

## An analysis of monthly rainfall and the meteorological conditions associated with the deficient rainfall towards the end of 2017 southwest monsoon season

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**सार –** इस शोध पत्र में ग्रीष्मकालीन मॉनसून 2017 का अध्ययन किया गया है और कई प्राचलों की जांच की गई है जिससे यह ज्ञात किया जा सके कि भारत में मॉनसून उत्तरार्द्ध में क्यों विफल हुआ। प्राचलों की सूची में निम्नलिखित क्षेत्रों के मासिक माध्य या विसंगतियों को शामिल किया गया है: समुद्र की सतह का तापमान, बहिर्गामी दीर्घ तरंग विकिरण, निम्न और ऊपरी वायुमंडल का धारा फलन, वेग की क्षमता और मासिक तथा ऋतुनिष्ठ वर्षा। एन्सो (ENSO) की स्थितियाँ मुख्य रूप से पूर्वार्द्ध में गर्म ENSO के साथ तटस्थ और उत्तरार्द्ध में ठंडी ENSO की स्थितियों के साथ तटस्थ देखी गईं। परिणामस्वरूप, प्रशांत महासागर से बड़े पैमाने पर आने वाले समुद्र सतह तापमान (SST) का प्रभाव ऋतु के दौरान लगभग नगण्य रहा। हालांकि, मॉनसून ऋतु के दौरान हिंद महासागर के ऊपर सकारात्मक आई ओ डी की स्थिति, विशेष रूप से मॉनसून के पूर्वार्द्ध के दौरान प्रमुख रहीं। सामान्य से अधिक गर्म एसएसटी (जून और जुलाई) का संक्रमण सामान्य एसएसटी (अगस्त) में होना और फिर सामान्य से अधिक ठंडा SSTs (सितंबर) में संक्रमण होना मॉनसून को उत्तरार्द्ध में विफल करने में प्रभावशाली कारण बना।

**ABSTRACT.** This paper studies the summer monsoon 2017 and examines the number of parameters which we believe were important in understanding why monsoon failed in second half over India. The list of parameters includes monthly mean or anomalies of the following fields : sea surface temperature, outgoing longwave radiation, stream function of lower and upper atmosphere, velocity potential and monthly and seasonal precipitation. ENSO conditions were mainly neutral with warm ENSO neutral conditions observed in the first half and cool ENSO neutral conditions observed in the second half. As a result, influence on the monsoon from the large scale SST forcing from Pacific Ocean was nearly absent during the season. However, Positive IOD conditions over the Indian Ocean during the monsoon season, particularly during first half of the monsoon were prominent. The transition of warmer than normal SSTs (June and July) to normal SSTs (August) and then becoming cooler than normal SSTs (September) in the equatorial Indian Ocean had a significant influence which lead monsoon to fail in second half.

**Key words –** Southwest monsoon, Deficient, ENSO, Positive IOD, Meridional circulation, Equatorial circulation.

### 1. Introduction

No two monsoon seasons are similar and 2017 southwest monsoon was also quite a different one. The first stage forecast for the seasonal (June-September) rainfall over the country as a whole issued in April was 96% of LPA with a model error of  $\pm 5\%$  of LPA. The update issued in June for this forecast was (98% of LPA) with a model error of  $\pm 4\%$  of LPA. The actual season rainfall for the country as a whole was 95% of LPA, which is 1% & 3% of LPA less than the April and June forecasts respectively. Thus the actual seasonal rainfall over the country as a whole was within the lower forecast range. The onset of southwest monsoon is also a complex task. Heating of land mass and moisture availability leads to convective activities over India. This year, 2017, Madden Julian Oscillation (MJO) helped Monsoon to advance in the Andaman Sea and Bay of Bengal after 13<sup>th</sup> May. Southwest monsoon reached parts of southeast

Bay of Bengal, south Andaman Sea and Nicobar Islands on 14<sup>th</sup> May (6 days ahead of its normal date). It advanced over Kerala on 30<sup>th</sup> May (2 days ahead of the normal schedule) and covered the entire country by 19<sup>th</sup> July (4 days later than the normal date). The forecast for monsoon onset over Kerala for this year was very accurate, as both the forecasted and realized date of onset of monsoon over Kerala was 30<sup>th</sup> May.

The rainfall over the country as a whole during the monsoon season (June-September) was 95% of its long period average (LPA). Seasonal rainfall over Northwest India, Central India, south Peninsula and Northeast (NE) India were recorded at 90%, 94%, 100% and 96% of respective LPAs. Out of the total 36 meteorological sub-divisions, 25 sub-divisions constituting 65% of the total area of the country received normal seasonal rainfall, 5 sub-divisions received excess rainfall (18% of the total area) and 6 sub-divisions (17% of the total area) received

deficient seasonal rainfall. Monthly rainfall over the country realized as a whole was 104% of LPA in June, 102% of LPA in July, 87% of LPA in August and 88% of LPA in September. The forecasts for the seasonal rainfall over country as whole and the four broad geographical regions and the forecast for July rainfall over the country as whole were within the forecast range. However, the forecasts for the rainfall during the second half of the monsoon season and the August rainfall were found to be over estimated to the observed rainfall. So here we have made our efforts to understand as how conducive the conditions were for the monsoon to get establish, how was the monsoon flow for the 3 major months (June, July and August), how it failed in the second half and why monsoon withdrawal was delayed.

