0.15	0.34	0.13	**0.59**
UAP	0.01	**0.66**	0.01	-0.05	**0.62**	-0.02	0.02	0.23	-0.14
Karnataka	-0.32	-0.07	-0.32	-0.32	-0.22	-0.33	**-0.53**	**-0.53**	**-0.46**
Odisha	0.02	0.13	0.02	-0.02	0.06	0.02	0.15	-0.09	0.01

Table 4.5 suggests that the observed dataset is significantly able to capture the correlations between the KRP of various states and various climate indices. For example, considering the linkage of the NINO3 index with the state-wise KRP, states like Haryana, UP, UAP and Karnataka show significantly negative correlations. While, the KRP of Haryana, Bihar, Punjab, UP, UAP and Karnataka is negatively correlated with the ENSO Modoki events. Considering the IITM-CFSv2 extended-range skills, the correlation of EMI with the respective state-wise KRP for Bihar & Karnataka with a magnitude of -0.44 & -0.43, respectively, are statistically significant at a 95% confidence interval. Furthermore, there are significant correlations for the NINO3 index & KRP of Bihar with a magnitude of 0.61, which is opposite to that of the observed one. The UP has a significant correlation of hindcast NINO 3.4 index and the state-wise KRP with a magnitude of 0.62which is also unrealistic. So, the model fidelity is not good enough to capture the sign of the observed skill score while predicting the association with the state-wise KRP.

Table 4.6 suggests that the correlation of IODMI with the KRP of Bihar after removing the concurrent association of the NINO3 index, NINO 3.4 index & EMI is 0.61, 0.69 & 0.62, respectively. These values are statistically significant at a confidence level of 99% from the one-tailed student t-test. In this case, both the data sets (T126 & T382) exhibit equally good skills for Bihar. Also, the correlation of IODMI with the KRP of Karnataka after removing the impact of EMI is -0.53, a statistically significant skill. We observe that the skill for IODMI with KRP is also significant for Bihar. Also, the slightly weaker correlations, such as the correlation between IODMI and KRP (Adjusted for NINO3) for Karnataka state; the correlation between the IODMI and KRP (Adjusted for EMI) for MP state, exhibit relevant sign convention concerning the observed skills.

4.4 Conclusions:

In India, the economy of most of the states are governed by agricultural yield, and agriculture mainly depends on monsoon rainfall. Although recent studies (ref) have demonstrated the utility of dynamical models in predicting various weather and climate parameters like rainfall, SST, temperature etc., the use of these model forecasts for agricultural purposes in India has not been attempted widely. The present study assesses the skill and feasibility of variability in Kharif rice production in India associated with various climate indices like NINO3, EMI and IODMI. The above analysis and discussion suggest that the association between local summer monsoon rainfall and KRP rice production is strong over UAP, Bihar, MP, Odisha, UP, and WB; interestingly, these associations are well simulated by the seasonal forecasting model. Pacific Ocean SST conditions significantly influence the KRP rice production of AP, Karnataka and UP. In contrast, the IOD influences the rice production of Odisha, Bihar and Haryana. Although the seasonal forecasts simulate the sign of the association of climate Indices with rice production for these states well, the association is statistically significant for a few states like Odisha, Bihar and Kerala.

Similarly, the IODMI exhibits a significant association with the KRP production in WB, Bihar and Karnataka, which is predicted well is in the extended range dataset at W01 lead. We observe that the various tropical equatorial climate driver indices from ERP hindcast hold some value in predicting the KRP of the states located at the east coast of India and in the monsoon trough regions. Understandably, the KRP could be affected by local factors and, on intraseasonal time scales, processes other than the seasonally-persistent signals from drivers such as ENSO. These relatively high-frequency processes are sometimes difficult to predict. In addition, many times, even the observational findings are suspect, particularly if established through a linear methodology. For example, the excess amount of rainfall will damage the crops sown in that particular region. The impact of weather extremes causes agro-meteorological risks in different parts of the country. States like Kerala with a tremendous amount of rainfall indicate a negative correlation impact on the Kharif rice production by causing crops damage.

Given the positive implications of the IITM hindcasts for the states like Bihar, Odisha, and UAP, a district-wise analysis could be more helpful in understanding the dynamics of inter-annual and inter-seasonal crop productions and exploring the use of the hindcasts in predicting the district level KRP. Further, producing a high-resolution model hindcast may improve some dynamical seasonal prediction skills for the Kharif rice productions of several other Indian states.

Chapter- 5

Exploring the viability prediction of Kharif rice yield in the Telangana state of India using the IITM-CFSv2 hindcasts and DSSAT crop model

This chapter explores using the IITM-CFSv2 Extended-range products in forecasting as inputs for an agriculture model in order to predict the Kharif rice yield for the State of Telangana, India.

5.1 Introduction:

With the recent advancements in Information Communication Technology (ICT) and its widespread reach into rural regions of India, the demand for early weather forecasts concerning agriculture productions has increased exceptionally among the farmer community. Considering this, India Meteorological Department (IMD), in collaboration with the Indian Institute of Tropical Meteorology (IITM), Pune has started operational extended range and seasonal forecast. There is an Agricultural Meteorology Division at IMD dealing with the agro-meteorological advisories for each season for the whole country. Historically, in the earlier days, the National Centre for Medium range Weather Forecasting (NCMRWF) medium-range weather forecasts (3-5 days in advance) have been used (Lal et al. 1994; Rathore et al., 2009; Rathore et al., 2013(a), 2013(b); Chattopadhyay et al., 2016) for various purposes such as the scheduling of the plantation, irrigation, flood warning, and food grain security. Furthermore, an extensive impact assessment (Sharma A, 2015) has been carried out by the National Council of Applied Economic Research (NCAER) in association with Earth System Science Organization-National Centre for Medium-Range Weather Forecasting (ESSO-NCMRWF), Noida, and the Earth System Science Organization Indian National Centre for Ocean Information Services (ESSO-INCOIS), Hyderabad. This exercise suggests that the agro-met advisory by IMD has the potential of generating net economic benefit up to massive Rs. 3.3 lakh crores. Sharma (2012) suggests that IMD's agriculture advisory service could be useful in tackling various emerging problems, such as, "(i) *scheduling of the sowing dates according to monsoon onset for a particular region*, (ii) *management of conventional crops with alternative crops in case of long-term delay of the monsoon rainfall*, (iii) *managing the application of pesticides for disease control based on the water availability for a particular crop,* and (iv) *managing the irrigation process in case of* *surplus/deficit rainfall for a particular region"*. Hence, expanding the agro-met advisory service beyond the medium-range time scale based on prior forecast information of the IITM-CFSv2 extended-range (10-20 days) and seasonal (1-3 months) scale could be very useful in suggesting a comprehensive seasonal farming plan to the farmers (Tyagi and Pattanaik, 2012; Abhilash et al.,2012; Borah et al.,2013; Pattanaik et al., 2013a; Chattopadhyay et al., 2018, Pattanaik et al.,2019). Indeed, Pattanaik and Das (2015) have demonstrated that a skillfully extended range forecast could be useful for regulating the reservoir operation for monitoring flood situations. They carried out a case study for the 2011 flood situation of Mahanadi in Odisha. In addition, chapter 4 suggested that the IITM-CFSv2 extended range prediction hindcast captures the linkage of local state-wise Kharif rice production (KRP) with summer monsoon rainfall in various Indian states. Correspondingly, the association of Indian Ocean sea surface temperature(SST) conditions and state-wise KRP for West Bengal, Bihar, and Karnataka are clearly indicated in the analysis of extended range products. Pattanaik et al. (2021) showed that the agro-met advisory generated from the IITM-CFSv2 extended-range hindcast skill of local rainfall forecast is more useful because of the significant met-subdivision level forecast skills of week 1, week 2, week 3 at 89%, 83%, and 80% confidence intervals respectively. What's more, we believe the recent utilization of agriculture crop models, such as the CERES-rice module of the Cropping System Model (CSM) of the Decision Support System for Agro-technology Transfer (DSSAT) (Jones et al.,2003, Singh et al.,2014), among the agro-climate researcher community could benefit immensely through using t the IITM-CFSv2 extended-range data products,. The CERES-rice model, for instance, has been used in various studies such as those for irrigation process management (Ahmad et at., 2013), nitrogen balance (Ahmad et al., 2012; Zhang et al., 2018), studying the effects of environmental conditions (Phakamas et al., 2013), crop yield forecasting (Jha et al., 2019; Kaeomuangmoon et al., 2019), and the potential impacts of climate change on crop yields (Singh and Ritchie, 1993; Rauff et al.,2015; Ahmad et al., 2019; Gupta and Mishra, 2019; Nasir et al., 2020, Stella et al., 2020, Javed et al.,2021). Concerning IITM-CFSv2 extended range products, Javed et al.(2021) has been successfully able to utilize the extended-range data to forecast Kharif rice yield using the CERES-rice module of the CSM-DSSAT for the Gangetic West Bengal region.

In this chapter, I attempt to use the IITM-CFSv2 extended-range hindcast skills for the seasonal Kharif rice yield (KRY) forecast using the CERES-rice module of DSSAT for Warrangal district of Telangana state. The Telangana state, formerly part of the erstwhile UAP, is one of the rice-producing states of India.

5.2 Study area

The Warangal district is situated in Telangana state, on the Deccan Plateau in the central part of the Indian Peninsula. This district comes under the 'central Telangana agro-climatic zone' according to the Telangana State Development Planning Society (TSDPS) & Directorate of Economics and Statistics (DES), Planning Department, Government of Telangana.

According to the TSDPS and DES report, this region normally receives annual monsoon rainfall that ranges from 800 to 1300 mm. Additionally, Guhathakurta et al.(2020) observed significantly increasing trend of annual rainfall over the region. Further, the minimum and maximum temperatures during the peak winter season and summer season range between 18°C- 25°C and 32°C-38°C, respectively. Red soils are predominantly found in this region, which includes chalks, red sands, and deep red loams. Therefore, the crops like rice, cotton, maize, and green gram are found to be suitable for this region concerning the climatic condition and soil properties. It is said that the red soils of Telangana are the reason why the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) was set up in Hyderabad, the capital city of Telangana.

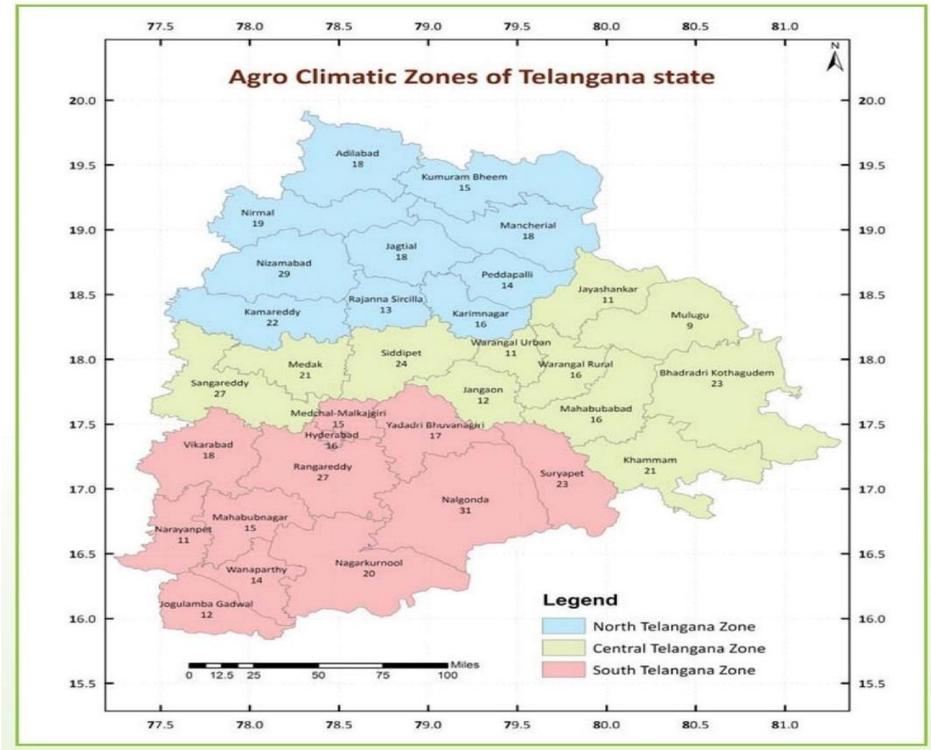

Figure 5.1 The Agro-Climatic Zones Map of Telangana (Source: *Weather and Climate of Telangana, TSDPS & DES*)

5.3 Rice variety information:

We used the MTU-1010 rice variety for this study. Anila et al.(2018) has described MTU 1010 as a widely popular mega-rice variety in India. Also, estimated data shows it has been cultivated in an area of more than 3 million hectares. However, the area used for MTU 1010 has significantly increased over the last few years, primarily because of its high productivity in a relatively shorter period. More information about MTU-1010 is available from the y Andhra Pradesh Rice Research Institute (APRRI), Regional Agricultural Research Station (RARS) and the Directorate of Rice Development, Ministry of Agriculture & Farmer's Welfare, Government of India (*https://drdpat.bih.nic.in/Rice%20Varieties%20-%2010.htm*). The following information on

MTU-1010 has been acquired from APRRI, particularly for Warangal region and is mentioned in table 5.1.

Table 5.1 gives the information about the rice variety MTU-1010 used in this study.

Variety Name	*Cotton dora Sannalu (MTU-1010) IET 15644*
Parentage	*Krishnaveni /IR 64*
Duration (Days)	*120*
Average yield	*40-45 q/ha*
Grain type	*long slender*
Special features	*Semi-dwarf (108 cm), resistant to blast & tolerant to BPH*

For this study, the genotype coefficients for MTU-1010 rice variety have been adopted from Vijaylaxmi et al.(2016), and they have been mentioned in chapter 2.

5.4 Phase of rice growth:

As per the '*Rice Knowledge Bank'* of the International Rice Research Institute (http://www.knowledgebank.irri.org/), the growth of a rice plant is usually divided into three different phases, namely *(i) the Vegetative Phase, (ii) the Reproductive Phase and (iii) the Ripening/Harvesting Phase.* The International Rice Research Institute (IRRI) (https://www.irri.org/) combines information on rice from various major rice-growing countries from South Asia, South-East Asia, East Asia, and Africa. A brief description of each of these phases follows.

(i) The Vegetative phase:

This phase begins with the seed germination till the tillering stage. Further, this stage can further be subdivided into the seedling and tillering phases. This phase is crucial for a better yield and needs proper management such as choosing the proper rice quality, soaking the seeds, land levelling and others.

(ii) ***The Reproductive phase:***

This phase begins with what is known as the panicle initiation (PI) and lasts till the flowering stage. The duration for this phase varies among the varieties of rice. This phase is sensitive to cold temperature (below 55º to 60º F), which can cause pollen formation and excessive blanking. For maximum spikelets, the water level must be raised above the developing panicle to mitigate the cold temperature factor, which is a major management practice in this phase. The flowering occurs over the next two to three weeks, depending upon the rice varieties. In addition, flowering is sensitive to high temperatures (more than 104º to 105º F), which can cause dryness to the germinating pollen tube and more blanking. Evidently, nothing can be done to overcome this high-temperature issue by any management practice.

(iii) ***The Ripening/Harvesting phase:***

This phase begins at the completion of the flowering and lasts till physiological maturity. The weight of the kernel is determined after this ripening phase. The process of physiological maturity includes filling the kernel with new carbohydrate materials, which are synthesized by the leaves and stem through photosynthesis. During this physiological maturity, the kernel carries up to 28% moisture. These processes of photosynthesis and moisture retention should continue till the kernel reaches its utmost maturity. The weight of a kernel depends upon its genetic potential. Therefore, it is impossible to increase the weight beyond that threshold. However, the kernel weight can be reduced by drying out the soil moisture so early. So, this is a critical decision to be made regarding the field drainage management during this phase.

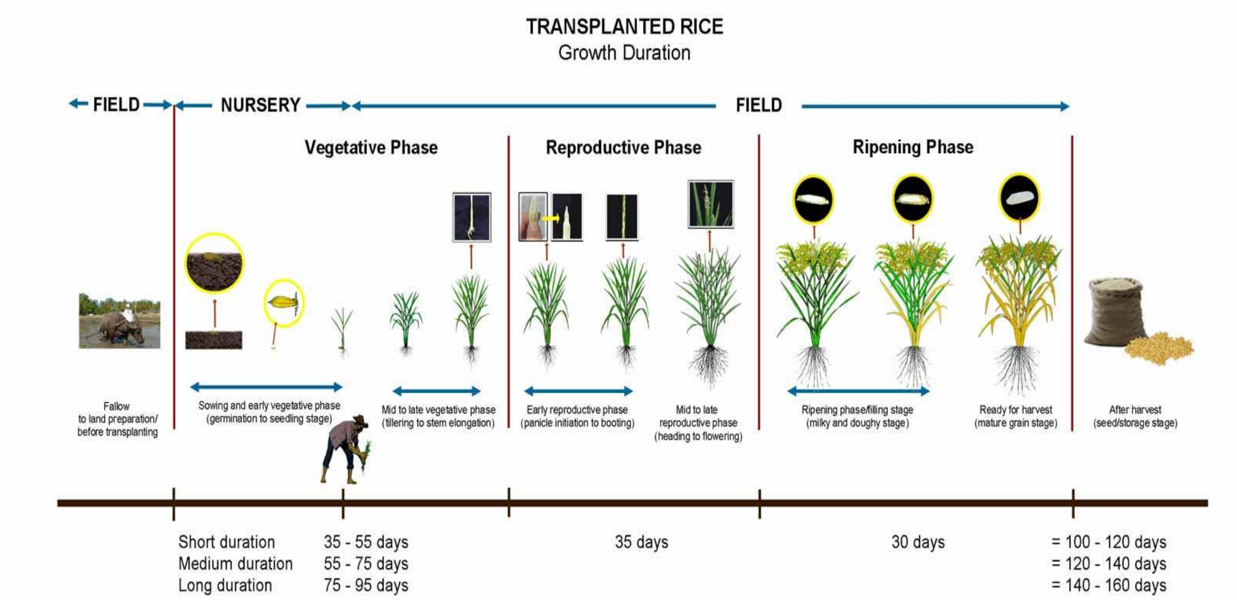

Figure 5.2 A schematic of transplanted rice growth with duration. (*Source: Rice Knowledge Bank, IRRI*)

I carried out this case study using the observed IMD and IITM-CFSv2 extended-range hindcast datasets available from 2004 to 2010. The observed crop yield datasets provided by the DES have been used for validation. All of my results have been discussed in the subsections.

5.5 Results:

5.5.1 Warangal's seasonal rainfall

Warangal receives most of its annual rainfall during the southwest monsoon. The daily rainfall plays a major role in the growth of rainfed Kharif rice. The rainfall distribution is also very important for the different growth phases of a rice plant. According to the IRRI, during nursery time or the vegetative phase, rice requires 50 to 60mm (~5%). The main field preparation requires 200 to 250mm of rainfall (~20%). From planting to panicle initiation (PI) requires 350-450mm of rainfall (~35%). From PI to flowering, it requires 300-400mm rainfall (~25%), and from flowering to maturity, it requires 100-150mm rainfall (~15%), which is 1000-1300mm rainfall in total a season. Statistically, on average, 6-10mm of daily rainfall is required for the healthy growth of rice plants.

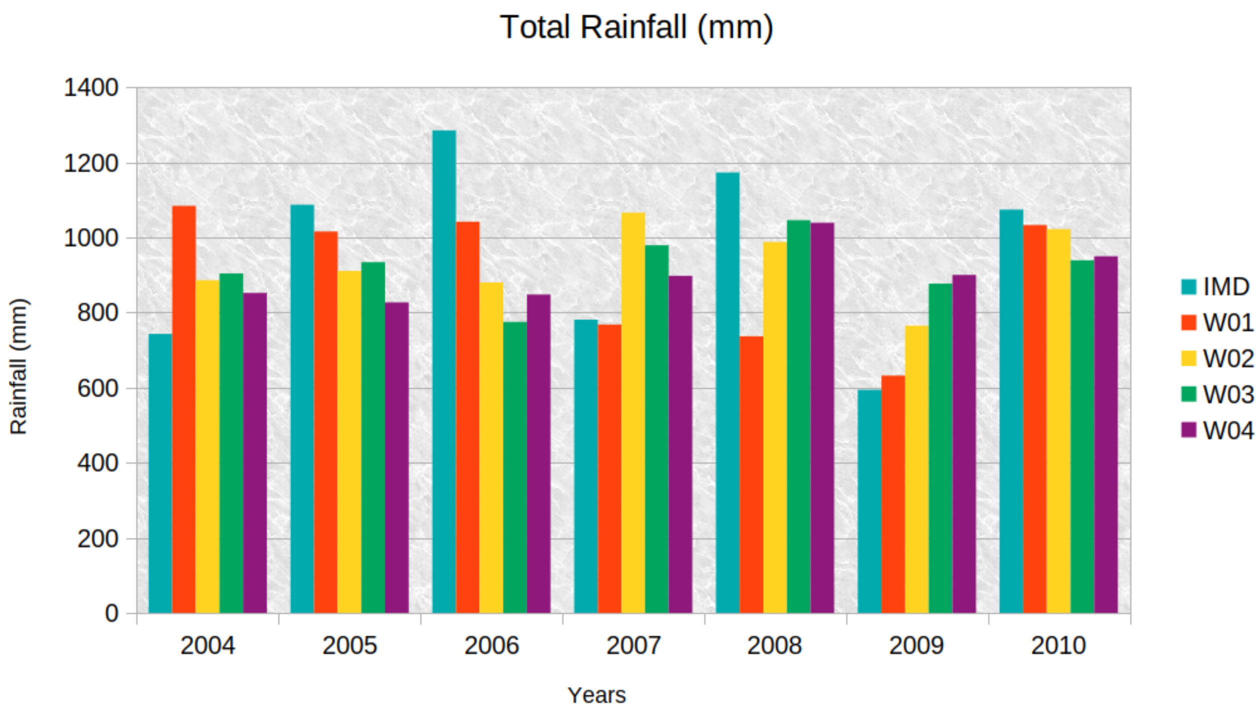

Figure 5.3 Warangal's monsoon rainfall received based on IMD and IITM-CFSv2 extended-range hindcast for week-1 lead(W01), week-2 lead(W02), week-3 lead(W03), week-4 lead(W04) during 2004-2010.

Figure 5.3 suggests that Warangal has received an average of 1100mm seasonal rainfall during 2004-2010, which is a substantial amount of rainfall for Kharif rice cultivation. On the other hand, the IITM-CFSv2 extended range shows reasonable predictability of summer monsoon rainfall at different week leads. Here, the correlation coefficients of the CFS2 extended hindcast rainfall with the IMD rainfall for Warangal at W01, W02, W03, and W04 leads are 0.44, 0.32, 0.26 and 0.17, all of which are significant at an 85% confidence interval from a one-tailed t-test. This implies that week-1 lead shows better skill, and beyond that, the skills gradually weaken with increasing weeks.

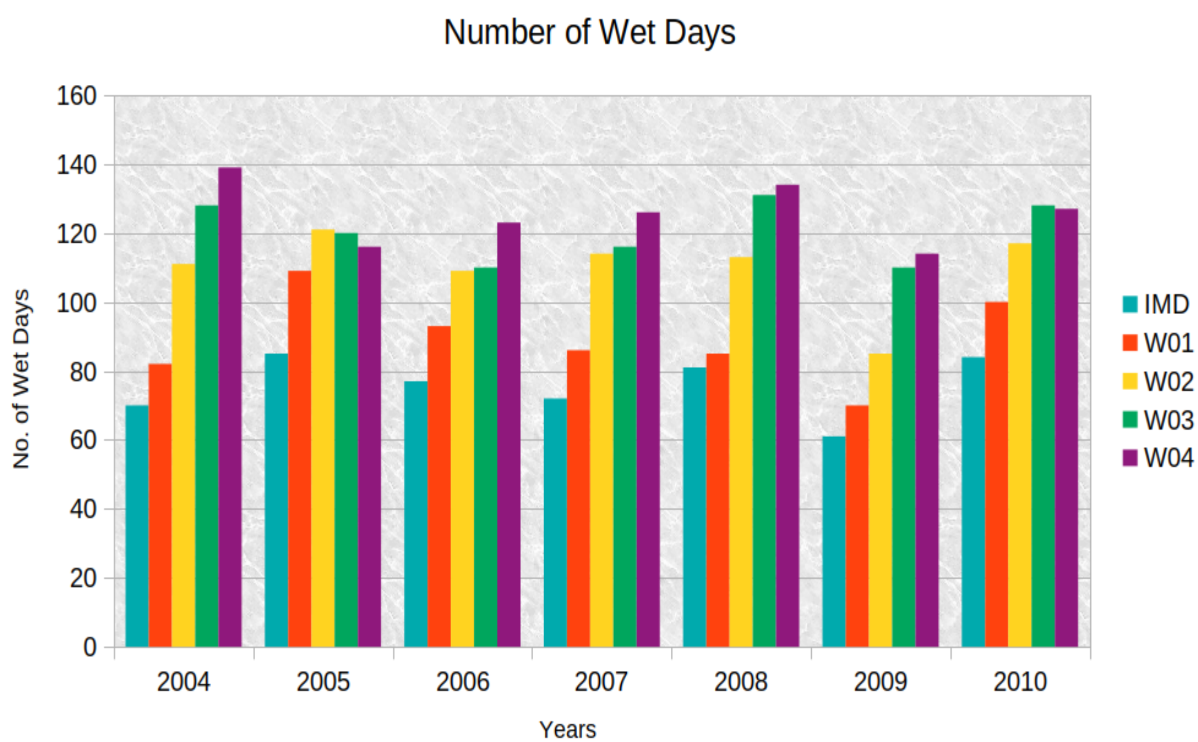

Figure.5.4 Number of wet days based on IMD and IITM-CFSv2 extended-range hindcast for week-1 lead(W01), week-2 lead(W02), week-3 lead(W03), week-4 lead(W04) during 2004-2010.

Similarly, the number of rainy/wet days is also important for the agriculture yield, as we already have discussed, from the context of usage and importance of water management during the various growth phases of a rice plant. According to IMD's definition, a rainy/wet day is a day with rainfall of 2.5 mm or more rainfall. Following the definition, we calculated the number of days during each season over Warangal (figure 5.4). The result suggests that the correlation coefficients of

IMD's observed wet days to that from the IITM-CFSv2's W01, W02, W03 and W04 lead hindcasts are 0.89, 0.86, 0.5 and 0.1, significant between 99%-95% confidence interval.

5.5.2 The CERES-rice DSSAT model calibration and validation

For the MTU-1010 crop variety, Vijayalaxmi et al.(2016) conducted various field experiments at *Professor Jayashankar Telangana State Agricultural University, Rajendranagar, Hyderabad*. Their collected field experiment data has been used to calibrate and validate the CERES-rice of DSSAT (Vijayalaxmi et al.,2016). As far as Telangana state is concerned, Naik et al.(2016) have estimated, using the CERES-rice of DSSAT, an optimum sowing window of 15 days gap for better production of a variety of rice in the region, including the MTU-1010. Apart from that, Jain et al.(2018) and Murari et al.(2018) have studied the crop production of various rice varieties, including MTU-1010 under rainfed and irrigation conditions for Raipur (Chhattisgarh State) region using the CERES-rice of DSSAT. Recently, Satpute et al.(2018) attempted to determine the suitable transplanting dates for MTU-1010 rice variety using the CERES-rice of DSSAT for Cooch Behar district, West Bengal. Therefore, the CERES-rice of DSSAT is already a well-calibrated and well-validated model for the MTU-1010 rice variety.

5.5.3 CERES-rice DSSAT model simulations:

The observed and model-simulated rice yields have been presented graphically (Figure 5.5, Figure 5.6 & Figure 5.7). Here we have simulated the rice yields using the observed IMD dataset and the IITM-CFSv2 extended-range hindcast datasets with four different weeks lead skills against three different transplanting dates. Therefore, we have five simulations for each transplanting date against an observed crop yield value.

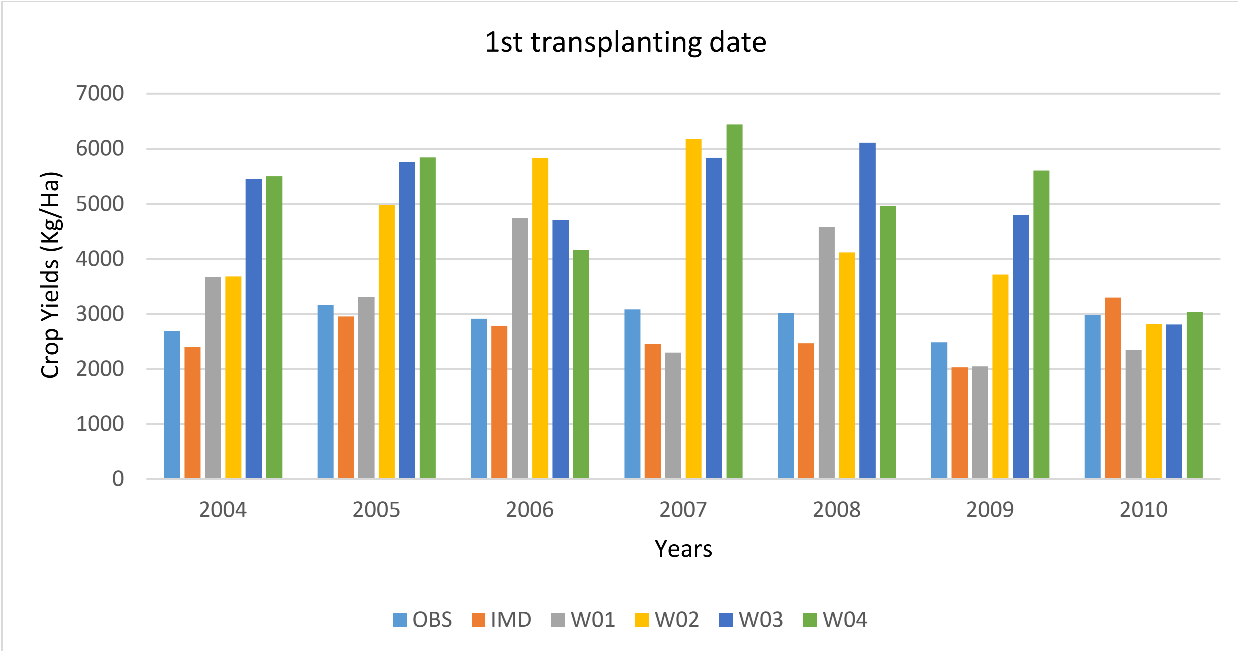

Figure 5.5 Simulations of MTU-1010 rice yields for the 1st transplant date for IMD, W01, W02, W03, W04 with respect to the observed dataset from 2004-2010.

