Seasonal Extreme Rainfall Over Indian Monsoon Region: A Moisture Budget Analysis to Distinguish the Role of ENSO and non-ENSO Forcing

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Seasonal extreme rainfall over Indian monsoon region: A moisture budget analysis to distinguish the role of ENSO and non-ENSO forcing

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Abstract

Indian summer monsoon rainfall (ISMR) variability of $\pm 10\%$ of its long-term mean leads to flood and drought, affecting the life and economic situation of the country. It is already established that the interannual variability of ISMR is influenced by large scale boundary forcing such as SST anomalies of tropical Pacific, Indian and Atlantic Oceans. The ISMR association between Pacific SST anomalies in the form of El Nino Southern Oscillation (ENSO) is only studied in detail. Meanwhile, the present and previous studies show that the ENSO accounts for around 50% of the extreme years, while the other half is associated with other processes. A differentiation between extremes induced by ENSO and non-ENSO processes are attempted here with the help of moisture and moist static energy budget. The significant contribution to the rainfall extremes comes from moisture advection induced by anomalous winds generated by the boundary forcing and the secondary contribution from moisture convergence. For the non-ENSO cases, there is a contribution from local fluxes, which are not prominent in the cases of ENSO induced cases. In the ENSO cases, anomalous winds are from the equatorial central Pacific, while EQWIN/IOD cases influence extremes through the local evaporation and moisture advection from the Indian Ocean. Extreme years independent of ENSO/IOD/ EQWIN have moisture advection from the anomalous winds across Africa and the Atlantic and are associated with moisture advection toward the northern parts of India. These differences in moisture processes are responsible for the difference in rainfall distribution over India also.

Keywords: Flood and drought, Indian summer monsoon rainfall, ENSO, IOD, EQWIN, moisture budget, MSE budget

Introduction

The seasonal rainfall (June to September, JJAS) receiving over India, called Indian summer monsoon rainfall (ISMR), accounts for 70-80% of the annual rainfall over India. The ISMR has a seasonal mean of 84 cm with a coefficient of variability of less than 10%. Still, the variability of the ISMR to a flood (above average) or drought (below normal) is crucial for the Indian economy, which depends on rain-fed agriculture for the life of millions of its population. Variations in the monsoon rainfall affect India's total food grain yield and the country's economy, which largely depends on agriculture (Krishna Kumar et al. 2004). These extremes cause a million dollars of damage to the country's economy as the rainfall variability is directly related to crop yield and food production (Gadgil et al., 2006). Even a modest decrease of 10% of the long term mean rainfall leads to a significant reduction in rice production over India (Swaminathan 1987; Abrol and Gadgil 1999). In addition, the interannual variability of ISMR shows a more substantial impact on the gross domestic product (GDP) and agricultural production of the country (Gadgil 1996; Webster et al. 1998). Thus, a better knowledge of the mechanism of different causes of these extremes is needed, leading to better prediction of them.

Earlier studies identified that interannual variability of ISMR is mainly controlled by slow varying factors such as sea surface temperature (SST), snow cover and sea ice extent etc. (Charney and Shukla 1981). In these boundary forcing, ISMR association with the SST anomalies of tropical east Pacific (El Niño- Southern Oscillation, ENSO, Walker 1924, Rasmussen and Carpenter 1983) and Indian Ocean (Indian Ocean Dipole, IOD, Saji et al. 1999, Webster et al. 1999) are well known for past 3-4 decades. The ENSO influences ISMR through modifications of east-west Walker circulation, while the IOD influence is through the modification of local Hadley circulation over the Indian Ocean. An El Niño event leads to anomalously low ISMR through the associated Southern Oscillation, suppressing convection over the Indian subcontinent, and vice versa for La Niña. By contrast, a positive IOD, when free of an El Niño's influence, induces atmospheric circulation anomalies, resulting in anomalously high ISMR. In particular, the cold anomalies in the eastern Indian Ocean are conducive to vapour transport by generating anomalous meridional circulation. Meanwhile, these boundary forces such as ENSO-IOD etc. are related to each other and influence the ISMR independently. Thus how these boundary forces contribute to ISMR separately and in combination is not clear yet. Annamalai and Liu (2005) noted that regional SST anomalies influence the magnitudes of monsoon-related rainfall and circulation anomalies. Gadgil et. al.

