The Indian summer monsoon rainfall and ENSO

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ABSTRACT. The El Niño-Southern Oscillation (ENSO) is deemed as the most important driver of the Indian summer monsoon variability. In this paper we make an effort to document the research so far on the impacts of ENSO on the Indian summer monsoon and the various mechanisms that have been proposed to explain the tele-connection from the tropical Pacific to the monsoon region. We also briefly discuss about the distinctions between impacts of canonical El Niño and El Niño Modoki. We believe that the recent apparent weakening of the ENSO impact on the monsoon may simply be due to a combination of several inter-annual to decadal processes, as evidence by the deficit monsoon conditions during 2015 which co-occurred with an extreme El Niño.

Key words – Indian Summer Monsoon, El Niño, ENSO, El Niño Modoki.

1. Introduction

The Indian Summer Monsoon (ISM) has been the focus of considerable fascination for a long time. Agriculturists have revered and seafaring traders and sailors have depended on the ISM since centuries. The scientific allure of ISM probably might have started with Henry Blandford and Sir Gilbert Walker with their early attempts at ISM observations and prediction (Blandford, 1884, 1886; Walker, 1923, 1924, 1928). The Indian Meteorological Department (IMD) has been studying and predicting ISM for over 100 years now. Importantly, Walker’s attempts to find lead predictions skills for the Indian summer monsoon rainfall have resulted in the discovery of what has been later known as the Southern Oscillation, the atmospheric component of the El Niño-Southern Oscillation (ENSO). Incidentally, ENSO is known as the strongest driver of the Indian summer monsoon rainfall variability.

The present manuscript is divided into five sections. Sections 2 and 3 provide brief introductions to ISM and ENSO. Section 4 describes the relationship between ISM-ENSO, followed by a discussion is in Section 5.

For the few figures presented in this general review note, IMD gridded rainfall data for Indian regional/sub-divisional Monthly Rainfall are used (Rajeevan et al., 2006). We also use the Met Office Hadley Centre Sea Ice and Sea Surface Temperature dataset (HadISST; Rayner et al., 2003).

2. Indian summer monsoon

Monsoon is an Arabic term, which, it is believed, to have been derived from the Arabic/Persian word ‘Mausam’, alluding to a seasonal reversal of winds. Therefore, it is not surprising that Ramage, in the year 1971, defined a few characteristics of monsoonal regions, mainly based on the kinematic consideration of the winds (Ramage, 1971). Summed up, the four criteria talk about seasonal reversal, persistence, sufficient strength. Having said this, a critical component that is missing from the definition is the rainfall, which is not only important for societal purposes, but plays a major role in monsoonal dynamics and variability (Rao, 1976).
heating (Murakami and Ding, 1982) or the dynamical influences of Tibetan Plateau (Yanai et al., 1992; Yanai et al., 2006). From June to September, ISM remains over India as a stationary wave (Goswami and Shukla, 1984). ISM rainfall shows great spatial variability (Fig. 1) with highest rainfall along the western coast of India, due to the orographic effects and over the head of Bay of Bengal with a northwest-ward stretch along the monsoon trough. This northwestward stretching region is called the Monsoon Zone (Sikka and Gadgil, 1980). There are several publications and reports that have characterized the mean monsoonal features and variability. Rao (1976), Pant and Kumar (1997) and the Monsoon Monograph series (Tyagi et al., 2012) provide excellent summaries of all these aspects.

The interannual variability of an area-averaged ISM rainfall index is shown in Fig. 2. It has a 10% standard deviation (Gadgil, 2003). Contributions from various Sea Surface Temperature (SST) anomalies, particularly the tropical pacific, affect the ISM resulting in a prominent interannual variability (Fig. 3). The interannual variability of ISM shows about 10% standard deviation from the mean (Gadgil, 2003). ENSO is one of the primary drivers of ISM, accounting for about 40% of its interannual variability (Sikka, 1980; Keshavamurty, 1982; Shukla and Paolina, 1983; Rasmussen and Carpenter, 1983). Along with ENSO, drivers from other tropical oceans, such as strong Indian Ocean Dipole (IOD; Webster et al., 1999; Saji et al., 1999; Murtugudde et al., 2000) events also affect ISM interannual variability. Strong IOD events modulate the effects of any co-occurring ENSO on ISM (Ashok et al., 2001; Ashok and Saji, 2007). Furthermore, Atlantic is also receiving attention as a driver of the Indian summer monsoon rainfall (Kucharski et al., 2008; Pottapinjara et al., 2015; Yadav, 2017). Of all these, ISM-ENSO relationship naturally demands a weighty attention.