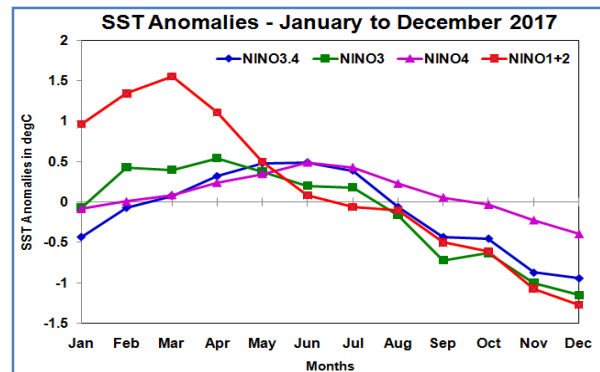
## 2. Data source

NCEP NOAA Extended Reconstructed Sea Surface Temperature (ERSST) version 5 monthly data is used for monthly and seasonal analysis during monsoon season. NCEP NOAA Uninterpolated OLR anomaly data and NCEP NOAA meridional and zonal wind (850 hPa and 200 hPa) anomalies were analyzed on monthly and seasonal basis for June to September 2017. The wind anomalies of 850 hPa and 200 hPa were overlaid over OLR anomalies for the monsoon season. NCEP NOAA meridional vertical circulation anomaly (latitude height cross section) and zonal vertical circulation anomaly (longitude height cross section) Omega, Standardized rainfall in monsoon core zone, IMD real time rainfall subdivision wise data, High resolution IMD  $0.25^\circ \times 0.25^\circ$  gridded rainfall dataset for 1901 to 2018 were used for circulation and rainfall analysis. NCEP NOAA stream function along with rotational winds anomaly at 850 hPa for the August and September month were also used. Japan Meteorological Agency (JMA) best track Typhoon data for June to September, 2017, Beauru of Meteorology (BOM) MJO RMM1 and RMM2 dataset for June to September 2017 was used to understand convection pattern during the season.

## 3. Sea Surface Temperature (SST) anomalies

### 3.1. Equatorial Pacific Ocean

The anomalies in the tropical sea surface temperature have profound effect on the tropical and global atmospheric circulation through ocean-atmosphere interactions. The normal ocean temperatures are sufficiently high so that a positive SST anomaly of a few degrees can enhance the moist convection over the region greatly. A negative anomaly of few degrees can suppress the convective processes. The above normal sea surface temperatures over the equatorial central and eastern



**Fig.1.** Time series of area-averaged sea surface temperature (SST) anomalies ( $^{\circ}\text{C}$ ) in the Niño regions [Niño 1+2 ( $0^{\circ}$ - $10^{\circ}$  S,  $90^{\circ}$  W- $80^{\circ}$  W), Niño 3 ( $5^{\circ}$  N- $5^{\circ}$  S,  $150^{\circ}$  W- $90^{\circ}$  W), Niño 3.4 ( $5^{\circ}$  N- $5^{\circ}$  S,  $170^{\circ}$  W- $120^{\circ}$  W), Niño 4 ( $150^{\circ}$  W- $160^{\circ}$  E and  $5^{\circ}$  N- $5^{\circ}$  S)]. (Data Source : ERSSTv5, NOAA)

Pacific associated with El Niño events shift the monsoon convection zones eastward, often resulting in poor monsoon. Likewise, the sea surface temperature anomalies over the Indian Ocean also influence the performance of monsoons (Ashok & Saji, 2007). Here, we examine the sea surface temperature anomalies over tropical oceans in the context of 2017 monsoon. Evolution of SST anomalies in the four Niño regions since January, 2017 to December, 2017 is shown in the Fig. 1. During early part of 2017, ENSO-neutral conditions were observed. These ENSO-neutral conditions continued in the subsequent months also. However, cooler than normal SSTs along the equatorial Pacific Ocean during January 2017, later, warmed up leading to slightly warmer than normal SST anomalies up to August 2017. From September cooler than normal SST anomalies were prevailing along the east equatorial Pacific Ocean. By the mid of October, 2017, they turned to weak/borderline La Niña conditions which continued till December. Niño 3.4 average SST anomaly index in January, 2017 was  $-0.4^{\circ}\text{C}$  and that in end of May, 2017 was  $0.4^{\circ}\text{C}$ . Warm SSTs over Niño 3.4 region continued and reached to the maximum in July, 2017. From the month of September 2017, cool SST anomalies were observed over Niño 3.4 and reach threshold value of  $-0.5^{\circ}\text{C}$  *i.e.*, weak/borderline La Niña conditions during (mid of) October 2017 and were prevailing over east Pacific thereafter.

Overall, neutral ENSO conditions prevailed during entire monsoon season 2017 and its effect on monsoon season was quiet insignificant. The evolution of SST anomaly in the Niño 3 and Niño 4 regions was nearly similar to Niño 3.4 region. In the Niño 1+2 region, SST anomalies were positive initially till July and then turned to negative.

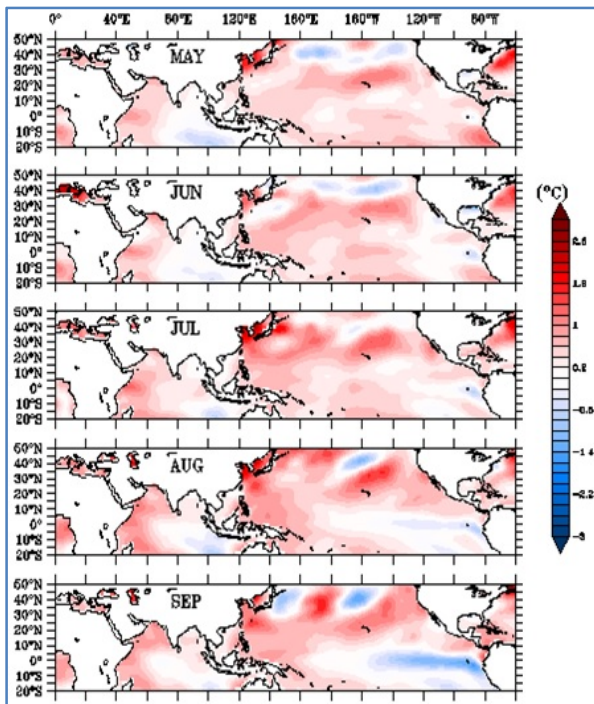


Fig. 2. Monthly SST anomalies in the Indo-Pacific region for May to September, 2017 (Data Source : ERSSTv5, NOAA).