(2004) showed that the extremes of ISMR are related to the equatorial Indian Ocean in the form of EQUINOO. Many studies such as Rajeevan and Sridhar(2008); Yadav(2017), etc. indicated that the SST anomalies in the Atlantic Ocean can also influence the ISMR on the interannual time scale. Even though these boundary forcing influencing monsoon are recognised by many studies, the mechanism of their interaction with the extreme rainfall is not studied in detail.

Table 1 below shows the years of positive and negative seasonal monsoon years ($\pm 10\%$ of LPA, long-period average) based on Indian summer monsoon rainfall (land-point average rainfall for Indian region from India meteorological Department, IMD) during the 1950-2020 period. Severe monsoons are based on threshold cutoffs of $\pm 10\%$ LPA for the climatology period 1950-2020. The deficit (drought) monsoon of 2014 accounted for 90% and 1972 recording 77% rain of LPA. Similarly, the flood year of 1956 received 110% of LPA with 1988 recording 120 % of the long period average. The extreme years are again divided based on their co-occurrence with other SST forcing such as ENSO, IOD, etc. The table clearly shows that only around 50% of the severe years are associated with El Nino/La Nina. Thus, it is clear that some other factors are responsible for severe monsoon. Many factors such as IOD, EQWIN, Atlantic ocean SST, etc can contribute to the extreme monsoon years (Rajeevan 2008, Ajaymohan and Rao 2008, Gadgil et.al 2004). The role of ENSO in modulating the ISMR is studied in detail (Webster and Yang 1992, Webster et al. 1998, Chung et.al. 1999, Pillai and Annamalai 2012 and many other studies) and the interaction is explained well (Pillai and Annamalai, 2012 etc). Meanwhile, the interaction with other boundary forcing is not studied in detail. The mechanism is not explained mainly due to the fewer co-occurrence with ISMR and their interrelationship with ENSO. Here in the present study, we try to differentiate the extreme monsoon years for ENSO and non-ENSO years and the mechanism leading to extremes based on moisture and moist static energy budget. An early study by Pillai and Annamalai (2012) used the same budget analysis to understand the mechanism associated with severe monsoons (>1.5 standard deviations) and the majority of these years were associated with ENSO. In this study, we are looking at whether there is any difference between the moisture mechanism for ENSO and non-ENSO extreme rainfall and how other boundary forces such as Indian Ocean processes contribute to observed ISMR extremes.

Data and Methodology

The present study uses long term data of Indian summer monsoon rainfall (ISMR) obtained from the gridded data of IMD (Pai et al 2014) for 1950-2020. Severe monsoons are based on $\pm 10\%$ LPA threshold cutoffs for long term (1950-2020) climatology. Sea surface temperature from the Hadley Centre (HadISST, Rayner et al., 2003) is also used for the same period. Moisture and moist static energy budget analysis are performed using three-dimensional wind data, specific humidity and temperature from surface to 100 hPa along with surface temperature, pressure, sensible and latent heat flux and radiation fluxes at the surface and top of the atmosphere from the NCEP reanalysis (Kalney, et.al 1996). Moisture and moist static energy budget analysis are performed similar to Su and Neelin (2002), Pillai and Annamalai (2012) and the equations are summarised below.

$$\partial_t \langle T \rangle' + \langle D_T T \rangle' + \langle \omega \partial_p s \rangle' = \langle Q_c \rangle' + \frac{g}{P_T} (F'_{rad} + H') \dots \dots equ (1)$$

$$\partial_t \langle q \rangle' + \langle D_T q \rangle' + \langle \omega \partial_p q \rangle' = \langle Q_q \rangle' + \frac{g}{P_T} (E') \dots \dots equ (2)$$

$$D_T = D_q = V \cdot \nabla - K_H \nabla^2 \dots \dots equ (3)$$

$$\langle \omega \partial_p h \rangle' = -\langle D_T T \rangle' - \langle D_q q \rangle' + \frac{g}{P_T} (F'_{rad} + H' + E') \dots equ (4)$$

We can calculate the moisture equation for rainfall based on equation 2 and the MSE budget can be calculated from equation 4. Meanwhile, the moisture advection term can be split into the contribution from the mean and anomaly of wind and moisture in equation 5 below.