3. The El Ninò - Southern Oscillation

Due to various reasons beyond the scope of the current manuscript, in some years, we find a large-scale anomalous warming in the tropical eastern Pacific Ocean, associated with anomalous cooling in the tropical western Pacific, causing widespread ramifications globally. This anomalous condition, normally seasonally phase locked from boreal spring through ensuing boreal winter when it peaks, is referred to as an El Niño. As mentioned earlier, this oceanic signature of the ENSO is strongly coupled to the anomalous changes in the associated see-saw of sea level pressure between the equatorial eastern and western Pacific Ocean, referred to as the Southern Oscillation (Bjerkenes, 1969). A positive SST anomaly in the equatorial eastern Pacific reduces the east-west thermal gradient, weakening the trade winds and thereby the Walker circulation (Gill, 1980; Lindzen and Nigam, 1987). The weaker trades further enhance the warming and this form a positive ocean-atmosphere feedback causing a very warm state - The El Niño. Conversely, a cold phase, with cooler than normal SST anomalies in the equatorial eastern Pacific strengthens the trade winds and the Walker circulation - The La Niña (Philander, 1985, 1990).

ENSO, to a significant extent, can be deemed as a self-sustaining positive ocean-atmosphere feedback. The delayed oscillator theory explains that the Rossby waves generated in the eastern Pacific propagate west and reflect from the western boundary returning as Kelvin waves and reverse ENSO effect (Zebiak and Cane, 1987; Suarez and Schopf, 1988; Battisti and Hirst, 1989). From another perspective, the divergence by Sverdrup transport discharges the equatorial heat content which gets recharged by climatological upwelling. This is known as the recharge-discharge oscillator theory (Jin, 1997a). Another hypothesis is that off-equatorial SST anomalies induce equatorial easterly wind anomalies (off-equatorial anomalous anticyclones), causing upwelling and subsequent cooling. This mechanism is called the western Pacific oscillator mechanism (Weisberg and Wang, 1997; Wang et al., 1999). In addition, external land heating and interaction with the previous coupled anomalies play a role (Masumoto and Yamagata, 1991).

In addition to the well-known canonical El Niño, a new type of El Niño with anomalous warming in the central tropical Pacific straddled by cooling of SST anomalies on its both flanks, have been occurring with increased frequency since mid-1970s (Ashok et al., 2007;...
Fig. 2. The interannual variability of the Indian summer rainfall area-averaged over the Indian land region (66.5° E-101.5° E; 6.5° N-39.5° N) during the 1951-2009 period. Here WE, ME, SE and VSE stand for weak, moderate, strong and very strong El Niños, respectively; WL, ML and SL stand for Weak, Moderate and Strong La Ninás, respectively, as per <https://ggweather.com/enso/oni.htm>

Fig. 3. Simultaneous linear correlation between the Indian summer monsoon rainfall index with the JJAS SST for the 1901-2009 period. Only significant correlation values have been plotted (±0.20 is the 0.05 significance level from a 2-tailed Student's t-test)

Kao and Yu, 2009; Kug et al., 2009; Marathe et al., 2015). These events, which occurred recently are seasonally phase-locked from boreal summer through ensuing winter and are named as the El Niño Modoki. Furthermore, the location of the heat source has relevance on the domain of its impacts (Matsuno, 1966; Gill, 1980; Keshavamury, 1982; Soman and Slingo, 1987; Larkin and Harrison, 2005; Annamalai and Liu, 2005). This is particularly applicable to the ISM as well, as would be discussed later. Therefore, a study of ISM-ENSO dynamics and its variability is incomplete without considering El Niño Modoki.