Spatial pattern of monthly SST anomalies for the period April to August are shown in Fig. 2. As seen in Fig. 2, the positive SST anomalies were observed over most parts of the Pacific Ocean. During April month, the central and east Pacific thought was warmer than normal, but it was observed that the atmospheric conditions were showing more of like La Niña type. This is indicated by drier conditions near the Date Line and wetter conditions over Indonesia (It can be seen in the OLR anomalies Fig. 6). Also, surface winds over the west-central Pacific have been blowing stronger than average (a stronger Walker circulation, more like La Niña). During month of May, normal to warmer than normal SST anomalies were observed in the eastern equatorial Pacific. There was a slight decrease in above average SSTs over eastern equatorial Pacific during the June and July months and was towards warmer side of the anomaly. The negative SST anomaly emerged over eastern equatorial Pacific in the month of August and prevailed till September month which extended up to central equatorial Pacific Ocean. Meanwhile, the surface temperatures in the central Pacific were cooler than average, also more like La Niña than El Niño. Even the sub-surface ocean temperatures were below average in the central Pacific during monsoon. There were positive SST anomalies observed over the North Pacific Ocean during most of the months from May to September.

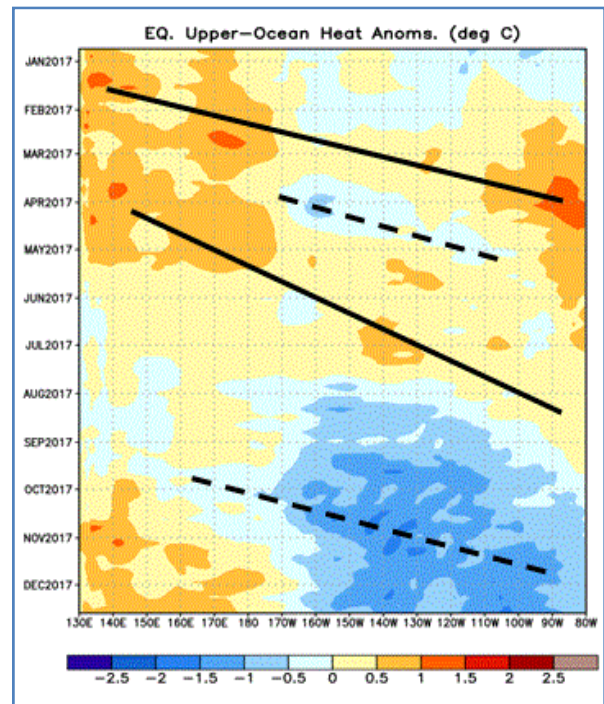


Fig. 3. The equatorial upper-ocean heat anomalies (°C) over equatorial Pacific (Source : Climate Prediction Centre)

These features are also seen in the Hovmöller diagram (time vs longitude) of equatorial heat content anomalies as shown in Fig. 3. It is seen that upper ocean of equatorial Pacific was warmer than normal especially in the eastern side during May, June and July month of monsoon season. While, from the month of August slight cooling in SSTs over east equatorial Pacific Ocean is observed. The alternate cooling and warming trend is seen in Fig. 3 with oceanic heat anomalies being positive and then negative in the upper (0-300 m) of tropical east Pacific Ocean during the monsoon season. The decrease in the oceanic heat anomalies across the equatorial Pacific is caused by the eastward propagation of upwelling Kelvin wave. The warm (down-welling) phase is indicated by solid lines and cool (upwelling) phase indicate by dashed line. The down-welling and warming occur in the leading portion of a Kelvin wave and up-welling and cooling occur in the trailing portion. There were two up-welling phases of a Kelvin wave propagation events observed, first one in March-April and second one from August-September. With the passage of an upwelling equatorial oceanic Kelvin wave in April 2017, below average subsurface temperatures extended across much of the equatorial Pacific. Also, there were two down-welling phases of an equatorial oceanic Kelvin wave observed during February-March and mid of April to early July month.

### 3.2. Indian Ocean

It is seen in the Fig. 2 that the prevailing basin wide warming of Indian Ocean (except south-east Indian Ocean off the western Australian coast) in the month of May turned in to positive IOD condition and continued throughout the monsoon season with weak positive SST anomalies over the eastern equatorial Indian Ocean. The Fig. 4 shows the time series of Dipole Mode Index (DMI) for the year 2017. The DMI represents the intensity of the IOD defined as the anomalous SST gradient between the western equatorial Indian Ocean ( $50^{\circ}$  E- $70^{\circ}$  E and  $10^{\circ}$  S- $10^{\circ}$  N) and the south eastern equatorial Indian Ocean ( $90^{\circ}$  E- $110^{\circ}$  E and  $10^{\circ}$  S- $0^{\circ}$  N). The DMI was in the positive side during most part of the monsoon season. It is seen from the Fig. 4 that rapid weakening of DMI observed just before the end of the monsoon season. The strong positive IOD features with respect to atmosphere were also observed over the Indian Ocean throughout the monsoon season.