$$\langle V \cdot \nabla q' \rangle = \langle V^c \cdot \nabla q' \rangle + \langle V' \cdot \nabla q^c \rangle + \langle V' \cdot \nabla q' \rangle + \overline{\langle V'' \cdot \nabla q'' \rangle} \dots equ (5)$$

Standardised anomalies of JJAS season above (below) ± 1 SD are chosen to represent the positive and negative years of ENSO, IOD and EQUINOO. Niño 3.4 is calculated over the region (5N-5S, 170W-120W, Trenberth, 1997). Values more than $+1$ SD are termed as El Nino and those below -1 SD are referred to as La Nina events. The intensity of the IOD is represented by anomalous SST gradient between the western equatorial Indian Ocean (50E-70E and 10S-10N) and the southeastern equatorial Indian Ocean (90E-110E and 10S-0N). This gradient is named as Dipole Mode Index (DMI). When the DMI is positive then, the phenomenon is referred to as the positive IOD and when it is negative, it is referred to as negative IOD (Saji et. al., 1999). EQWIN index is the negative of the anomaly of the zonal component of the surface wind at the equator (60°E–90°E, 2.5°S–2.5°N) normalized by its

standard deviation (Gadgil et. al., 2004). Easterly wind anomaly is treated as positive EQWIN and vice versa.

Composite of anomalies of rainfall, SST, wind, SLP etc of strong and weak monsoon years with different combinations (co-occurring) with ENSO, IOD, EQWIN are carried out. The moisture and MSE analysis are performed separately for all these co-occurrence years in composite to understand the similarities and differences of these different processes which can contribute to monsoon extremes. Extremes independent of all these are also treated separately to interpret the possible mechanism.

RESULTS

a) Rainfall distribution of excess years associated with different boundary forcing.

Figure 1 shows the spatial distribution of rainfall for excess rainfall year composite from all the boundary forcing based on Table 1. The La Nina co-occurred positive rainfall anomalies spread all over the Indian land region with a maximum over the southern and western part of the Indian land region. At the same time, the non-ENSO cases have stronger rainfall over the central monsoon core region in association with positive IOD and south-western parts of India for the third independent category. For the drought cases, weak ISMR anomalies are distributed over the entire monsoon region. The rainfall anomalies are mainly concentrated over the north-eastern part of India and western coast for negative eqwin and are over north-western India for the independent case. Thus, both figure 1 and table 1 indicate strong variation in intensity and distribution of extreme rainfall in the presence of different boundary forcing. It will be interesting to analyse whether the difference in spatial distribution is also the result of large scale circulation features associated with different types of boundary forcing.

b) Anomalous large scale features associated with seasonal extremes

Figure 2 shows the large scale SST and circulation features of different categories of flood and drought years. Sea level pressure (SLP) anomalies and upper-level velocity potential (VP) for the same are shown in figure 3. During the La Nina years (fig 2a), the SST is anomalously cool in the equatorial east Pacific with strong easterly wind anomalies in the Indian land region. There is reduced SLP and increased convergence over the Indian land region (fig 3a), with the opposite pattern observed over the tropical east and central Pacific regions (Fig 2a). This indicates that the divergence aids the strong ascent over the monsoon region. Strong

easterly flow from the central Pacific to the monsoon region is associated with the occurrence of La Nina in the Pacific. Meanwhile, for the non-La Nina cases, there are no strong SST anomalies in the tropics. It has a stronger dipole structure and cross-equatorial flow for positive IOD case and has stronger winds over AS and African region for the third category (Fig 2 b and c). The SLP and divergence centre differences are between the west and east Indian Ocean for the IOD case and between the Indian region and the Atlantic for the third category (Figure 3 b and c). Thus the local circulation (i.e., south-westerly flow from the Indian ocean to monsoon region is stronger in the case of non-ENSO extremes, while the easterly flow from the equatorial central Pacific is stronger for La Nina co-occurred flood years.

Meanwhile, for drought cases, there is an easterly wind anomaly to the Indian Ocean from the Indian land region induced by the strong divergence over the monsoon region. There is additional flow from India and Bay of Bengal (BoB) to equatorial central Pacific for ENSO cases (Fig2 d), while the easterly over the Indian region converge to the central Indian Ocean during negative EQWIN years and it flows to the African area for the third category (Fig 2f). Thus the easterly flow to the Indian Ocean is common in all drought cases.

c) Moisture and MSE budget

Moisture and MSE budget as performed by earlier studies such as (Pillai and Annamalai 2012 etc) will help us find out the different roles of moisture, fluxes etc in the formation of the extremes under the influence of different categories of external forcing.