3.1 ENSO impacts on the Indian summer monsoon and mechanisms

Most of severe summer monsoon droughts over India are associated with the El Niño events. However, as Rajeevan (Monsoon Monographs, Ed. Tyagi et al., 2012) mentions, there is no one-to-one relationship between them. On the simplest terms, El Niño events show a propensity to be associated with a weaker than normal summer monsoon rainfall over India, while the La Niña events with a greater than normal rainfall, as indicated by several studies. The relationship between ISM and ENSO, has been studied extensively for the past few decades (Sikka, 1980; Keshavamury, 1982; Shukla and Paolina, 1983; Rasmussen and Carpenter, 1983; Ropelewski and Halpert, 1987; Webster and Yang, 1992; Nigam, 1994; Ju and Slingo, 1995; Yang, 1996; Zhang et al., 1996; Kawamura, 1998; Navarra et al., 1999; Slingo and Annamalai, 2000; Lau and Nath, 2000; Wang, 2000; Ashok et al., 2004; Ashok and Saji, 2007). Fig. 4 shows the simultaneous linear correlations between the NINO3.4 index and local rainfall anomalies over India during June-September (JJAS), the summer monsoon season. It is seen that most of the correlations are negative, implying that the anomalously warm conditions during boreal summer

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1 NINO3.4 Index: defined as the area-averaged SST anomaly over the region bounded by 170° W-120° W; 5° S-5° N, which is used to represent the ENSO variability.
over the eastern tropical Pacific can result in anomalously
deficit rainfall over India during summer monsoon season. How-
ever, Kumar et al. (2006) suggest that the El Niño
Modoki events reduce the ISM rainfall more effec-
tively than the conventional El Niño. From linear consid-
erations, there is an apparent propensity for the canonical El Niños
to be associated with negative rainfall anomalies along the
monsoon trough, while the Modoki El Niños cause
anomalously deficit rainfall more in the peninsular India
(Figs. 5 & 6 from Ashok et al., 2007; Amat and Ashok,
2018). The composite rainfall anomalies shown in Fig. 5
indeed give a qualitative indication that Modoki El Niños
are not associated with negative rainfall anomalies along the
monsoon trough. This conforms to results from
various AGCM experiments (Ashok et al., 2009; Chen
and Tam, 2010) etc.

Further, for the first time, a hitherto unnoticed
anomalous basin wide warming across the tropical Pacific
has occurred in the tropical Pacific during JJAS season of
2009, which collapsed the Walker circulation across the
basin (Ashok et al., 2012). AGCM experiments suggest
that the severe drought observed over India that season
was associated with this warming (Ratnam et al., 2010;
Ashok et al., 2012). The year 2014 also experienced
similar conditions in the tropical Pacific and at least
partially responsible for the anomalous dry conditions
during summer monsoon season (Jadhav et al., 2015).

Several mechanisms have been proposed to explain
the ENSO impact on the ISM. This section revisits some
of the mechanisms and attempts to introduce some
outstanding issues. The suggested mechanisms to explain
the ENSO teleconnections could be broadly classified into
two groups.

3.1.1. The Walker and Hadley cell connections

Given the intimate connection between the tropical
Pacific SST with the Walker circulation/southern
oscillation, it is reasonable to consider that a mechanism
of how the SST changes in the eastern tropical Pacific
transmit into the Indian summer monsoon region involves
through a Walker circulation changes. Bhalme and Jadhav
(1984), analyzing Indian rainfall datasets for the 1875-
1980 period, reported a drier Indian Ocean and large
monsoon rainfall deficiency occurring concurrently with
weak Walker circulations. Shukla and Paolino (1983),
through an analysis of Indian summer monsoon rainfall of
and the Darwin pressure associated intimately with ENSO
datasets for the 1901-1950, suggested that an anomalously
high (low) Darwin pressure coincides with anomalously
low (high) monsoon rainfall. Pant and Parthasarathy (1981)
also have documented the relevance of the southern
oscillation changes for the Indian summer monsoon.