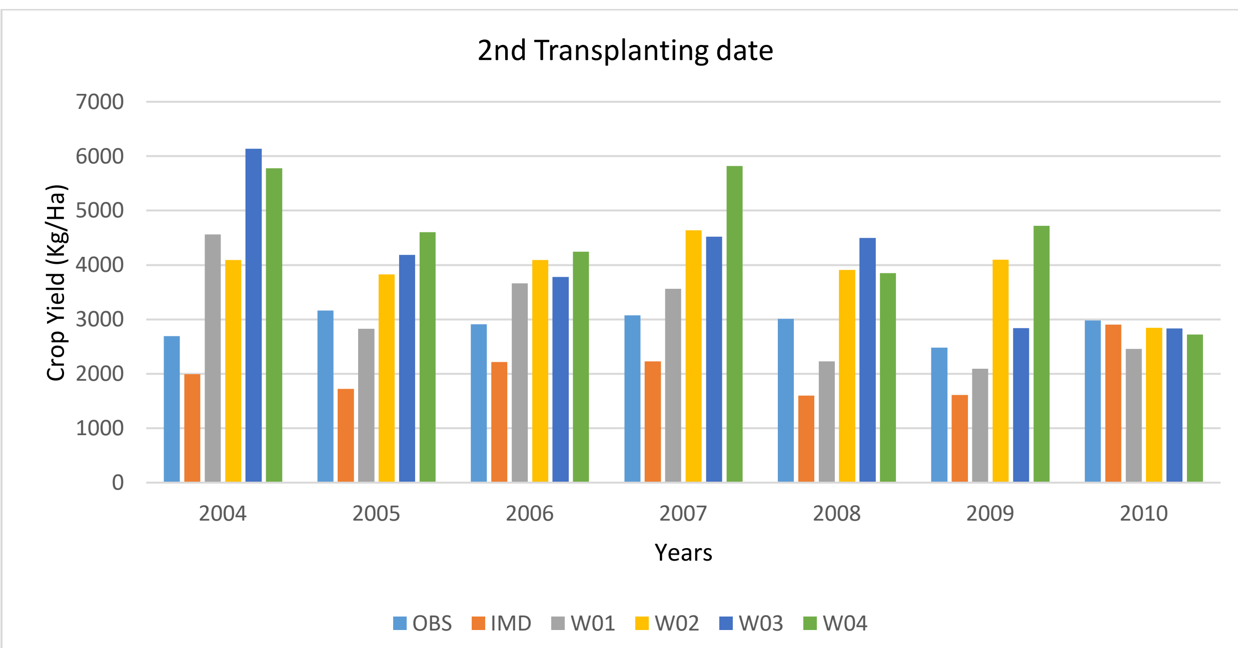

Figure.5.6 Simulations of MTU-1010 rice yields for the 2nd transplant date for IMD, W01, W02, W03, W04 with respect to the observed dataset from 2004-2010.

Based on the simulations for the 1st transplant date (Figure.5.5), we carried out a correlation analysis against the observed crop yield. The correlations between the DSSAT-simulated crop yield, based on the IMD observations, with that from the observations, is 0.66, significant at a 90% confidence interval. When IITM-CFSv2 hindcasts at the W01, W02 leads are used instead of IMD datasets to drive the DSSAT model, the correlations of the DSSAT-predicted yields with corresponding observations are 0.48 and 0.43, significant at 85% and 80% confidence level, respectively. However, the skills are insignificant for the simulations beyond 2nd week leads, that is, for W03 and W04 lead hindcasts. Similarly, the simulations for the 2nd transplant (Figure 5.6) and 3rd transplant (Figure 5.7) suggest that only the IMD observed dataset based simulation captures a reasonable skill with respect to the observed rice yield.

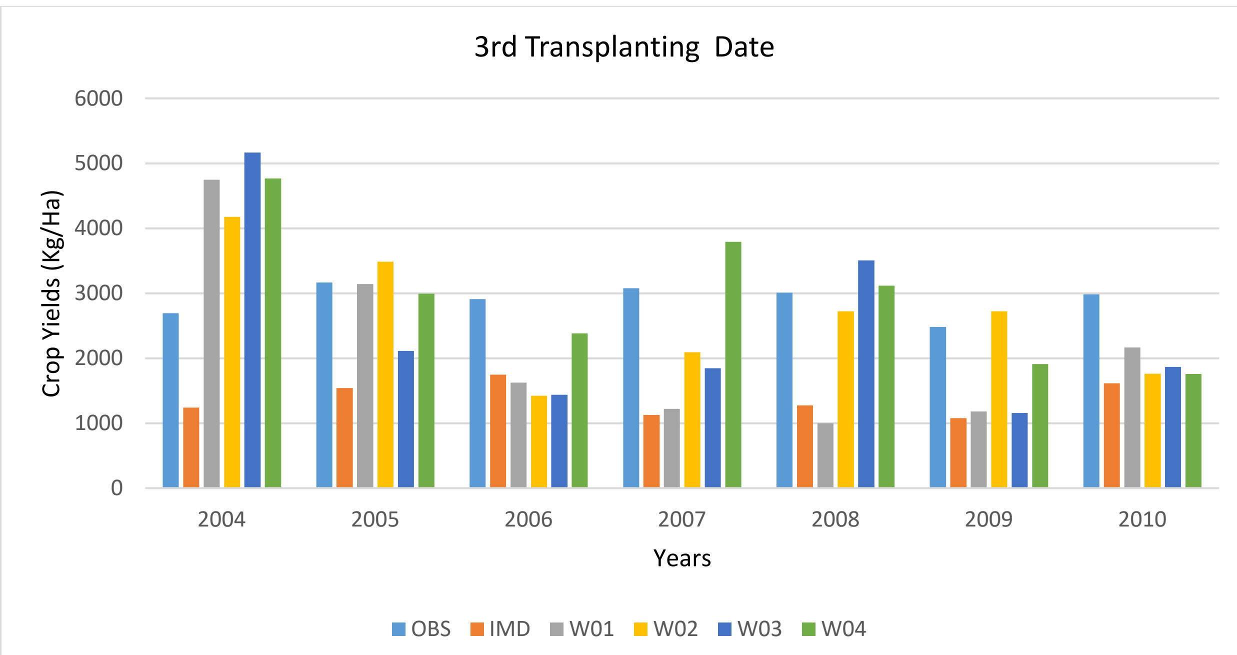

Figure.5.7 Simulations of MTU-1010 rice yields for the 3rd transplant date for IMD, W01, W02, W03, W04 with respect to the observed dataset from 2004-2010.

Thus, Identical to IITM-CFSv2 extended range skills for monsoon rainfall where the skill gradually decreases with increasing week leads, the CERES-rice exhibits the same kind of skills for the MTU-1010 rice yield. To determine the accuracy of the model predicted yield against the observed yield, we calculated the Root Mean Square Error for all transplanting dates.

Table 5.2 presents the Root Mean Square Error of CERES-rice predicted crop yields against an average observed Kharif rice yield of 3000kg/ha from 2004 to 2010.

Transplant date	IMD (Kg/Ha)	W01 (Kg/Ha)	W02 (Kg/Ha)	W03 (Kg/Ha)	W04 (Kg/Ha)
1st July	404.44	486.74	1897.62	2395.7	2435.27
11 July	964.6	881	1176.74	1608.58	1952.8
21 July	1546.29	1498.6	1008	1421.71	996.35

The average observed Kharif rice yield for the Warangal region was roughly around 3000kg/ha during 2004-2010, including multiple rice varieties other than the MTU-1010 rice variety (Vijayalaxmi et al.,2016). Table 5.2 shows the RMSE, determined with respect to the observed Kharif rice yield. It shows that 1st transplant based on IMD observations results in the DSSAT predicted the yield of the rice in Telangana with the least error of 13%, while that with the CFS2 extended range forecast at W01 lead is 16%. For the 2nd transplant date, the yield simulation errors were 30% and 29% for IMD and W01 lead, respectively. Observing the skills of IITM-CFSv2 extended range hindcast and their respective CERES-rice model simulations (Figure 5.5, Figure 5.6 and Figure 5.7), it is evident that the rice yield forecast errors gradually increase with an increasing number of week leads.

5.6 Conclusions:

In this chapter, I use the IITM-CFSv2 extended range hindcast datasets as inputs to the Decision Support System for Agro-technology Transfer (DSSAT, version 4.7) model to predict the Kharif rice yield from the Warangal district of Telangana) and the hindcast skills have been compared with the skills for the DSSAT model run using the IMD observations as inputs. Note that the genotype coefficients from Vijaylaxmi et al.(2016) for MTU-1010 rice variety, a widely used rice variety in the region, has been adopted for the DSSAT simulations.

This chapter shows that using the IITM-CFSv2 W01 hindcasts predict the summer monsoon rainfall in the region with significant skills. The W02, W03 and W04 lead skills for Warangal rainfall are statistically significant but weaker than W1 lead skills. Further, for all the three transplanting dates, the CERES-Rice model predicted Kharif rice yields using IMD observations and W01 for the first transplant date show the correlations of 0.66 and 0.48, towards the observed Kharif rice production, significant at 85% confidence level, and with RMSE of 13% and 16% respectively. This demonstrates the importance of local rainfall, despite the irrigation facilities, in local crop yield. The corresponding correlation and RMSE using the 1st transplant date from the IITM-CFSv2 hindcasts. However, the error percentages gradually grow with delays in transplanting.

Chapter- 6

Conclusions and Future Scope

The Indian Summer Monsoon is a boon to over a billion people living on the Indian subcontinent. Its impact on India's agro-economic development is significant. In addition to that, any notable study associated with monsoon forecast and observation is important in improving the lead prediction skills, which are important for efficient and economical agriculture practices and food security. For example, an early monsoon forecast would be beneficial to the local farmers to plan various aspects of their seasonal cultivation, such as sowing dates, transplanting dates and irrigation management. This thesis aims to study and harness the predictive skills of IITM-CFSv2's retrospective monsoon seasonal hindcast and extended-range products towards the Kharif rice yield Through application to a crop yield model to forecast rice yield for a district in India.

6.1 Summary

Chapter 1 of this thesis introduces the available literature on the Indian Summer Monsoon(ISM), such as the ISM various features and its variability attributable to various the well-known Indo-Pacific tropical climate drivers of ENSO, ENSO Modoki and IOD. I present a brief description of the evolutions of these drivers and the relationships between these tropical Indo-Pacific drivers and the ISM. Then, I sum up the literature on the emergence of the ISM model forecasting over the decades and the recent improvements in the dynamical forecasting of the ISM f at seasonal and extended-range timescales. From the perspective of applications, I talk about the status of agriculture in India, focusing on the state of Telangana, which produces a major share of rice from India. Finally, I introduce the DSSAT crop model and its various applications. Based on the above exhaustive literature review, I proposed my thesis objectives to deal with various research gaps . These objectives are:

1. Understanding the relevance of various tropical Indo-pacific climate drivers to the state-wise Kharif rice yield across India.
2. Evaluating the capability of the IITM-CFSv2 extended and seasonal scale hindcast products in reproducing the association of state-wise Kharif rice yield with the tropical Indo-pacific climate drivers and that with the local climate.
3. Exploring the viability of Kharif rice yield prediction in an Indian state using the IITM-CFSv2 hindcast products and a state-of-the-art crop yield model.

In **Chapter 2**, I give a complete description of all the datasets used, that is, those from observations, reanalysis, and model outputs. The model whose outputs have been used for this study is also adequately described. All the statistical techniques employed in the study have been discussed.

In **Chapter 3**, I examine the relationship between the state-wise response of the KRP to the SMR and its climate drivers through linear anomaly correlation and partial correlation analyses. My results show that the KRP is still significantly dependent on the concurrent rainfall during the summer monsoon season in many states of India. The El Niño and El Niño Modoki events are significantly associated with a fall in the KRP of many states such as Haryana, UP, UAP and Karnataka. On the other hand, the positive IOD events cause an increase in the KRP of various states such as Haryana, Bihar, UP and UAP. The results suggest that the central tropical Pacific SST variations can critically influence the KRP over most of the Indian states under consideration. I analyze the response of the dynamical aspects such as the moisture convergence, wind divergence and velocity potential during the ISM season concerning the Indo-Pacific climate drivers using composite analysis. The results show that, in addition to a reduction in the local rainfall typically associated with El Niños, an anomalous moisture divergence over the Indian region during a co-occurring El Niño and that during El Niño Modoki reduces the KRP of most states. The results show that the KRP of UAP, of one of whose districts we try to predict the KRP, is well associated with all the three climate drivers from the Indo-pacific.

In **Chapter 4,** I explore the fidelity of the hindcast indices of the major tropical Indo-Pacific climate drivers, and we examine whether the IITM-CFSv2 successfully simulates the association of the tropical Indo-Pacific climate drivers with the local rainfall in many states during the summer monsoon. We also check whether IITM-CFSv2 retrospective seasonal and extended-range hindcast ISM rainfall capture the observed relationship of the state-wise KRP with the respective state-wise ISM rainfall. And Also, The IITM-CFSv2 seasonal hindcasts, available for the period

1981-2008, qualitatively capture the observed association of state-wise SMR rainfall and the state-wise KRP of UAP, Bihar, MP, Odisha, UP, and WB. This is probably because the hindcasts reasonably reproduce the significant impacts of various tropical Indo-Pacific drivers on the state-wise KRP of UAP, Odisha, and Bihar with a maximum lead prediction skill of 2-3 months. The hindcasts particularly capture the significant influence of both ENSO variants on the state-wise KRP of UAP, Karnataka and UP. The hindcasts also capture the observed positive association of the IOD with the state-wise KRP of Odisha, Bihar and Haryana are influenced.

In **Chapter 5,** I discuss the various growth and development phases of a rice plant. I attempt to use the IITM-CFSv2 extended-range hindcast product for the Kharif rice yield forecast of the Warangal region, using the CERES-rice module of the DSSAT crop model system. The IITM-CFSv2 W01 hindcasts significantly capture the summer monsoon rainfall in the region with good skills. At the same time, the IITM-CFSv2's W02, W03 and W04 lead skills for Warangal rainfall are statistically significant but weaker than W1 lead skills. Based on IMD's observed monsoon onset dates over Warangal, I determine the date of sowing and transplanting. The DSSAT simulations show that the corresponding correlation and RMSE at the 1st transplant date significantly gives the best rice yield simulation. Beyond week 01, the results are not significant.

6.2 Future Scope

In general, there is always room for improvement in most of the application studies, and this study is no exception. While this thesis can address the few questions we raised relevant to my objectives, several other relevant questions related to this field of study remain, or arise newly based on my results, for posterity.

While the application of the IITM extended range prediction to the DSSAT model suggests that the KRP of Warangal district can be predicted a weeks ahead, improving the lead extended range prediction skills should improve those for the KRP of the district. Equally important, my results provide a proof of concept that there is potentially at least a medium-range forecast skill for the KRP in the other regions of the nation whose climate is influenced by the ISM and its drivers, and paddy is grown. This needs to be explored. The ongoing research on Machine Learning (ML) and Artificial Intelligence (AI) for weather forecast and statistical downscaling of low resolution observational and model data is interesting. Researchers have serious competition to develop better computer algorithms to improve the weather forecast. My results suggest a potential value in carrying out ML/AI-based statistical downscaling techniques to downscale the IITM-CFSv2 hindcast products and examine whether the forecasts skills improve, and if they do, use those downscaled datasets for crop yield forecasts by a dynamical crop growth model such as DSSAT and APSIM. By giving the importance to the IITM-CFSv2 hindcasts towards an early prediction of the KRP, the data sets can also be used in explorative predictive capability for other crops.

REFERENCES

Abhilash, S., Sahai, A. K., Pattnaik, S., Goswami, B. N., & Kumar, A. (2013). Extended range prediction of active-break spells of Indian summer monsoon rainfall using an ensemble prediction system in NCEP Climate Forecast System. International Journal of Climatology, 34(1), 98–113. https://doi.org/10.1002/joc.3668

Adams, R. M., Chen, C., Mccarl, B. A., Weiher, R. F., Adams, R. M., Chen, C., … Weiher, R. F. (1999). The economic consequences of ENSO events for agriculture. 13(3), 165–172.

Agricultural Statistics at a glance, 2015, Directorate of Economics and Statistics (DES), Ministry of Agriculture, Government of India.

Ahmad, S., Ahmad, A., Soler, C. M. T., Ali, H., Zia-Ul-Haq, M., Anothai, J., … Hasanuzzaman, M. (2012). Application of the CSM-CERES-Rice model for evaluation of plant density and nitrogen management of fine transplanted rice for an irrigated semiarid environment. Precision Agriculture, 13(2), 200–218. https://doi.org/10.1007/s11119-011-9238-1

Ahmad, S., A. Ahmad, H. Ali, A. Hussain, A. Garcia y Garcia, M.A. Khan, M. Zia-Ul-Haq, M.Hasanuzzaman, and G. Hoogenboom. 2013. Application of the CSM-CERES-Rice model for evaluation of plant density and irrigation management of transplanted rice for an irrigated semiarid environment. Irrigation Science 31(3):491-506.

Ahmad, S., G. Abbas, M. Ahmed, Z. Fatima, M.A. Anjum, G. Rasul, M.A. Khan, and G. Hoogenboom. 2019. Climate warming and management impact on the change of phenology of the rice-wheat cropping system in Punjab, Pakistan. Field Crops Research 230(1):46-61

Akhter, J., Mandal, R., Chattopadhyay, R., Joseph, S., Dey, A., Nageswararao, M. M., … Sahai, A. K. (2021). Kharif rice yield prediction over Gangetic West Bengal using IITM-IMD extended range forecast products. Theoretical and Applied Climatology, 145(3–4), 1089 1100. https://doi.org/10.1007/s00704-021-03679-w

Amien, I., Redjekiningrum, P., Kartiwa, B., & Estiningtyas, W. (1999). Simulated rice yields as affected by interannual climate variability and possible climate change in Java. Climate Research, 12(2-3 SPEC. ISS. 6), 145–152. https://doi.org/10.3354/cr012145

Amiri, E., Rezaei, M., Rezaei, E. E., & Bannayan, M. (2014). Evaluation of Ceres-Rice, Aquacrop and Oryza2000 Models in Simulation of Rice Yield Response to Different Irrigation and Nitrogen Management Strategies. Journal of Plant Nutrition, 37(11), 1749–1769. https://doi.org/10.1080/01904167.2014.888750

Amri Khairul., Study of primary productivity on Indian ocean dipole mode event and its relationships to pelagic fish catch abundance in Western Part of Sumatera Waters". In: (2012).

Ananthakrishnan R, Srinivasan V, Ramakrishna AR, Jambunathan R. 1968. Synoptic features associated with onset of southwest monsoon over Kerala. IMD Forecasting manual, Report IV–18.2.

Anchal Dass, Nain, A. S., Sudhishri, S., & Chandra, S. (2012). Simulation of maturity duration and productivity of two rice varieties under system of rice intensification using DSSAT v 4.5/CERES-Rice model. Journal of Agrometeorology, 14(1), 26–30.

Anila, M., Mahadeva Swamy, H. K., Kale, R. R., Bhadana, V. P., Anantha, M. S., Brajendra, … Sundaram, R. M. (2018). Breeding lines of the Indian mega-rice variety, MTU 1010, possessing protein kinase OsPSTOL (Pup1), show better root system architecture and higher yield in soils with low phosphorus. Molecular Breeding, 38(12), 1–10. https://doi.org/10.1007/s11032-018-0903-1

Ankit Kumar, Nath, S., Balpande, R., Kumar, P., Mishra, A., & Kumar, V. (2019). Decision support system for agro technology (DSSAT) modeling for estimation of rice production and validation. Journal of Pharmacognosy and Phytochemistry, 8(3), 3883–3886. Retrieved from https://www.phytojournal.com/archives/2019/vol8issue3/PartBF/8-3-573-952.pdf

Ashok, K., Z. Guan, and T. Yamagata (2001), Impact of the Indian Ocean dipole on the relationship between the Indian Monsoon rainfall and ENSO, Geophys. Res. Lett., 28, 4499–4502.

Ashok K, Guan Z, Yamagata T (2003) A look at the relationship between the ENSO and the Indian Ocean dipole. J Meteorol Soc Jpn 81(1):41–56

Ashok, K., Z. Guan, and T. Yamagata (2003), Influence of the Indian Ocean Dipole on the Australian winter rainfall, Geophys. Res. Lett., 30(15),1821, doi:10.1029/2003GL017926.

Ashok, K., Guan, Z., Saji, N. H. and Yamagata, T., 2004, "Individual and combined influences of the ENSO and Indian Ocean Dipole on the Indian summer monsoon", J. Climate, 17, 3141 3155.

Ashok, K., Behera, S. K., Rao, S. A., Weng, H., & Yamagata, T. (2007). El Nino Modoki and its possible teleconnection. Journal of Geophysical Research: Oceans, 112(11), 1–27. https://doi.org/10.1029/2006JC003798

Ashok, K. and Saji, N. H., 2007, "Impacts of ENSO and Indian Ocean Dipole Events on the Sub Regional Indian Summer Monsoon Rainfall", Journal of Natural Hazards, 42, 273-285.

Ashok, K., Yamagata, T., 2009b. Climate change: the El Niño with a difference. Nature 461, 481 484. doi:10.1038/461481a.

Ashok, K., Sabin, T. P., Swapna, P., & Murtugudde, R. G. (2012). Is a global warming signature emerging in the tropical Pacific? Geophysical Research Letters, 39(2), 1–5. https://doi.org/10.1029/2011GL050232

Ashok, K., Feba, F., & Tejavath, C. T. (2019). The Indian summer monsoon rainfall and ENSO. Mausam, 70(3), 443–452.

Ashok, K., Soraisam, B., Tejavath, C. T., & Cubasch, U. (2022). Summer monsoon over northeastern India during the last millennium. *International Journal of Climatology*, *42*(3), 1742–1753. https://doi.org/10.1002/joc.7332

Ashok Kumar, D. S. Pai, J. V. Singh, Ranjeet Singh, D. R. Sikka (2012): Statistical Models for Long-range Forecasting of Southwest Monsoon Rainfall over India Using Step Wise Regression and Neural Network, Atmospheric and Climate Sciences, 2, 322-336

Azdawiyah, A. T. S., Hariz, A. R. M. & Fairuz, M. S. M. 2015, Simulating the effects of changing planting date towards rice production in MADA area, Malaysia. J. Trop. Agric. Food Sci.43, 73–82.

Balderama, O. F., Alejandro, L. S., Barbosa, O. O. & Mata, M. B. 2016 Assessment of potential yield and climate change sensitivity of selected dryland crops in Cagayan Valley, Philippines using simulation models. BIMP-EAGA J. Sustain. Tour. Dev. 5, 102–113.

Banacos, P. C., & Schultz, D. M. (2005). The Use of Moisture Flux Convergence in Forecasting Convective Initiation: Historical and Operational Perspectives. Weather and Forecasting, 20(3), 351–366. https://doi.org/10.1175/WAF858.1

Banerjee, A. K., P. N. Sen and C. R. V. Raman, 1978: On foreshadowing southwest monsoon rainfall over India with midtropospheric circulation anomaly of April. Indian J. Meteor. Geophys.,29, 425-43

Basak J K, M. Ashraf Ali, Md. Nazrul Islam and Md. Abdur Rashid, Assessment of the effect of climate change on boro rice production in Bangladesh using DSSAT model, Journal of Civil Engineering (IEB), 38 (2) (2010) 95-108.

Basak J.K., M Ashraf Ali, Jiban Krishna Biswas and Md Nazrul Islam. Assessment of the Effect of Climate Change on Boro Rice Yield and Yield Gap using DSSAT Model, Bangladesh Rice Journal (2012),ISSN 1025-7330,VOL. 16, Page 63-70.

Behera S K, R. Krishnan, and T. Yamagata. "Unusual ocean-atmosphere conditions in the tropical Indian Ocean during 1994". In: Geophysical Research Letters 26.19 (1999), pp. 3001 3004.

Behera S.K.,Lau J.J,Sebastien Masson, Pascale Delecluse, Silvio Gualdi, Antonio Navarra,and T. Yamagata. "Paramount Impact of the Indian Ocean Dipole on the East African Short Rains: A CGCM Study". In: Journal of Climate 18.21 (2005), pp. 4514–4530. DOI:10.1175/JCLI3541.1.

Behera S and Yamagata T (2010) Imprint of the El Niño Modoki on decadal sea level changes, Geophys Res Lett, 37 L23702 doi: 10.1029/2010GL045936

Bemal, S., Singh, D., & Singh, S. (2013). Impact analysis of climate variability on rice productivity in eastern agroclimatic zone of Haryana by using DSSAT crop model. Journal of Agrometeorology, (Special Issue-II), 80–85.

Bhuvaneswari, K., Geethalakshmi, V., Lakshmanan, A., Anbhazhagan, R., & Nagothu Udaya Sekhar, D. (2014). Climate change impact assessment and developing adaptation strategies for rice crop in western zone of Tamil Nadu. Journal of Agrometeorology, 16(1), 39–43.

Bjerknes, J., 1969, "Atmospheric teleconnections from the equatorial Pacific", Mon. Weather Rev., 97, 163-172.

Blanford, H. F., 1884: On the connection of the Himalaya snowfall with dry winds and seasons of drought in India. Proc. Roy. Soc. London, 37, 3–22.

Bódai, T., Drótos, G., Ha, K. J., Lee, J. Y., & Chung, E. S. (2021). Nonlinear Forced Change and Nonergodicity: The Case of ENSO-Indian Monsoon and Global Precipitation Teleconnections. Frontiers in Earth Science, 8(April), 1–24. https://doi.org/10.3389/feart.2020.599785

Borah N. , Abhilash S., Joseph S. , Chattopadhyay R., S. S. and S. a. K. (2013). Development of Extended Range Prediction System Using CFSv2 and Its Verification. In IITM Research Report.

Boyaj, A., Ashok, K., Ghosh, S., Devanand, A., & Dandu, G. (2018). The Chennai extreme rainfall event in 2015: The Bay of Bengal connection. Climate Dynamics, 50(7–8), 2867–2879. https://doi.org/10.1007/s00382-017-3778-7

Boyaj A (2021), (UoH, Doctorate Thesis) Deciphering the relevance of background changes to extreme rainfall events in southern India.

Bryan C Weare. “A statistical study of the relationships between ocean surface temperatures and the Indian monsoon”. In: Journal of the Atmospheric Sciences 36.12 (1979), pp. 2279 2291.

Chang, C. P., Harr, P. and Ju, J., 2001, “Possible roles of Atlantic circulation on the weakening Indian monsoon rainfall-ENSO relationship”, Journal of Climate, 14, 11, 2376-2380.

Chattopadhyay R, SA Rao, CT Sabeerali, G George, DN Rao, A Dhakate, (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.

Chattopadhyay et al.(2018), Usability of extended range and seasonal weather forecast in Indian agriculture, MAUSAM, 69, 1 (January 2018), 29-44

Chen L, L Wang, T Li, and D-Z Sun (2018) Contrasting cloud radiative feedbacks during warm pool and cold tongue El Niños, SOLA, 14 126−131 doi:10.2151/sola.2018-022

Chen G Tam C-Y (2010) Different impact of two kinds of Pacific Ocean warming on tropical cyclone frequency over western North Pacific, Geophys Res Lett, 37 L01803 doi:10.1029/2009GL041708

Clough, S. A., Shephard, M. W., Mlawer, E. J., Delamere, J. S., Iacono, M. J., Cady-Pereira, K.,Boukabara, S., and Brown, P. D.: Atmospheric radiative transfer modeling: a summary of the AER codes, J. Quant. Spectrosc. Radiat. Transfer., 91, 233–244, 2005.

Congbin Fu, H. F. Diaz, and J. O. Fletcher.1986. Characteristics of the response of the sea surface temperature in the central Pacific associated with warm episodes of the Southern Oscillation. Mon. Weather Rev. 114:1716-1738.

Conway Declan. “Extreme rainfall events and lake level changes in East Africa: recent events and historical precedents”. In: The East African great lakes: limnology, palaeolimnology and biodiversity. Springer, 2002, pp. 63–92.

Conway Declan, Edward Allison, Richard Felstead, and Marisa Goulden. “Rainfall variability in East Africa: implications for natural resources management and livelihoods”. In: Philosophical Transactions of the Royal Society of London A: Mathematical, Physical and Engineering Sciences 363.1826 (2005), pp. 49–54. ISSN: 1364-503X. DOI: 10.1098/rsta.2004.1475.eprint:URL:http://rsta.royalsocietypublishing.org/content/363/1 26/49.

Dai, A. and Wigley, T. M. L., 2000, “Global patterns of ENSO induced precipitation”, Geophys. Res. Lett., 27, 1283-1286.

Dar, M. U. D., Aggarwal, R. & Kaur, S. 2017 Effect of climate change scenarios on yield and water balance components in rice-wheat cropping system in Central Punjab, India. J. Agrometeorol. 19, 226–229

Dharmarathna et al., 2011, Application of Decision Support System for Agrotechnology Transfer (DSSAT) Model to Optimize Irrigated Paddy Cultivation under changing Hydro-Climate. Annual Transactions of IESL, pp.[207-211],2011

Dhekale, B. S., Nageswararao, M. M., Nair, A., Mohanty, U. C., Swain, D. K., Singh, K. K. and Arunbabu, T., 2018, "Prediction of kharif rice yield at Kharagpur using disaggregated extended range rainfall forecasts", Theor Appl Climatol., 133, 1075-1091, doi: https://doi.org/10.1007/s00704-017-22.

DelSole T and J. Shukla, 2002: Linear prediction of Indian monsoon rainfall. J. Climate, 15, 3645 3658.

DelSole T. & Shukla J. Climate models produce skillful predictions of Indian summer monsoon rainfall. Geophys. Res. Lett. 39, L09703 (2012).

Dias, M. P. N. M., Navaratne, C. M., Weerasinghe, K. D. N., & Hettiarachchi, R. H. A. N. (2016). Application of DSSAT Crop Simulation Model to Identify the Changes of Rice Growth and Yield in Nilwala River Basin for Mid-centuries under Changing Climatic Conditions. Procedia Food Science, 6(Icsusl 2015), 159–163. https://doi.org/10.1016/j.profoo.2016.02.039

Economic Survey 2021-22, Ministry of Finance, Department of Economic Affairs, Economic Division, Government of India.

Ek, M. B., Mitchell, K. E., Lin, Y., Rogers, E., Grunmann, P., Koren, V., … Tarpley, J. D. (2003). Implementation of Noah land surface model advances in the National Centers for Environmental Prediction operational mesoscale Eta model. Journal of Geophysical Research: Atmospheres, 108(22), 1–16. https://doi.org/10.1029/2002jd003296

Feba, F., Ashok, K., & Ravichandran, M. (2019). Role of changed Indo-Pacific atmospheric circulation in the recent disconnect between the Indian summer monsoon and ENSO. Climate Dynamics, 52(3–4), 1461–1470. https://doi.org/10.1007/s00382-018-4207-2

Findlater, J. (1969) A Major Low-Level Air Current near the Indian Ocean during the Northern Summer. Quarterly Journal of the Royal Meteorological Society, 95, 362-380. http://dx.doi.org/10.1002/qj.49709540409.

Francis, P.A., Gadgil, S. A note on new indices for the equatorial Indian Ocean oscillation. J Earth Syst Sci 122, 1005–1011 (2013). https://doi.org/10.1007/s12040-013-0320-0

Freund, M. B., Brown, J. R., Henley, B. J., Karoly, D. J., & Brown, J. N. (2020). Warming patterns affect El Niño diversity in CMIP5 and CMIP6 models. Journal of Climate, 33(19), 8237 8260. https://doi.org/10.1175/JCLI-D-19-0890.1

Frisinger HH. Aristotle's legacy in meteorology. Bull Am Meteorol Soc 1973, 54: 198–204.

Gadgil Sulochana, Vinayachandran P N and Francis P A (2003) Droughts of Indian summer monsoon: Role of clouds over the Indian Ocean; Curr. Sci. 85 1713–1719.

Gadgil, Sulochana and Vinayachandran, PN and Francis, PA and Gadgil, Siddhartha (2004) Extremes of the Indian summer monsoon rainfall, ENSO and equatorial Indian Ocean oscillation. In: Geophysical Research Letters, 31 (12). L12213-1-4.