1) Budget analysis for severe flood years

Figure 4 shows the moisture budget as per equation 2 above for the flood years of different categories. For La Nina composites, the increased rainfall over the Indian land region is balanced by moisture advection and moisture convergence, while the evaporation is anomalously weak and is in the opposite phase (Fig 4 a,b,c). In comparison with the wind structure, we can interpret that the wind from the Pacific induced by La Nina may be the reason for anomalous moisture advection over the monsoon region. Similarly, for the MSE budget, the significant contribution is from moisture advection and a weaker contribution from net fluxes (not shown). Temperature and sensible heat play a very minute role in the increased rainfall over the Indian land region. Meanwhile, in the non-ENSO cases associated with positive IOD, moisture convergence and moisture advection along with evaporation play a major role in increased rainfall, while MSE convergence is by moisture advection (Fig 4 e-

h). In the other independent category, there is moisture convergence over India and the equatorial African region, with increased moisture convergence and increased local evaporation over the Indian Ocean and Indian land region (Fig 4 i-l). MSE convergence is contributed by moisture and temperature advection, while the contribution from net heat flux and SHF is balanced. In both these non-ENSO induced cases, wind anomalies are more robust over the Indian ocean region and they got converged in the north-eastern part of India, coinciding with increased moisture advection, while the convergence over southern parts has coincided with increased local evaporation processes.

2) Budget analysis for drought years

Figure 5 shows the budget for drought years with and without El Nino co-occurrence. El Nino co-occurrence years have decreased rainfall over the monsoon region balanced by the moisture divergence there aided by dry air advection due to moisture transport to the western Indian Ocean and equatorial Pacific (Fig 5 a-d). Evaporation also favours drought over the monsoon region. MSE divergence is also contributed mainly by dry air advection and temperature advection. Net radiation also contributed to decreased MSE, while SHF contribution is the opposite (not shown). Meanwhile, for non-ENSO cases, reduced rainfall is mainly balanced by moisture divergence. At the same time, the dry air advection is stronger over the north-central Indian region, and there is evaporation contributing to the rainfall budget in the southern part of India. For the MSE budget, temperature advection is also contributing. The non-ENSO cases are further split into the contribution from negative EQWIN and cases independent of ENSO and IOD. In the case of negative EQWIN, rainfall is mainly balanced by moisture divergence over the monsoon region, while MSE divergence is balanced by moisture advection (Fig 5 e-h). In independent cases, rainfall decreases are balanced by moisture divergence and dry air advection is in the northern part of India, while evaporation is important for southern regions (Fig 5 i-l). Moisture advection itself will contribute to MSE divergence also.

d) Role of anomalous circulation in moisture advection

The above analysis indicates that anomalous moisture advection is the major contributor to these composites' moisture and MSE budget. As per equation 5, anomalous moisture advection can be split into the contribution from the climatological and anomalous contributions of moisture and wind. Here in this section, we split the moisture advection by its components in the equation and explained the difference for different events.

Figure 6 shows the components of the equation for flood years. In this first figure is the contribution from anomalous wind advecting on climatological moisture (term1, ADV1), second is the contribution by climatological moisture advected by climatological wind (term2, ADV2) and third is the contribution from anomalous moisture advected by anomalous wind (term3, ADV3). In the cases of flood introduced by La Nina in the Pacific, moisture advection by anomalous wind acting on climatological moisture is to western and northern parts of India (Fig6 a-c). In contrast, the climatological wind working on the anomalous wind will contribute to the southern part of India. In the north-eastern region, the major contribution is from the climatological moisture advected by the climatological wind. In the positive IOD case (Fig6 d-f), anomalous wind advect moisture to the north-eastern parts and there is dry air advection in the southern part of India. The second component also contributes to moisture advection in north-east India with weak positive advection in the southern peninsular region, while the advection contributed by anomalous terms have a negative contribution. Thus acting all these terms will result in increased moisture advection to the north and eastern part of India, with weak negative moisture advection to the southern region of the Indian subcontinent. In the third category of flood cases (Fig6 g-i), both the first and second component contributes to the total moisture advection. Thus in the case of La Nina induced flood, climatological moisture over the Indian region advected by anomalous wind contributes to moisture advection leading to moisture convergence and rainfall. During IOD years also, the anomalous wind is causing moisture advection to cause convergence. But in the third case anomalous advection by both anomalous wind and climatological wind contribute to moisture convergence.