### 4. OLR anomalies

Spatial distribution of monthly Outgoing Long Wave Radiation (OLR) anomalies during June to September is shown in Figs. 5 (a-d). The negative (positive) OLR anomalies indicate above (below) normal convection. In the month of June, negative OLR anomalies were observed over most parts of Arabian Sea as well as western parts of Bay of Bengal. Negative OLR anomalies were also observed over peninsular Indian region. The positive OLR anomalies were seen over most parts of  $10^{\circ}$  N- $10^{\circ}$  S of western Indian Ocean and parts of east central India. The magnitude of maximum negative anomaly more than  $30 \text{ W/m}^2$  observed over Maritime Continent. Negative anomalies exceeding  $20 \text{ W/m}^2$  were observed over Indian peninsula, north Arabian Sea and head Bay of Bengal indicated that ITCZ was at its normal position. The positive OLR anomalies over equatorial west Pacific (a small patch) and along west and south of equatorial Indian Ocean indicated below normal convection over that region. The strength of convective pattern associated with the strong positive IOD was normal with the progress of monsoon season. During the month of July, the negative OLR anomalies were observed over central and northern parts of the country. Also, position of convection associated with the ITCZ was in its normal position. A positive OLR anomaly was observed over the central peninsular region including parts of south-western Arabian Sea. As a whole, the July OLR anomaly pattern over Indian region showed improved convective activity. In the month of August, the positive OLR anomalies observed over Indian region except east-central and north-eastern parts of the country. The strengthening of the dipole pattern of positive IOD feature was also

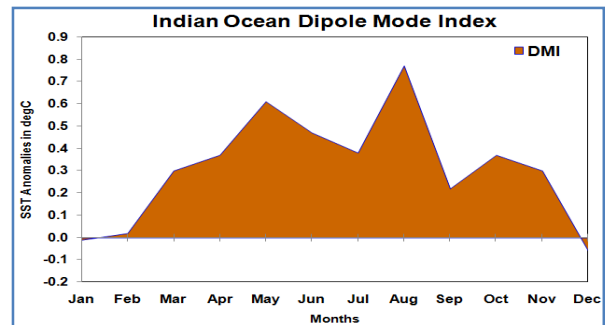


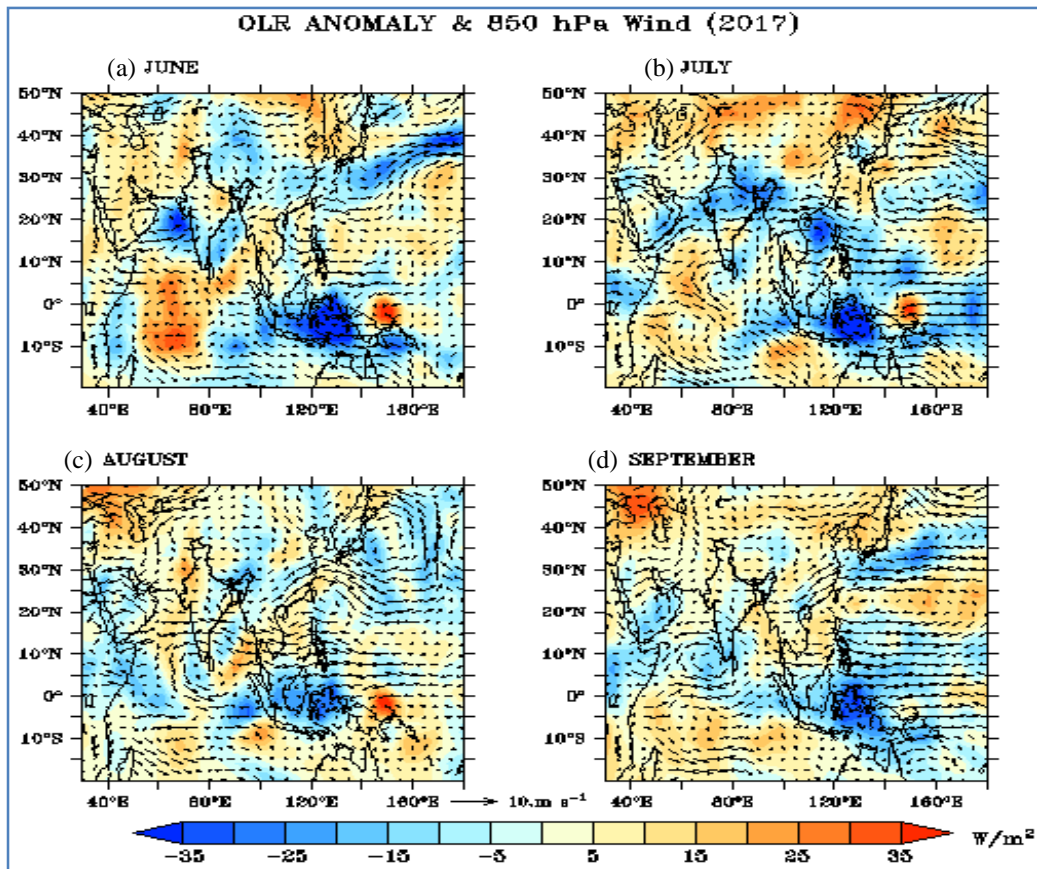
Fig. 4. The time series of Dipole Mode Index (DMI) representing Indian Ocean Dipole Condition (Source : ERSSTv5, NOAA) from January 2017 to December 2017

observed. The negative OLR anomaly less than  $40 \text{ W/m}^2$  over North West Pacific indicates above normal typhoon activity over the region. The similar kind of OLR anomaly pattern was observed during September with decreased strength of dipole pattern associated with positive IOD and decreased convective activity over North West Pacific.