Webster et al. (1998) indicated that boundary
anomalies, such produced by ENSO, produce a temporally
persistence and spatially large-scale descent over the
Indian monsoon region, reducing rainfall either by
producing a displacement of the seasonal mean rainfall
patterns. All these studies imply that changes in the
Walker Circulation with ENSO are considered to affect
the ISM.

Atmospheric GCM experiments by 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; Ashok et al. (2004),
etc. demonstrate that the tropical Pacific SST anomalies
associated with ENSO indeed influence the Indian
summer monsoon through modulation of zonal circulation
cells. Broadly, these studies suggest that large scale
circulation changes due to eastward (westward) shift of
Walker Circulation and decreased (increased) equatorial
divergence over the tropical Indian Ocean during El Niño
(La Niña) years. The anomalous convergence in the
tropical Indian Ocean results in the modulation of the
cross-equatorial meridional circulation, which causes an
anomalous divergence over the Indian region and thereby
a drier (wetter) than normal ISM. Indeed, this type of
signals can be seen in the Indian region and the Indian
Ocean to its south, in years such as 1987 (Ashok et al.,
2001) when the El Niño event does not co-occur with any
other tropical oceanic climate driver such as the strong
IOD - which can interfere with the anomalous signal of
ENSO.

Among these studies, Keshavamurty (1982) and
several others explore the relative importance of
anomalous signals in the western, central and eastern

Fig. 4. Simultaneous linear correlations between Niño3.4 index with
the JJAS rainfall for the period of CE1901-2009. Only
significant correlation values have been plotted (±0.20 is value
for 0.05 significance level from a 2-tailed Student’s t-test)
3.1.2. ISM-ENSO: Impacts through extratropics and upper atmosphere

Suggesting a different mechanism, Ju and Slingo (1995) noted that weak ISM years are associated with an increased upper-level westerlies. This is associated with the latitudinal shift in the position of the subtropical westerly jet over northern India influenced by Pacific SST anomalies. AGCM studies by Krishnan et al. (1998) indicate that, in addition to the Walker circulation changes introduced by ENSO and ensuing and Hadley cell modulations, the anomalous ENSO divergent forcing over the tropical Pacific Ocean can act as a potential source for Rossby wave dispersion. Furthermore, Krishnan et al. (2009) suggest that meridionally propagating Rossby waves, which emanate from the El Niño forcing region, interact with the subtropical westerlies and generate quasi-stationary anomalous highs and lows in the subtropics and extratropics over west Asia, Pakistan and northwest India during drought years co-occurring with El Niños.

According to Wang et al. (2000), during El Niño years, as a Rossby response to the SST anomalies in the western tropical Pacific, an anomalous anti-cyclonic pattern appears from the Philippine Sea through the core Indian summer monsoon region, teleconnections.

As far as the El Niño Modoki is concerned, AGCM experiments (Ashok et al., 2009) suggest that during these events a Rossby response to the anomalous warming in the neighboring central tropical Pacific (Chen and Tam, 2010); this not only exacerbates the local typhoon frequency (Chen and Tam, 2010; Pradhan et al., 2011), but also facilitates an east-west out-of-phase precipitation variability over the NW Pacific and the Indian summer monsoon region (Mujumdar et al., 2007) and thereby a drought-like condition in El Niño Modoki years such as 2002 and 2004 in the peninsular India.

Goswami and Xavier (2005) argue that ENSO affects the meridional tropospheric temperature gradient over the Indian region thereby effectively modulating the strength and duration of the monsoon. Shaman and Tziperman (2007) claim that ENSOs affect the upper tropospheric meridional temperature gradient during ISM through the subtropical jet.