The same components of anomalous advection for drought cases are provided in Figure 7. El Nino droughts have anomalous wind advecting climatological wind that causes dry air advection to the northern part of India, while the anomalous moisture advected by climatological wind induces dry advection to southern India and the BoB region (Fig 7 a-c). The anomalous wind causes moisture advection and convergence for negative EQUINOO cases (Fig7 d-f), while for the third category, anomalous wind acting on mean moisture causes dry air advection to the northern part of India, while that by the climatological wind causes that over the southern peninsular region (Fig7 g-h). These analyses indicate different wind structures and associated moisture processes, leading to anomalous convection induced by different boundary forcing over the monsoon region.

4. Discussion and Conclusion.

275 Indian summer monsoon seasonal extremes, which accounts for more than 10% variability of
276 long-term mean, account for the flood/drought affecting the livelihood of millions of people
277 in the subcontinent. Earlier studies on these extremes accounted for SST anomalies
278 associated with El Nino Southern Oscillation (ENSO) as the major factors responsible for
279 these extremes and explained the relationship between these two in detail. But it will account
280 for half of the extremes in the last century and further studies conclude that other factors such
281 as Indian Ocean Dipole, EQWIN, Atlantic SST, mid-latitude interactions etc can also account
282 for extremes, but how these different mechanisms contribute to the extremes are not
283 examined well. The preset study understands the moisture mechanism behind these different
284 contributors of extreme ISMR.

285 The extremes induced by different boundary forcing have a difference in the spatial
286 distribution of rainfall anomalies over the Indian land region. The La Nina co-occurred
287 stronger rainfall anomalies spread all over the Indian land region with a maximum over the
288 southern and western part of the Indian land region, while the non-ENSO cases have stronger
289 rainfall over the central monsoon core region and south-western parts of India. Meanwhile,
290 for the drought cases, weak ISMR anomalies are distributed over the entire monsoon region,
291 while it is mainly concentrated over the north-eastern part of India and western coast for
292 negative EQWIN and is over north-western India for the independent case.

293 The study points that the ENSO induced extremes have stronger wind patterns from the
294 Pacific Ocean associated with convergence/divergence centres over India covering the Indian
295 Ocean and the Pacific Ocean. The rainfall is mainly contributed by moisture advection and
296 convergence process. The anomalous wind acting on climatological moisture is the major
297 process in these remote influenced ISMR extremes. Meanwhile, in the case of non-ENSO
298 cases induced severe monsoon, both mean and anomalous wind induces moisture advection
299 to the monsoon region and also local evaporation plays a secondary role. Thus the
300 mechanisms by which the rainfall anomalies are formed in these different cases are different.

301 The budget analysis also explains the difference in the distribution of rainfall anomalies
302 during different cases. The difference in the area of extreme rainfall is in accordance with the
303 wind anomalies and associated moisture transport and convergence. Thus, the study
304 concludes that even though many external factors induce the extremes of ISMR, the
305 mechanism behind each external factor is also different. Capturing these different
306 mechanisms is needed for the better prediction of these different categories of extremes.

307

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317 variables) <https://psl.noaa.gov/data/gridded/data.ncep.reanalysis.html>., HadISST from
318 <https://www.metoffice.gov.uk/hadobs/hadisst/data/download.html> and IMD rainfall from
319 https://www.imdpune.gov.in/Clim_Pred_LRF_New/Gridded_Data_Download.html.
320 Processed data can be made available on request.

321 **Competing Interests**

322 The authors declare no competing interests.

323 **Author's contribution**

324 A. R Dhakate- Formal analysis, Conceptualization, Validation, Software, writing original
325 draft. P.A Pillai- Conceptualisation, supervision, methodology and validation., writing-
326 reviewing and editing.