Gadgil, S., M. Rajeevan, and R. Nanjundiah, (2005): Monsoon prediction - Why yet another failure?, Curr. Sci., 88(9), 1389–1400.

Gadgil, S. and Gadgil, S. 2006. The Indian Monsoon, GDP and Agriculture. Economic and Political Weekly, 41 (47): 4887-4895.

Gadgil, S., 2018: The monsoon system: Land–sea breeze or the ITCZ? Journal of Earth System Science, 127 (1), 1.

Ghofar Abdul. “Co-existence in Small-pelagic Fish Resources of The South Coast of East Java,Straits of Bali, Alas and Sape-Indonesia”. In: ILMU KELAUTAN: Indonesian Journal of Marine Sciences 10.3 (2005), pp. 149–157.

Geethalakshmi, V., Lakshmanan, A., Rajalakshmi, D., Jagannathan, R., Sridhar, G., Ramaraj, A. P., … Anbhazhagan, R. (2011). Climate change impact assessment and adaptation strategies to sustain rice production in Cauvery basin of Tamil Nadu. Current Science, 101(3), 342–347.

Gill, A. E., 1980, “Some simple solutions for heat-induced tropical circulation”, Quarterly Journal of Royal Meteorological Society, 106, 447-462.

Godbole, R. V. (1977). The composite structure of the monsoon depression. Tellus, 29, 25–40.

Goswami B.N., Venugopal V., Sengupta D., Madhusoodanan M.S. and Xavier P.K. (2006): Increasing trend of extreme rain events over India in a warming environment.Science, 314, 1442–1445.

Goswami, B., & Chakravorty, S. Dynamics of the Indian Summer Monsoon Climate. Oxford Research Encyclopedia of Climate Science. https://oxfordre.com/climatescience/view/10.1093/acrefore/9780190228620.001.001/acefore-9780190228620-e-613.

Gowariker, V., V. Thapliyal, R. P. Sarker, G. S. Mandal, and D. R. Sikka, 1989: Parametric and power regression models: New approach to long range forecasting of monsoon rainfall in India. Mausam, 40, 115–122.

Gowariker, V., V. Thapliyal, S. M. Kulshrestha, G. S. Mandal, N. S. Roy, and D. R. Sikka, 1991: A power regression model for long range forecast of southwest monsoon rainfall over India. Mausam, 42, 125–130.

Griffies, S. M., Harrison, M. J., Pacanowski, Ronald, C., & Rosati, A. (2004). A Technical Guide to MOM4, GFDL OCEAN GROUP TECHNICAL REPORT NO. 5. NOAA/Geophysical Fluid Dynamics Laboratory, Available online atwww.gfdl.noaa.gov.

Guan, Z., K. Ashok, and T. Yamagata (2003a), The summertime response of the tropical atmosphere to the Indian Ocean sea surface temperature anomalies, J. Metor. Soc. Japan, 81, 533 – 561.

Guan, Z., and T. Yamagata (2003b), The unusual summer of 1994 in East Asia: IOD teleconnections, Geophys. Res. Lett., 30(10), 1544, doi:10.1029/2002GL016831.

Guhathakurta, P. (2006). Long range monsoon rainfall prediction of 2005 for the districts and sub division kerala with artificial neural network. Current science, Vol. 90, pp. 773-79.

Gupta, R., Mishra, A., 2019. Climate change induced impact and uncertainty of rice yield of agro ecological zones of India. Agricultural Systems 173, 1–11. https://doi.org/10.1016/j.agsy.2019.01.009

Hirst Anthony C and JS Godfrey. "The response to a sudden change in Indonesian throughflow in a global ocean GCM". In: Journal of Physical Oceanography 24.9 (1994), pp. 1895–1910.

Hisard Philippe. "Observation de réponses de types El Niño dans l'Atlantique tropical oriental Golfe de Guinée". In: Oceanologica Acta 3.1 (1980), pp. 69–78.

Horii, T., Ueki, I., & Hanawa, K. (2012). Breakdown of ENSO predictors in the 2000s: Decadal changes of recharge/discharge-SST phase relation and atmospheric intraseasonal forcing. Geophysical Research Letters, 39(10), 2–6. https://doi.org/10.1029/2012GL051740

Hrudya, P.H., Varikoden, H. & Vishnu, R. A review on the Indian summer monsoon rainfall, variability and its association with ENSO and IOD. Meteorol Atmos Phys 133, 1–14 (2021). https://doi.org/10.1007/s00703-020-00734-5

Iacono MJ, Mlawer EJ, Clough SA, Morcrette J-J. Impact of an improved longwave radiation model RRTM, on the energy budget and thermodynamic properties of the NCAR community climate model, CCM3. J Geophys Res 2000;105(14):873–90.

IBSNAT, 1994, "Decision Support Systems for Agrotechnology Version 3.0 (DSSAT V3.0)", International Benchmark Sites Network for Agrotechnology Transfer Project, Honolulu, Hawaii: University of Hawaii, College of Tropical Agriculture and Human Resources, Deptt. of Agronomy and Soil Science.

Izumo T, Lengaigne M, Vialard J, Luo JJ, Yamagata T, Madec G (2014) Influence of Indian Ocean Dipole and Pacific recharge on following year's El Niño: interdecadal robustness. Clim Dyn 42(1–2):291–310

Jadhav J, Swapna P, Shamal M, & Ashok K (2015)On the possible cause of distinct El Niño types in the recent decades, Scientific Reports, 5, 1–21. https://doi.org/10.1038/srep17009

Jagannathan P (1960) Seasonal forecasting in India: A review; Published by India Meteorological Department Pune, 67 pp.

Jain, S., Sastri, A., & Kumar, B. (2018). Comparison of DSSAT and InfoCrop simulation model for rice production under irrigated and rainfed conditions. 6(4), 665–669.

Jeong, H., Jang, T., Seong, C., & Park, S. (2014). Assessing nitrogen fertilizer rates and split applications using the DSSAT model for rice irrigated with urban wastewater. Agricultural Water Management, 141, 1–9. https://doi.org/10.1016/j.agwat.2014.04.009

Jha, R. K., Kalita, P. K., & Jat, R. (2020). Development of production management strategies for a long-duration rice variety: Rajendra Mahsuri—using crop growth model, DSSAT, for the state of Bihar, India. Paddy and Water Environment, 18(3), 531–545. https://doi.org/10.1007/s10333-020-00799-3

Jones, J. W., Hoogenboom, G., Porter, C. H., Boote, K. J., Batchelor, W. D., Hunt, L. A., … Ritchie, J. T. (2003). The DSSAT cropping system model. In European Journal of Agronomy (Vol. 18). https://doi.org/10.1016/S1161-0301(02)00107-7

Joseph, P. V., R. K. Mukhopadhyaya, W. V. Dixit, et al., 1981: Meridional wind index for the long range forecasting of Indian summer monsoon rainfall, Mausam, 32, 31–34.

Joseph PV, Eishcheid JK, Pyle RJ. 1994. Interannual variability of the onset of the Indian summer monsoon and its association with atmospheric features, El Nino and sea surface temperature anomalies. ˜ Journal of Climate 7: 81–105.

Joseph S, Sahai AK, Sharmila S, Abhilash S, Borah N, Pillai PA, Chattopadhyay R, Kumar A (2013) Extended Range Prediction of Uttarakhand Heavy Rainfall Event by an Ensemble Prediction System based on CFSv2. IITM Res Rep ISSN 0252-1075 ESSO/IITM/SERP/SR/03(2013)/180

Ju, J. and Slingo, J., 1995, "The Asian summer monsoon and ENSO", Q. J. R. Meteorol. Soc., 121, 525, 1133-1168.

Kaeomuangmoon, T., A. Jintrawet, C. Chotamonsak, U. Singh, C. Buddhaboon, P. Naoujanon, S. Kongton, Y. Kono, and G. Hoogenboom. 2019. Estimating seasonal fragrant rice production in Thailand using a spatial crop modelling and weather forecasting approach. The Journal of Agricultural Science 157(7). https://doi:10.1017/S0021859619000881

Kalnay, E., Kanamitsu, M., Kistler, R., Collins, W., Deaven, D., Gandin, L., et al., 1996. The NCEP/NCAR 40-year reanalysis project. B. Am. Meteorol. Soc. 77, 437–471. doi:10.1175/1520-0477(1996)077<0437:TNYRP>2.0.CO;2.

Kant, K., Bora, P. K., & Saikia, U. S. (2018). Calibration of dssat-CERES-rice model for rice cultivars under different N-levels in Meghalaya, India. Journal of Agrometeorology, 20(4), 322–324.

Kao, H. Y., & Yu, J. Y. (2009). Contrasting Eastern-Pacific and Central-Pacific types of ENSO. Journal of Climate, 22(3), 615–632. https://doi.org/10.1175/2008JCLI2309.1

Kawamura, R., 1998, "A possible mechanism of the Asian summer monsoon-ENSO coupling", J. Meteorol. Soc. Japan, 76, 1009-1027.

Kawamura, R., Uemura, K., & Suppiah, R. (2005). On the Recent Change of the Indian Summer Monsoon-ENSO Relationship. Sola, 1, 201–204. https://doi.org/10.2151/sola.2005-052

Keshavamurty, R. (1982). Response of the atmosphere to sea surface temperature anomalies over the equatorial Pacific and the teleconnections of the Southern Oscillation. Journal of the Atmospheric Sciences, Vol. 39, pp. 1241–1259. https://doi.org/10.1175/1520 0469(1982)039<1241:ROTATS>2.0.CO;2

Kim, Y.-J., and A. Arakawa (1995), Improvement of orographic gravitywave parameterization using a mesoscale gravity-wave model,J. Atmos.Sci.,52, 875–1902.

Kim H-M, Webster PJ and Curry JA. Impact of shifting patterns of Pacific Ocean warming on North Atlantic tropical cyclones. Science 2009; 325: 77–80.

Koteswaram, P., 1958, "Easterly jet streams in the tropics", Tellus, 10, 43-57.

Kobayashi, N. 1974, Interannual variations of tropical easterly jet stream and rainfall in South Asia, Geophys. Mag. 37, 123-134

Kothawale, D., and M. Rajeevan, 2017: Monthly, seasonal and annual rainfall time series for all India,homogeneous regions and meteorological subdivisions: 1871–2016. IITM Research Report No. RR-138.

Krishnamurthy, V., and B. N. Goswami, 2000: Indian monsoon-ENSO relationship on inter decadal time scales. J. Climate, 13, 579–595.

Krishnamurthy, V., & Kirtman, B. P. (2003). Variability of the Indian Ocean: Relation to monsoon and ENSO. Quarterly Journal of the Royal Meteorological Society, 129(590 PART A), 1623–1646. https://doi.org/10.1256/qj.01.166

Krishnaswamy, Jagdish & Vaidyanathan, Srinivas & Rajagopalan, Balaji & Bonell, Mike & Sankaran, Mahesh & Bhalla, Ravinder & Badiger, Shrinivas. (2014). Non-stationary and non-linear influence of ENSO and Indian Ocean Dipole on the variability of Indian monsoon rainfall and extreme rain events. Climate Dynamics. 45. 1-10. 10.1007/s00382 014-2288-0.

Kucharski Fred, Arne Biastoch, Karumuri Ashok and Dongliang Yuan, Interacting Climates of Ocean Basins Observations, Mechanisms, Predictability, and Impacts, Cambridge University Press,(2020), pp. 153 - 185 DOI: https://doi.org/10.1017/9781108610995.006

Kug J-S, Kang I-S (2006) Interactive feedback between the Indian Ocean and ENSO. J Clim 19:1784–1801.

Kug, J. S., Jin, F. F. and An, S. I., 2009, “Two-types of El Niño events: Cold Tongue El Niño and Warm Pool El Niño”, J. Climate, 22, 1499-1515.

Kug, J. S., Choi, J., An, S. Il, Jin, F. F., & wittenberg, A. T. (2010). Warm pool and cold tongue El Ni??o events as simulated by the GFDL 2.1 coupled GCM. Journal of Climate, 23(5), 1226–1239. https://doi.org/10.1175/2009JCLI3293.1

Kumar KK, Rajagopalan B, Cane MA (1999) On the weakening relationship between the Indian Monsoon and ENSO. Science 284(5423):2156–2159. https ://doi.org/10.1126/science.284.5423.2156

Kumar, K. K., Kumar, K. R., Ashrit, R. G., Deshpande, N. R. and Hansen, J. W.: 2004, 'Climate impacts on Indian agricutlure, International Journal of Climatology 24(11), 1375–1393.

Kumar KK, Rajagopalan B, Hoerling M, Bates G, Cane M (2006) Unraveling the Mystery of Indian Monsoon Failure During El Niño. Science 314(5796):115–119 http://www.sciencemag.org/cgi/doi/10.1126/science.1131152

Lal, H.; Rao, N.H.; Sarma, P.B.S (1994) Can medium-range weather forecasts influence irrigation scheduling? Current Science 66(1): 60-63

Lal, M., Singh, K. K., Rathore, L. S., Srinivasan, G., & Saseendran, S. A. (1998). Vulnerability of rice and wheat yields in NW India to future changes in climate. Agricultural and Forest Meteorology, 89(2), 101–114. https://doi.org/10.1016/S0168-1923(97)00064-6

Lal P, Prakash A, Kumar A, Srivastava PK, Saikia P, Pandey AC, Srivastava P, Khan ML (2020) Evaluating the 2018 extreme flood hazard events in Kerala, India. Remote Sens Lett 11(5):436–445. https://doi.org/10.1080/2150704X.2020.1730468

Lanie Alejo (2020). Assessing the impacts of climate change on aerobic rice production using the dssat-ceres-rice model. Journal of Water and Climate Change, 12(3), 696–708. https://doi.org/10.2166/wcc.2020.286

Larkin, N. K. and Harrison, D. E., 2005, "Global seasonal temperature and precipitation anomalies during El Niño autumn and winter", Geophys. Res. Lett., 32, L16705, doi:10.1029/2005GL022860.

Lau, N. C. and Nath, M. J., 2000, "Impact of ENSO on the variability of the Asian-Australian monsoons as simulated in GCM experiments", J. Climate, 13, 4287-4309.

Lee, T., McPhaden, M.J., 2010. Increasing intensity of El Niño in the central equatorial Pacific. Journal of Geophysical Research Letters 37, L14603. http://dx.doi.org/10.1029/2010GL044007.

Li C. Interaction between anomalous winter monsoon in East Asia and El Nino events. Adv Atmospheric Sci 1990; 7: 36–46.

Lott, B. F., & Miller, M. J. (1997);A new subgrid-scale orographic drag parametrization: Its formulation and testing.Q. J. R. Mefeorol. SOC. (1997), 123, pp. 101-127

Lumban-Gaol Jonson et al. "Variability of satellite-derived sea surface height anomaly, and its relationship with Bigeye tuna (Thunnus obesus) catch in the Eastern Indian Ocean". In: European Journal of Remote Sensing 48 (2015), pp.465-477

Marathe, S., Ashok, K., Swapna, P., & Sabin, T. P. (2015). Revisiting El Niño Modokis. Climate Dynamics, 45(11–12), 3527–3545. https://doi.org/10.1007/s00382-015-2555-8

Marathe S, Ashok Karumuri,4 - The El Niño Modoki,Editor(s): Swadhin Kumar Behera,Tropical and Extratropical Air-Sea Interactions, Elsevier, (2021), Pages 93 114,ISBN 9780128181560, https://doi.org/10.1016/B978-0-12-818156-0.00009-5.

Marathe, Shamal & Terray, Pascal & Ashok, Karumuri. (2021). Tropical Indian Ocean and ENSO relationships in a changed climate. Climate Dynamics. 56. 10.1007/s00382-021-05641-y.

Masumoto Yukio and Yamagata T. "Seasonal variations of the Indonesian throughflow in a general ocean circulation model". In: Journal of Geophysical Research: Oceans 101.C5 (1996),pp. 12287–12293. Meyers

McPhaden MJ (2012) A 21st century shift in the relationship between ENSO SST and warm water volume anomalies, Geophys Res Lett, 39 L09706 doi: 10.1029/2012GL051826

Mehraj Dar,. U. D. (2017). Modeling Climate Change Impact; A Study on Different Procedures and Strategies: A Review. International Journal of Pure & Applied Bioscience, 5(6), 183 200. https://doi.org/10.18782/2320-7051.6016

Meyers G. M. "Variation of Indonesian throughflow and the El Niño-Southern Oscillation". In:Journal of Geophysical Research: Oceans 101.C5 (1996), pp. 12255–12263

Moorthi, S., H.-L. Pan, and P. Caplan, 2001: Changes to the 2001 NCEP operational MRF/AVN global analysis/forecast system. Tech. Procedures Bull. 484, Office of Meteorology, National Weather Service, 14 pp. [Available online at http://205.156.54.206/om/tpb/484.htm.]

Murakami, T, 1987.: Effects of the Tibetan Plateau. In Monsoon Meteorology, edited by C. P. Chang and T. N. Krishnamurti, Oxford University Press, New York, 235–270.

Murari, K., Das, G. K., Chaudhary, S. J. L., & Puranik, H. V. (2018). Prediction of grain yield of rice using simulation model in Chhattisgarh plains. 7(5), 2314–2317.

Murtugudde, R., and A. J. Busalacchi (1999), Interannual variability of the dynamics and thermodynamics of the Indian Ocean, J. Clim.,12, 2300– 2326.

Murtugudde, R., J. P. McCreary, and A. J. Busalacchi, 2000: Oceanic processes associated with anomalous events in the Indian Ocean with relevance to 1997–98. J. Geophys. Res., 105, 3295–3306.

Naik Banoth Balaji, Gade Sreenivas, Danda Raji Reddy and Padamati Leela Rani (2016). Application of CERES-Rice Model to Identify Optimum Sowing Window for Different Rice Varieties under Aerobic Culture. Int. J. Curr. Res. Biosci. Plant Biol. 2016, 3(4):75-82, doi: http://dx.doi.org/10.20546/ijcrbp.2016.304.012

Nanjundiah R S, Francis P A, Ved M and Gadgil S, (2013) Predicting the extreme of Indian summer monsoon rainfall with coupled ocean-atmosphere models Curr. Sci. 104 1380–93

Nasir, I.R., F. Rasul, A. Ahmad, H.N. Asghar, and G. Hoogenboom. 2020. Climate change impacts and adaptations for fine, coarse, and hybrid rice using CERES-Rice. Environmental Science and Pollution Research 27:9454–9464.

Navarra, A., Ward, M. N. and Miyakoda, K., 1999, "Tropical-wide teleconnection and oscillation I: Teleconnection indices and type I/type II states", Quart. J. Roy. Meteor. Soc., 125, 2909 2935.

Nicholls, N. (1983). Predicting Indian monsoon rainfall from sea–surface temperature in the Indonesia–north Australia area. Nature, 306, 576–577.

Nigam, S., 1994, "On the dynamical basis for the Asian summer monsoon rainfall-El Niño relationship", J. Climate, 7, 1750-1771.

Ngar-Cheung Lau and Mary Jo Nath. "The role of the "atmospheric bridge" in linking tropical Pacific ENSO events to extratropical SST anomalies". In: Journal of Climate 9.9 (1996), pp. 2036–2057.

Nyang'au WO, Mati BM, Kalamwa K, Wanjogu RK, Kiplagat LK., 2014. Estimating rice yield under changing weather conditions in Kenya using CERES rice model. International Journal of Agronomy. vol 2014.

Pai, D. S., Sridhar, L., Rajeevan, M., Sreejith, O. P., Satbhai, N. S., & Mukhopadyay, 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 data sets of different spatial resolutions and time period. 1(January), 1 18.

Pai, D. S., Sridhar, L., Rajeevan, M., Sreejith, O. P., Satbhai, N. S., & Mukhopadhyay, B(2014). (1901-2010) daily gridded rainfall data set over India and its comparison with existing data sets over the region. 1(January), 1–18.

Pai DS, Bandgar A, Devi S, Musale M, Badwaik MR, Kundale AP, Gadgil S, Mohapatra M, Rajeevan M. 2020. New normal dates of onset/progress and withdrawal of southwest monsoon over India. Mausam Vol. 71 No. 4 (2020); Pages 553-570.

Palmer, T. N., Brankovic, C., Viterbo P. and Miller, M. J., 1992, "Modeling interanual variations of summer monsoons", J. Climate, 5, 399-417.

Pant G.B. and Parthasarathy B. 1981 : 'Some aspects of an association between the Southern Oscillation and Indian summer monsoon' Arch. Meteor. Geophys. Bioklimatol., Vol. 29, pp. 245–251.

Parthasarathy, B., and D. A. Mooley, 1978: Some features of a long homogeneous series of Indian summer monsoon rainfall. Mon. Wea. Rev., 106, 771–781.

Parthasarathy, B., Rupa Kumar, K., & Munot, A. (1993). Homogeneous Indian monsoon rainfall: Variability and prediction. Proceedings of the Indian Academy of Sciences - Earth and Planetary Sciences, 120, 121–155

Pattanaik, D. R., Rathore, L. S., & Kumar, A. (2013). Observed and Forecasted Intraseasonal Activity of Southwest Monsoon Rainfall over India During 2010, 2011 and 2012. Pure and Applied Geophysics, 170(12), 2305–2328. https://doi.org/10.1007/s00024-013-0670-1

Pattanaik, D. R., & Das, A. K. (2015). Prospect of application of extended range forecast in water resource management: a case study over the Mahanadi River basin. Natural Hazards, 77(2), 575–595. https://doi.org/10.1007/s11069-015-1610-4

Pattanaik et al. (2019), Evolution of operational extended-range forecast system of IMD : Prospects of its applications in different sectors. MAUSAM, 70, 2 (April 2019), 233-264

Phakamas, N., A. Jintrawet, A. Patanothai, P. Sringam, and G. Hoogenboom. 2013. Estimation of solar radiation based on air temperature and application with the DSSAT v4.5 peanut and rice simulation models in Thailand. Agricultural and Forest Meteorology 180(1):182-193.

Picaut J, Masia F and Du Penhoat Y. An advective-reflective conceptual model for the oscillatory nature of the ENSO. Science 1997; 277: 663–6.

Pickering N.B., Hansen J.W., Jones J.W., Wells C.M., Chan V.K., and Godwin D.C. 1994. WeatherMan: a utility for managing and generating daily weather data. Agron. J. 86: 332 337.

Pradhan, PK, B Preethi, K Ashok, R Krishnan, and AK Sahai (2011)Modoki, Indian Ocean Dipole, and western North Pacific typhoons: Possible implications for extreme events, JGeophys Res, 116, D18108, doi:10.1029/2011JD015666.

Prajeesh, A. G., Ashok, K., & Rao, D. V. B. (2013). Falling monsoon depression frequency: a Gray-Sikka conditions perspective. Scientific Reports, 3(1), 2989. https://doi.org/10.1038/srep02989.

Prakash SMC, Sathiyamoorthy V, Gairola RM (2013) Increasing trend of northeast monsoon rainfall over the equatorial Indian Ocean and peninsular India. Theor Appl Climatol 112(1 2):185–191. doi:10.1007/s00704-012-0719-6

Preethi B, Kripalani RH, Kumar KK (2010) Indian summer monsoonrainfall variability in global coupled ocean-atmospheric models.Clim Dyn 35:1521–1539. doi:10.1007/s00382-009 0657-x

Preethi B et al., (2015), Impacts of the ENSO Modoki and other Tropical Indo Pacific Climate Drivers on African Rainfall, Sci Rep, 5, 16653; doi: 10.1038/srep16653.

Rajagopal V. (2009), Characterization and Classification of Soils of Warangal District of Central Telangana Zone.

Rajeevan M, P.Guhathakurta and V.Thapliyal, 2000, New Models for Long range forecasts of summer monsoon rainfall over NW India and Peninsular India, Met and Atmos. Phys.,73, 211-225

Rajeevan M, Prediction of Indian summer monsoon: Status, Problems and prospects, , Current Science, 2001, 81, 101- 107.

Rajeevan M, Pai. D S, Anil Kumar R, 2005: New statistical models for long range forecasting of southwest monsoon rainfall over India, NCC Research Report, 1, India Meteorological Department.

Rajeevan M, Pai. D S, Anil Kumar R and Lal B, 2007: New statistical models for long range forecasting of south west monsoon rainfall over India, Climate Dynamics, 28, 813-828.

Rajeevan, M. ; Unnikrishnan, C. K. ; Preethi, B. (2012) Evaluation of the ENSEMBLES multi model seasonal forecasts of Indian summer monsoon variability Climate Dynamics, 38 (11-12). pp. 2257-2274. ISSN 0930-7575

Ramage, C., 1971: [Monsoon Meteorology]. Academic Press.

Ramu, D. A., C. T. Sabeerali,R. Chattopadhyay, D. N. Rao, G. George,A. R. Dhakate, K. Salunke, A. Srivastava,and S. A. Rao (2016), Indian summer monsoon rainfall simulation and] prediction skill in the CFSv2 coupled model: Impact of atmospheric horizontal resolution, J. Geophys. Res. Atmos., 121, 2205–2221, doi:10.1002/2015JD024629.

Ramu, D. A., Rao, S. A., Pillai, P. A., Pradhan, M., George, G., Rao, D. N., … Rajeevan, M. (2017). Prediction of seasonal summer monsoon rainfall over homogenous regions of India using dynamical prediction system. Journal of Hydrology, 546, 103–112. https://doi.org/10.1016/j.jhydrol.2017.01.010

Rao, Y., 1976: Southwest monsoon (meteorological monograph, synoptic meteorology no. 1). Indian Meteorological Department, New Delhi, 367pp.

Rao, S. A., S. K. Behera, Y. Masumoto, and T. Yamagata, Interannual variability in the subsurface tropical Indian Ocean with a special emphasis on the Indian Ocean Dipole, Deep-Sea Res. II, 49, 1549–1572, 2002

Rao Suryachandra A , SK BEHERA, T YAMAGATA (2002): On the relative influence of IOD and ENSO on the tropical Indian Ocean., Nippon Kaiyo Gakkai Taikai Koen Yoshishu, 2003, 60.

Rao, S.A., Goswami, B.N., Sahai, A.K., Rajagopal, E.N., Mukhopadhyay, P., Rajeevan, M., Nayak, S., Rathore, L.S., Shenoi, S.S.C.,Ramesh, K.J., Nanjundiah, R.S., Ravichandran, M., Mitra, A.K.,Pai, D.S., Bhowmik, S.K.R., Hazra, A., Mahapatra, S., Saha,S.K., Chaudhari, H.S., Joseph, S., Sreenivas, P., Pokhrel, S., Pillai, P.A., Chattopadhyay, R., Deshpande, M., Krishna, R.P.M.,Das, R.S., Prasad, V.S., Abhilash, S., Panickal, S., Krishnan, R.,Kumar, S., Ramu, D.A., Reddy, S.S., Arora, A., Goswami, T.,Rai, A., Srivastava, A., Pradhan, M., Tirkey, S., Ganai, M., Mandal, R., Dey, A., Sarkar, S., Malviya, S., Dhakate, A., Salunke,K., Maini, P.: Monsoon Mission: A Targeted Activity to Improve Monsoon Prediction across Scales. Bull. Am. Meteorol. Soc. 100,2509–2532 (2019a). https://doi.org/10.1175/BAMS-D-17-0330.1

Rasmusson, E. M. and Carpenter, T. H., 1983, “The relationship between the eastern Pacific Sea surface temperature and rainfall over India and Sri Lanka”, Mon. Weather. Rev., 111, 517 528.

Rathore, L. S., Bhowmik, S. K. Roy and Chattopadhyay, N., 2009, “Integrated Agromet Advisory Services in India”, Challenges and Opportunities in Agrometeorology, Springer Publication, New York, 195-205.

Rathore, L. S., Chattopadhyay, N. and Singh, K. K., 2013(a,) “Delivering advisory services by mobile phones’ in the book of Climate Exchange”, World Meteorological Organisation (WMO), Tudor Rose publication, United Kingdom, (UK), 35-38.

Rathore, L. S., Chattopadhyay, N. and Singh, K. K., 2013(b), “Reaching farming communities in India through Farmer Awareness Programmes”, in the book of “Climate Exchange, World Meteorological Organisation (WMO), Tudor Rose publication, United Kingdom, (UK), 20-23.

Rauff, K.O. and Bello, R. (2015) A Review of Crop Growth Simulation Models as Tools for Agricultural Meteorology. Agricultural Sciences, 6, 1098-1105

Rawlinson, H. G. (1916). Intercourse between India and the Western World. Cambridge University Press.

Ray, M., Roul, P. K., & Baliarsingh, A. (2018). Application of DSSAT Crop Simulation Model to Estimate Rice Yield in Keonjhar District of Odisha (India) under Changing Climatic Conditions. International Journal of Current Microbiology and Applied Sciences, 7(04), 659–667. https://doi.org/10.20546/ijcmas.2018.704.075

Rayner, N. A., Parker, D. E., Horton, E. B., Folland, C. K., Alexander, L. V., Rowell, D. P., … Kaplan, A. (2003). Global analyses of sea surface temperature, sea ice, and night marine air temperature since the late nineteenth century. Journal of Geophysical Research, 108(D14), 4407. https://doi.org/10.1029/2002JD002670

Reppin Jörg, Friedrich A Schott, Jürgen Fischer, and Detlef Quadfasel. "Equatorial currents and transports in the upper central Indian Ocean: Annual cycle and interannual variability". In: Journal of Geophysical Research: Oceans 104.C7 (1999), pp. 15495–15514.

Risbey James S, Michael J Pook, Peter C McIntosh, Matthew C Wheeler, and Harry H Hendon, "On the remote drivers of rainfall variability in Australia". In: Monthly Weather Review 137.10(2009), pp. 3233–3253.

Ritchie, J. T., Singh, U., Godwin, D. and Bowen, W. T., 1998, "Cereal Growth Development and Yield", In: Understanding Options for Agricultural Production, Tsuji, G. Y., Hoogenboom, G. and. Thornton, P. K. (Eds.), Kluwer Academic Publishers, , The Netherlands, 79-97.

Ropelewski CF and Halpert MS. North American precipitation and temperature patterns associated with the El Ni˜no/Southern Oscillation (ENSO). Mon Weather Rev 1986; 114: 2352–62.

Roy, I., Tedeschi, R. G., & Collins, M. (2019). ENSO teleconnections to the Indian summer monsoon under changing climate. International Journal of Climatology, 39(6), 3031–3042. https://doi.org/10.1002/joc.5999

Saha, S., Moorthi, S., Pan, H. L., Wu, X., Wang, J., Nadiga, S., … Goldberg, M. (2010). The NCEP climate forecast system reanalysis. Bulletin of the American Meteorological Society, 91(8), 1015–1057. https://doi.org/10.1175/2010BAMS3001.1

Saha, S., Moorthi, S., Wu, X., Wang, J., Nadiga, S., Tripp, P., et al. (2013). The NCEP climate forecast system version 2. Journal of Climate, 27(6), 2185–2208. https://doi.org/10.1175/JCLI-D-12-00823.1

Saha, S., Moorthi, S., Wu, X., Wang, J., Nadiga, S., Tripp, P., Behringer,D., Hou, Y.T., Chuang, H.Y., Iredell, M., Ek, M., Meng, J., Yang,R., Mendez, M.P., Van Den Dool, H., Zhang, Q., Wang, W., Chen,M., Becker, E.: The NCEP climate forecast system version 2. J. Clim. (2014). https://doi.org/10.1175/JCLI-D-12-00823.1

Sahai, A. K., A. M. Grimm, V. Satyan, and G. B. Pant, 2003: Long-lead prediction of Indian summer monsoon rainfall from global SST evolution. Climate Dyn., 20 (7/8), 855– 863.