The OLR anomalies averaged over the season (June to September) is shown in the Fig. 6. The normal to negative OLR anomaly was seen associated with neutral ENSO conditions in the season average and pattern associated with positive IOD observed over Indian Ocean. Over the Indian region, the OLR anomalies were negative except northernmost and north-west Indian region. Also, above normal convective activity observed over the Northwest Pacific region with negative OLR anomalies in the seasonal average.

### 5. Lower and upper tropospheric circulation anomalies

The wind anomalies at 850 hPa for the month of June to September are shown in Figs. 5(a-d). During June, the most prominent feature was the anomalous cyclonic circulation over southwest Arabian Sea and surrounding region. This caused good rainfall activity over southwest, central and peninsular Indian region. Anomalous northeasterly winds prevailed over the Indian region but they were not so significant. Southeasterly winds were also observed over south of monsoon trough region, helped to incur moisture over peninsular region. This caused reduced rainfall activity especially over east and northeast India in June. During July a stronger cross equatorial flow was observed over southern parts of India. Cyclonic circulation which was located over the central parts of India within the monsoon trough, resulted in weak anomalous easterlies over peninsular India. It caused increase in rainfall activity over central and northern parts



Figs. 5(a-d). Monthly OLR anomalies and wind anomalies at 850 hPa during (a) June, (b) July, (c) August and (d) September

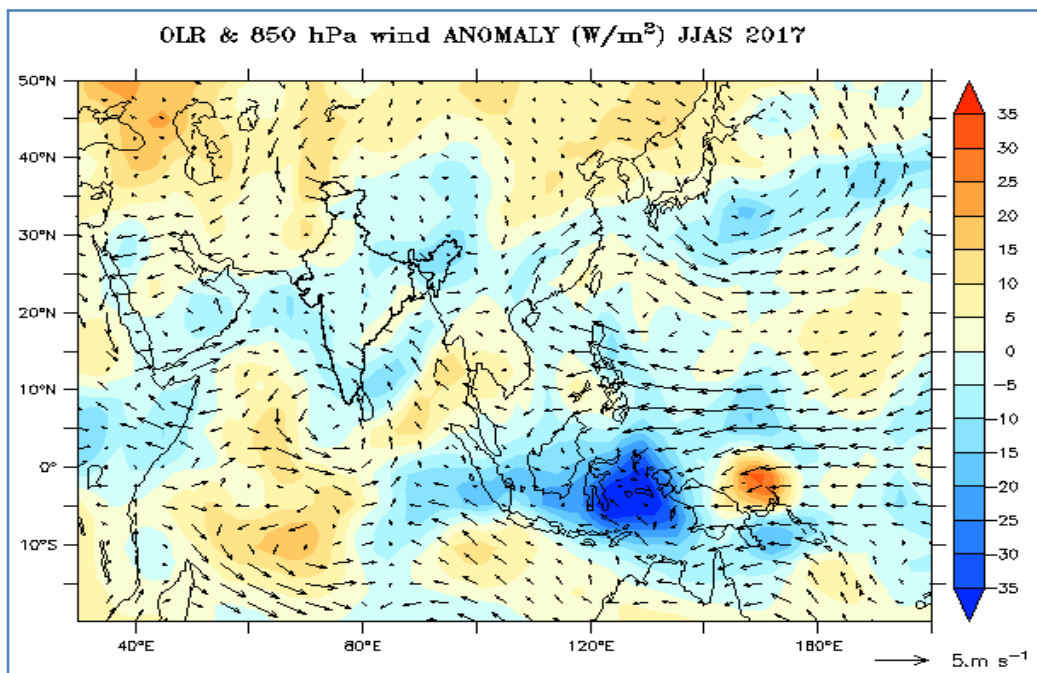
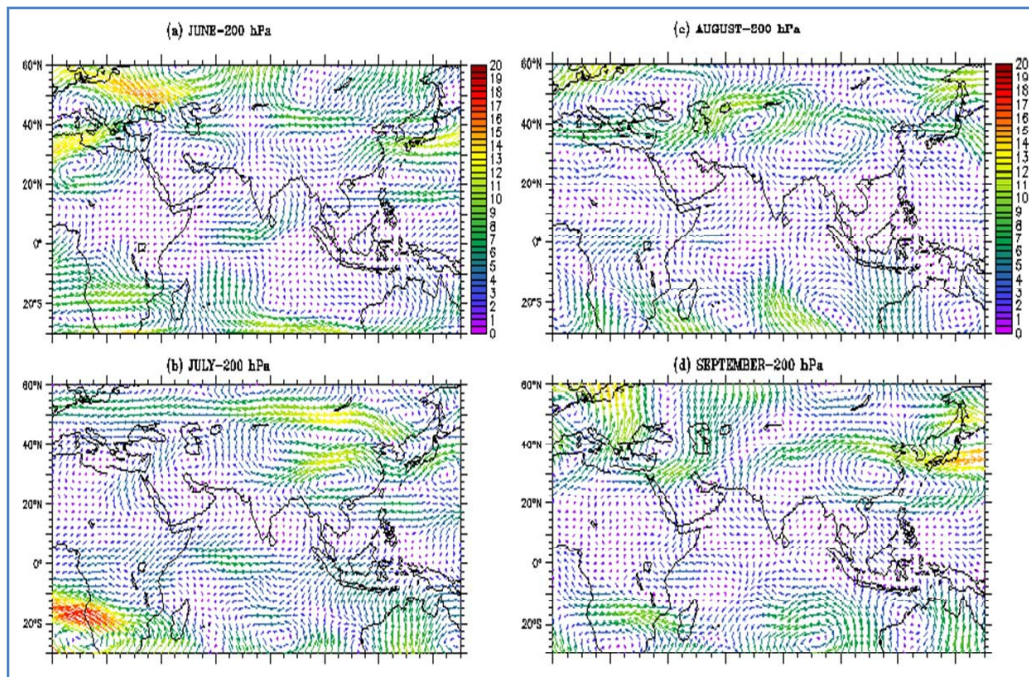