327 **Code availability:**

328 Moisture and moist static energy budget calculation code can be made available on request.

329 **Ethics Declaration**

330 **Ethics Approval:**

331 Not applicable.

332 **Consent to participate:**

333 Not applicable

334 **Consent to publish**

335 Not applicable.

336 **Conflict of Interest**

337 The authors have no conflicts of interest to declare.

338 **References:**

- 339 Abrol Y.P., and Gadgil S., Eds., 1999: Rice- in a Variable Climate. *APC Publications Pvt*
340 *Ltd.*
- 341 Ajayamohan R.S., Rao S. A., 2008: Indian Ocean dipole modulates the number of extreme
342 rainfall events over India in a warming environment. *Journal of the Meteorological Society of*
343 *Japan* Ser II 86:245-252 DOI: 10.2151/jmsj.86.245 .
- 344 Annamalai H., Liu Ping, and Xie Shang-Ping., 2005: Southwest Indian Ocean SST
345 Variability: Its Local Effect and Remote Influence on Asian Monsoon. *Journal of Climate*,
346 DOI: <https://doi.org/10.1175/JCLI3533>, pp. 4150–4167 .
- 347 Charney, J. G., and Shukla J., 1981: Predictability of monsoons. Monsoon Dynamics, J.
348 Lighthill and R. P. Pearce, Eds., Cambridge University Press, pp. 99–108
- 349 Chung, C., and Nigam S., 1999: Asian summer monsoon—ENSO feedback on the Cane–
350 Zebiak model ENSO. *J. Climate*, **12**, 2787–2807.
- 351 Gadgil S., and Rupa Kumar K., 2006: The Asian Monsoon-Agriculture and economy. Book:
352 The Asian Monsoon, Chapter 18, Ed. B. Wang, Springer, Berlin , Heidelberg, 2006.
- 353 Gadgil Sulochana., Vinayachandran P. N., Francis P. A., Gadgil Siddhartha., 2004: Extremes
354 of the Indian summer monsoon rainfall, ENSO and equatorial Indian Ocean oscillation,
355 *Geophysical Research Letters*, Vol. 31, L12213, doi:10.1029/2004GL019733.
- 356 Gadgil, S., 1996: Climate change and agriculture-An Indian perspective. Climate Variability
357 and Agriculture, Book Eds. Y. P. Abrol, S. Gadgil, and G. B. Pant, Narosa Publications, pp.
358 1–18.
- 359 Krishna Kumar K., Rupa Kumar K., Ashrit R. G., Deshpande N. R., Hansen J. W. , 2004 :
360 Climate impacts on Indian agriculture. *International Journal of Climatology*, 24: pp. 1375 –
361 1393 , <https://doi.org/10.1002/joc.1081>.
- 362 Pai D.S., Latha Sridhar, Rajeevan M., Sreejith O.P., Satbhai N.S. and Mukhopadhyay B.,
363 2014: Development of a new high spatial resolution (0.25° X 0.25°)Long period (1901-2010)
364 daily gridded rainfall data set over India and its comparison with existing data sets over the
365 region; *MAUSAM*, 65, 1(January 2014), pp1-18.

366 Pillai P., and Annamalai M., 2012: Moist Dynamics of Severe Monsoons over South Asia:
367 Role of the Tropical SST, *Journal Of The Atmospheric Sciences*, Volume 69, pp. 97-115.

368 Rajeevan M., and Sridhar L., 2008: Inter-annual relationship between Atlantic sea surface
369 temperature anomalies and Indian summer monsoon, *Geophysical Research Letters*, Vol. 35,
370 L21704, doi:10.1029/2008GL036025.

371 Rajeevan M., Bhate Jyoti, and Jaswal A.K., 2008: Analysis of variability and trends of
372 extreme rainfall events over India using 104 years of gridded daily rainfall data, *Geophysical*
373 *Research Letters*, 35, L18707, doi:10.1029/2008GL035143.

374 Rasmussen E. M., and Carpenter T. H., 1983: The relationship between eastern equatorial
375 Pacific sea surface temperature and rainfall over India and Sri Lanka. *Mon. Wea. Rev.*, 111,
376 pp. 517–528.