Sahai AK, Sharmila S, Abhilash S, Chattopadhyay R, Borah N, Krishna RPM, Joseph S, Roxy M, De S, Pattnaik S, Pillai PA (2013) Simulation and extended range prediction of monsoon intraseasonal oscillations in NCEP CFS/GFS version 2 framework. Curr Sci 104(10):1394–1408. http://www.jstor.org/stable/24092513

Sailaja B, Voleti S.R, Subrahmanyam D and Kumar R. N. (2014), Conference Paper, Evaluation and Application of DSSAT-Rice Model to irrigated ecosystem. Agricultural & Horticultural Sciences. 2(4), 9881.

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

Saji H. and Yamagata T. “Possible Impacts of Indian Ocean Dipole mode events on global climate”. In: Climate Research 25(2) (2003), pp. 151–169. DOI: 10.3354/cr025151.

Saji N. Hameed. The Indian Ocean Dipole, in Oxford Research Encyclopaedia of Climate Science (ed. Hans von Storch) (Oxford University Press, Oxford, 2018)

Sarachik, Edward S and Cane, Mark A. The El Niño-Southern Oscillation Phenomenon. Cambridge University Press

Sastri A. S. R. A. S, Rai S.K, Srivastava A.K and Chaudhury J.L: Effect of temperature and sunshine on the productivity of rice crop. Mausam, (1995).47.1, 85-90

Satpute, S. B., Bandyopadhyay, S., & Ulemale, P. H. (2018). Simulation modeling of Kharif rice cultivars at different dates of transplanting using ceres 4 . 5v model for coochbehar district , West Bengal. 7(4), 482–485.

Schiller A, JS Godfrey, PC McIntosh, G. M. Meyers, and SE Wijffels. "Seasonal near-surface dynamics and thermodynamics of the Indian Ocean and Indonesian Throughflow in a global ocean general circulation model". In: Journal of Physical Oceanography 28.11 (1998), pp. 2288–2312.

Schneider Niklas. "The Indonesian Throughflow and the global climate system". In: Journal of Climate 11.4 (1998), pp.

Schott FA, Xie S-P and McCreary JP, Jr. Indian Ocean circulation and climate variability. Rev Geophys 2009; 47: RG1002, doi:10.1029/2007RG000245

Selvaraju, R. (2003). Impact of El Niño-southern oscillation on Indian foodgrain production. *International Journal of Climatology*, *23*(2), 187–206. https://doi.org/10.1002/joc.869

Sikka, D., 1980: Some aspects of the large-scale fluctuations of summer monsoon rainfall over India in relation to fluctuations in the planetary and regional scale circulation parameters. Proceedings of the Indian Academy of Sciences-Earth and Planetary Sciences, 89 (2), 179 195.

Sikka, D. R., and Sulochana Gadgil, 1980: On the maximum cloud zone and the ITCZ over India longitude during the southwest monsoon. Mon. Weather Rev.,108, 1840-1853.

Singh, U., Ritchie, J.T., 1993. Simulating the Impact of Climate Change on Crop Growth and Nutrient Dynamics using the CERES-Rice Model. Journal of Agricultural Meteorology, 48(5):819-822. https://doi.org/10.2480/agrmet.48.819

Singh, R.P., S. Pal, and M. Morris. 1995. Maize Research and Development and Seed Production in India: Contributions of the Public and Private Sectors. CIMMYT Economics Working Paper 95-03. Mexico, D.F.: CIMMYT.

Singh, P. K., Singh, K. K., Bhan, S. C., Baxla, A. K., Akhilesh, G., Balasubramanian, R. & Rathore, L. S. (2015) Potential yield and yield gap analysis of rice (Oryza sativa L.) in eastern and north eastern regions of India using CERES-rice model. J. Agrometeorol. 17, 194–198

Shams S. Islam, and Ahmed Khairul Hasan (2021). Determination of Upland Rice Cultivar Coefficient Specific Parameters for DSSAT (Version 4.7)-CERES-Rice Crop Simulation Model and Evaluation of the Crop Model under Different Temperature Treatments conditions. American Journal of Plant Sciences, 12(05), 782–795. https://doi.org/10.4236/ajps.2021.125054

Sharma A. K (2015), Economic Benefits of Dynamic Weather and Ocean Information and Advisory Services in India and Cost and Pricing of Customized Products and Services of ESSO-NCMRWF & ESSO-INCOIS. https://incois.gov.in/documents/ImpactAssessment-NCAER2015.pdf

Sharmila S, Pillai PA, Joseph S, Roxy M, Krishna RPM, Chattopadhyay R, Goswami BN (2013) Role of ocean-atmosphere interaction on northward propagation of Indian summer monsoon intra-seasonal oscillations (MISO). Clim Dyn 41(5–6):1651–1669. https://doi.org/10.1007/s00382-013-1854-1

Shrivastava, S., Kar, S. C., & Sharma, A. R. (2018). The DSSAT model simulations of soil moisture and evapotranspiration over central India and comparison with remotely-sensed data. Modeling Earth Systems and Environment, 4(1), 27–37. https://doi.org/10.1007/s40808-018-0414-4

Shukla, J. and Paolina, D. A., 1983, "The southern oscillation and long range forecasting of the summer monsoon rainfall over India", Mon. Weather Rev., 111, 1830-1837, doi: 10.1175/1520-0493.

Shukla, J. and J. M. Wallace, 1983, "Numerical simulation of the atmospheric response to equatorial sea surface temperature anomalies", J. Atmos. Sci., 40, 1613-1630.

Slingo, J. M. and Annamalai, H., 2000, "1997: The El Niño of the century and the response of the Indian summer monsoon", Mon. Weather Rev., 128, 1778-1797.

Socio-Economic Outlook-2017, Planning Department, Government of Telangana.

Soman, M. K. and Slingo, J., 1997, "Sensitivity of the Asian summer monsoon to aspects of sea surface-temperature anomalies in the tropical Pacific Ocean", Q. J. R. Meteor. Soc., 123, 309-336.

Sood Ruchi, 2013, An interface for running crop models over gridded land surfaces, CCAFS Technical Report, CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS), Copenhagen, Denmark.

Sprintall Janet, Susan E. Wijffels, Robert Molcard, and Indra Jaya. "Direct estimates of the Indonesian Throughflow entering the Indian Ocean: 2004-2006". In: Journal of Geophysical Research:Oceans 114.C7 (2009), p. C07001. DOI: 10.1029/2008JC005257.

Subash, N., & Ram Mohan, H. S. (2012). Evaluation of the impact of climatic trends and variability in rice-wheat system productivity using Cropping System Model DSSAT over the Indo Gangetic Plains of India. Agricultural and Forest Meteorology, 164, 71–81. https://doi.org/10.1016/j.agrformet.2012.05.008

Sudharsan, D., Adinarayana, J., Reddy, D. R., Sreenivas, G., Ninomiya, S., Hirafuji, M., … Merchant, S. N. (2013). Evaluation of weather-based rice yield models in India. International Journal of Biometeorology, 57(1), 107–123. https://doi.org/10.1007/s00484-012-0538-6

Stella. J.Varghese, Surendran, S., Ajithkumar, B., Rajendran, K., & Kitoh, A. (2020). Future changes in rice yield over Kerala using climate change scenario from high-resolution global climate model projection. Journal of Earth System Science, 129(1). https://doi.org/10.1007/s12040-020-01459-0

Swain, D. K., Herath, S., Saha, S., & Dash, R. N. (2007). CERES-Rice model: Calibration, evaluation and application for solar radiation stress assessment on rice production. Journal of Agrometeorology, 9(2), 138–148.

Tang Y and Yu B. MJO and its relationship to ENSO. J Geophys Res 2008; 113:D14106, doi: 10.1029/2007JD009230.

Tian, Z., Fan, Y., Wang, K., Zhong, H., Sun, L., Fan, D., … Liu, J. (2020). Searching for "Win Win" solutions for food-water-GHG emissions tradeoffs across irrigation regimes of paddy rice in China. Resources, Conservation and Recycling, 166(January), 105360. https://doi.org/10.1016/j.resconrec.2020.105360

Timmer, C.P. (2009). A World Without Agriculture: The Structural Transformation in Historical Perspective.Washington, D.C.: American Enterprise Institute Press. Retrieved from https://obealimentaria.files.wordpress.com/2017/01/a-world-without-agriculture-the-structural-transformation-in-historical-perspective_145442400043.pdf

Timsina J, Sing U, Singh Y, Lansigan FP (1995) Addressing suitability of RW systems: testing and applications of CERES and SUCROS models. In: Proceedings of the International Rice Research Conference. 13–17 February 1995. IRRI, Los Banos, Philippines. pp. 656–663

Timsina J. and Humphreys E. (2003). Performance and application of CERES and SWAGMAN Destiny models for rice-wheat cropping systems in Asia and Australia: a review. CSIRO Land and Water Technical

Report 16/03. CSIRO Land and Water, Griffith, NSW 2680, Australia. 57 pp.

Thapliyal, V., 1982: Stochastic dynamic model for long-range pre- diction of monsoon rainfall in peninsular India. Mausam, 33, 399-404.

Thapliyal, V. & Kulshrestha, S. M. (1992) Recent models for long range forecasting of southwest monsoon rainfall in India. Mausam 43: 239–248

Thapliyal V, (1997), Preliminary and final long range forecast of seasonal monsoon rainfall over India, J.Arid Environment, 36, 385-403.

Thapliyal V. and M.Rajeevan, 2003, Updated operational model for long range forecasts of Indian summer monsoon rainfall, Mausam, 54, 495-504.

Thornton Philip K., Gerrit Hoogenboom, Paul W. Wilkens and Walter T.Bown, 1995, Agronomy Journal, Vol, 87.

Trenberth, K.E., and D. P. Stepaniak, 2001: Indices of El Niño evolution.J. Clim., 14, 1697–1701.

Tyagi, A., Asnani, P. G., De, U. S., Hatwar, H. R. and Mazumdar, A. B. 2012. The Monsoon Monograph, Vols. 1 and 2. Indian Meteorological Department.

Tyagi, A and Pattanaik D. R. (2012). Operational Extended Range Forecast Activity in IMD and its Applications in different sectors.

Ummenhofer CC, Mathew H England, Peter C. McIntosh, G. M. Meyers, Michael J. Pook,James S. Risbey, Alexander Sen Gupta, and Andréa S. Taschetto. “What causes southeast Australia’s worst droughts?” In: Geophysical Research Letters 36.4 (2009), p. L04706. DOI: 10.1029/2008GL036801.

Vijayalaxmi, G., Sreenivas, G., & Leela Rani, P. (2016). Evaluation of CERES-Rice Model under Various Plant Densities and Age of Seedlings in Transplanted Rice in Southern Telangana Zone of Telangana State, India. International Journal of Current Microbiology and Applied Sciences, 5(4), 667–674. https://doi.org/10.20546/ijcmas.2016.504.076

Vilayvong, S., Banterng, P., Patanothai, A. & Pannangpetch, K. 2015 CSM-CERES-Rice model to determine management strategies for lowland rice production. Sci. Agric. 72,229–236.

Vinayachandran P. N., N. H. Saji, and T. Yamagata. “Response of the equatorial Indian Ocean to an unusual wind event during 1994”. In: Geophysical Research Letters 26.11 (1999), pp. 1613–1616.

Vinayachandran, P. N., Murty, V. S. N., & Babu, V. R. (2002). Observations of barrier layer formation in the Bay of Bengal during summer monsoon. Journal of Geophysical Research: Oceans, 107(12), 1–9. https://doi.org/10.1029/2001jc000831

Wallace JM, EM Rasmusson, TP Mitchell, VE Kousky, ES Sarachik, and H von Storch. “On the structure and evolution of ENSO-related climate variability in the tropical Pacific: Lessons from TOGA”. In: Journal of Geophysical Research: Oceans 103.C7 (1998), pp. 14241 14259.

Walker, G. T., 1923: Correlation in seasonal variations of weather. III: A preliminary study of world weather. Mem. Indian Meteorol. Dept, 24, 75–131.

Walker, G. T., 1924, “Correlation in seasonal variations of weather, IX: A further study of world weather”, Memoirs of the India Meteorological Department, 24, 9, 275-333.

Wang B, Lee JY, Xiang B. 2014. Asian summer monsoon rainfall predictability: A predictable mode analysis. Clim. Dyn. 44: 61–74.

Webster, P. J. and Yang, S., 1992, “Monsoon and ENSO: Selectively Interactive Systems”, Quart. J. Roy. Meteor. Soc., 118, 877-926.

Webster, P. J., V. O. Magana, T. Palmer, J. Shukla, R. Tomas, M. Yanai, and T. Yasunari, 1998: Monsoons: Processes, predictability, and the prospects for prediction. Journal of Geophysical Research: Oceans, 103 (C7), 14 451–14 510.

Webster, P. J, A. Moore, J. Loschnigg, and M. Leban, 1999: Coupled dynamics in the Indian Ocean during 1997–1998. Nature, 401, 356–360.

Weng H, Ashok K, Behera SK, Rao SA, Yamagata T (2007) Impacts of recent El Niño Modoki on dry/wet conditions in the Pacific rim during boreal summer. Clim Dyn 29(2–3):113 129. https://doi.org/10.1007/s00382-007-0234-0

White J. W, G. Hoogenboom, and L. A. Hunt, 2005, A Structured Procedure for Assessing How Crop Models Respond to Temperature, Agron. J. 97:426, American Society of Agronomy.

Wijffels S.E.and Meyers G. M. “An Intersection of Oceanic Wave guides: Variability in the Indonesian Throughflow Region”. In: J. Phys. Oceanogr. 34 (2004), pp. 1232–1253.

Wilks, D. S. (1995), Statistical Methods in the Atmospheric Sciences: An Introduction, 467 pp., Academic, San Diego, Calif.

Winton, M., 2000. A reformulated three-layer sea ice model. J. Atmos. Ocean.Technol. 17, 525 531.

Wu, X., Budd, W.F., Simmonds, I., 1997. Sensitivity of the Antarctic sea ice distribution to its advection in a general circulation model. Antarct. Sci. 9, 445–455.

Wyrtki Klaus "Indonesian through flow and the associated pressure gradient". In: Journal of Geophysical Research: Oceans 92.C12 (1987), pp. 12941–12946.

Xiang, B., Wang, B., Yu, W., & Xu, S. (2013). How can anomalous western North Pacific Subtropical High intensify in late summer? Geophysical Research Letters, 40(10), 2349 2354. https://doi.org/10.1002/grl.50431

Xie S.P., H. Annamalai, Friedrich A Schott, and McCreary J. P. "Structure and mechanisms of South Indian Ocean climate variability". In: Journal of Climate 15.8 (2002), pp. 864–878.

Xu J and Chan JCL. The role of the Asian-Australian monsoon system in the onset time of El Ni˜no events. J Clim 2001; 14: 418–33.

Yadav RK (2012) Why is ENSO influencing Indian northeast monsoon in the recent decades? Int J Climatol 32(14):2163–2180. doi:10.1002/joc.2430

Yang, F., Pan, H. L., Krueger, S. K., Moorthi, S., & Lord, S. J. (2006). Evaluation of the NCEP global forecast system at the ARM SGP site. Monthly Weather Review, 134(12), 3668-3690. https://doi.org/10.1175/MWR3264.1

Yeh, S-W, Y-G Ham, and BP Kirtman (2014) A possible explanation on the changes in the spatial structure of ENSO from CMIP3 to CMIP5,Geophys Res Lett, 41, 140 145,doi:10.1002/2013GL058478.

Yeh, S. W., Cai, W., Min, S. K., McPhaden, M. J., Dommenget, D., Dewitte, B., … Kug, J. S. (2018). ENSO Atmospheric Teleconnections and Their Response to Greenhouse Gas Forcing. Reviews of Geophysics, 56(1), 185–206. https://doi.org/10.1002/2017RG000568

Yu J-Y and Lau KM. Contrasting Indian Ocean SST variability with and without ENSO influence: a coupled atmosphere-ocean GCM study. Meteorol Atmos Phys 2005; 90: 179–91

Yu, J-Y., and H-K. Kao, 2007: Decadal changes of ENSO persistence barrier in SST and ocean heat content indices: 1958-2001. J. Geophys. Res., 112 , D13106. doi:10.1029/2006JD007654.

Yu, J-Y., and H-K. Kao, 2009. Contrasting Eastern-Pacific and Central-Pacific types of ENSO. Journal of Climate, 22(3), 615–632. https://doi.org/10.1175/2008JCLI2309.1

Yu JY, Kao HY, Lee T (2010) Subtropics-related interannual sea surface temperature variability in the central equatorial Pacific, J Clim, 23 2869–2884 doi:10.1175/2010JCLI3171.1

Yu JY, Y Zou, ST Kim, and T Lee (2012) The changing impact of El Niño on US winter temperatures, Geophys Res Lett, 39 L15702, doi:10.1029/2012GL052483.1

Yuan C and Yamagata T. "Impacts of IOD, ENSO and ENSO Modoki on the Australian Winter Wheat Yields in Recent Decades". In: Scientific Reports 5 (2015). DOI: 10 . 1038 /srep17252.

Zebiak Stephen E "Air–sea interaction in the equatorial Atlantic region". In: Journal of Climate 6.8 (1993), pp. 1567–1586.

Zhang, Y., Wallace, J. M. and Iwasaka, N., 1996, "Is climate variability over the North Pacific a linear response to ENSO?", Journal of Climate, 9, 1468-1478.

Zhang R-H Effects of tropical instability wave (TIW)-induced surface wind feedback in the tropical Pacific Ocean. Clim Dyn 2014; 42: 467–85.

Zhang, J., Miao, Y., Batchelor, W.D., Lu, J., Wang, H., Kang, S., 2018. Improving High-Latitude Rice Nitrogen Management with the CERES-Rice Crop Model. Agronomy 8, 263. https://doi.org/10.3390/agronomy8110263

Zheng Y, Zhang R and Bourassa MA. Impact of East Asian winter and Australian summer monsoons on the enhanced surface westerlies over the western tropical Pacific Ocean preceding the El Ni˜no onset. J Clim 2014; 27: 1928–44.

Viability of a dynamical climate prediction system for the kharif rice production in Indian states

by Hemadri Bhushan Amat

Viability of a dynamical climate prediction system for the kharif rice production in Indian states

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Relevance of Indian Summer Monsoon and its Tropical Indo-Pacific Climate Drivers for the Kharif Crop Production

HEMADRI BHUSAN AMAT[1] and KARUMURI ASHOK[1]

Abstract—While the Indian agriculture has earlier been dependent on the Indian summer monsoon rainfall (ISMR), a multifold increase in irrigation and storage facilities raise a question whether the ISMR is still as relevant. We revisit this question using the latest observational climate datasets as well as the crop production data and find that the ISMR is still relevant for the Kharif crop production (KCP). In addition, in the recent changes in the tropical Indo-Pacific driver evolutions and frequency, particularly more frequent occurrence of the ENSO Modokis in place of the canonical ENSOs, we carry out a correlation analysis to estimate the impact of the various Indo-Pacific climate drivers on the rainfall of individual Indian states for the period 1998–2013, for which crop production data for the most productive Indian states, namely West Bengal, Odisha, United Andhra Pradesh (UAP), Haryana, Punjab, Karnataka, Kerala, Madhya Pradesh, Bihar and Uttar Pradesh are available. The results suggest that the KCP of the respective states are significantly correlated with the summer monsoon rainfall at the 95–99% confidence levels. Importantly, we find that the NINO 3.4 and ENSO Modoki indices have a statistically significant correlation with the KCP of most of the Indian states, particularly in states such as UAP and Karnataka, through induction of anomalous local convergence/divergence, well beyond the equatorial Indian Ocean. The KCP of districts in UAP also has a significant response to all the climate drivers, having implication for prediction of local crop yield.

Key words: Indian summer monsoon, Kharif crop production, ENSO, ENSO Modoki, IOD, Walker circulation.

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1. Introduction

The Gross Domestic Product (GDP) of India depends primarily on the agriculture. The agriculture sector is deemed to generally rely on the Indian Summer Monsoon Rainfall (ISMR), which occurs from June to September (JJAS). India has two cropping seasons, named as the Kharif and Rabi. The Kharif season crops grow during the summer monsoon period and are harvested in the consecutive late fall/or early winter months of October and November. The Rabi crops are grown during October–March months and reaped in the consecutive spring (April–May). The ISMR is deemed to be a significant contributor to both the cropping seasons, through the direct supply of water for the Kharif crops and through the provision of soil moisture content and irrigated water for the Rabi crops. Of course, most of the Kharif crops such as rice mainly require more water than the Rabi crops. However, there are several other issues that are also important for the crop production in India. A recent official report published in 2014 by the Directorate of Economics and Statistics (DES), Ministry of Agriculture, Government of India, suggests that all India crop production for the period 1966–2013 has an average value of 163.73 Million Tonnes/year. However, the corresponding time series shows (Fig. 1a) a strong increasing trend, with the total production increasing from 74.23 Million Tonnes in the year 1966–1967 to 257.13 Million Tonnes in the year 2012–2013. The production in 2012–2013 is 54.66% more as compared to the 1966–1967 period. However, this increasing trend in productivity is not associated with any such increasing trend in the ISMR (e.g. Krishnan et al. 2012). Studies by Goswami et al. (2006), Guhathakurta and Rajeevan

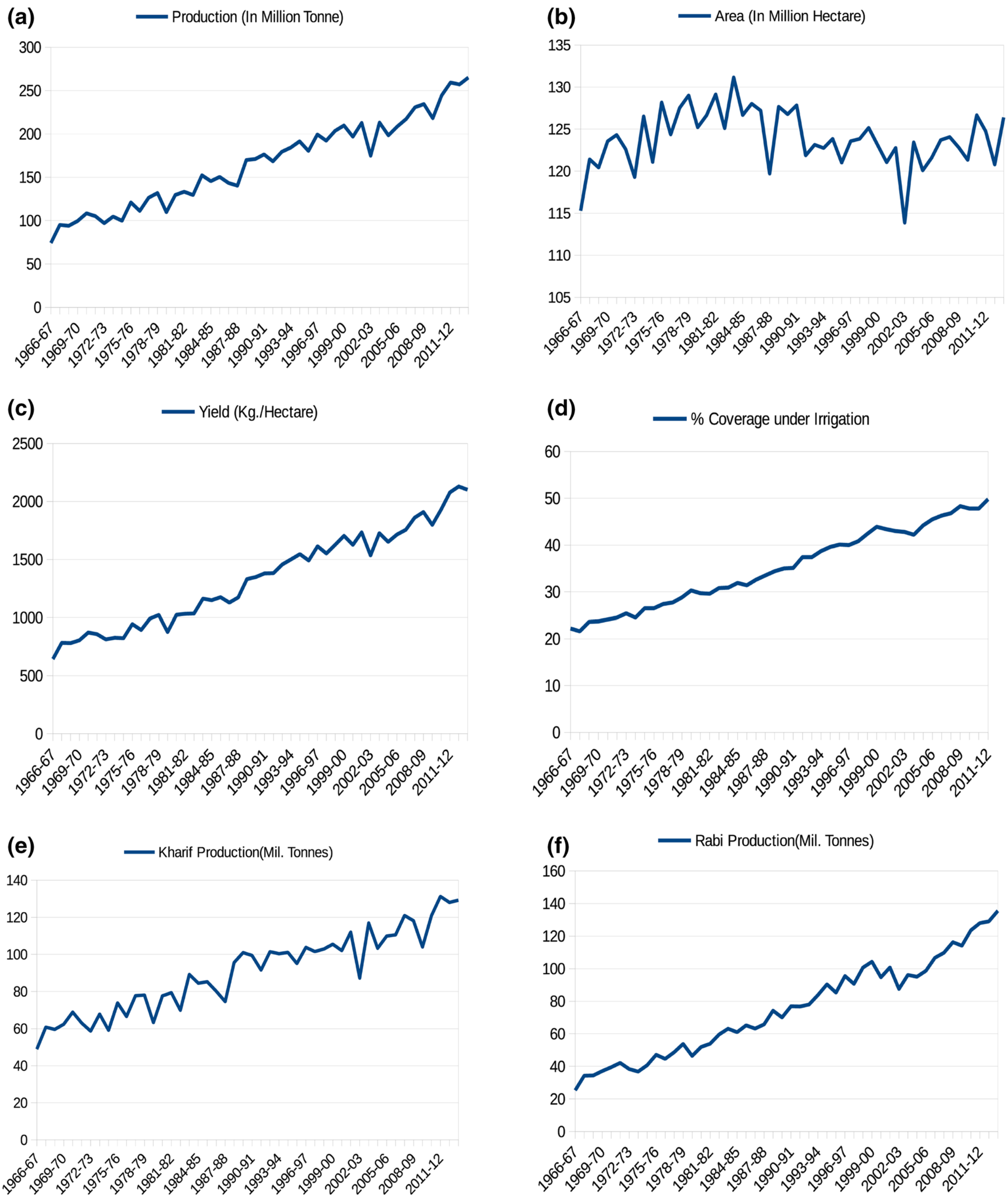


Figure 1

Interannual variation of **a** total annual agricultural production (in Million Tonnes) during the period 1966–2013; **b** area used for agriculture (in million Hectare) during the 1966–2013 period; **c** total yield (in Kg/hector) during the period 1950–2013; **d** percentage of area under irrigation during the period 1966–2013; **e** total Kharif crop production (in million tonnes) during the period 1966–2013 and **f** total Rabi crop production (in million tonnes) during the period 1966–2013

(2007), Dash et al. (2007), Rajendran et al. (2012) and Krishnan et al. (2012) show that the ISMR has a weak to moderately decreasing trend. Interestingly, the DES report from 2014 also shows that with an annual average of 123.83 Million Hectares of area is being used for agriculture from 1966 to 2013 (Fig. 1b). Also, the area under agriculture in India has only increased by approximately 6.9%. The increasing trend in the crop yield per acre also attests to the fact that the increasing production is not primarily due to an increase in the area under agriculture.

In this background, it is apt to attribute such an increase in total production, among other things, the increasing use of fertilizers and modern agricultural practices. However, as per the aforementioned DES report, we see that the improvement in the irrigation has also played a major role in the increasing crop production. We see a noticeable increasing trend in the agricultural area under irrigation (Fig. 1d). Increasing irrigation is a crucial factor that helps the increase in crop productivity. An average of 35.22% of aggregate land used for agriculture has been irrigated annually since 1966–2012. The irrigated area is 36.97% less than the sample's mean during 1966–1967. During the financial year 2011–2012, it has increased by 41.37% of the mean (Fig. 1d).

Thus, we can make a general observation that many factors in addition to rainfall, such as the irrigation, crop variety, fertilizers, pesticides, cropping pattern, and various modern technological advancement have contributed to the increasing the crop production growth in recent decades. Particularly, with increasing irrigation facilities one is apt to ask a question whether the Indian summer monsoon rainfall is still an important factor for crop production. Despite the fact that there is a noteworthy increase in crop production since the early days of the green revolution in the 1960s, it is also true that the country has confronted numerous drought conditions in between, which has apparently affected the crop production. For example, a less than normal summer monsoon rainfall in years such as 1987, 2002, 2004, and 2009 (Ashok et al. 2004; Nanjundiah et al. 2013), is also associated with decreased crop productivity (Fig. 1a), suggesting that vagaries in monsoon rainfall, particularly the extreme years, may still be significant for crop production.

It is known that the El Niño-Southern Oscillation (ENSO) is one of the most important drivers of the Indian summer monsoon rainfall variability (e.g. Sikka and Gadgil 1980; Rasmusson and Carpenter 1983; Ashok et al. 2007). Strong El Niños are associated with a drier than normal summer monsoon condition over the Indian region. Interestingly, since the late 1970s, we see an increasing frequency in the El Niño Modokis, also referred to as central Pacific El Niños as against the canonical El niños (Ashok et al. 2007; Kao and Yu 2009; Kug et al. 2009; Marathe et al. 2015). The El Niño Modokis are distinguished by a warmer than normal central tropical Pacific flanked on both sides by cooler than normal anomalies. While both types of El Niños cause drier than normal rainfall conditions during summer monsoons, the Modoki events have an apparently stronger impact from a linear perspective (e.g. Kumar et al. 1999; Ashok et al. 2007). There is, of course, some non-linearity in the relation between the rainfall–crop yield links. For example, the impact of deficit rainfall on GDP and grain production is more effective than the impact of surplus rainfall (Gadgil et al. 2006). In addition, the crop yield is more in La Nina years rather than El Nino years (Kumar and Barbosa 2012). In addition, studies suggest that climate drivers other than ENSOs, such as the Indian Ocean Dipole events (Saji et al. 1999; Webster et al. 1999; Murtugudde et al. 2000), can also influence the Indian summer monsoon (Ashok et al. 2004; Ashok and Saji 2007). A strong positive IOD co-occurring with an El Niño can reduce the negative influence of the El Niño. A recent study by Krishnaswamy et al. (2015) suggests an increasing influence of the IOD events as compared to the ENSOs.

In this manuscript, we explore the relevance of the summer monsoon rainfall (SMR) and the tropical Indo-Pacific climate drivers on the crop production in various states of India during the Kharif season, when the importance of concurrent rainfall, to be used directly for crop production rather than through irrigation, is relatively stronger as compared to the Rabi crops.

This paper has been structured as follows: In the next section, we introduce the details of various datasets used and the methodology of our analysis. We present our results in Sect. 3 and our conclusions in Sect. 4.

2. Data and Methodology

For this study, we use the area-averaged regional Indian monthly Rainfall (Parthasarathy et al. 1993, 1994) data Sets from the Indian Institute of Tropical Meteorology (IITM), Pune Data Archive (http://www.tropmet.res.in/), available for the period of 1950–2012. These datasets provide area-averaged rainfall for various states and/subdivisions, and also statistically identified homogenous regions. The Hadley Centre Global Sea Ice and Sea Surface Temperature (HadISST) available for the 1871–2016 (Rayner et al. 2003) and the monthly mean of specific humidity, wind (*u* and *v*-components), mean sea level pressure and global precipitation data sets from the National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) reanalysis (Kalnay et al. 1996), available from 1948 to 2014, are also used; henceforth, for convenience, we refer these as the NCEP data sets. The data on major crops production (Rice, Wheat, Cereals and Pulses) in India, available for the 1950–2013 period from the Directorate of Economics and Statistics (DES), Ministry Of Agriculture, Government of India, and the state-wise Kharif crop production data available from the same agency for the 2001–2013, have also been used.

Our analysis to establish the dynamics behind the impact of ENSOs on the state levels is carried out for the 2001–2013 period. However, owing to the limitations of the availability of state-level crop production data, our analysis to understand the impact of monsoons and its drivers on the crop production in various states, for which the datasets are available, has been carried out only for the 2001–2013 period. As an example, to see the response of the local level KCP in the state of the UAP to the SMR and its climate drivers, we use the linear correlation and Student's *t* test to assess the statistical significance of the correlation analysis. We use the district-wise KCP data for the period of 1999–2013.