Fig. 6. OLR anomaly overlay with 850 hPa wind during June to September 2017



**Figs. 7(a-d).** Wind Anomalies at 200 hPa during (a) June, (b) July, (c) August and (d) September 2017

of the country. There was one more anomalous cyclonic circulation over the equatorial Indian Ocean just south of peninsular India, which carried away moisture from land to sea, resulted below normal rainfall over south peninsula in the month of July. During August also, a strong anomalous cyclonic circulation with center located south of southern peninsula persisted, which lead to above normal rainfall over south Peninsula. Another important feature observed was a strong anomalous anti-cyclonic circulation over the Head Bay of Bengal which supported moisture transport to Northeast India giving good rainfall over the region. In the month of September, a strong anomalous cyclonic circulation over southern peninsula shifted over south east Arabian Sea and resulted in above normal rainfall activity over south peninsula. The strong anomalous cross equatorial flow over northwest Pacific indicated above normal typhoon activity over the region and it caused reduced rainfall over Indian region. There was weak anomalous cyclonic circulation centered at Head Bay of Bengal. In the month of September, the anomalous easterlies were observed over the central Indian region indicate weak monsoon condition during the month. Figs. 7(a-d), show wind anomalies at 200 hPa. In June, anomalous cyclonic circulation located near the Tibetan Plateau, indicates that one of the major semi-permanent feature was weak. As a result, anomalous north-easterly winds prevailed over peninsular Indian region. It can be seen that tropical easterly jet stream also shifted south of its normal position. Anomalous anti cyclonic

circulation was also observed over Iran and surrounding region in the month of June. In July, a weak anomalous cyclonic circulation was seen over China and anomalous south-easterly wind over northern parts of India.

An anomalous anti cyclonic circulation which observed over Iran was shifted further northwestwards in the month of July. However, tropical easterly jet stream found more organized but south of its normal position and weak in its intensity. During the subsequent month of August, anomalous upper air anti-cyclonic circulation persisted over China, which indicate shift in tropical easterly jet stream further north of its normal position. Anomalous weak westerlies prevailed over peninsular Indian region. In the month of September, the upper air anomalous anti-cyclonic circulation observed over China further moved eastward. The cyclonic circulation over Iran and surrounding region was shifted southwestwards.

The wind anomalies averaged over the season (June to September) is shown in the Fig. 6 (850 hPa) and Fig. 8 (200 hPa). In the season averaged (June-September) 850 hPa wind anomaly (Fig. 6) an anomalous cyclonic circulation observed over the Somali coast which caused a weak cross equatorial flow over Arabian Sea. As a result, the weak low level jet was seen over peninsular Indian region. In the season average, value shows weak 200 hPa westerly wind anomalies (Fig. 8) over equatorial Indian Ocean and weak tropical easterly jet stream.

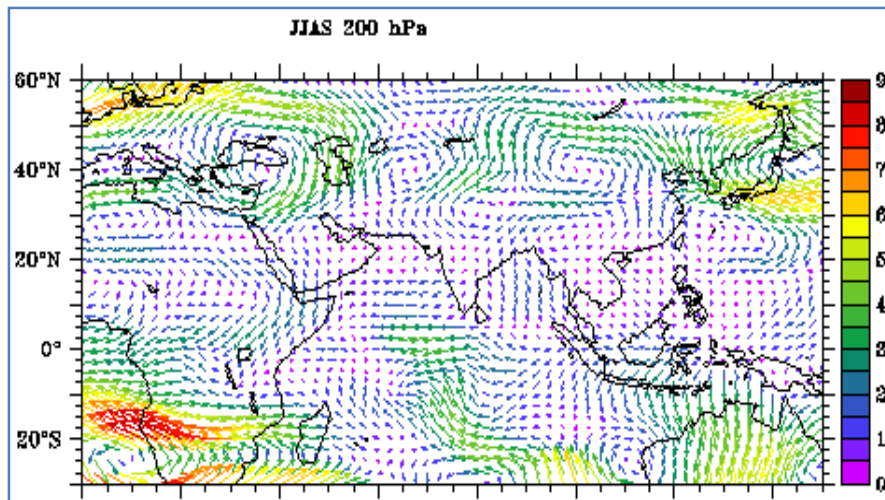


Fig. 8. Wind anomalies at 200 and 850 hPa during monsoon season (June to September) 2017