377 Rayner, N. A., Parker, D. E., Horton E. B., Folland C. K., Alexander L. V., Rowell, D. P.,
378 Kent, E. C., Kaplan, A., 2003: Global analyses of sea surface temperature, sea ice, and night
379 marine air temperature since the late nineteenth century *J. Geophys. Res.* Vol. 108, No. D14,
380 4407 10.1029/2002JD002670

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

383 Su Hui and Neelin David J., 2002 Teleconnection Mechanisms for Tropical Pacific Descent
384 Anomalies during El Niño, *Journal of the Atmospheric Sciences*, Volume 59, pp. 2694-2712.

385 Swaminathan, M. S., 1987: Abnormal monsoons and economic consequences: The Indian
386 experiment. Monsoons, Book Eds. J. S. Fein and P. L. Stephens, Wiley and Sons, pp. 121–
387 134.

388 Trenberth Kevin E., 1997: The Definition of El Niño. *BAMS*, Vol 78, no.12, pp 2771-2777.
389 doi.org/10.1175/1520-0477(1997)078<2771:TDOENO>2.0.CO;2

390 Walker G. T., 1924: Correlation in seasonal variations of weather. IV : A further study of
391 world weather. Mem. Indian Meteorol. Dept, 24, pp. 275–332.

392 Webster Peter J., Moore Andrew M., Loschnigg Johannes P., Leben Robert R.; 1999:
393 Coupled ocean–atmosphere dynamics in the Indian Ocean during 1997–98.
394 *Nature*, volume 401, pp. v356–360 .

395 Webster P. J., Magana V.O., Palmer T. N., Shuka J., Tomas R. T., Yanai M, and Yasunari
396 T., 1998: Monsoons: Processes, predictability and the prospects of prediction. *J. Geophys.*
397 *Res.*, 103(C7), 14, pp. 451–510.

398 Webster, P. J., and Yang S., 1992: Monsoon and ENSO: Selectively interactive
399 systems. *Quart. J. Roy. Meteor. Soc.*, **118**, pp. 877–926.

Webster, P. J., . Magaña V. O, T. N. Palmer, , J. Shukla, , R. A. Tomas, , M. Yanai, ,
and T. Yasunari, 1998: Monsoons: Processes, predictability, and the prospects for
prediction. *J. Geophys. Res.*, **103**, 14 451–14 510.

Yadav R. K., 2017: On the relationship between east equatorial Atlantic SST and ISM
through Eurasian wave. *Cli. Dyn.*, 48, pp. 281–295.

Figure captions:

Fig.1 Anomalous precipitation (JJAS) over the Indian Land region (mm day^{-1}). Left Panel is
for Flood years composite associated with a) La Nina cases, b) Positive IOD, and c)
Independent of IOD and La Nina. Right Panel shows composite of Drought years for d) El-
Nino cases e) Negative EQWIN f) and Independent cases

Fig.2 June–September composite of SST anomalies ($^{\circ}\text{C}$, shaded) and 850 hPa winds (vector,
 m s^{-1}). Left Panel is for Flood years composite for a) La Nina cases, b) Positive IOD, and c)
Independent of IOD and La Nina. Right Panel shows composite of Drought years for d) El-
Nino cases e) Negative EQWIN and f) Independent cases

Fig. 3 June–September composite of SLP anomalies (hPa, shaded) and 0.2101 (sigma level)
Velocity Potential (contours, m^2s^{-1}). Left Panel is for Flood years composite for a) La Nina
cases, b) Positive IOD, and c) Independent of IOD and La Nina. Right Panel shows
composite of Drought years for d) El-Nino cases e) Negative EQWIN and f) Independent
cases

Fig. 4 Dominant terms in moisture budget for JJAS period for Flood Cases co-occurred with
La Nina: a) MADV (vertically integrated horizontal moisture advection, W m^{-2}) b) MDIV
(vertically integrated moisture divergence, W m^{-2} , positive values for divergence and
negative for convergence); c) EVAP, evaporation and d) MSE (moist static energy, W m^{-2}).
(e)-(h) and (i)-(l) are the same as (a-d), but for flood years with positive IOD and independent
cases respectively. Units are W m^{-2} with different scales in each panel

Fig. 5 Dominant terms in moisture budget for JJAS period for drought Cases co-occurred
with El Nino: a) MADV (vertically integrated horizontal moisture advection, W m^{-2}) b)
MDIV (vertically integrated moisture divergence, W m^{-2} , positive values for divergence and
negative for convergence); c) EVAP, evaporation and d) MSE (moist static energy, W m^{-2}).
(e)-(h) and (i)-(l) are the same as (a-d), but for drought years with Negative EQWIN and
independent cases respectively. Units are W m^{-2} with different scales in each panel