We use the partial correlation method (Wilks et al. 1995; Nicholls 1983) to quantify the impact of the ISMR and that of its tropical Indo-Pacific climate drivers on the crop production in major Kharif crop producing states of India. The partial correlation method is used in many studies, which aims to delineate the individual teleconnections and impacts of the tropical Indo-Pacific drivers such as the ENSO and IOD from each other (e.g. Nicholls 1983; Ashok et al. 2001, 2003, 2007; Ashok and Saji 2007; Guan et al. 2003a; Saji et al. 1999; Rao 1976; Behera et al. 2005). Such a technique of some delineation is necessary, because of the evolution of tropical Indo-Pacific climate drivers, particularly the ENSO and IOD, are seasonally phase locked through boreal summer, and most of the time they co-occur together (Yamagata et al. 2004) and their impacts get smeared up. Further, we use the Student's *t* test to assess the statistical significance for the correlation analysis. The seasonal anomaly statistics of any parameter 'X' for any particular year have been obtained by subtracting the corresponding seasonal mean for the summer monsoon of the observed value of 'X' in that particular year (Yuan and Yamagata 2015). The indices used to represent the various tropical Indo-Pacific drivers are presented below:

- *NINO3* The area-averaged sea surface temperature anomaly (SSTA) of the region bounded by (5°N–5°S, 150°W–0°W) (Trenberth 1997), which represents the impacts of the canonical ENSO.
- *Indian Ocean Dipole Mode Index (IODMI)* The area-averaged SSTA difference between the western box (50°E–70°E, 10°S–10°N) and the eastern box (90°E–110°E, 10°S to the equator) of the Indian Ocean (Saji et al. 1999).
- *ENSO Modoki (EMI)* It is defined by Ashok et al. (2007) as

$$\mathrm{EMI} = [\mathrm{SSTA}]_{\mathrm{A}} - 0.5 \times [\mathrm{SSTA}]_{\mathrm{B}} - 0.5 \times [\mathrm{SSTA}]_{\mathrm{C}},$$

where $[\mathrm{SSTA}]_{\mathrm{A}}$ = the area-averaged SSTA bounded by the region A (165°E–140°W, 10°S–10°N), $[\mathrm{SSTA}]_{\mathrm{B}}$ = the area-averaged SSTA bounded by the region B (110°W–70°W, 15°S–5°N), $[\mathrm{SSTA}]_{\mathrm{C}}$ = the area-averaged SSTA bounded by the region C (125°E–145°E, 10°S–20°N).

- *NINO 3.4* The area-averaged SSTA of the region bounded by (5°N–5°S, 170°W–120°W) (Trenberth 1997). This index was originally coined to represent the impacts of the canonical ENSO. Weng et al. (2007) show that this index, owing to the region over which it has been defined, represents the impacts from both Modoki and canonical ENSOs. As far as the ISMR is concerned, this index can be used for evaluating impacts from both types of ENSOs. As both, the flavours influence the Indian summer monsoon in a similar way, though the magnitudes may differ (Kumar et al. 1999). Also, it may not be an appropriate choice for impact assessment at local regions, given that the Modokis may impact more in peninsular India, while canonical ENSOs seem to influence along the monsoon trough region (e.g. Ashok et al. 2007). We shall anyway report some analyses using this index as well, just for the purpose of any usefulness in predictability/prediction studies.

As the canonical ENSOs and ENSO Modokis do not co-occur in a calender year, we carry out partial correlation of the state level summer monsoon rainfall with (a) the NINO3 index and IODMI as the predictor, and (b) EMI and IODMI as independent predictors.

The climate drivers such as the ENSO events also affect the large-scale surface temperature, and the longevity and intensity of the event may also affect the local soil moisture available for the crops. Notwithstanding this, the local conditions such as orography, soil type, may act in such a way that these drivers may not significantly influence the local rainfall and/or crop production. In this context, it will be worthwhile to establish a dynamical linkage between the tropical Indo-Pacific drivers with the local crop production. To explore the background mechanisms through which the climate drivers influence the state/district level crop production, as detailed in the next paragraph we carry out a composite analysis of the low-level velocity potential anomalies during various ENSO flavours. We also carry out a correlation analysis of local horizontal moisture convergence with the climate indices such as the NINO3, NINO3.4, EMI and IOD indices for the monsoon season during the 1983–2013 period. For this period of 1983–2013, a correlation coefficient of value 0.34 (0.23) is statistically significant at 95% (90%) of confidence level from a one-tailed Student's t test.

Many earlier studies (Keshavamurty 1982; Webster et al. 1998; Ashok et al. 2004) suggest that the ENSOs influence the Indian summer monsoon through modulation of Walker circulation, which is manifested as horizontal anomalous centres of low-level convergence and divergence with a baroclinic structure in the vertical. We revisit this aspect using the velocity potential fields (850 hPa) derived from the NCEP data sets, which are, incidentally, an updated reanalysis as compared to those used in many earlier ENSO-Monsoon teleconnection studies (e.g. Guan et al. 2003a, b; Ashok et al. 2004, etc.). Further, the composite analysis for the divergence of wind anomalies and velocity potential of the major El Niño and El Niño Modoki has been carried out for the satellite data era of 1976–2013. Following Marathe et al. (2015) and Preethi et al. (2015), for the composite analysis, we choose two major El Niño years, both 1982 and 1997, and four major El Niño Modoki years such as 1991, 1994, 2002 and 2004. Another relevant statistic that is also used in this study is the moisture convergence. As known, the moisture Flux Convergence comprises of contributions from both an advection and convergence terms (Banacos et al. 2005). As discussed by Banacos et al. (2005), the constituent moisture advection term represents the vertical transport of moisture, while the constituent moisture convergence term deals with the horizontal transport of moisture, referred to as moisture convergence (MC) in literature (e.g. Guan and Yamagata 2003a; Ashok et al. 2003, 2004, etc.). We use the MC, defined in the Eq. (1), at the 850 hPa as a diagnostic to ascertain that ENSO-related dynamics play a role in the inter-annual variability of the local moisture convergence, which is critical for the crop production at district and state levels.

$$\begin{aligned} \mathrm{MC} &= -qV\,(u,v)\cdot\nabla = \frac{\mathrm{d}\,(-uq)}{\mathrm{d}x} + \frac{\mathrm{d}\,(-qv)}{\mathrm{d}y} \\ &= -q\left(\frac{\mathrm{d}u}{\mathrm{d}x} + \frac{\mathrm{d}v}{\mathrm{d}y}\right) = -q\cdot\nabla V. \end{aligned} \tag{1}$$

Here q, u and v represent the specific humidity, zonal wind and meridional wind component, respectively.

3. Results and Analysis

3.1. State-Wise Response of SMR and its Climate Drivers to that of the KCP

In this subsection, we evaluate the relevance of the summer monsoon rainfall (SMR) on the Kharif crop production in various states that grow crops in the Kharif season through a correlation analysis. As per the DES report, the major states that produce Kharif crops are West Bengal, Odisha, Undivided Andhra Pradesh (UAP),[1] Haryana, Punjab, Karnataka, Kerala, Madhya Pradesh, Bihar and Uttar Pradesh. Table 1 shows the correlations between the KCP in each of these states with the area-averaged SMR (Parthasarathy et al. 1993).

The results from Table 1 demonstrate that in most of the states, which do Kharif farming, crop production during the season in a majority of states is dependent on the SMR. The states of Andhra Pradesh, Karnataka, Madhya Pradesh, Odisha and Uttar Pradesh show a strong positive correlation, though the crop production of Uttar Pradesh has a slightly lower association with the SMR as compared to the other states in the list. This implies a strong influence of regional monsoon rainfall on the KCP in most of the states. An exception is the state of Kerala, whose crop production is negatively correlated with the SMR. This is contrary to what is expected and needs a thorough study. Therefore, in this study, we do not carry out any further analysis related to the Kerala crop production.

We now present the partial correlations of the SMR in various states with the indices of tropical Indo-Pacific drivers, which can be interpreted as an estimate of the association of local state-wise SMR with the tropical Indo-Pacific climate drivers. Table 2 suggests that the local SMR across the Kharif states is indeed influenced by the various Indo-Pacific climate drivers. Mostly, the El Niño as well as the El Niño Modoki exhibits a significant impact on the states such as WB, Haryana, Kerala, Bihar, UAP and Karnataka. In tune with Table 1, the rainfall in various the states is negatively correlated with El Niño and El Niño Modoki indices, which is usual. The IOD only influences the rainfall in relatively fewer states events. The local SMR of the states such as WB and Bihar along the monsoon trough show some statistically significant positive association with the IODMI, in agreement with earlier studies such as Ashok and Saji (2007).

The correlations between the state level KCP with large-scale MC are presented in Fig. A1. The

Table 1

Correlations between the state-wise Kharif crop production with the SMR of that state for the 2001–2013 period

States	Correlation cofficients (r)
WB	− 0.17
Haryana	− 0.26
Kerala	**− 0.47**
Bihar	0.34
Punjab	− 0.04
Uttar Pradesh	0.44
Madhya Pradesh	**0.76**
UAP	**0.74**
Karnataka	**0.81**
Odisha	**0.50**

Correlations with magnitude above 0.47 are statistically significant at 95% from a one-tailed t test and are shown in bold

Table 2

Partial correlations between the state-wise SMR with the Indo-Pacific climate driver indices during 2001–2013 period

States	Partial correlation of El Niño and SMR adjusted for IOD	Partial correlation of IOD and SMR adjusted for El Niño	Partial correlation of EMI and SMR adjusted for IOD	Partial correlation of IOD and SMR ajusted for EMI
WB	**− 0.51**	**0.60**	0.05	**0.45**
Haryana	**− 0.40**	− 0.34	**− 0.58**	**− 0.62**
Kerala	**− 0.59**	0.16	− 0.20	− 0.10
Bihar	**− 0.55**	**0.71**	− 0.10	**0.53**
Punjab	− 0.13	0.06	**− 0.58**	− 0.27
UP	− 0.32	0.18	**− 0.40**	− 0.09
MP	− 0.22	0.09	− 0.19	− 0.05
UAP	**− 0.75**	0.27	**− 0.50**	− 0.23
Karnataka	**− 0.47**	0.03	**− 0.43**	− 0.28
Odisha	− 0.11	0.36	− 0.11	0.28

Correlations with magnitude above 0.38 and 0.47 are statistically significant at 90 and 95%, respectivel,y from a one-tailed t test and are shown in bold

[1] The erstwhile undivided-AP has been divided into two states, namely AP and Telangana in 2014. The result shown here is for the Undivided Andhra Pradesh (UAP).

Table 3

Partial correlations between the state-wise KCP with the Indo-Pacific climate driver indices during 2001–2013 period

States	Partial correlation of NINO 3 and KCP adjusted for IOD	Partial correlation of IOD and KCP adjusted for NINO3	Partial correlation of EMI and KCP adjusted for IOD	Partial correlation of IOD and KCP ajusted for EMI	Partial correlation of NINO 3.4 and KCP adjusted for IOD	Partial correlation of IOD and KCP adjusted for NINO 3.4
WB	**0.38**	− 0.07	0.22	0.13	**0.42**	0.03
Haryana	**− 0.38**	**0.48**	**− 0.56**	0.17	**− 0.54**	**0.46**
Kerala	**0.42**	**− 0.54**	**0.58**	− 0.24	**0.56**	**− 0.52**
Bihar	− 0.11	**0.68**	− 0.30	**0.60**	− 0.21	**0.69**
Punjab	− 0.01	0.23	**− 0.52**	− 0.01	− 0.22	0.24
UP	**− 0.39**	**0.48**	**− 0.49**	0.19	**− 0.50**	**0.44**
MP	− 0.17	0.24	− 0.14	0.13	− 0.17	0.21
UAP	**− 0.68**	**0.66**	**− 0.60**	0.23	**− 0.77**	**0.62**
Karnataka	**− 0.43**	− 0.07	**− 0.68**	**− 0.53**	**− 0.63**	− 0.22
Odisha	− 0.30	0.13	− 0.31	− 0.09	− 0.36	0.06

Correlations with magnitude above 0.38 and 0.47 are statistically significant at 90 and 95% confidence level, respectively, from a one-tailed *t* test and are shown in bold

figures suggest that the local KCP of each state is structured beyond the domain of the respective states, which indicates the association with the large-scale monsoon circulation, and possibly its intra-seasonal variations. This, associated with the correlations presented in Table 3, suggests that the local moisture availability is subject to the large-scale tropical Indo-Pacific climate drivers.

As the next step, we examine that the association of the Kharif crop production with the inter-annual variability of the tropical Indo-Pacific climate drivers (ENSO, IOD and ENSO Modoki) during the concurrent season of JJAS.

From Table 3 and Fig. 2, we observe that there are several states whose KCP demonstrates a noteworthy response to one or several of the climate drivers listed indices. In particular, the SST variability in the NINO 3.4 and ENSO Modoki region apparently has a tremendous influence over the KCP for most number of Indian states, as seen by the significant negative correlations. From Weng et al. (2007), we know that the NINO 3.4 index captures signals from both flavours of ENSO. This, coupled with the relatively weak correlations of the regional KCP, suggest us a relatively dominant impact of the Modoki events on the crop production between the two ENSO flavours. From a slightly different context of non-linearity, it may also be noted that the KCP of a couple of states has different signs of correlations with different ENSO flavours. This is in conformation with studies such as those by Ashok et al. (2007), which show that the negative impact of various El Niño flavours differs in magnitude in the sub-regions of India. For example, the EMI has a strong negative correlation with the summer monsoon rainfall in the peninsular India and a moderately positive correlation in the north India (Ashok et al. 2007). This type of local distinctions in the ENSO impacts on India is because the Indian region is well outside the Walker circulation footprint in the tropical Pacific, which is the direct impact region of the ENSO. The type and level of impact depend on the flavour and strength of the individual ENSOs (Kumar et al. 1999).

Importantly, Selvaraju (2003), studying the correlations between the NINO3 index and all India annual crop production (inclusive of both Kharif and Rabi) production, observes a non-linearity of the impacts between ENSOs. Specifically, during the warm phase of El Niños, there is a significant reduction of 1% in the probability of above-average production relative to that during the neutral ENSO phase; on the other hand, the probability of above-average food grain production increases for the La Niña events by 5% relative to the neutral ENSO phase. However, one has to be mindful of the fact that the ENSO impacts on the rainfall in India change based on the background circulation, which is

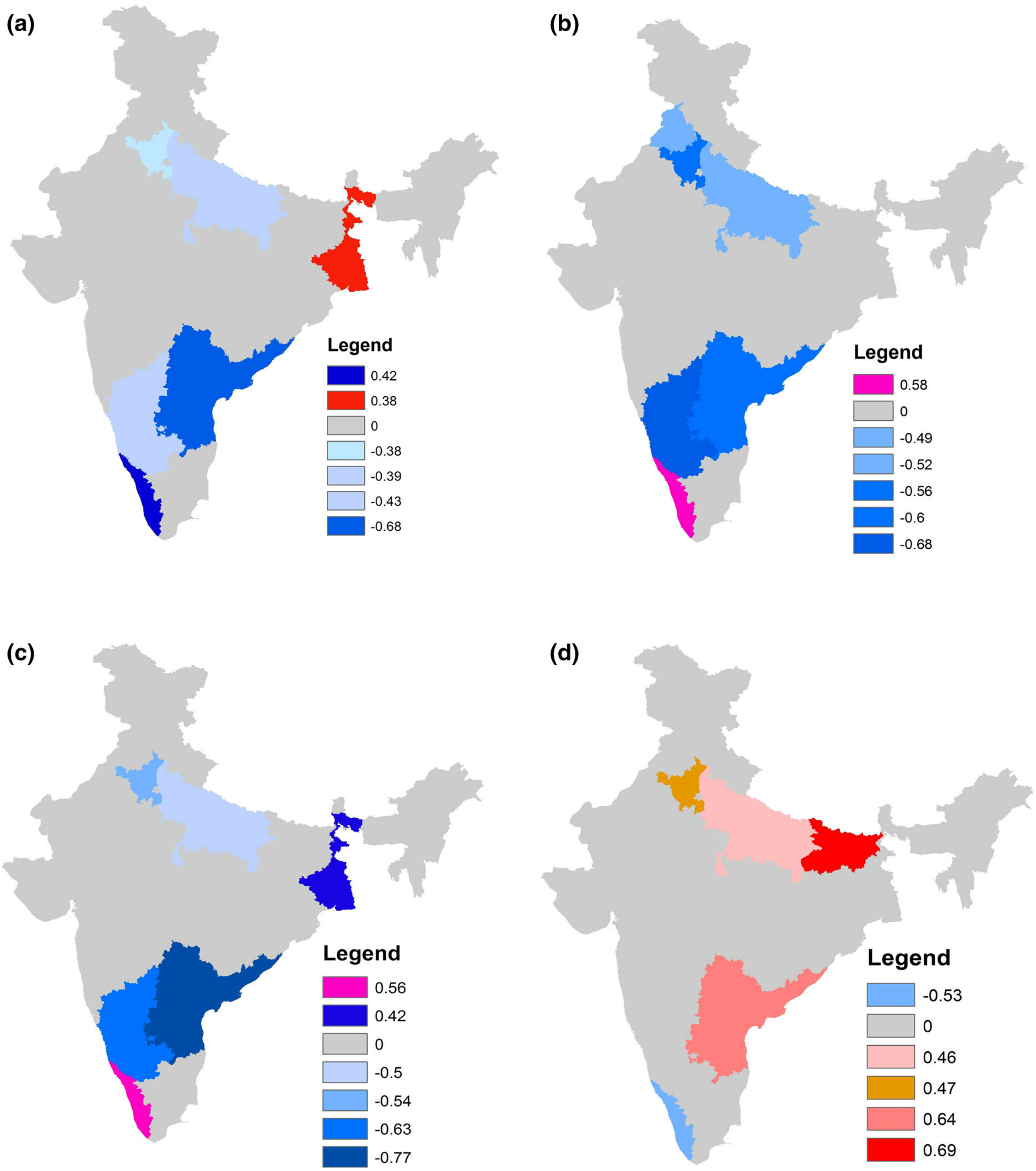


Figure 2
Potential Indian states having significant correlation between the Kcp with the Indo-Pacific climate driver indicies, i.e. **a** EL-Niño, **b** El-Niño Modoki, **c** Nino 3.4 and **d** IOD during 2001–2013 Period

strongly phase locked to the seasons. To be clearer, while El Niños cause below normal rainfall in India during summer monsoons, they cause either above normal rainfall in the regions of Tamilnadu and Andhra Pradesh and no significant impacts elsewhere during the northeast monsoons that occur during

October–December, owing to the change of direction in mean circulation from summer (e.g. Yadav 2012; Prakash et al. 2013).

3.2. *Response of Kharif Crop Production of the State of Andhra Pradesh to the District-Wise SMR and its INDO-Pacific Climate Drivers*

In the previous sections, we have seen that the signature of the ENSO can be seen in the impacts of the state level KCP. For proper planning, it will be useful to check if such impacts can be discerned at more local levels. In India, states are further divided into districts for efficient administrative management.

Therefore, in this section, we discuss and explore the response of the district level KCP in the state of the UAP to the SMR and its climate drivers, as an example. Indeed, among several states that experience the ENSO impacts on the KCP, the UAP particularly shows a significant response to all the Indo-Pacific climate drivers and is a major crop-producing state during the Kharif season. The UAP has 23 districts. We present the correlations of the district level KCP with the local SMR as well as those with the individual tropical Indo-Pacific climate drivers.

The outcome demonstrates that the KCP of each individual district is prominently associated with on or more of the tropical the Indo-Pacific drivers. From Table 4, we can discern that the KCP of 13 districts is significantly correlated with the SMR at statistically confident levels of 90–95%. The relatively less importance of the SMR in other districts may be due various factors such as better managed irrigation facilities, higher use of fertilizers, or simply because the KCP is relatively less owing to the limited SMR. Interestingly, the numbers of districts whose KCP is significantly associated with the various ENSO drivers of NINO3, NINO3.4 and ENSO Modoki are 13, 13, 15, and 14, respectively. We have to be mindful that all these results are based only on linear correlations. Hence, in the next section, we carry out an analysis to explore if such apparent relationship of the KCP in India, specifically the UAP taken as an example, can be also be explained through atmospheric dynamics.

Table 4

Correlation table for the district-wise Kharif crop production of United Andhra Pradesh with the district-wise SMR index and its Indo-Pacific climate driver indices during 1999–2013 period

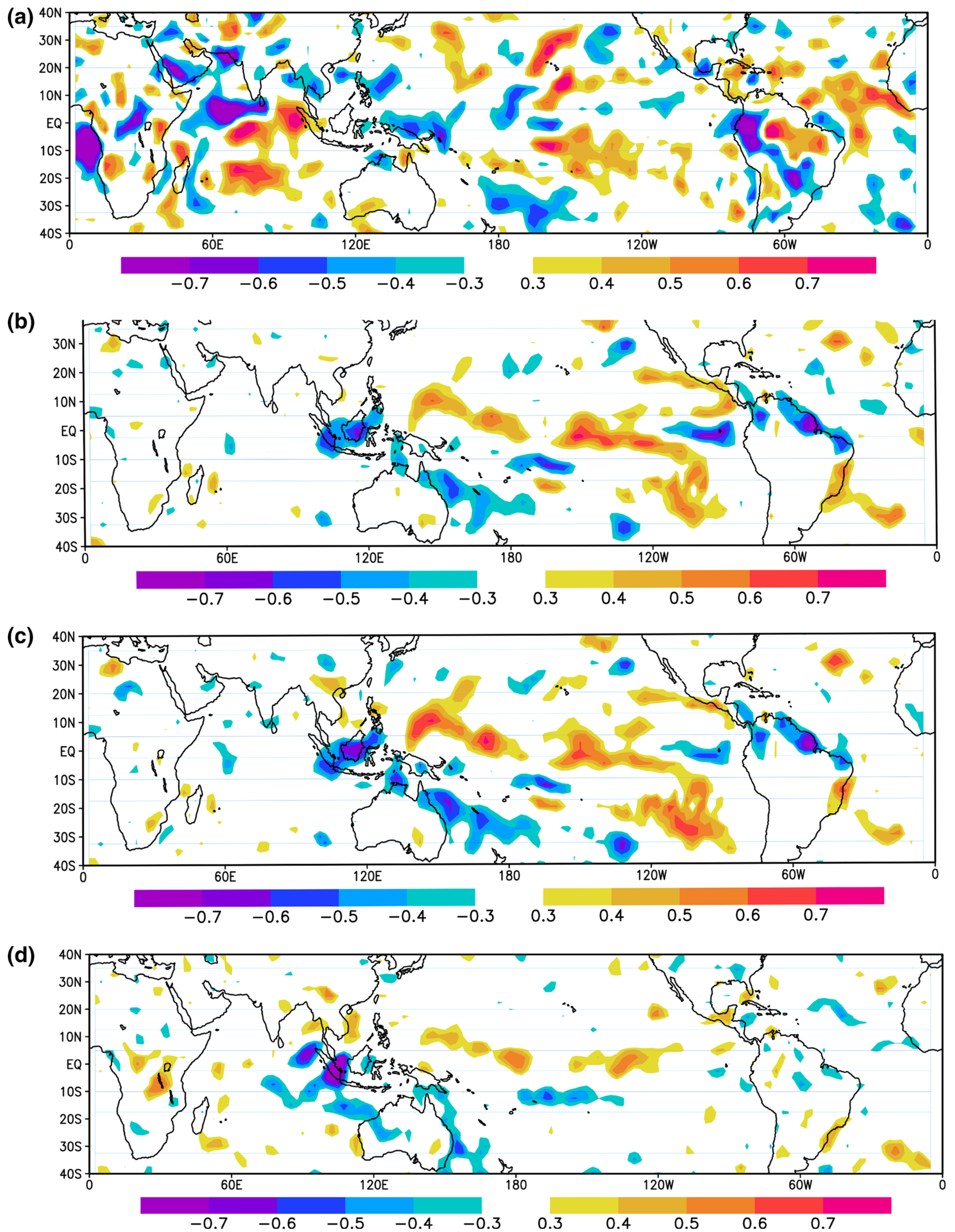
Sl. no.	Districts	Rainfall	Niño 3	Niño 3.4	DMI	EMI
1	Adilabad	**0.67**	**− 0.40**	**− 0.54**	− 0.20	− 0.3
2	Ananthpur	**0.41**	**− 0.46**	**− 0.54**	− 0.11	**− 0.34**
3	Chittoor	− 0.01	− 0.26	**0.34**	0.19	**− 0.41**
4	Cuddapah	− 0.06	0.16	0.14	**0.50**	− 0.13
5	East Godavari	0.02	0.02	0.05	**0.49**	− 0.03
6	Guntoor	0.09	0.31	**− 0.34**	0.17	− 0.18
7	Karimnagar	**0.52**	**− 0.40**	**− 0.61**	0.17	**− 0.40**
8	Khammam	**0.68**	**− 0.68**	**− 0.71**	− 0.04	**− 0.43**
9	Krishna	− 0.11	**− 0.41**	**− 0.40**	− 0.34	0.01
10	Kurnool	**0.39**	− 0.06	− 0.17	**0.42**	**− 0.37**
11	Medak	**0.57**	**− 0.49**	**− 0.69**	**0.34**	**− 0.46**
12	Mehbubnagar	**0.46**	**− 0.49**	**− 0.62**	**0.36**	**− 0.54**
13	Nalgonda	NA	**− 0.54**	− 0.71	0.29	**− 0.57**
14	Nellore	0.02	− 0.04	− 0.28	**0.54**	**− 0.47**
15	Nizamabad	0.68	− 0.28	**− 0.56**	**0.42**	**− 0.43**
16	Prakasham	0.27	**− 0.54**	**− 0.68**	0.15	**− 0.57**
17	Rangareddi	**0.52**	**− 0.54**	**− 0.68**	− 0.05	**− 0.57**
18	Srikakulam	**0.34**	0.08	0.20	**0.54**	0.28
19	Vizag	**0.55**	**− 0.66**	**− 0.64**	0.2	− 0.31
20	Vizianagaram	**0.48**	**− 0.40**	**− 0.42**	**0.47**	**− 0.35**
21	Warrangal	**0.87**	**− 0.42**	**− 0.57**	0.16	**− 0.51**
22	West Godavari	− 0.07	− 0.14	− 0.19	0.27	0.17

Correlations with magnitude above 0.34 and 0.43 are statistically significant at 90 and 95% confidence level, respectively, from a one-tailed *t* test and are shown in bold

3.3. *Response of the Dynamical Aspects of the Atmosphere with Respect to the Indo-Pacific Climate Drivers*

3.3.1 *Response of Moisture Convergence to the Indo-Pacific Climate Drivers*

Our correlation analysis between the 850 hPa moisture convergence and indices of various tropical Indo-Pacific drivers suggests that the El Niño Modokis are associated with a statistically significant anomalous reduction in the Moisture convergence over the east coast of India, including the UAP (Fig. 3a). This is also supported by the zone of anomalous divergence in the region, seen from the composite analysis of 850 hPa velocity potential (Fig. 4). This anomalous divergence is apparently due to the anomalous manifestation to its north-east zone of anomalous


(a)
40N
30N
20N
10N
EQ
10S
20S
30S
40S
0
60E
120E
180
120W
60W
0
−0.7 −0.6 −0.5 −0.4 −0.3
0.3 0.4 0.5 0.6 0.7
(b)
(c)
(d)

◀Figure 3
The correlation signature of the **a** EMI **b** NINO **c** NINO 3.4 and **d** the IODMI to that of MC over the Indian region during the month of June through September

convergence, which extends south-west through the Philippines to the equatorial central tropical Pacific, in agreement with earlier studies such as Chen and Tam (2010) and Pradhan et al. (2011). These studies show that such a convergence is associated with a low-level cyclonic circulation over the northwest tropical Pacific as a Rossby response to the central tropical Pacific. These findings, when combined with the results from Table 3, show that Modoki event indeed modifies the moisture convergence in India and affect the crop production in many states.

Figures 3a, b, 4, 5, while qualitatively agreeing with the results from tables, suggest that the impact of the canonical ENSOs on the moisture content in the subcontinent during boreal summer is relatively weak. This is reasonable, given the fact that the canonical ENSO events have been relatively few as compared to the Modoki events and also that their impacts are deemed to be relatively weaker (e.g. Kumar et al. 1999; Ashok et al. 2007). Furthermore, the IODMI index also shows some positive association with that of the moisture convergence over the Indian region such as the Coastal Andhra Pradesh and Odisha (Fig. 3d), suggesting the relevance of the strong IOD events for the crop production.