Interestingly, (Rajeevan and McPhaden, 2004) suggest that warm water volume over the entire tropical Pacific 3-4 months earlier to the monsoon has the highest lead predictive skill for the Indian summer monsoon
rainfall. The decaying ENSO may also be relevant to the following ISM (Choudary et al., 2015; Chakraborty et al., 2018)

3.2. ISM & ENSO - Weakening links or a slow variability?

Kripalani and Kulkarni (1997) suggest a natural decadal variability of the Monsoon and therefore, that the ENSO impacts may not be as strongly perceived in the strong monsoonal epochs as could be in the weaker monsoonal epochs. The ISM-canonical ENSO links have shown a weakening in the recent decades (Kumar et al., 1999; Kawamura et al., 2005) argue that the recent weakening of the ISM-ENSO is in fact, a change in dominance of the spatial correlation pattern, from northwest to northeast after the late 1970s. Background and circulation changes associated with global warming have been proposed as a potential reason for the weakening by Kumar et al. (1999) and Ashrit et al. (2001). Kumar et al. (1999) attribute, through a running correlation analysis, that the weakening observed in late 1990s due to a shift in background circulation associated with global warming. On the other hand, Gershunov et al. (2001) suggest that the monsoon-ENSO relationship is less variable on decadal scales. In other words, even though many physical processes may be partially responsible for the modulation of the interannual correlation, it is not possible to distinguish their effects from stochastic noise in running correlation analyses and therefore, it could just be an issue of sampling (Cash et al., 2017). Having said this, from a predictability point of view, it will indeed be useful to understand if a random interaction with impacts on the monsoon from any other events could be playing a role in such weakening of an interannual variability beyond a few years. Chang et al. (2001) attribute this weakening to the strengthening and simultaneous poleward shift of the jet stream over the North Atlantic region. Ashok et al. (2001, 2004, 2007) indicate that the apparent ENSO-Monsoon weakening during the late 20th century is due to increased frequency of positive IOD events of 1994 and 1997. This is attributed to the anomalous convergence in the Head Bay of Bengal and neighboring monsoonal trough (Behera et al., 1999; Guan et al., 2003; Rao et al., 2004) induced by the subsidence from the eastern colder-than-normal pole of the positive IOD and that in the northwest portion of the monsoonal trough (Ashok et al., 2004) associated with the modulated meridional circulation owing to the anomalous warm conditions in the western box of the IOD region, this zone of anomalous convergence associated with strong positive IOD events in years such as 1997 results in anomalous surplus rainfall along the monsoon trough and reduces the ENSO influence. On a related note, EQUINOO (Equatorial Indian Ocean Oscillation), an atmospheric index associated with the IOD, along with an ENSO index, seems to account for most of the interannual variability of the ISM rainfall (Francis and Gadgil, 2013). In addition, as mentioned earlier, the El Niño Modoki events, which have occurred in years such as 1986, 1990, 1991, 1994, 2002 and 2004 summers are also associated anomalously dry conditions over India.

Some studies have also observed the impact of Pacific Decadal Oscillation (PDO) on ISM-ENSO relations (Krishnamurthy and Goswami, 2000; Krishnan and Sugi, 2003; Krishnamurthy and Krishnamurthy, 2014). Krishnamurthy and Goswami (2000) show that during the eastern Pacific warm (cold) phase of the interdecadal SST variation, the regional Hadley circulation associated with El Niño (La Niña) strengthens the prevailing anomalous interdecadal Hadley circulation while that associated with La Niña (El Niño) opposes the prevailing interdecadal Hadley circulation. Therefore, during the warm (cold) phase of the interdecadal oscillation, El Niño (La Niña) events are expected to be strongly related to monsoon droughts while La Niña (El Niño) events may not have a significant relation. Krishnamurthy and Krishnamurthy (2014) propose that the PDO modulates ISM-ENSO relationship by enhancing (counteracting) ENSO effects when in (out of) phase. Sreejith et al. (2015) claim that the reason for the recent monsoon-ENSO weakening is the change in air-sea coupled interactions over the tropical Indian Ocean. A shift in the mean ISM winds, with a cyclone-like intensification over northwestern Pacific is seen in the recent decades (Mujumdar et al., 2012; Feba et al., 2017). Feba et al. (2018) suggest that this decadal cyclonic intensification opposes the anomalous anticyclonic signature associated with the canonical El Niños (Lau and Nath, 2000) and therefore ‘disconnects’ the impact of the El Niño through this pathway. Interestingly, Feba et al. (2018) also find a simultaneous strengthening of cross equatorial winds over the equatorial Indian Ocean in recent decades in association with the weakening of ISM-ENSO links.