Fig. 6 Dominant terms of the moisture advection averaged for JJAS for Flood Cases
associated with La Nina: (a) Anomalous winds acting on climatological moisture gradient
(b) Climatological wind acting on anomalous moisture gradient and (c) anomalous wind
acting on anomalous moisture gradient. (d)-(f) and (g)-(i) are the same as (a)-(c), but for
flood years with positive IOD and independent cases respectively. Units are W m^{-2} with
different scales in each panel

Fig. 7 Dominant terms of the moisture advection averaged for JJAS for Drought Cases associated with El Nino: (a) Anomalous winds acting on climatological moisture gradient (b) Climatological wind acting on anomalous moisture gradient and (c) anomalous wind acting on anomalous moisture gradient. (d)-(f) and (g)-(i) are the same as (a)-(c), Negative EQWIN and independent cases respectively. Units are W m^{-2} with different scales in each panel

Tables:

Table 1 All India Summer Monsoon Rainfall anomaly (land points) for extreme years (Flood/Drought) in order of increasing intensity/severity. The abbreviation in bracket indicates the association of these extreme years with ENSO, IOD, EQWIN or independent

Figures

Figure 1

Anomalous precipitation (JJAS) over the Indian Land region (mm day⁻¹). Left Panel is for Flood years composite associated with a) La Nina cases, b) Positive IOD, and c) Independent of IOD and La Nina.

Right Panel shows composite of Drought years for d) El-Nino cases e) Negative EQWIN f) and Independent cases

Figure 2

June-September composite of SST anomalies (°C, shaded) and 850 hPa winds (vector, m s⁻¹). Left Panel is for Flood years composite for a) La Nina cases, b) Positive IOD, and c) Independent of IOD and La Nina. Right Panel shows composite of Drought years for d) El-Nino cases e) Negative EQWIN and f) Independent cases

Figure 3

June–September composite of SLP anomalies (hPa, shaded) and 0.2101 (sigma level) Velocity Potential (contours, m^2/s). Left Panel is for Flood years composite for a) La Nina cases, b) Positive IOD, and c) Independent of IOD and La Nina. Right Panel shows composite of Drought years for d) El-Nino cases e) Negative EQWIN and f) Independent cases

Figure 4

Dominant terms in moisture budget for JJAS period for Flood Cases co-occurred with La Nina: a) MADV (vertically integrated horizontal moisture advection, W m^{-2}) b) MDIV (vertically integrated moisture divergence, W m^{-2} , positive values for divergence and negative for convergence); c) EVAP, evaporation and d) MSE (moist static energy, W m^{-2}). (e)-(h) and (i)-(l) are the same as (a-d), but for flood years with positive IOD and independent cases respectively. Units are W m^{-2} with different scales in each panel

Figure 5

Dominant terms in moisture budget for JJAS period for drought Cases co-occurred with El Nino: a) MADV (vertically integrated horizontal moisture advection, W m^{-2}) b) MDIV (vertically integrated moisture divergence, W m^{-2} , positive values for divergence and negative for convergence); c) EVAP, evaporation and d) MSE (moist static energy, W m^{-2}). (e)-(h) and (i)-(l) are the same as (a-d), but for drought years with Negative EQWIN and independent cases respectively. Units are W m^{-2} with different scales in each panel

Figure 6

Dominant terms of the moisture advection averaged for JJAS for Flood Cases associated with La Nina: (a) Anomalous winds acting on climatological moisture gradient (b) Climatological wind acting on anomalous moisture gradient and (c) anomalous wind acting on anomalous moisture gradient. (d)-(f) and (g)-(i) are the same as (a)-(c), but for flood years with positive IOD and independent cases respectively. Units are W m^{-2} with different scales in each panel

Figure 7

Dominant terms of the moisture advection averaged for JJAS for Drought Cases associated with El Niño: (a) Anomalous winds acting on climatological moisture gradient (b) Climatological wind acting on anomalous moisture gradient and (c) anomalous wind acting on anomalous moisture gradient. (d)-(f) and (g)-(i) are the same as (a)-(c), Negative EQWIN and independent cases respectively. Units are W m⁻² with different scales in each panel