3.3.2 *Composite Analysis of Divergence of Wind Anomalies and the Velocity Potential for the El Niño and El Niño Modoki Years for the Period of 1978–2013*

Figure 5 demonstrates a strong divergence zone over the Indian region during the El Niño years, which

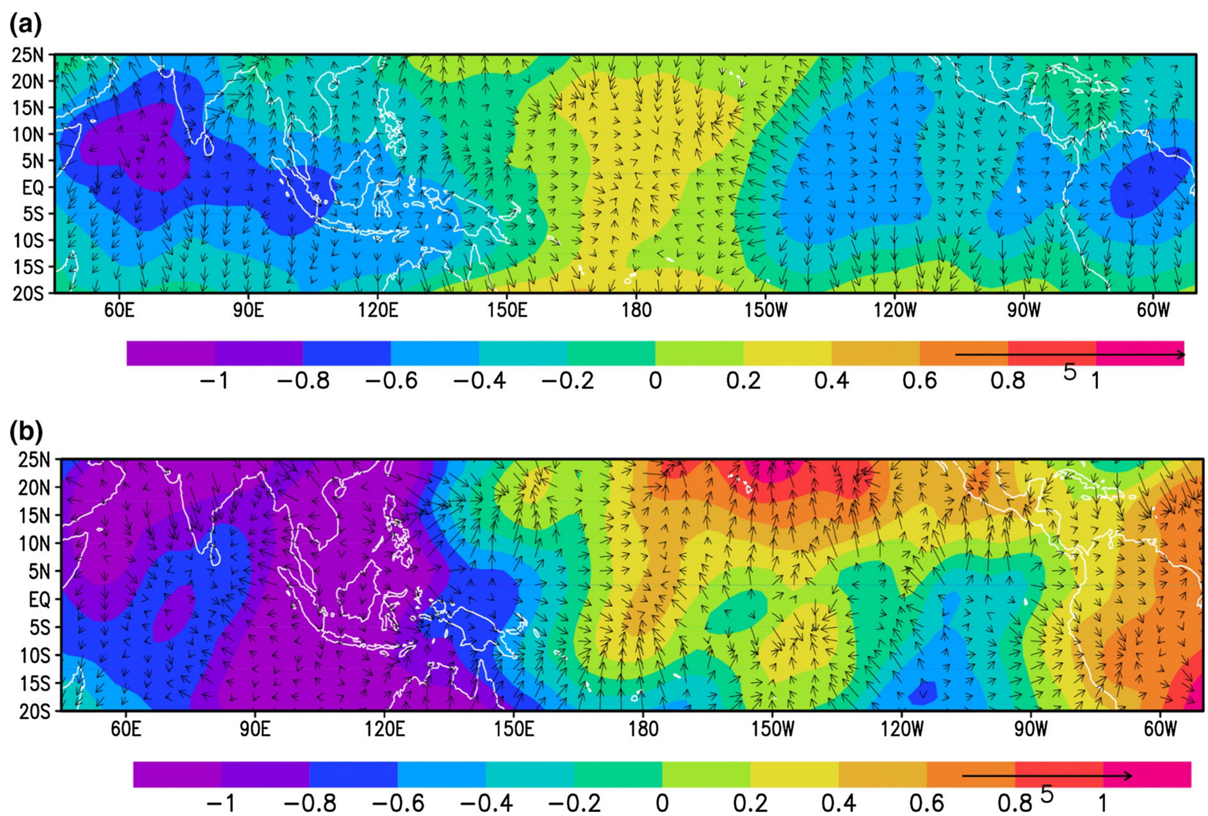


Figure 4
Composite plot of the divergence of wind anomalies (m/s) and the velocity potential (m^2/s) at 850 hpa during the month of June through September of the major **a** EL-Niño Modikis (1991, 1994, 2002 and 2004) and **b** El-Niños (1982 and 1997 years for the period of 1978–2013)

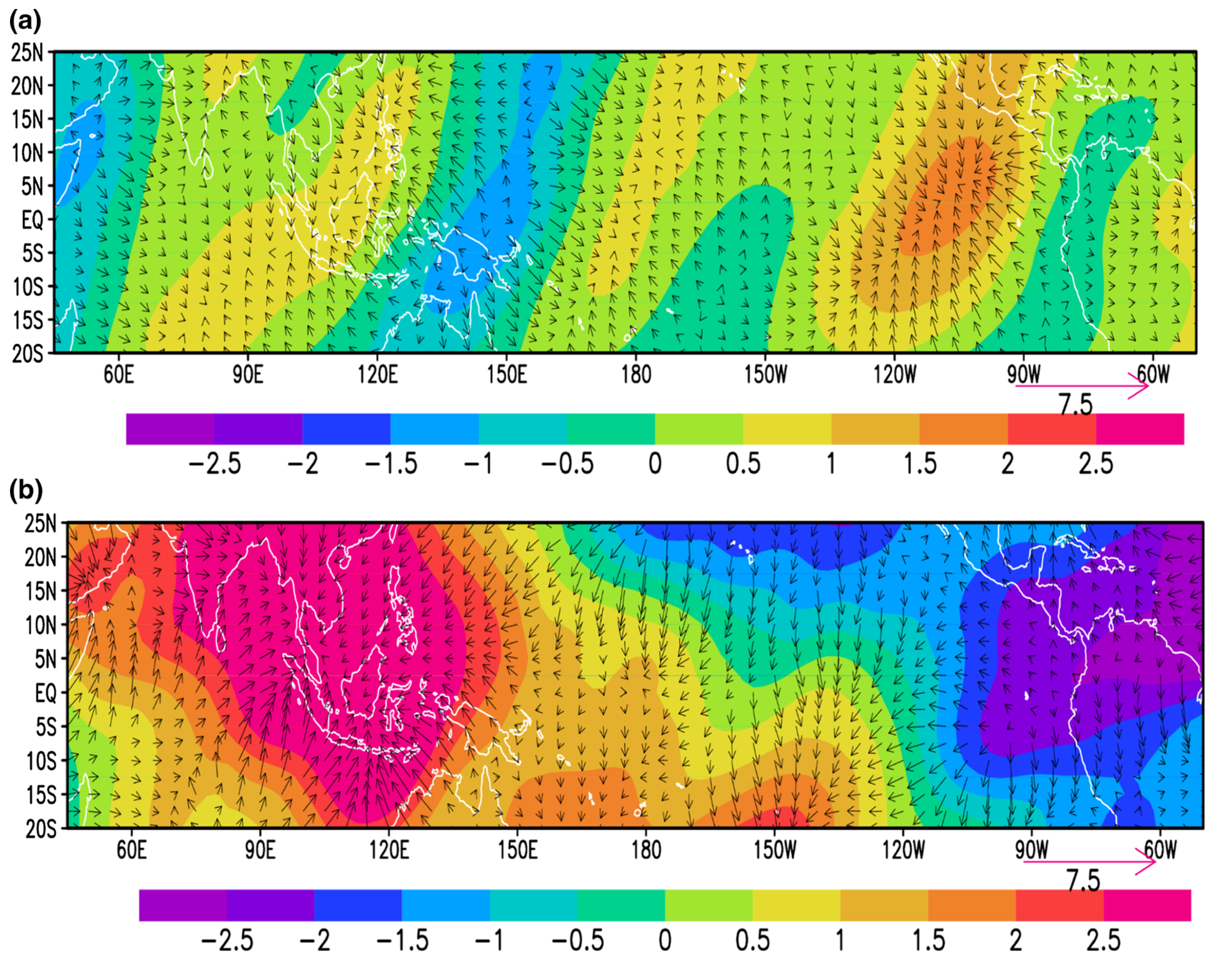


Figure 5

Composite plot of the divergence of wind anomalies (m/s) and the velocity potential (m^2/s) at 200 hpa during the month of June through September of the major **a** EL-Niño Modikis (1991, 1994, 2002 and 2004) and **b** El-Niños (1982 and 1997 years for the period of 1978–2013)

further helps in triggering a dry condition over the region. Subsequently, there could be a significant impact on the agriculture production. Also, it has been stated that during the warm phase of ENSO, there is a significant reduction of 1% in the probability of above-average production over the neutral ENSO phase (Selvaraju 2003). So the divergence characteristics of the wind at 850 hPa over the Indian region implies the weakening of monsoon and the further consequences on agriculture production. While the composite plot (Fig. 4b) for Modokis makes a difference compared to that of the canonical El Niños. It suggests that there is significant divergence over the south-west Indian region, which is close to the monsoon core region. Apart from that, there is also a comparatively less divergence zone appears near to the eastern coast (Odisha, Andhra Pradesh & West Bengal) of the Indian sub-continent. As a result, over the coastal region of Bay of Bengal may get adequate rainfall due to the convergence of anomalous wind. Also, in the earlier analysis, we have demonstrated that the impact of El Niño Modoki over the KCP in the region is significantly good compared to the other Indo-Pacific climate drivers. In particular, we also have demonstrated that the district-wise KCP of UAP is well associated with the El Niño Modoki region. So this is because of a reasonable zone of convergence over the east coast of

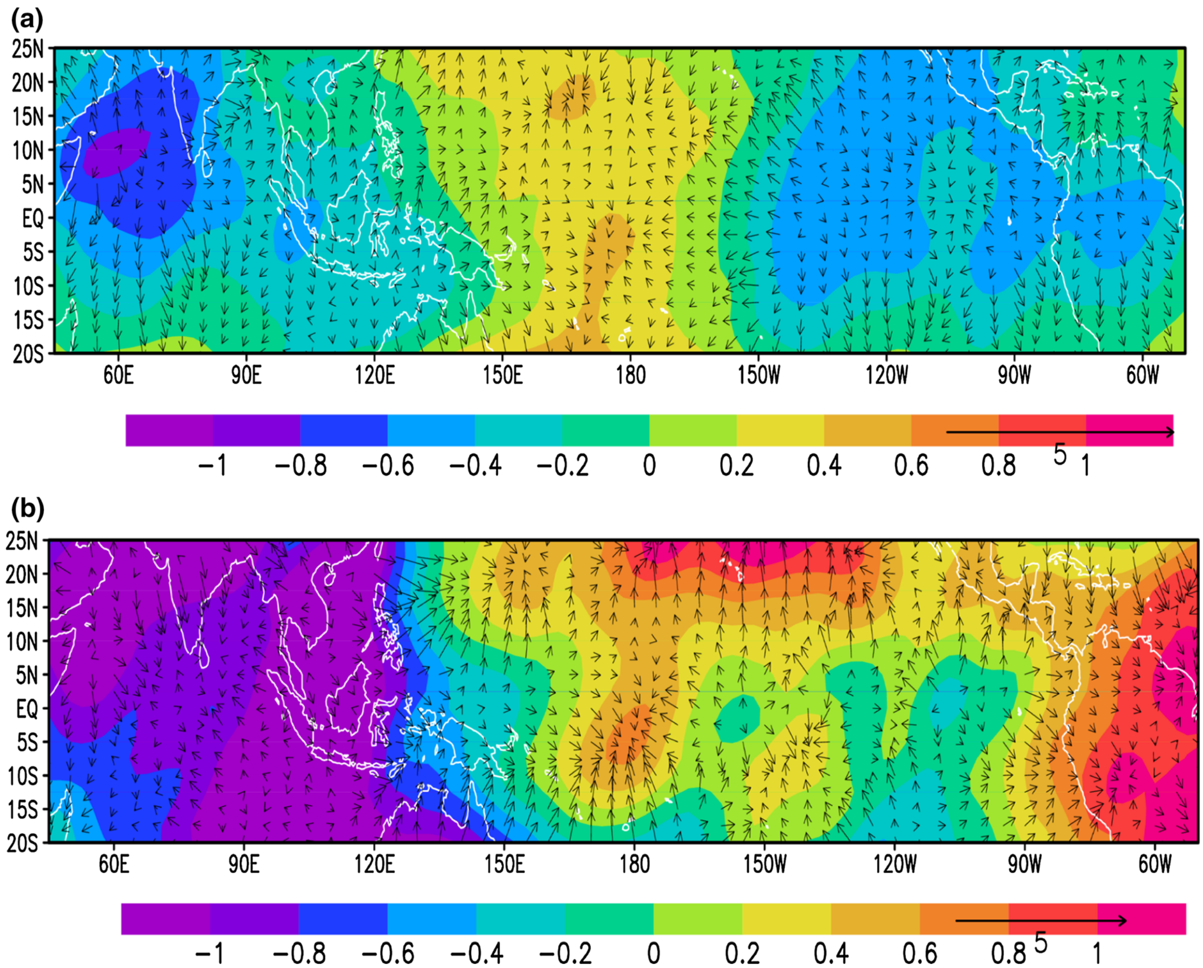


Figure 6

Composite plot of the divergence of wind anomalies (m/s) and the velocity potential (m^2/s) at 925 hpa during the month of June through September of the major **a** EL-Niño Modikis (1991, 1994, 2002 and 2004) and **b** El-Niños (1982 and 1997 years for the period of 1978–2013)

India that shows tremendous production during the El Niño Modoki period of time.

3.3.3 Linkage of the Regional Rainfall Over India to the Large-Scale Circulation Patterns

The surface "monsoon trough", extending from Rajasthan in northwest India through Head bay of Bengal is the most distinct stationary feature of the Indian summer monsoon. This is a manifestation of land–sea thermal gradient, starting sometime in April (Rao 1976). Associated with this is the well-known low-level monsoon circulation (Fig. 7). The summer monsoon rainfall in most of the region along the monsoon trough, and to a signifiant extent in peninsular India, is associated with the day-to-day variability in monsoon trough location and its intensity. Orography also plays an important role. The regions in western peninsular India located west of western ghats, and those in the northeast India, receive a lot of summer monsoon rainfall due to orographic influence. East coastal peninsular India also receives a significant portion of the summer monsoon rainfall from transient disturbances (Godbole 1977; Ashok et al. 2000; Prajeesh et al. 2013). Further details about the relationship between regional summer monsoon rainfall over India can be availed from Rao (1976), Pant and Rupa Kumar (1997), etc.

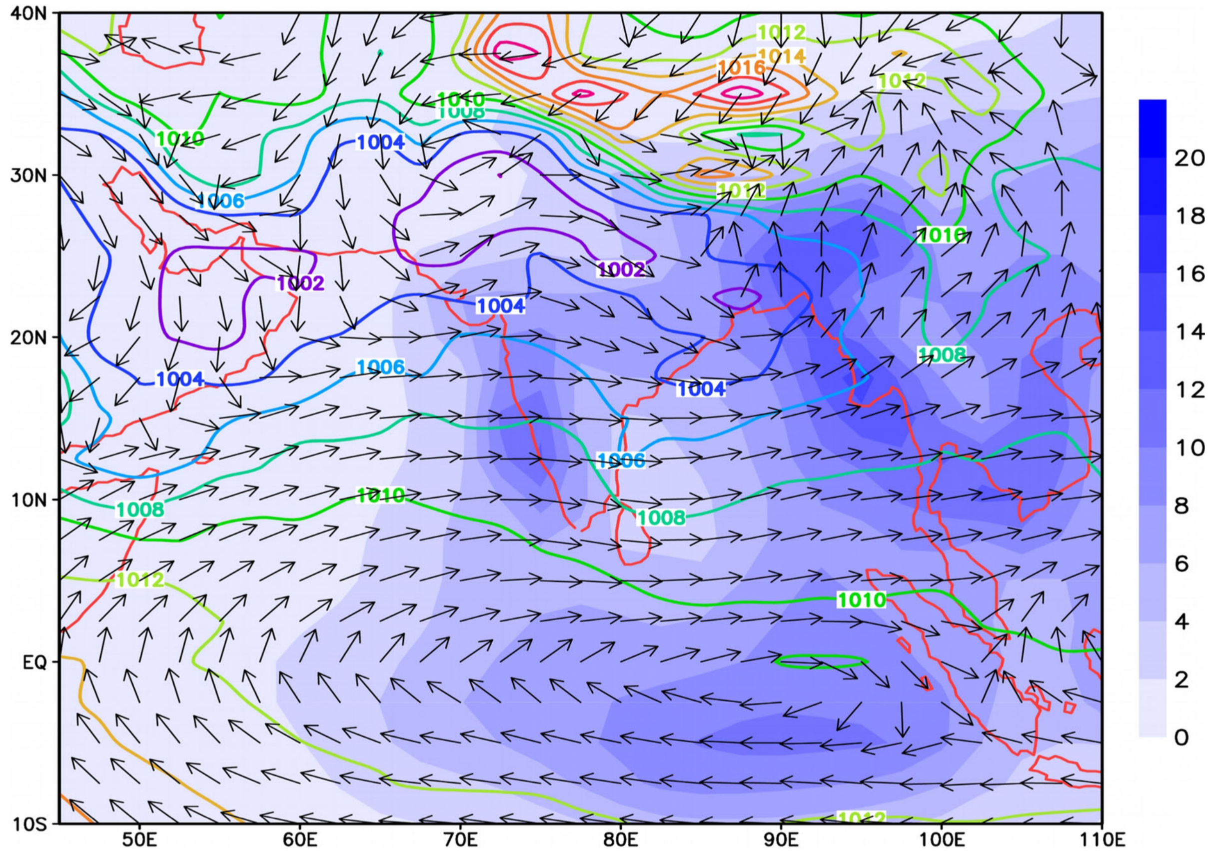


Figure 7
The climatology of wind, mean sea level pressure and rainfall over the indian region for the month of June through September during the period 1979–2013

4. Conclusion

Using the NCEP datasets mainly for the 1983–2013 period, we explore the relevance of the Indian summer monsoon rainfall and that of the tropical Indo-Pacific climate drivers to the Kharif crop production. The results suggest that, despite the improvements in irrigation, technology, availability of fertilizers, etc., the KCP is still significantly dependent on the concurrent rainfall during the summer monsoon season in many states of India. The results suggest that the two ENSO flavours, particularly the ENSO Modoki, have a strong impact on the inter-annual variability of the KCP in several states of India.

Important from prediction point is that these signatures are prominent even at sub-regional levels, for example, in rice-producing states such as the UAP, Karnataka, etc. In particular, the local KCP of UAP responds quite significantly to the variations in the tropical Pacific, as seen by its strong correlations with the NINO 3.4 and the ENSO Modoki indices. An analysis of the NCEP/NCAR reanalysis datasets shows that the impact of these tropical Pacific is through an anomalous modulation of the Walker circulation. We find that an anomalous divergence over the Indian region during a co-occurring El Niño of any type, which influences the KCP over most of the Indian states. In addition, the ENSO Modokis also affect the KCP in the south-east India through a Rossby response associated with the anomalies SST changes in the central tropical Pacific. We found that the KCP of UAP is well associated with most of the drivers. The results suggest that particularly the central tropical Pacific SST variations can critically influence the KCP over most of the Indian states under consideration. The relevance of the IOD events is also seen, though not for as many states as for the case of ENSO flavours.

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References

Ashok, K., & Saji, N. H. (2007). On the impacts of ENSO and Indian Ocean Dipole events on sub-regional Indian summer monsoon rainfall. *Natural Hazards, 42*(2), 273–285. https://doi.org/10.1007/s11069-006-9091-0.

Ashok, K., Soman, M. K., & Satyan, V. (2000). Simulation of monsoon disturbances in a GCM. *Pure and Applied Geophysics, 157,* 1509–1539.

Ashok, K., Guan, Z., & Yamagata, T. (2001). Impact of the Indian Ocean Dipole on the relationship between the Indian monsoon rainfall and ENSO karumuri ashok, Zhaoyong Toshio Yamagata technique. *Geophysical Research Letters, 28*(23), 4499–4502. https://doi.org/10.1029/2001GL013294.

Ashok, K., Guan, Z., & Yamagata, T. (2003). A look at the relationship between the ENSO and the Indian Ocean Dipole. *Journal of the Meteorological Society of Japan, 81*(1), 41–56. https://doi.org/10.2151/jmsj.81.41.

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 Climate, 17,* 3141–3155. https://doi.org/10.1175/1520-0442(2004)017<3141:IACIOE>2.0.CO;2.

Ashok, K., Behera, S. K., Rao, S. A., Weng, H., & Yamagata, T. (2007). El Nino Modoki and its possible teleconnection. *Journal of Geophysical Research: Oceans, 112*(11), 1–27. https://doi.org/10.1029/2006JC003798.

Banacos, P. C., & Schultz, D. M. (2005). The use of moisture flux convergence in forecasting convective initiation: historical and operational perspectives. *Weather Forecast., 20*(3), 351–366.

Behera, S. K., Luo, J. J., Masson, S., Delecluse, P., Gualdi, S., Navarra, A., et al. (2005). Paramount impact of the Indian Ocean Dipole on the East African short rains: A CGCM study. *Journal of Climate, 18,* 4514–4530.

Chen, G., & Tam, C. Y. (2010). Different impacts of two kinds of Pacific Ocean warming on tropical cyclone frequency over the western North Pacific. *Geophysical Research Letters, 37,* L01803. https://doi.org/10.1029/2009GL041708.

Dash, S. K., Jenamani, R. K., Kalsi, S. R., & Panda, S. K. (2007). Some evidence of climate change in twentieth-century India. *Climate Change, 85,* 299–321. https://doi.org/10.1007/s10584-007-9305-9.

Gadgil, S., & Gadgil, S. (2006). The Indian monsoon, GDP and agriculture. *Economic and Political Weekly, 41*, 4887–4895.

Godbole, R. V. (1977). The composite structure of the monsoon depression. *Tellus, 29,* 25–40.

Goswami, B. N., Venugopal, V., Sengupta, D., Madhusoodanan, M. S., & Xavier, P. K. (2006). Increasing trend of extreme rain events over India in a warming environment. *Science, 314,* 1442–1445. https://doi.org/10.1126/science.1132027.

Guan, Z., & Yamagata, T. (2003). The unusual summer of 1994 in East Asia: IOD teleconnections. *Geophysical Research Letters, 30*(10), 1544. https://doi.org/10.1029/2002GL016831.

Guan, Z., Ashok, K., & Yamagata, T. (2003). The summertime response of the tropical atmosphere to the Indian Ocean sea surface temperature anomalies. *Journal of the Meteorological Society of Japan, 81,* 533–561.

Guhathakurta, P., & Rajeevan, M. (2007). Trends in the rainfall pattern over India. *International Journal of Climatology, 28,* 1453–1469. https://doi.org/10.1002/joc.1640.

Kalnay, E., Kanamitsu, M., Kistler, R., Collins, W., Deaven, D., Gandin, L., et al. (1996). The NCEP/NCAR 40-year reanalysis project. *Bulletin of the American Meteorological Society*. https://doi.org/10.1175/1520-0477(1996)077<0437:TNYRP>2.0.CO;2.

Kao, H. Y., & Yu, J. Y. (2009). Contrasting Eastern-Pacific and Central-Pacific types of ENSO. *Journal of Climate, 22*(3), 615–632. https://doi.org/10.1175/2008JCLI2309.1.

Keshavamurty, R. N. (1982). Response of the atmosphere to sea surface temperature anomalies over the equatorial Pacific and the teleconnections of the southern oscillation. *Journal of Atmospheric Science, 39,* 1241–1259.

Krishnan, R., Sabin, T. P., Ayantika, D. C., Kitoh, A., Sugi, M., Murakami, H., et al. (2012). Will the South Asian monsoon overturning circulation stabilize any further? *Climate Dynamics, 40*(1–2), 187–211.

Krishnaswamy, J., Vaidyanathan, S., Rajagopalan, B., et al. (2015). Non-stationary and non-linear influence of ENSO and Indian Ocean Dipole on the variability of Indian monsoon rainfall and extreme rain events. *Climate Dynamics, 45,* 175–184. https://doi.org/10.1007/s00382-014-2288-0.

Kug, J. S., Jin, F-F., & An, S. I. (2009). Two types of El Niño events: cold tongue El Niño and warm pool El Niño. *Journal of Climate, 22*, 1499–1515. https://doi.org/10.1175/2008JCLI2624.1

Kumar, T. V. L., & Barbosa, H. A. (2012). Anomalous changes in summer monsoon rainfall and crop yields over India. *Disaster Advances, 5,* 52–62.

Kumar, K., Rajagopalan, B., & Cane, M. (1999). On the weakening relationship between the indian monsoon and ENSO. *Science (New York), 284*(5423), 2156–2159. https://doi.org/10.1126/science.284.5423.2156.

Marathe, S., Ashok, K., Swapna, P., & Sabin, T. P. (2015). Revisiting El Niño Modokis. *Climate Dynamics, 45*(11–12), 3527–3545. https://doi.org/10.1007/s00382-015-2555-8.

Murtugudde, R., McCreary, J. P., & Busalacchi, A. J. (2000). Oceanic processes associated with anomalous events in the Indian Ocean with relevance to 1997–1998. *Journal of Geophysical Research, 105*(C2), 3295. https://doi.org/10.1029/1999JC900294.

Nanjundiah, R. S., Francis, P. A., Ved, M., & Gadgil, S. (2013). Predicting the extremes of Indian summer monsoon rainfall with coupled ocean–atmosphere models. *Current Science, 104*(10), 1380–1393.

Nicholls, N. (1983). Predicting Indian monsoon rainfall from sea–surface temperature in the Indonesia–north Australia area. *Nature, 306,* 576–577.

Pant, G. B., & Rupa Kumar, K. (1997). *Climates of South Asia* (p. 317). Hoboken: Wiley.

Parthasarathy, B., Rupa Kumar, K., & Munot, A. (1993). Homogeneous Indian monsoon rainfall: Variability and prediction. *Proceedings of the Indian Academy of Sciences - Earth and Planetary Sciences, 120*, 121–155

Parthasarathy, B., Munot, A. A., Kothawale, D. R. (1994). All-India monthly and seasonal rainfall series: 1871–1993. *Theoretical and Applied Climatology, 49* (4), 217–224.

Pradhan, P. K., Preethi, B., Ashok, K., Krishnan, R., & Sahai, A. K. (2011). Modoki, Indian Ocean dipole, and Western North Pacific typhoons: possible implications for extreme events. *Journal of Geophysical Research, 116,* D18108. https://doi.org/10.1029/2011JD015666.

Prajeesh, A. G., Ashok, K., & Rao, D. V. B. (2013). Falling monsoon depression frequency: a Gray-Sikka conditions perspective. *Scientific Reports, 3*(1), 2989. https://doi.org/10.1038/srep02989.

Prakash, S., Mahesh, C., Sathiyamoorthy, V., & Gairola, R. (2013). Increasing trend of northeast monsoon rainfall over the equatorial Indian Ocean and peninsular India. *Theoretical and Applied Climatology, 112*(1–2), 185–191. https://doi.org/10.1007/s00704-012-0719-6.

Preethi, B., Sabin, T. P., Adedoyin, J. A., & Ashok, K. (2015). Impacts of the ENSO Modoki and other tropical Indo-Pacific climate-drivers on African rainfall. *Scientific Reports, 5,* 16653.

Rajendran, K., Kitoh, A., Srinivasan, J., Mizuta, R., & Krishnan, R. (2012). Monsoon circulation interaction with Western Ghats orography under changing climate: projection by a 20-km mesh AGCM. *Theoretical and Applied Climatology, 110*(4), 555–571. https://doi.org/10.1007/s00704-012-0690-2.

Rao, Y. P. (1976). Southwest monsoon. *Synoptic Meteorology, Meteorological Monograph, India Meteorological Department, 1,* 367.

Rasmusson, E. M., & Carpenter, T. H. (1983). The relationship between eastern equatorial Pacific SSTs and rainfall over India and Sri Lanka. *Monthly Weather Review, 111,* 517–528.

Rayner, N. A., Parker, D. E., Horton, E. B., Folland, C. K., Alexander, L. V., Rowell, D. P., et al. (2003). Global analyses of sea surface temperature, sea ice, and night marine air temperature since the late nineteenth century. *Journal of Geophysical Research, 108*(D14), 4407. https://doi.org/10.1029/2002JD002670.

Saji, N. H., Goswami, B. N., Vinayachandran, P. N., & Yamagata, T. (1999). A dipole mode in the tropical Indian Ocean. *Nature, 401*(6751), 360–363. https://doi.org/10.1038/43854.

Selvaraju, R. (2003). Impact of El Niño-southern oscillation on Indian foodgrain production. *International Journal of Climatology, 23*(2), 187–206. https://doi.org/10.1002/joc.869.

Sikka, D. R., & Gadgil, S. (1980). On the maximum cloud zone and the ITCZ over Indian, longitudes during the southwest monsoon. *Monthly Weather Review*. https://doi.org/10.1175/1520-0493(1980)108<1840:OTMCZA>2.0.CO;2.

Trenberth, K. E. (1997). The definition of El Niño. *Bulletin of the American Meteorological Society, 78,* 2771–2777. https://doi.org/10.1175/1520-0477(1997)078,2771:TDOENO.2.0.CO;2.

Webster, P. J., Magaña, V. O., Palmer, T. N., Shukla, J., Tomas, R. A., Yanai, M., et al. (1998). Monsoons: processes, predictability, and the prospects for prediction. *Journal of Geophysical Research, 103*(C7), 14451–14510. https://doi.org/10.1029/97JC02719.

Webster, P. J., Moore, A. M., Loschnigg, J. P., & Leben, R. R. (1999). Coupled ocean-atmosphere dynamics in the Indian Ocean during 1997–98. *Nature, 401,* 356–360.

Weng, H., Ashok, K., Behera, S. K., Rao, S. A., & Yamagata, T. (2007). Impacts of recent El Niño on Modoki dry/wet conditions in the Pacific rim during boreal summer. *Climate Dynamics, 29,* 113–129. https://doi.org/10.1007/s00382-007-0234-0.

Wilks, D. S. (1995). Statistical Methods in the Atmospheric Sciences: An Introduction, (pp. 467). San Diego, Calif: Academic.

Yadav, R. K. (2012). Why is ENSO influencing Indian northeast monsoon in the recent decades? *International Journal of Climatology, 32*(14), 2163–2180. https://doi.org/10.1002/joc.2430.

Yamagata, T., Behera, S. K., Luo, J.-J., Masson, S., Jury, M. R., & Rao, S. A. (2004). The coupled ocean-atmosphere variability in the tropical Indian Ocean. In C. Wang et al. (Eds.), *Earth's climate: The ocean atmosphere interaction* (Vol. 147, pp. 189–211). Washington, DC: AGU.

Yuan, C., & Yamagata, T. (2015). Impacts of IOD, ENSO and ENSO Modoki on the Australian winter wheat yields in recent decades. *Scientific Reports, 5,* 17252. https://doi.org/10.1038/srep17252.

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ORIGINAL PAPER

Value addition to forecasting: towards Kharif rice crop predictability through local climate variations associated with Indo-Pacific climate drivers

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Abstract
The Indian Institute of Tropical Meteorology (IITM) has generated seasonal and extended range hindcast products for 1981–2008 and 2003–2016, respectively, using the IITM-Climate Forecast System (IITM-CFS) coupled model at various resolutions and configurations. Notably, our observational analysis suggests that for the 1981–2008 period, the tropical Indo-Pacific drivers, namely, the canonical *El Niño*-Southern Oscillation (ENSO), ENSO Modoki, and Indian Ocean Dipole (IOD). are significantly associated with the observed Kharif rice production (KRP) of various rice-growing Indian states. In this paper, using the available hindcasts, we evaluate whether these state-of-the-art retrospective forecasts capture the relationship of the KRP of multiple states with the local rainfall as well as the tropical Indo-Pacific drivers, namely, the canonical ENSO, ENSO Modoki, and the IOD. Using techniques of anomaly correlation, partial correlation, and pattern correlation, we surmise that the IITM-CFS successfully simulate the observed association of the tropical Indo-Pacific drivers with the local rainfall of many states during the summer monsoon. Significantly, the observed relationship of the local KRP with various climate drivers is predicted well for several Indian states such as United Andhra Pradesh, Karnataka, Odisha, and Bihar. The basis seems to be the model's ability to capture the teleconnections from the tropical Indo-Pacific drivers such as the IOD, canonical and Modoki ENSOs to the local climate, and consequently, the Kharif rice production.

1 Introduction

The importance of the Indian summer monsoon rainfall (ISMR), which spans from June through September (JJAS), for the growth of the Indian agro-economy, is well-known (Gadgil and Gadgil 2006). A reasonably skilled long-lead prediction of ISMR at regional and local scales in India would be immensely useful to the Indian farmer community as well as policymakers in planning the agricultural practices in advance, crop management, food security/decision-making. However, successful dynamical prediction of Indian summer monsoon on extended and seasonal time scales has not been feasible till a decade back owing to the limitations in model fidelity in the simulation of the intraseasonal and interannual variability, owing to factors such as coarse model resolution, and lack of necessary observational data for the necessary data assimilation. In this context, the Ministry of Earth Sciences (MoES), Government of India, launched the Monsoon Mission Project in 2012 to develop dynamical models from weather through seasonal scale prediction of the ISMR (Rao et al. 2019). The National Centers for Environmental Prediction (NCEP) based Climate Forecast System version 2 (CFSv2), a state-of-the-art Ocean-Atmospheric coupled model, has been chosen as the basic model, on which scientists in India as well as abroad have worked intending to improve the extended and seasonal monsoon prediction. The efforts have been successful, and the retrospective forecasts on different timescales have been shown to be skillful, and some of the products operational as well, e.g., the applications in the forecast of long-range monsoon outlook, monsoon onset, intraseasonal monsoon oscillation, monsoon active-break spells, extreme events like heat and cold waves,

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etc. (Sahai et al. 2016; Pai et al. 2017; Pradhan et al. 2017; Chattopadhyay et al. 2018, 2019; Pattanaik et al. 2019).

The CFSv2 retrospective seasonal forecasts are a set of 9-month long hindcasts initiated on every 5th day of the month with four cycles per day (i.e., 00, 06, 12, 18 GMT), starting from 1st, from the period of 1981–2008. Initial conditions for the ocean and atmospheric component come from the NCEP Climate Forecast System Reanalysis (CFSR) (Saha et al. 2010). An ensemble prediction system (EPS) has been used to generate numerous forecasts of ISMR in an extended range scale from different initial conditions using the CFSv2 model. The extended range prediction (ERP) refers to a meteorological forecast of more than 10–20 days in advance. The EPS generates many forecasts from different initial conditions, and the ensemble forecast could be informed to the user community as an end product, in term of probability. Such estimations of uncertainties will add more decision-making capabilities to the user community in a practical sense. The importance of ERP has been used for determining the Monsoon Intraseasonal Oscillations (MISOs) (Sahai et al. 2013; Sharmila et al. 2013) in terms of active and break spells, which could be a crucial factor for farmers for agricultural scheduling. So, these lead seasonal and extended range monsoon rainfall prediction skills motivate us to make an attempt to explore the usefulness of the climate prediction skills for the Kharif rice production forecast. Indeed, the all India crop production is significantly correlated with the ISMR (e.g. Gadgil and Gadgil 2006; Krishna Kumar et al. 2004; Prasanna 2014; Amat and Ashok 2018), i.e., the crops are grown during both the monsoon and the post-monsoon seasons are highly influenced by the ISMR.