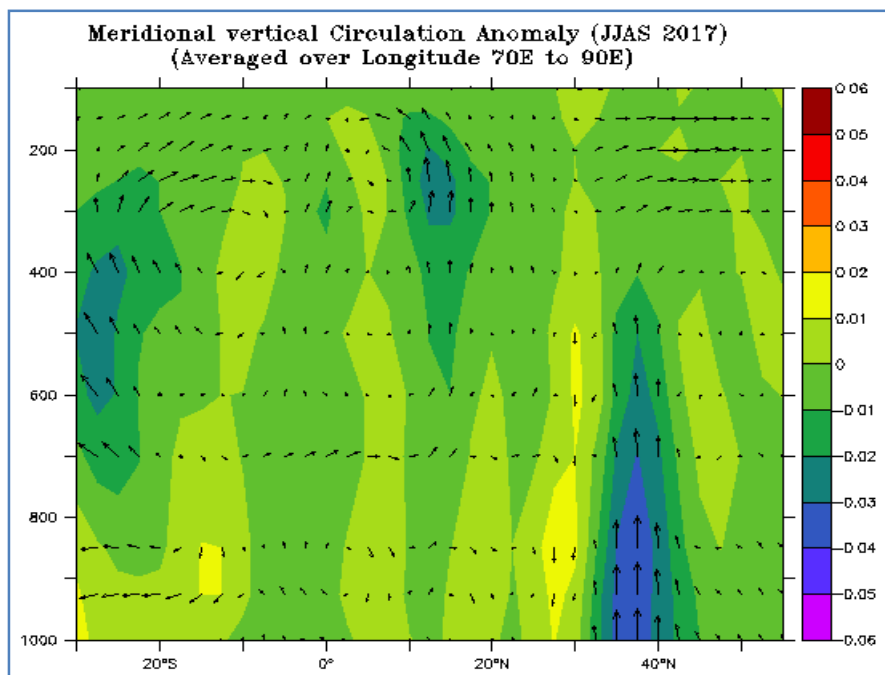
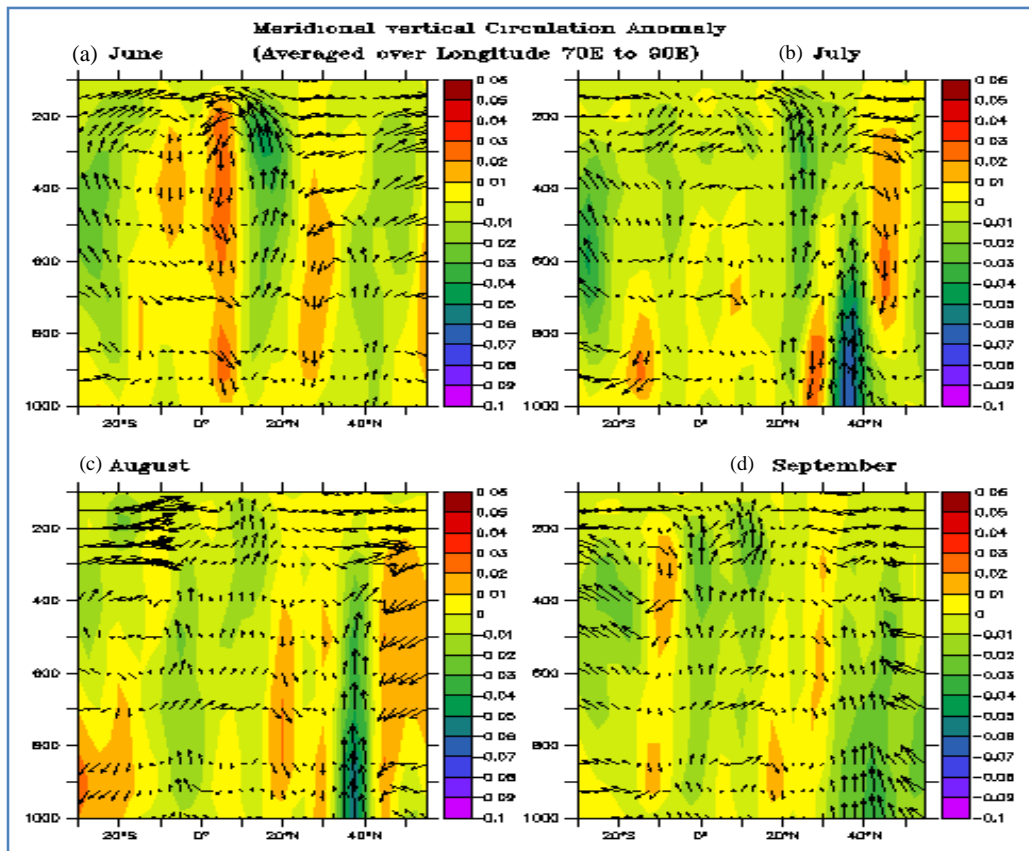


Fig. 9. Vertical cross-section of Pressure vertical velocity overlay with Meridional vertical circulation for the monsoon season (June-September, 2017). Pressure vertical velocity (Omega) is shaded. The anomalies are averaged over longitudes 70° E to 90° E

### 6. Meridional and zonal circulation anomalies over Indian region

To examine the changes in the meridional circulation over Indian region during the monsoon season, latitude - height cross section of vertical velocity (omega) anomalies averaged over longitudinal zone of 70° E-90° E was plotted for the monsoon season (Fig. 9). It can be seen

that there were two anomalous meridional circulation cells over Indian region, one circulation having strong ascending branch over north of about 35° N and descending branch over the south of latitude 30° N. Another weak meridional cell with its ascending branch near 15° N and descending branch over south of 20° N was also observed. These indicate overall, subsidence motion prevailed in the Indian region during the monsoon season. Figs. 10 (a-d) which



**Figs. 10(a-d).** Latitude Height Circulation Cross-section and Omega during (a) June, (b) July, (c) August and (d) September 2017. Pressure vertical velocity (Omega) is shaded. The anomalies are averaged over longitudes 70° E-90° E

depict the monthly meridional circulation anomaly over Indian monsoon region during June to September. It can be seen that the strength of the ascending motion near latitude 40° N observed during June increased in the subsequent month. A strong descending branch was observed over south of 30° N during July month. There was anomalous descending motion observed over Indian region during the second half of the season, *i.e.*, August and September. This unfavorable vertical circulation caused below normal convective activity and resulted in rainfall deficiency during the second half of the season.