The last millennium climate is supposed to be the nearest to the current day climate, at least prior to 1970s when the anthropogenic warming is dominant. Climate simulations of the PMIP3 vintage are a valuable source to understand the long term variations of the ISM-ENSO links. Tejavath et al. (2019), through an analysis of model outputs from nine models, find a multi-decadal through centennial fluctuations in the correlation between an ENSO index with the area-averaged Indian summer monsoon rainfall. Their results show that the simulated interannual ISM-ENSO negative correlations are statistically significant in the two dominant epochs of the last millennium, known as the 'Medieval Warm Period' (CE 950-1350), roughly followed by a relatively cooler
period, the Little Ice Age (CE 1500-1850). Importantly, these correlations are significantly modulated by slow background changes (a multi-centennial modulation), which modulate the anomalous east-west zonal circulation and the meridional circulation in the Indian Ocean-Indian region. Such changes are associated with slow changes in summer monsoon rainfall in various sub-regions of the subcontinent and not necessarily the whole India. This indicates a strong influence in the interplay of various temporal scales, which have implications for impacts at regional level.

4. Discussions

As a community, we can now ascertain that Indian summer monsoon is indeed significantly influenced by the ENSO types on interannual timescales. This relationship is of course subject to impacts from other interannual climate drivers as well as decadal processes and phenomena, which can result in an apparent weakening of the ISM-ENSO links. The important outcome of the studies such as Tejavath (2019) and Kawamura et al. (2005) is that any change in the association may be owing to interannual through centennial processes external to the ENSO-monsoon system. It may be that the apparent weakening is due to a shift in the impacted region, which may not be clear when a rainfall index area-averaged over the whole region is considered. The inherent decadal variability either in the monsoons and/or ENSO can also result in a stochastic weakening of the monsoon-ENSO relationship. This conclusion of course points out to a need to explore if there are mechanisms other than those proposed so far to explain the ENSO impact on monsoons. Importantly, the severe weak monsoon condition in India during 2015 was associated with one of the most extreme El Niño events. This suggests that strong El Niños indeed affect the ISM rainfall. Further, it is not just the occurrence of the ENSO that needs to be predicted with a lead time, but its intensity and, to some extent, its type.

There are studies indicating that the ENSO events can influence the intraseasonal processes of the ISM. For example, as per Joseph (2014), during a co-occurring El Niño year, the low level Jet stream can be modulated to extend eastwards up to the date line creating an area of shallow ocean mixed layer there, which in turn is proposed to lengthen the active-break cycle to two months in an El Niño year. Webster et al. (1998) summed up that seasonally persistent ENSO-induced boundary anomalies and spatially large-scale descent over the Indian monsoon region, reduce rainfall either by reducing the intensity and life cycle of the monsoon disturbances or by producing a displacement of the seasonal mean rainfall patterns. Discussing these scale interactions and time scales higher than interannual teleconnections is beyond the scope of the current note.

There are several other topics relevant to the association of the ENSO with the Indian monsoons, such as the impact of the Indian summer monsoon on the ENSO (Krishnamurthy and Goswami, 2000; Kirtman and Shukla, 2006), which have not been discussed in this note. For example, the tropical pacific SST indices exhibit a positive correlation with the northeastern monsoon rainfall over the southeastern peninsular India (Raj et al., 2004 and Boyaj et al., 2017 for more details, including the references on earlier works). This is owing to the fact that, unlike the summer monsoon period, the seasonal climatological winds are northeasterlies, which are enhanced by the ENSO-induced anomalous easterlies. This is a situation analogous to that in Australia where the ENSO impact is stronger during austral spring rather than austral summer (Hendon et al., 2007).

Recent studies even suggest that aerosol loadings can influence the Indian summer monsoon (Ramanathan et al., 2005; Lau et al., 2006; Krishnamurti et al., 2013; Sarangi et al., 2018) and these can have implications for the ENSO impacts on monsoon (Fadnavis et al., 2017). Needless to say, we need more observations and better models to understand the monsoon-ENSO relationship and extraneous factors that influence the relationship.

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