The rationale for considering the dynamical forecast, despite a challenge that the local rainfall may not be predicted with very high skill, comes from the fact that the current day climate models successfully predict the tropical ocean drivers such as the *El Niño* Southern Oscillation (ENSO), which are instrumental in affecting the global climate variability, with excellent lead skills (e.g. Jeong et al. 2012; Srivastava et al. 2015). Indeed, the ENSO is known to influence the ISMR variability (Sikka and Gadgil 1980; Keshavamurty 1982; Palmer et al. 1992; Shukla and Paolina 1983; Navarra et al. 1999; Ju and Slingo 1995; Soman and Slingo 1997; Dai and Wigley 2000; Ashok et al. 2004, Ashok et al. 2019). In a linear sense, stronger *El Niños* are linked with a drier condition over the Indian region. The *El Niño* Modoki events, the other type of *El Niños*, have shown an increase in frequency after the mid-1970s (Ashok et al. 2007; Kao and Yu 2009; Kug et al. 2010; Marathe et al. 2015; Jadhav et al. 2015) and are also associated with the anomalously drier condition over the Indian region (Kumar et al. 2006; Weng et al. 2007; Ratnam et al. 2010), particularly the peninsular region (Ashok et al. 2007, 2009, 2019). Other than the *El Niño* and *El Niño* Modoki, strong Indian Ocean Dipole (IOD) (Saji et al. 1999; Webster et al. 1999; Murtugudde et al. 2000), also plays a major role on the ISMR variability (Ashok et al. 2004; Ashok and Saji 2007; Varikoden and Preethi 2013; Krishnaswamy et al. 2015). Several IOD events are known to occur simultaneously with *El Niños*, owing to their seasonal phase locking characteristics (e.g. Yamagata et al. 2003; Saji et al. 1999; Hameed 2018). Strong positive IOD events co-occurring with an *El Niño*, such as in 1997, reduce the anomalously negative ISMR induced by a co-occurring the *El Niño* (e.g., Ashok et al. 2001). Given all this, the variability of the tropical Indo-Pacific drivers is obviously important for local crop production in many regions of India. In fact, Amat and Ashok (2018) show that the Kharif rice production in various states is statistically significantly correlated with one or more of the tropical Indo-pacific drivers.

In this study, we explore whether the extended-range and seasonal climate prediction skills of the IITM-CFS hindcast data-sets can translate into tenable lead forecasts skills for the observed Kharif rice production (KRP) in the various Indian states. The states considered are West Bengal (WB), Haryana, Kerala, Bihar, Punjab, Uttar Pradesh (UP), Madhya Pradesh (MP), United Andhra Pradesh (UAP), Karnataka, and Odisha. We structure this paper as follows. In the next section (Section 2), we introduce the details of various data-sets used and the methodology of our analysis. We present our results in Section 3 and our conclusions in Section 4.

2 Data and methodology

We use the CFSv2 seasonal hindcast rainfall and sea surface temperature (SST) at the T382 horizontal atmospheric resolution (~ 38 km), generated from 1981 to 2008 (Ramu et al. 2016). The data-set comprises of seasonal hindcast simulations for the March, April, and May initial conditions with 12 lagged ensemble members during this period. The initial conditions are obtained from the NCEP Climate Forecast System Reanalysis (CFSR) (Saha et al. 2010). The present study uses the latest version of the NCEP CFSv2 (Saha et al. 2013) model. For extended range predictions, the coupled model (CFS) is run at two horizontal resolution T126 (~ 100 km) and T382 (~ 38 km) with 64 vertical levels. The model, initialized every Wednesday, is run for the next 32 days. Four ensemble members each from CFST126 and CFST382 are run routinely. In the case of each model, a single forecast was obtained by averaging of four ensemble members. The ensembles have been designed by a perturbation technique, as described in Abhilash et al. (2014). In this study, the available extended range hindcast data-sets generated with T382 resolution for the 2003–2016 (excluding 2010) period have been utilized. The model variables are extracted at 1^0X1^0 horizontal resolutions for comparison with the observations. The week one lead forecast (denoted as W01) was prepared by averaging daily hindcasts for each day of week 1 (henceforth, W01). For example, based on the initial conditions (IC) of 31st May, we have generated the 1st–7th June data; based on 7th June IC, we have collected 8th–14th June data; and so on. The similar, procedure was adopted for weeks 2, 3, and 4 (denoted as W02, W03, and W04, respectively). Further details can be obtained from Abhilash et al. (2014).

This extended-range data was originally meant to provide forecast up to 4-week lead and evaluate the weekly skill. This is routinely done by taking the 7-day average for the given 18 weeks from 1st June to 4th October. But, as we consider the annual agriculture production, the relevance of the weekly forecasts cannot be easily estimated. In other words, we are interested in the estimation of the relevance of these weekly hindcasts from monthly to seasonal scales. We reconstructed the seasonal data from these individual week forecasts (W01, W02, W03, W04) for June through September (JJAS), as briefly described in the following. At first, we calculate for each individual year from 2003 through 2016 (or to be more specific each summer monsoon), the weekly mean of hindcast rainfall, etc., for each of the 18 weeks, at W01, W02, W03, and W04 lead. Then, we examine the skills of these hindcasts by comparing with 18 weeks from observation. Then, we calculate the correlations and partial correlations between the seasonal agriculture productions and the tropical Indo-Pacific climate driver indices. India meteorological department (IMD)'s high resolution ($0.25^0 \times 0.25^0$) gridded rainfall data-set (Pai et al. 2014) over India available from 1901 to 2018 and The Hadley Centre Global Sea Ice and Sea Surface Temperature (HadlSST) (Rayner et al. 2003), available from 1871 to 2018, have been used as the observed data-sets. The state-wise Kharif rice production data-set, available from the Directorate of Economics and Statistics (DES), Ministry of Agriculture, Government of India, for the period of 1981–2014, are also analyzed in the study.

The current study addresses two objectives. The first one is to ascertain how skilful the IITM CFS extended and seasonal hindcasts are in reproducing the observed association of the local KRP with local rainfall. Going further, the local rainfall variations are often dependent on the variations of the tropical Indo-pacific climate drivers such as the ENSO, ENSO Modoki and IOD. Consequently, the observed KRP also has a significant association with the variability of these climate drivers (e.g., Amat and Ashok 2018). In this context, our second objective is to examine the fidelity of the association of the hindcast variability of these tropical Indo-Pacific climate drivers with the observed local KRP. This is achieved by (a) computing the partial correlations of the observed local KRP with model-predicted NINO3, EMI, and IODMI and (b) comparing these with the corresponding partial correlations from the observations.

For determining the statistical significance of the correlation analysis, we used the one-tailed Student's *t* test, where the degree of freedom *(df)* has been taken as the limited number of years available. We use the pattern correlation, which is the linear correlation between the spatially distributed values of a particular parameter with another such parameter over the same domain; for example, the gridded JJAS 2009 rainfall observations and corresponding model predictions over the Indian subcontinent. This is a diagnostic estimate that quantifies the model's skill in predicting the particular variable over a designated domain at a single time point/stratum from the context of model evaluation. We also carry out the composite plot analysis to see the impact of the tropical Indo-Pacific drivers on the ISMR at a different period during 2003–2016.

Further, the partial correlation method (Nicholls 1983) has been used to linearly isolate the individual impacts of multiple co-occurring the prominent tropical Indo-Pacific climate drivers during the JJAS season, specifically, the ENSO, ENSO Modoki, and IOD (e.g. Ashok et al. 2001, 2007; Ashok and Saji 2007; Guan et al. 2003; Behera et al. 2005).

The relevant indices used in our analysis are:

- *NINO3*—Area-averaged sea surface temperature anomaly (SSTA) of the region bounded by (5°N–5°S, 150°W-90°W) (Trenberth 1997), which represents the variability of the canonical ENSO.
- *Indian Ocean Dipole Mode Index (IODMI)*—Area-averaged SSTA difference between the western box (50°E–70°E, 10°S–10°N) and the eastern box (90°E–110°E, 10°S to the equator) (Saji et al. 1999).
- *ENSO Modoki (EMI)*—It is defined, following Ashok et al. (2007)
- EMI= $[SSTA]_A$ -0.5*$[SSTA]_B$-0.5*$[SSTA]_C$
  where $[SSTA]_A$=the area-averaged SSTA bounded by the region A(165°E–140°W, 10°S- 10°N), $[SSTA]_B$= the area-averaged SSTA bounded by the region B (110°W–70°W, 15°S–5°N), $[SSTA]_C$= the area-averaged SSTA bounded by the region C (125°E–145°E, 10°S–20°N).
- *NINO3.4*—The area-averaged SSTA of the region bounded by (5°N-5°S,170°W–120°W) (Trenberth 1997). This index was originally coined to represent the impacts of the canonical ENSO.

Henceforth, we compare the model predicted climate skills with the state-wise observed KRP, to quantify the climatic impact on the state-wise KRP. Further, we have used the one-tailed Student's *t* test to assess the statistical significance of the correlation analysis. We calculate the area-averaged anomalous seasonal rainfall over the Indian subcontinent (5°N-40°N, 60°E-100°E) during each JJAS season for observed data-set as well as CFSv2 seasonal and extended range model hindcasts. The significance of correlations has been determined from a one-tailed Student's t test.

3 Results

3.1 Analysis from the CFSv2 T382 seasonal hindcast

3.1.1 Correlations of anomalous observed and model-predicted rainfall

The anomaly correlation coefficients between the observed ISMR and seasonal prediction hindcasts for the period 1981–2008 (Fig. 1) are found to be 0.5, 0.36, and 0.22 from March, April, and May initial conditions, respectively. As reported by Pokhrel et al. (2016) and Chattopadhyay et al. (2016), the 3-month lead forecast time has the maximum skill among the three, which is March's month. Here, the magnitude values of 0.5, 0.36, and 0.22 are statistically significant at 98, 95, and 90% confidence interval, respectively, from a one-tailed Student t test. This suggests that these seasonal forecasts of ISMR at 1–3 months lead are reasonably good.

We calculated the anomalous rainfall over the Indian region during *El Niño* (e.g., for the March initial condition—1984, 1987, 1988, 1993, 1995, 1997, 2001, 2002, 2004, 2006), El Niño Modoki (e.g., for the March initial condition—1981, 1984, 1991, 1992, 1993, 1996, 1998, 1999, 2002, 2004, 2008), and IOD (e.g., for the March initial condition—1982, 1984, 1986, 1988, 1992, 1994, 1998, 1999, 2004, 2005) events using both the observed and model-simulated for March, April, and May initial conditions. Figure 2(a) suggests that during the 1981–2008 period, the canonical *El Niño* events are associated with an anomalous deficit of rainfall across a significant part of the Indian subcontinent, such as along the monsoon trough, including central India, north India, and the west coast of India. The corresponding model hindcasts (Figs. 2d, g, and f) capture this signature. The aforementioned figures also suggest that the model hindcasts with April's initial condition are the most realistic, while the rainfall anomalies from those with March (May) initial condition are overestimated (underestimated) compared with observations. Figure 2(b) shows a strong summer monsoon rainfall reduction over India during the *El Niño* Modoki events, in conformation with the observational studies (e.g., Ashok et al. 2007, 2019). The hindcasts (Figs. 2e, h,

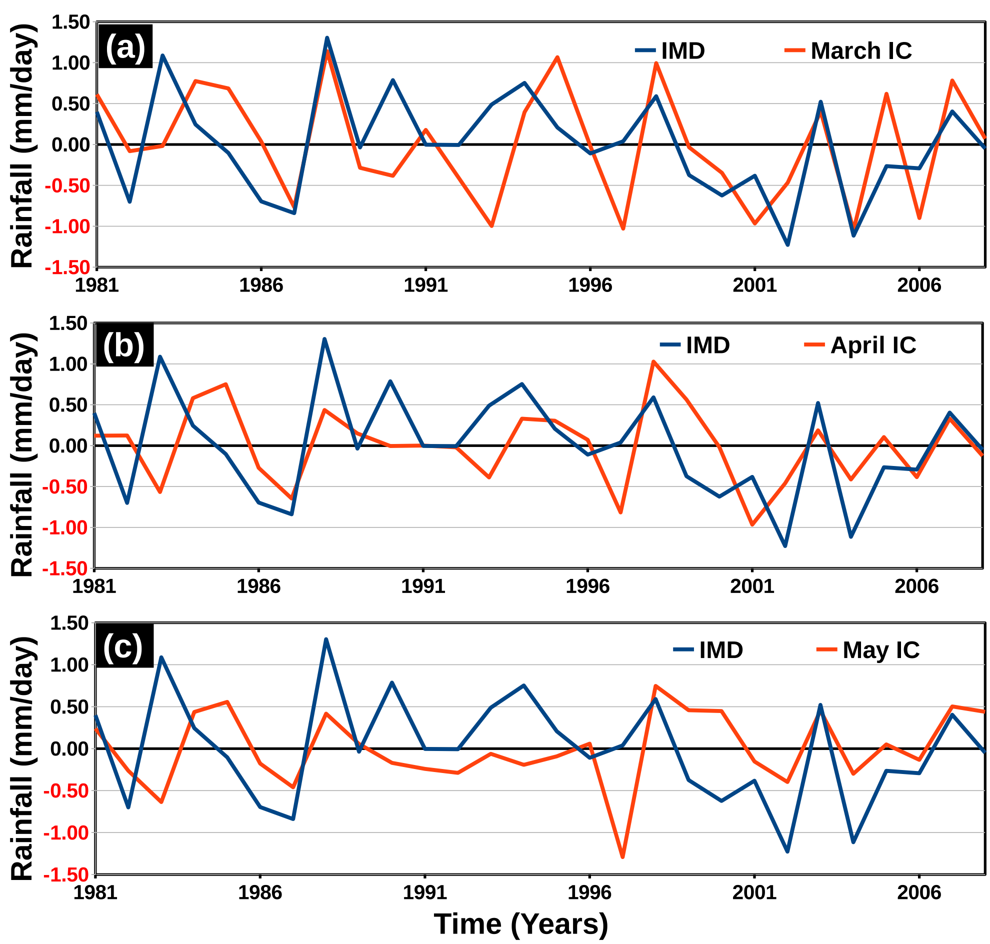
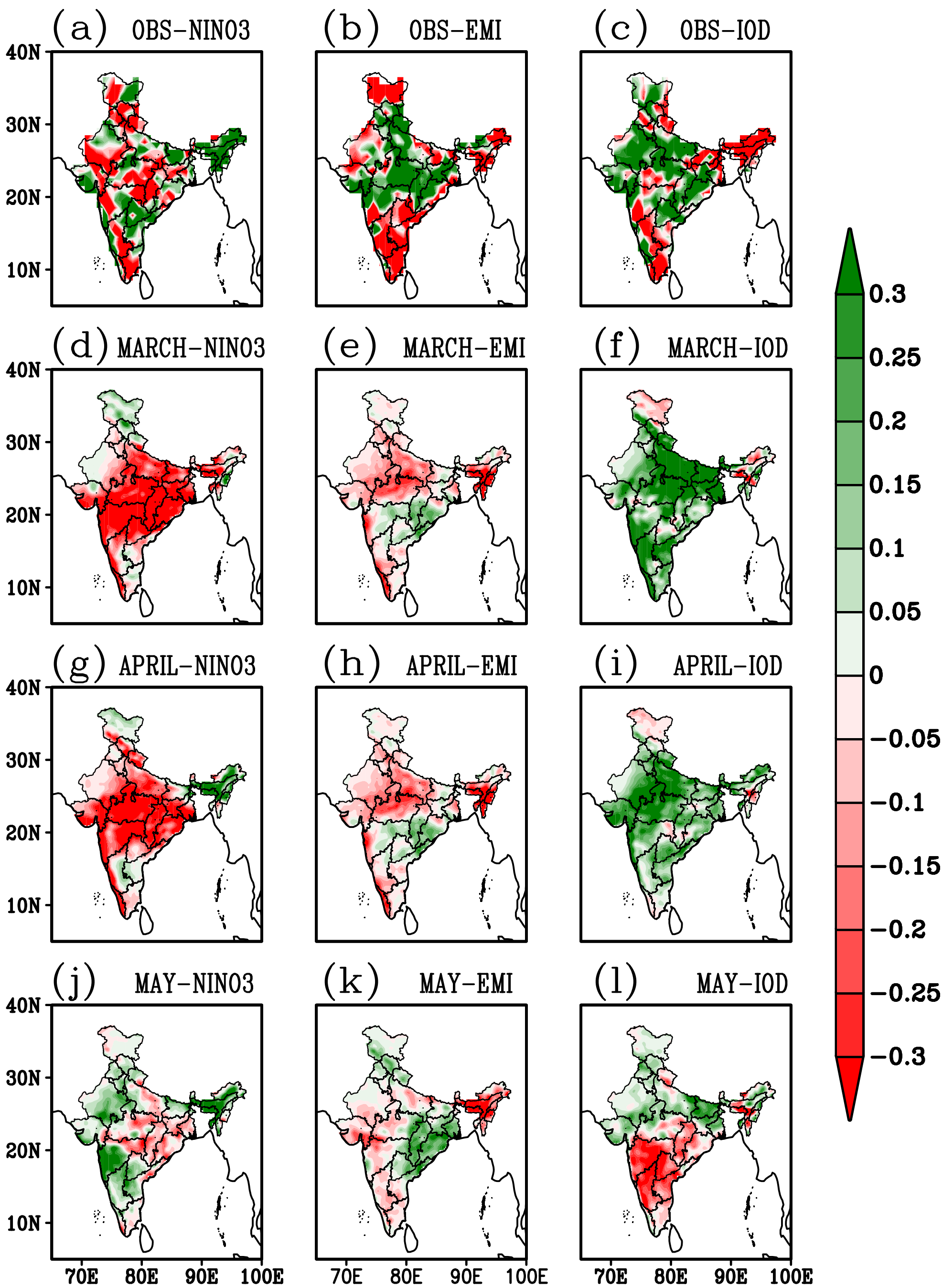


Fig. 1 Observed(IMD) time series of area-averaged JJAS rainfall anomaly (blue), shown with those from the CFSv2 T382 seasonal hindcast (mm/day; red) with different initial conditions (**a**) March, (**b**) April, and (**c**) May during 1981 to 2008 respectively

Fig. 2 Composite of anomalous rainfall during El Nino, El Nino Modoki and IOD events over India, during the period of 1981-2008, for the observed (**a**) to (**c**) and model simulations (**d**) to (**l**)



and k) are relatively good in the replication of the *El Niño* Modoki's impact, just like that of the *El Niños*. Also, the IOD linked anomalous rainfall with the March and April initial conditions can capture the surplus rainfall along the monsoon trough (Figs. 2(c), (f), and (i)).

3.1.2 State-wise SMR (observed and CFSv2 T382 hindcast) response to the KRP

The seasonal hindcasts give us general guidance for long-term strategic planning of water management for agriculture as well as other general purposes. Using linear correlation analysis, we evaluate the importance of summer monsoon rainfall (SMR) for the state-wide KRP from significant Kharif rice producing states in India. We carry out this analysis only for the 1990–2008 periods, owing to limited availability of seasonal hindcast data-sets.

Table 1 suggests that the correlations of the state-KRP with the observed local rainfall and CFSv2 hindcast, over the period of 1981–2008, are simultaneously significant at 90% confidence level from a one-tailed Student's *t* test for states like the UAP, Bihar, and Karnataka. These results are qualitatively

Table 1 Correlations between the state-wise Kharif rice production (KRP) with the observed and CFSv2 Seasonal (March, April and May initial conditions) hindcast rainfall of that state for the 1981–2008 period. All bold values are the correlations with value, and 0.24 are statistically significant at 90% confidence level from a one-tailed student *t* test.

States	***Observed***	***Model***		
		March	***April***	***May***
Bihar	**0.38**	0.18	**0.27**	**0.27**
Haryana	0.13	−0.13	−0.11	0.11
Karnataka	**0.26**	−0.11	0.06	**0.35**
Kerala	0.21	0.11	0.1	0.007
MP	**0.46**	0.12	0.11	−0.07
Odisha	**0.64**	0.006	0.02	0.007
Punjab	−0.12	−0.21	**−0.36**	0.1
UAP	**0.59**	**0.28**	0.12	**0.51**
UP	−0.02	−0.07	−0.11	0.05
WB	**0.3**	−0.22	0.11	0.1

similar to those for the shorter period of 2000-2013 (Amat and Ashok 2018). Interestingly, the May initial condition correlations showing more significant results compared to the March and April initial conditions. Also, the negative results could be caused by crop damage. Several studies show that such a relationship can be attributed to the frequent floods/heavy rainfall damaging the crops (Kumar et al. 2006; Lal et al. 2020). A similar negative correlation is seen between the local KRP from Kerala with the local rainfall for a shorter period of 2001–2013 (Amat and Ashok 2018).

The corresponding correlations of the observed state-level KRP with the model-predicted state-level SMR for the states like UAP, Bihar, Karnataka, MP, Odisha, and WB from the Table 1 are qualitatively realistic although model predicted skills for most of the states are statistically insignificant. Only the states like Bihar and UAP have shown some statistically significant results mostly for the March and May initial conditions, which is a significant result for both observed and model hindcast. Apart from that, Punjab's negative relationship is well captured, but this weak correlation maybe because of the dry biases of CFSv2 over Indian region.

3.1.3 Response of climate drivers (CFSv2 seasonal hindcast) to that of the KRP

In our recent publication (Amat and Ashok 2018), we show that the KRP from several states such as the Karnataka, UAP, Odisha, etc. is significantly associated over the 2001–2013 period with the inter-annual variability of the tropical Indo-Pacific ocean drivers, specifically, the canonical ENSO, ENSO Modoki, and the IOD. We also show that this is potentially due to the modulation of the local moisture convergence by these drivers.

We compute the partial correlations of the KRP with various indices of various tropical Indo-Pacific drivers over the 1990–2008 period. The results are presented in Table 2. From the Table 2, we see that the model hindcasts capture the skills for MP with significant correlation magnitudes of −0.38 and −0.3 from the April and May initial conditions respectively, while the observed correlation is found to be −0.31. The partial correlations from the hindcasts are comparable to that from the observations. Also, we find Bihar has some good results with the observed correlation magnitude −0.25 and −0.37 for April initial condition. Moreover, we find a high negative correlation of −0.47 between the observed NINO3 index and the observed KRP index over UAP. Also, the corresponding correlations of the KRP with hindcast NINO3 index from all initial conditions (March, April, and May) qualitatively capture the positive relationship, and the magnitudes are not significant for all three initial conditions. On the other hand, the observed IODMI exhibits a correlation of 0.26 with observed KRP over Odisha, and the May initial condition capture this association pretty well with a magnitude of 0.28. States like UAP, Punjab, and Haryana have also given some good results, but the model shows opposite results concerning all the initial conditions. Interestingly, the observed positive association of the IODMI with the KRP is well captured with the May initial once we partial out the correlations of the NINO3.4 index (Table 3). On the other hand, the predictive leads are not that impressive once we partial out the EMI impact (Table 4). The NINO3.4 index captures impact from both the canonical and Modoki ENSOs (e.g., Weng et al. 2007). The better representation of NINO3.4 index to isolate the effects over Bihar suggests that the summer monsoon rainfall is more sensitive to the sea surface temperature variations in the central tropical pacific (e.g., Krishna Kumar et al. 2006). This becomes clearer that because the hindcasts with April initial conditions also reasonably reproduce the observed positive correlations between the KRP over Bihar and the IODMI (Table 4) once the co-occurring impacts from the EMI are removed. Furthermore, the seasonal hindcasts with March, April, and May excellently recapture the significant negative correlations for Bihar between the KRP and the EMI (Table 4).

From Table 3, we observe a significant negative correlation for Odisha, UP, Bihar, and Haryana between the NINO3.4 index and the KRP index both for the observed and model-predicted different initial condition, mostly April and May. For Odisha, UAP, Bihar, and Haryana, there is a statistically significant positive correlation between the IODMI & KRP indices, after removing the impact of NINO3.4, in both the observed as well as the model outputs, in particular to April & May initial conditions.

Table 2 Partial correlations between the observed state-wise KRP with the observed Nino3 and IODMI for the period of 1981-2008, and those drivers from the model hindcast. The magnitude with 0.24 and 0.31 are statistically significant at 90 and 95% confidence interval, respectively, from one-tailed Student's t test and are shown in bold

States	*NIN03-KRP adjusted for (IODMI)*				*IODMI-KRP adjusted for (NINO3)*			
	Observed	March	April	May	Observed	March	April	May
Bihar	**−0.25**	−0.21	**−0.37**	−0.22	0.2	**−0.22**	0.15	0.01
Haryana	**−0.28**	**0.28**	**0.31**	**0.35**	**0.32**	−0.22	−0.2	**−0.29**
Karnataka	−0.2	**0.24**	0.19	**0.26**	0.19	−0.18	0.07	**−0.28**
Kerala	0.17	**−0.32**	**−0.27**	**−o.33**	−0.16	**0.34**	0.2	**0.35**
MP	**−0.31**	−0.18	**−0.38**	**−0.3**	−0.11	0.07	**0.38**	0.14
Odisha	**−0.27**	0.05	−0.06	0.05	**0.26**	−0.01	**0.28**	−0.01
Punjab	−0.2	**0.37**	**0.38**	**0.38**	**0.27**	**−0.29**	−0.21	**−0.30**
UAP	**−0.47**	0.05	0.05	0.13	**0.31**	**−0.28**	−0.02	**−0.3**
UP	**−0.26**	**0.26**	0.11	0.22	0.22	**0.30**	0.03	**−0.25**
WB	−0.19	**0.36**	**0.27**	**0.34**	0.19	**−0.28**	−0.07	**0.31**

We can thus conjecture that the seasonal hindcasts of the CFSv2 reasonably reproduce the significant impacts of various tropical Indo-Pacific drivers on the KRP of UAP, Odisha, and Bihar with a maximum lead of 2–3 months. The other skills include reproducing the observed and model-based negative correlations between the EMI and KRP over Bihar (Table 4) with all three initial conditions, i.e., March, April, and May. On the other hand, the IODMI impact looks significant for Odisha when we remove the impact of EMI. By observing the results from Tables 2, 3, and 4, we imply that the central Pacific SSTA index, i.e., NINO3.4, plays a significant role in the variation of seasonal Kharif rice production.

3.2 Analysis from the CFSv2 extended-range hindcast

3.2.1 Correlations of anomalous observed and model-predicted rainfall

We use the observed rainfall data-set and CFSv2 (T382 & T126) extended-range hindcast outputs with the initial conditions with a 4-week leads (W01, W02, W03, W04), with the week one initial condition dated 31st May of each year. We calculate the area-averaged anomalous rainfall over the Indian landmass during June through September (JJAS) from 2003 to 2016. For the extended range prediction, correlations with a magnitude of 0.7 and 0.4 are statistically significant at 99 and 95% confidence interval from a one-tailed Student's t test.

Table 3 Partial correlations between the observed state-wise KRP with the observed NINO3.4 & IODMI for the period of 1981-2008, and those drivers from the model hindcast. The magnitude with 0.24 and 0.31 are statistically significant at 90% and 95% confidence interval respectively from one-tailed Student t test and are shown in bold

States	*NIN03.4-KRP adjusted for (IODMI)*				*IODMI-KRP adjusted for (NINO3.4)*			
	Observed	March	April	May	Observed	March	April	May
Bihar	**−0.4**	−0.21	**−0.45**	**−0.29**	**0.28**	−0.21	**0.26**	**0.24**
Haryana	**−0.24**	**0.28**	**0.25**	**0.29**	**0.30**	−0.22	−0.18	**−0.26**
Karnataka	−0.23	**0.27**	0.15	0.2	0.19	−0.2	0.07	**−0.25**
Kerala	0.14	**−0.31**	−0.2	**−0.24**	−0.14	**0.33**	0.17	**0.31**
MP	−0.09	−0.15	**−0.25**	**−0.27**	−0.08	0.06	**0.38**	0.13
Odisha	**−0.26**	0.1	**−0.24**	−0.05	**0.24**	−0.03	**0.29**	**0.25**
Punjab	−0.12	**0.38**	**0.33**	**0.34**	0.23	**−0.25**	−0.21	**−0.27**
UAP	**−0.55**	0.16	−0.04	0.02	**0.34**	**−0.28**	0.02	**0.25**
UP	**−0.28**	**−0.26**	0.03	0.17	0.22	−0.3	0.06	−0.23
WB	−0.1	**0.39**	**0.24**	**0.35**	0.14	**0.3**	−0.07	**−0.31**

Table 4 Partial correlations between the observed state-wise KRP with the observed EMI and IODMI for the period of 1981-2008, and those drivers from the model hindcast. The magnitude with 0.24 and 0.31 are statistically significant at 90% and 95% confidence interval respectively from one-tailed Student's *t* test and are shown in bold

States	*EMI-KRP adjusted for (IOD)*				*IOD-KRP adjusted for (EMI)*			
	Observed	March	April	May	Observed	March	April	May
Bihar	**−0.35**	**−0.14**	**−0.39**	**−0.29**	0.09	−0.23	0.2	0.02
Haryana	0.01	**0.25**	−0.06	−0.05	0.21	−0.21	−0.03	−0.09
Karnataka	−0.08	**0.33**	−0.1	−0.04	0.09	**−0.24**	0.18	−0.14
Kerala	0.03	−0.19	0.09	0.1	−0.09	**0.28**	0.03	0.16
MP	−0.14	−0.05	−0.09	0.03	−0.13	−0.01	**0.25**	−0.03
Odisha	0.03	**0.31**	−0.15	0.03	**0.24**	−0.16	**0.32**	0.01
Punjab	0.13	**0.37**	0.04	0.04	0.2	**−0.25**	−0.06	−0.12
UAP	−0.23	0.17	**−0.36**	−0.07	0.05	**−0.28**	0.20	−0.14
UP	−0.06	**0.25**	0.2	−0.06	0.1	**−0.30**	0.17	−0.12
WB	0.15	**0.4**	0.05	0.18	0.11	**−0.31**	0.01	−0.22

Figure 3 suggests that T126 based extended range hindcasts have positive correlations with the magnitudes 0.71, 0.66, 0.56, and 0.44 for the respective week leads of W01, W02, W03, and W04, which is statistically significant at 99% confidence interval for W01 lead and then with a decreasing order as farther the week moves. We also observe that the variability of the predicted summer monsoon rainfall over the Indian region from extended range hindcast at both the resolution of ~ 38 km (T382) and ~ 110 km (T126) are reasonably realistic. Here, the observed rainfall during *El Niño* years has been depicted from the composite of 2007, 2012, and 2014. The observed IOD events, e.g., 2004, 2005, 2011, 2012, 2013, 2014, and the *El Niño* Modoki events, e.g., 2004, 2008 and 2010, have been considered. Figure 4(a), (d), and (g) suggest that the model captures a significant negative anomaly for the *El Niño* over central India. While Fig. 4(b), (e), and (h) suggest that model simulations are opposite to the observed negative rainfall anomaly over India, during the *El Niño* Modoki events. In the extended range simulations, the signal may not be visible as clear as the seasonal hindcast because of data availability limitation.

Table 5 suggests that the correlation of EMI with the respective state-wise KRP for Bihar and Karnataka with a magnitude of −0.44 and −0.43, respectively, are statistically significant at a 95% confidence interval. There is a significant correlation for NINO3 and KRP of Bihar with a magnitude of 0.61, which is irrelevant to the observed one. UP has a significant correlation of NINO3.4 and the state-wise KRP with a magnitude of 0.62, which is also irrelevant to the observed correlation. The model skills are not good enough to capture the skill for the state-wise Kharif rice forecast, while the observed data-set significantly captures it.

Table 6 suggests that the correlation of IODMI with the KRP of Bihar is statistically significant after removing the impact of NINO3, NINO3.4, and EMI, with the magnitude of 0.61, 0.69, and 0.62, respectively, at a confidence interval of 99% from the one-tailed student *t* test. In this case, both the data-sets (T126 & T382) exhibit equally good skill for Bihar. Also, the correlation of IODMI with the KRP of Karnataka has a statistically significant skill, after removing the impact of EMI. We observe that the skill for IODMI with KRP relation is significant for a few states. Also, the non-significant values exhibit relevant sign convention for the observed skills of all other states. While in the previous correlation table (Table 5), most of the states show unrealistic correlation coefficients, despite having a significant magnitude.

4 Conclusion

The economy of most Indian states is governed by agricultural yield, which still largely depends on monsoon rainfall (e.g., Amat and Ashok 2018). In the present study, we explore the potential utility of the hindcasts from the state of the art IITM dynamical seasonal and extended hindcast systems. To this end, we use the available (i) quasi-operational seasonal hindcast products available for 1981–2008 period at 38 km resolution (ii) and hindcasts of extended range prediction for the 2003–2016 period available at both 110 km and 38 km resolution. Observation-based data-sets have been used to ascertain the relevance of local rainfall variability and its association with its important drivers, specifically, the co-occurring ENSO, ENSO Modoki, and the Indian Ocean Dipole. Our observational analysis shows that the association between state-wise summer monsoon rainfall and KRP rice

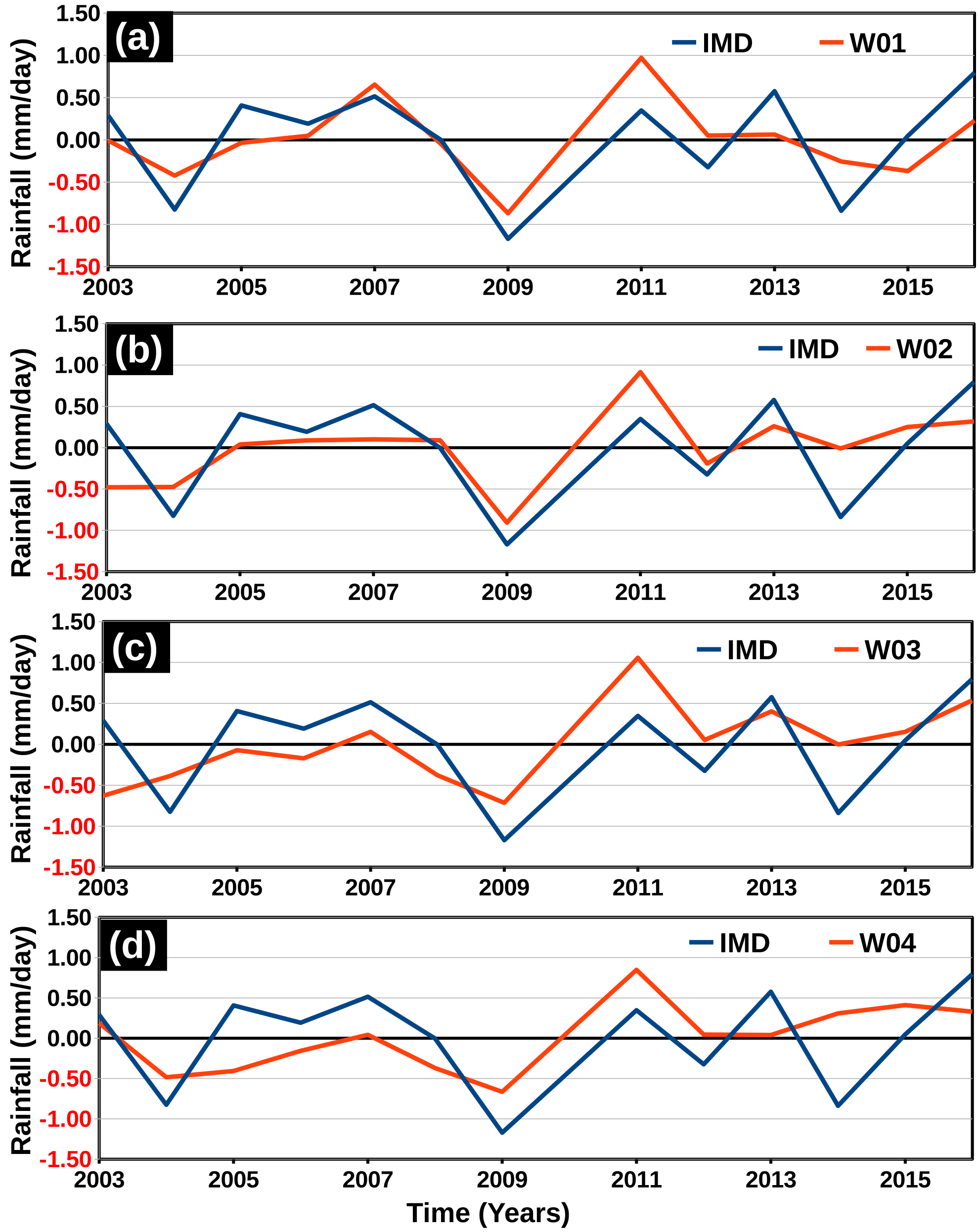


Fig. 3 Observed(IMD) time series of area-averaged JJAS rainfall anomaly (blue), shown with those from the CFSv2 T126 extended range hindcast (mm/day; red) with different week leads (**a**) W01, (**b**) W02, (**c**) W03, and (**d**) W04 during 2003–2016, respectively

production is statistically significant at 90–95% confidence level over UAP, Bihar, Karnataka, MP, Odisha, and WB for the period 1990–2008, for which the seasonal hindcast is available. The Kharif rice production (KRP) of UP, MP, Bihar, and Haryana are significantly associated with the NINO3 and NINO3.4 indices. The IOD events significantly influence the KRP of Odisha, Bihar, and Haryana states. Equipped with these observations, we estimate the correlations of (i) the simulated local rainfall with the local KRP and (ii) correlations of the indices each simulated climate driver with the observed KRP; and a realistic correlation would mean that the predicted climate signals from the IITM CFS system can be used to predict KRP of the relevant states statistically.

As far as the seasonal hindcasts are concerned, we find that the correlations between the predicted and observed area-averaged seasonal Indian summer monsoon rainfall anomaly with the initial conditions of March, April and May are, respectively, 0.5, 0.36, and 0.22. The March and April correlations are statistically significant at 95% confidence level at one-tailed t-test. The corresponding seasonal mean anomaly correlations for the generated by concatenating various extended range hindcasts, at various leads of 1, 2, 3 and 4 weeks are 0.71, 0.66, 0.56, and 0.44 respectively. All these lead forecasts are statistically significant at a 99% confidence level from a one-tailed Student's t test.

These moderate but significant skills motivated us to determine whether the rainfall forecasts have any statistically

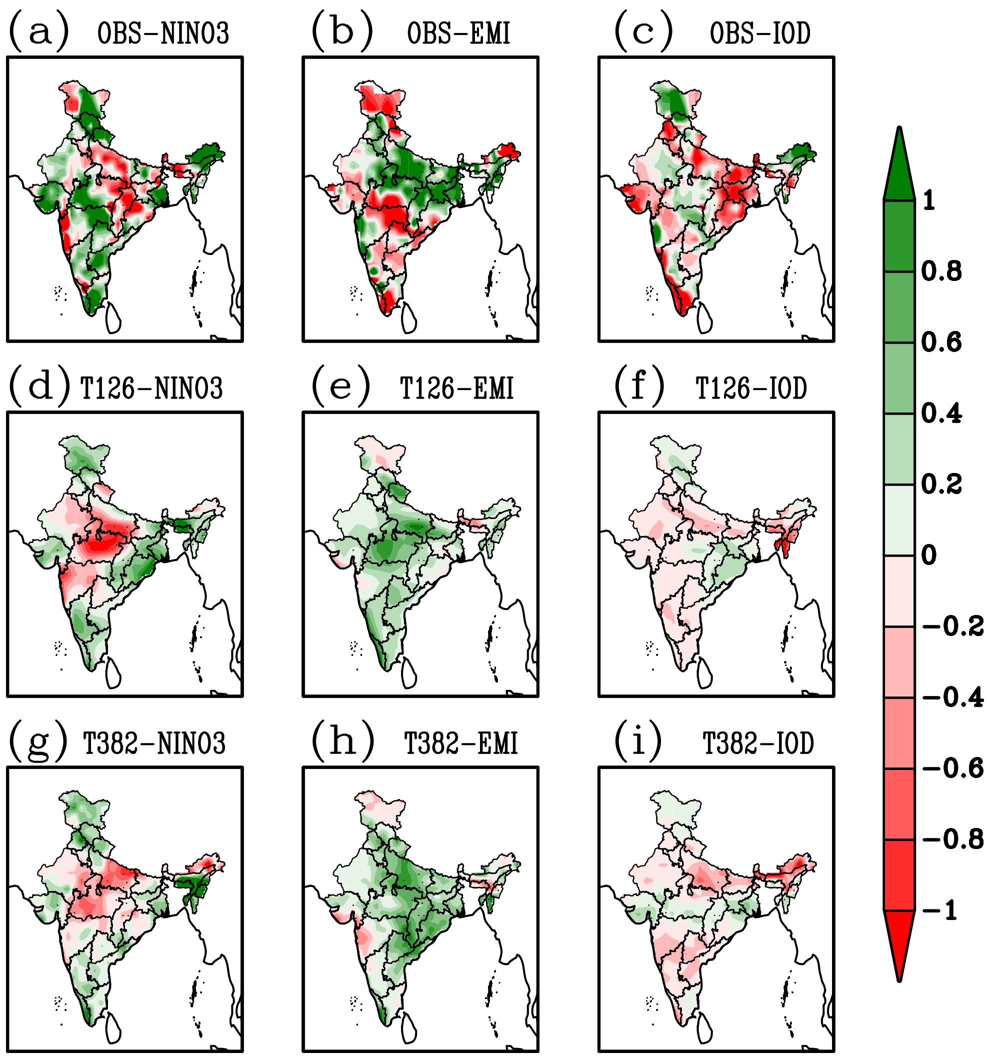


Fig. 4 Composite of anomalous rainfall during El Nino (El Nino Modoki and IOD) events over India, during the period of 2003-2015, for the observed (**a**) to (**c**) and extended range model simulations, T126 from (**d**) to (**f**) and T382 from (**g**) to (**i**)

Table 5 Partial correlations between the state-wise KRP with the NINO3, NINO3.4 & EMI, and removing the impact of IODMI for the period of 2003–2015. Correlations with a magnitude above 0.36 and 0.45 are statistically significant at 90%–95% confidence level respectively, from a one-tailed *t*-test and are shown in bold.

States	*Correlation of NINO3& KRP, adjusted for IODMI*			*Correlation of NINO3.4 & KRP, adjusted for IODMI*			*Correlation of EMI & KRP, adjusted for IODMI*		
	T126	OBS	T382	T126	OBS	T382	T126	OBS	T382
Bihar	**0.61**	−0.11	0.27	0.27	−0.21	0.27	**−0.44**	**−0.38**	**−0.44**
Haryana	0.07	**−0.38**	0.08	−0.29	**−0.54**	−0.29	0.37	**−0.56**	0.37
Karnataka	−0.32	**−0.43**	−0.07	0.22	**−0.63**	0.22	**−0.43**	**−0.68**	**−0.43**
Kerala	0.02	**0.42**	−0.06	0.14	**0.54**	0.14	**−0.42**	**0.58**	**−0.42**
MP	0.03	−0.17	0.56	−0.21	−0.17	−0.21	**0.56**	−0.14	**0.56**
Odisha	0.02	−0.30	−0.03	0.00	−0.36	0.00	0.37	−0.31	**0.37**
Punjab	−0.03	−0.01	0.14	0.16	−0.22	0.16	**0.43**	**−0.52**	**0.43**
UAP	0.01	**−0.68**	−0.2	−0.31	**−0.77**	−0.31	0.18	**−0.60**	0.18
UP	0.11	**−0.39**	0.04	**0.63**	**−0.50**	**0.63**	0.25	**−0.49**	0.25
WB	−0.05	**0.38**	0.15	0.25	**0.42**	0.25	**0.46**	0.22	**0.46**

Table 6 Partial correlations between the state-wise KRP with the IODMI & removing the impact of NINO3, NINO3.4 and EMI for the period of 2003–2015. Correlations with a magnitude above 0.36 and 0.45 are statistically significant at 90% and 95% confidence level respectively, from a one-tailed *t*-test and are shown in bold.

States	*Correlation of IODMI & KRP, adjusted for NINO3*			*Correlation of IODMI & KRP, adjusted for NINO 3.4*			*Correlation of IODMI & KRP, adjusted for EMI*		
	T126	OBS	T382	T126	OBS	T382	T126	OBS	T382
Bihar	**0.61**	**0.68**	**0.61**	**0.66**	**0.69**	**0.66**	**0.62**	**0.60**	**0.95**
Haryana	0.07	**0.48**	0.07	0.06	**0.46**	0.09	0.23	0.17	0.16
Karnataka	−0.32	−0.07	−0.32	−0.32	−0.22	−0.33	**−0.53**	**−0.53**	**−0.46**
Kerala	0.02	**−0.54**	0.02	0.05	**−0.52**	0.01	−0.15	−0.24	−0.03
MP	0.03	0.24	0.03	0.15	0.21	0.15	0.34	0.13	**0.59**
Odisha	0.02	0.13	0.02	−0.02	0.06	0.02	0.15	−0.09	0.01
Punjab	−0.03	0.23	−0.03	−0.04	0.24	0.02	0.16	−0.01	0.09
UAP	0.01	**0.66**	0.01	−0.05	**0.62**	−0.02	0.02	0.23	−0.14
UP	0.11	**0.48**	0.11	0.10	**0.44**	0.11	0.21	0.19	0.17
WB	−0.05	−0.07	−0.05	−0.07	0.03	−0.02	0.16	0.13	0.07

significant relationship with observed Kharif rice production. So we carried out further analysis in this context. Encouragingly, these associations are well captured by the seasonal forecasting hindcast data-set from a qualitative sense. To be clear, while the seasonal retrospective forecasts simulate the sign of the correlation of climate Indices with rice production for these states well, the association is statistically significant for few states such as Kerala. Moreover, we also found severe crop damage due to heavy rainfall and subsequent flooding (Kumar et al. 2006; Lal et al. 2020).

The extended range prediction hindcast captures the association of local Kharif rice production with summer monsoon rainfall in India's various states. Similarly, the association of Indian Ocean SST conditions and KRP production for WB, Bihar and Karnataka are clearly indicated in the analysis of extended range products. In a nutshell, the correlations between the local KRP with the co-occurring tropical Indo-pacific driver signals predicted by the models are better for the states located at the east coast of India and in the monsoon trough regions. While the current correlations between the KRP of several states with the hindcast rainfall and/or various tropical Indo-pacific drivers are statistically significant, these are realistic enough to be directly used to predict the local KRP, in a deterministic sense. However, the skills can be harnessed to develop a potentially useful forecast product of local KRP in states such as UAP, MP, Bihar, and Odisha by processing these significant skills of the IITM CFS forecasting system through various statistical-dynamical downscaling techniques.

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Availability of data and material The HadlSST data set has been downloaded from < https://www.metoffice.gov.uk/hadobs/hadisst/ >. IMD rainfall and CFSv2 seasonal and extended-range hindcast data sets have been collected from IITM, Pune. The crop data set has been downloaded from < www.indiastats.com >, which is provided by the Govt. of India.

Code availability All the calculations and plots have been done using various tools such as NCL, Grads, and CDO.

Authors' contributions ***Hemadri Bhusan Amat*** did all the calculations and analysis and wrote the manuscript by taking inputs from all the co-authors. ***Maheswar Pradhan*** and ***Suryachandra A. Rao*** provided the IITM-CFSv2 seasonal hindcast data set and co-wrote the manuscript. ***Charan Teja Tejavath*** helped in collecting the agriculture data sets used in this study and assisted in the analysis and co-wrote the manuscript. ***Avijit Dey*** *and* ***Atul Kumar Sahai*** provided the IITM-CFSv2 extended-range hindcast data analysis and contributed to the manuscript. ***Karumuri Ashok*** *(Corresponding author) conceived the problem and* co-wrote the manuscript.

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Declarations

Conflict of interest Not applicable

References

Abhilash S, Sahai AK, Pattnaik S, Goswami BN, Kumar A (2014) Extended range prediction of active-break spells of Indian summer monsoon rainfall using an ensemble prediction system in NCEP

Climate Forecast System. Int J Climatol 34(1):98–113. https://doi.org/10.1002/joc.3668

Amat HB, Ashok K (2018) Relevance of Indian Summer Monsoon and its Tropical Indo-Pacific Climate Drivers for the Kharif Crop Production. Pure Appl Geophys 175(6):2307–2322. https://doi.org/10.1007/s00024-017-1758-9

Ashok K, Saji NH (2007) On the impacts of ENSO and Indian Ocean dipole events on sub-regional Indian summer monsoon rainfall. Nat Hazards 42(2):273–285. https://doi.org/10.1007/s11069-006-9091-0

Ashok K, Guan Z, Yamagata T (2001) Impact of the Indian Ocean Dipole on the relationship between the Indian Monsoon Rainfall and ENSO. Geophys Res Lett 28(23):4499–4502. https://doi.org/10.1029/2001GL013294

Ashok K, Guan Z, Saji NH, Yamagata T (2004) Individual and Combined Influences of ENSO and the Indian Ocean Dipole on the Indian Summer Monsoon. Am Meterol Soc 17:3141–3155. https://doi.org/10.1175/1520-0442(2004)017<3141:IACIOE>2.0.CO

Ashok K, Behera S, Rao AS, Weng H, Yamagata T (2007) El Niño Modoki and its teleconnection. J Geophys Res 112:C11007. https://doi.org/10.1029/2006JC003798

Ashok K, Iizuka S, Rao SA, Saji NH, Lee WJ (2009) Processes and boreal summer impacts of the 2004 El Niño Modoki: An AGCM study. Geophys Res Lett 36(4):1–5. https://doi.org/10.1029/2008GL036313

Ashok K, Feba F, Tejavath CT (2019) The Indian summer monsoon rainfall and ENSO. Mausam 70(3):443–452

Behera SK, Luo J-J, Masson S, Delecluse P, Gualdi S, Navarra A, Yamagata T (2005) Paramount impact of the Indian Ocean dipole on the East African short rains: A CGCM study. J Clim 18:4514–4530

Chattopadhyay R, Rao SA, Sabeerali CT, George G, Rao DN, Dhakate A, Salunke K (2016) Large-scale teleconnection patterns of Indian summer monsoon as revealed by CFSv2 retrospective seasonal forecast runs. Int J Climatol 36(9):3297–3313. https://doi.org/10.1002/joc.4556

Chattopadhyay N, Rao KV, Sahai AK, Balasubramanian R, Pai DS, Pattanaik DR, Khedikar S (2018) Usability of extended range and seasonal weather forecast in Indian agriculture. Mausam 69(1):29–44

Chattopadhyay R, Joseph S, Abhilash S, Mandal R, Dey A, Phani R, Sahai AK (2019) Understanding the intraseasonal variability over Indian region and development of an operational extended range prediction system. Mausam 70(1):31–56

Dai A, Wigley T (2000) Global patterns of ENSO-induced precipitation. Geophys Res Lett **27**:1283–1286. https://doi.org/10.1029/1999GL011140

Gadgil S, Gadgil S (2006) The Indian monsoon, GDP and agriculture. Econ Polit Wkly, 41(25th November), 4887–4895. https://doi.org/10.2307/4418949

Guan Z, Ashok K, Yamagata T (2003) The summertime response of the tropical atmosphere to the Indian Ocean sea surface temperature anomalies. J Metor Soc Jpn 81:533–561

Hameed SN (2018) The indian ocean dipole. In: von Storch H (ed) Oxford Research Encyclopedia of Climate Science. Oxford University Press, Oxford

Jadhav J, Swapna P, Shamal M, Ashok K (2015) On the possible cause of distinct El Niño types in the recent decades. Sci Rep 5:1–21. https://doi.org/10.1038/srep17009

Jeong HI, Lee DY, Ashok K, Ahn JB, Lee JY, Luo JJ, Schemm JKE, Hendon HH, Braganza K, Ham YG (2012) Assessment of the APCC coupled MME suite in predicting the distinctive climate impacts of two flavors of ENSO during boreal winter. Clim Dyn 39(1–2):475–493. https://doi.org/10.1007/s00382-012-1359-3

Ju J, Slingo J (1995) The Asian summer monsoon and ENSO. Q J R Meteorol Soc 121(525):1133–1168

Kao HY, Yu JY (2009) Contrasting Eastern-Pacific and Central-Pacific types of ENSO. J Clim 22(3):615–632. https://doi.org/10.1175/2008JCLI2309.1

Keshavamurty R (1982) Response of the atmosphere to sea surface temperature anomalies over the equatorial Pacific and the teleconnections of the Southern Oscillation. J Atmos Sci 39:1241–1259. https://doi.org/10.1175/1520-0469(1982)039<1241:ROTATS>2.0.CO;2

Krishna Kumar K, Rupa Kumar K, Ashrit RG, Deshpande NR, Hansen JW (2004) Climate impacts on Indian agriculture. Int J Climatol 24(11):1375–1393. https://doi.org/10.1002/joc.1081

Krishnaswamy J, Vaidyanathan S, Rajagopalan B, Bonell M, Sankaran M, Bhalla RS, Badiger S (2015) Non-stationary and non-linear influence of ENSO and Indian Ocean Dipole on the variability of Indian monsoon rainfall and extreme rain events. Clim Dyn 45(1–2):175–184. https://doi.org/10.1007/s00382-014-2288-0

Kug JS, Choi J, An SI, Jin FF, Wittenberg AT (2010) Warm pool and cold tongue El Ni??o events as simulated by the GFDL 2.1 coupled GCM. J Clim 23(5):1226–1239. https://doi.org/10.1175/2009JCLI3293.1

Kumar KK, Rajagopalan B, Hoerling M, Bates G, Cane M (2006) Unraveling the Mystery of Indian Monsoon Failure During El Niño. Science 314(5796):115–119 http://www.sciencemag.org/cgi/doi/10.1126/science.1131152

Lal P, Prakash A, Kumar A, Srivastava PK, Saikia P, Pandey AC, Srivastava P, Khan ML (2020) Evaluating the 2018 extreme flood hazard events in Kerala, India. Remote Sens Lett 11(5):436–445. https://doi.org/10.1080/2150704X.2020.1730468

Marathe S, Ashok K, Swapna P, Sabin TP (2015) Revisiting El Niño Modokis. Clim Dyn 45(11–12):3527–3545. https://doi.org/10.1007/s00382-015-2555-8

Murtugudde R, McCreary JP, Busalacchi AJ (2000) Oceanic processes associated with anomalous events in the Indian Ocean with relevance to 1997–1998. J Geophys Res 105(C2):3295–3306. https://doi.org/10.1029/1999JC900294

Navarra A, Ward MN, Miyakoda K (1999) Tropical-wide teleconnection and oscillation. I: teleconnection indices and type I/type II states. Quart J Roy Meteor Soc 125:2909–2935

Nicholls N (1983) Predicting Indian monsoon rainfall from sea–surface temperature in the Indonesia–north Australia area. Nature 306:576–577

Pai DS, Sridhar L, Rajeevan M, Sreejith OP, Satbhai NS, Mukhopadyay 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 data sets of different spatial resolutions and time period, 1(January), 1–18.

Pai DS, Suryachandra Rao A, Senroy S, Pradhan M, Pillai PA, Rajeevan M (2017) Performance of the operational and experimental long-range forecasts for the 2015 southwest monsoon rainfall. Curr Sci 112(1):68–75. https://doi.org/10.18520/cs/v112/i01/68-75

Palmer TN, Branković, Viterbo P, Miller MJ (1992) Modeling interannual variations of summer monsoons. J Clim 5:399–417. https://doi.org/10.1175/1520-0442(1992)005<0399:MIVOSM>2.0.CO;2

Pattanaik DR, Sahai AK, Mandal R, Phani Muralikrishna R, Dey A, Chattopadhyay R, Mishra V (2019) Evolution of operational extended range forecast system of IMD: Prospects of its applications in different sectors. Mausam 70(2):233–264

Pokhrel S, Saha SK, Dhakate A, Rahman H, Chaudhari HS, Salunke K, Hazra A, Sujith K, Sikka DR (2016) Seasonal prediction of Indian summer monsoon rainfall in NCEP CFSv2: Forecast and predictability error. Clim Dyn 46(7–8):2305–2326. https://doi.org/10.1007/s00382-015-2703-1

Pradhan M, Rao AS, Srivastava A, Dakate A, Salunke K, Shameera KS (2017) Prediction of Indian Summer-Monsoon Onset Variability: A Season in Advance. Sci Rep 7(1):1–14. https://doi.org/10.1038/s41598-017-12594-y

Prasanna V (2014) Impact of monsoon rainfall on the total foodgrain yield over India. J Earth Syst Sci 123(5):1129–1145. https://doi.org/10.1007/s12040-014-0444-x

Ramu DA, Sabeerali CT, Chattopadhyay R, Rao DN, George G, Dhakate AR, Salunke K, Srivastava A, Rao SA (2016) Indian summer monsoon rainfall simulation and prediction skill in the CFSv2 coupled model: Impact of atmospheric horizontal resolution. J. Geophys. Res. Atmos. 121:2205–2221. https://doi.org/10.1002/2015JD024629

Rao SA, Goswami BN, Sahai AK, Rajagopal EN, Mukhopadhyay P, Rajeevan M, Nayak S, Rathore LS, Shenoi SSC, Ramesh KJ, Nanjundiah RS, Ravichandran M, Mitra AK, Pai DS, Bhowmik SKR, Hazra A, Mahapatra S, Saha SK, Chaudhari HS, Joseph S, Sreenivas P, Pokhrel S, Pillai PA, Chattopadhyay R, Deshpande M, Krishna RPM, Das RS, Prasad VS, Abhilash S, Panickal S, Krishnan R, Kumar S, Ramu DA, Reddy SS, Arora A, Goswami T, Rai A, Srivastava A, Pradhan M, Tirkey S, Ganai M, Mandal R, Dey A, Sarkar S, Malviya S, Dhakate A, Salunke K, Maini P (2019) Monsoon mission a targeted activity to improve monsoon prediction across scales. Bull Am Meteorol Soc 100(12):2509–2532. https://doi.org/10.1175/BAMS-D-17-0330.1

Ratnam JV, Behera SK, Masumoto Y, Takahashi T, Yamagata T (2010) Pacific ocean origin for the 2009 Indian summer monsoon failure. Geophys Res Lett 37:L07807. https://doi.org/10.1029/2010GL042798

Rayner NA, Parker DE, Horton EB, Folland CK, Alexander LV, Rowell DP et al (2003) Global analyses of sea surface temperature, sea ice, and night marine air temperature since the late nineteenth century. J Geophys Res 108(D14):4407. https://doi.org/10.1029/2002JD002670

Saha S, Moorthi S, Pan HL, Wu X, Wang J, Nadiga S, Goldberg M (2010) The NCEP climate forecast system reanalysis. Bull Am Meteorol Soc 91(8):1015–1057. https://doi.org/10.1175/2010BAMS3001.1

Saha S, Moorthi S, Wu X, Wang J, Nadiga S, Tripp P, Behringer D, Hou YT, Chuang HY, Iredell M, Ek M, Meng J, Yang R, Mendez MP, van den Dool H, Zhang Q, Wang W, Chen M, Becker E (2013) The NCEP climate forecast system version 2. J Clim 27(6):2185–2208. https://doi.org/10.1175/JCLI-D-12-00823.1

Sahai AK, Sharmila S, Abhilash S, Chattopadhyay R, Borah N, Krishna RPM, Joseph S, Roxy M, De S, Pattnaik S, Pillai PA (2013) Simulation and extended range prediction of monsoon intraseasonal oscillations in NCEP CFS/GFS version 2 framework. Curr Sci 104(10):1394–1408. http://www.jstor.org/stable/24092513

Sahai AK et al (2016) Extended Range Prediction System and its Application. Vayu Mandal 42(2):75–96

Saji NH, Goswami BN, Vinayachandran PN, Yamagata T (1999) A dipole mode in the tropical Indian Ocean. Nature 401(6751):360–363. https://doi.org/10.1038/43854

Sharmila S, Pillai PA, Joseph S, Roxy M, Krishna RPM, Chattopadhyay R, Goswami BN (2013) Role of ocean-atmosphere interaction on northward propagation of Indian summer monsoon intra-seasonal oscillations (MISO). Clim Dyn 41(5–6):1651–1669. https://doi.org/10.1007/s00382-013-1854-1

Shukla J, Paolina DA (1983) The southern oscillation and long range forecasting of the summer monsoon rainfall over India. Mon Weather Rev 111:1830–1837. https://doi.org/10.1175/1520-0493

Sikka DR, Gadgil S (1980) On the Maximum Cloud Zone and the ITCZ over Indian, Longitudes during the Southwest Monsoon. Mon Weather Rev 108:1840–1853. https://doi.org/10.1175/1520-0493(1980)108<1840:OTMCZA>2.0.CO;2

Soman MK, Slingo J (1997) Sensitivity of the Asian summer monsoon to aspects of sea-surface-temperature anomalies in the tropical Pacific ocean. Q J R Meteorol Soc 123(538):309–336. https://doi.org/10.1256/smsqj.53803

Srivastava A, Pradhan M, George G, Dhakate A, Salunke K, Rao S A. (2015). A Research Report on the 2015 Southwest Monsoon. (November), 58–62. Retrieved from http://www.tropmet.res.in/~lip/Publication/RR-pdf/RR-185.pdf

Trenberth KE (1997) The definition of El Nin˜o. Bull Amer Meteor Soc 78:2771–2777

Varikoden H, Preethi B (2013) Wet and dry years of Indian summer monsoon and its relation with Indo-Pacific sea surface temperatures. Int J Climatol 33(7):1761–1771. https://doi.org/10.1002/joc.3547

Webster PJ, Moore AM, Loschnigg JP, Leben RR (1999) Coupled ocean–atmosphere dynamics in the Indian Ocean during 1997–98. Nature 401(6751):356–360. https://doi.org/10.1038/43848

Weng H, Ashok K, Behera SK, Rao SA, Yamagata T (2007) Impacts of recent El Niño Modoki on dry/wet conditions in the Pacific rim during boreal summer. Clim Dyn 29(2–3):113–129. https://doi.org/10.1007/s00382-007-0234-0

Yamagata T, Behera S, Rao S, Guan Z, Ashok K, Saji H (2003) Comments on "Dipoles, Temperature Gradients, and Tropical Climate Anomalies". Bull Am Meteorol Soc 84(10):1418–1422 Retrieved 25th April, 2020, from www.jstor.org/stable/26216895