A zonal vertical circulation anomaly over the Indian region during the monsoon season, longitude-height cross section of vertical velocity (omega) anomalies averaged over longitudinal zone of 15° N-25° N was plotted for the monsoon season [Figs. 11(a-d)].

The strength of anomalous descending motion over the Indian region in the month of June increased in the subsequent months and reached maximum in the month of August. In the month of June descending motion observed

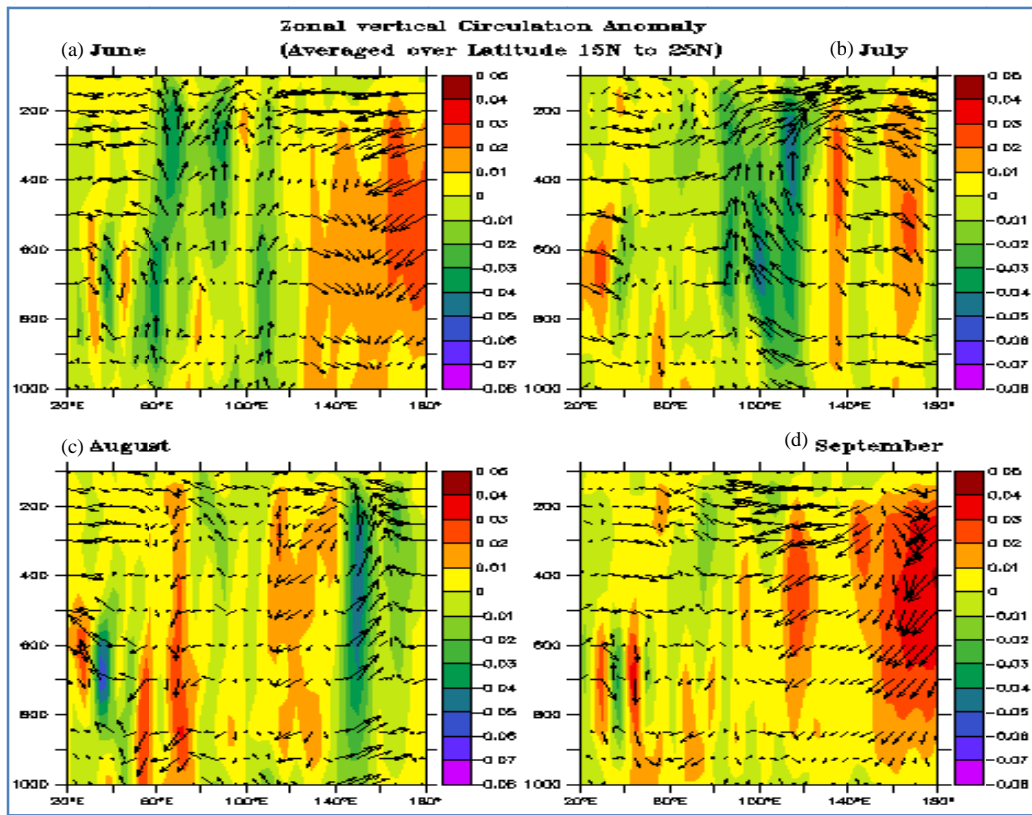
over the west pacific region turned in to ascending motion in the month of July. The Ascending branch over the west pacific region shifted eastward in the month of August. The strong ascending motion over the North West Pacific indicates enhanced typhoon activity over the region. There was an increase in strength of descending motion over the Indian region in the month of August which weakened slightly in the month of September.

## 7. Intra-seasonal variability during the monsoon season

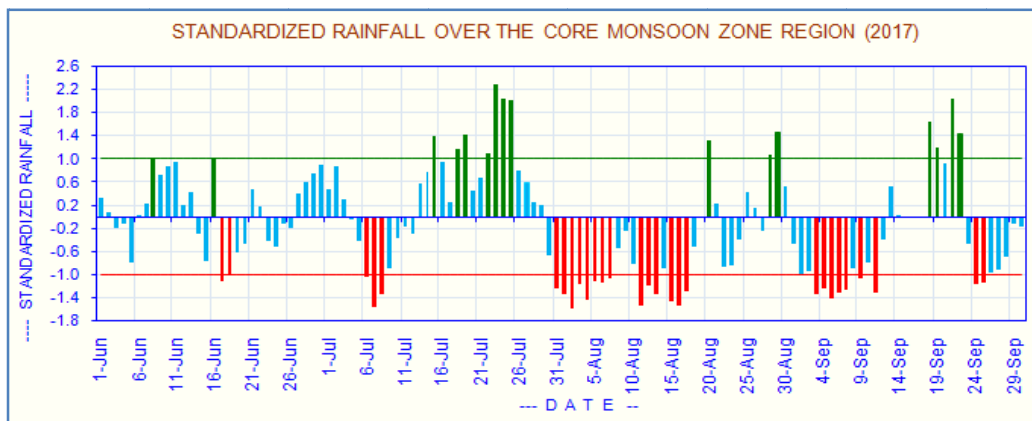
The intra-seasonal variation of rainfall during 2017 monsoon season is depicted in the Fig. 12, which shows the time series of daily rainfall anomaly over the core monsoon zone (Rajeevan *et al.*, 2008). It can be seen that, weak monsoon situation observed during few days of first week of July, during many days in first half of August and September months.

It can be also seen that, during second half of the monsoon, it experienced a few lull/break periods (31<sup>st</sup> July





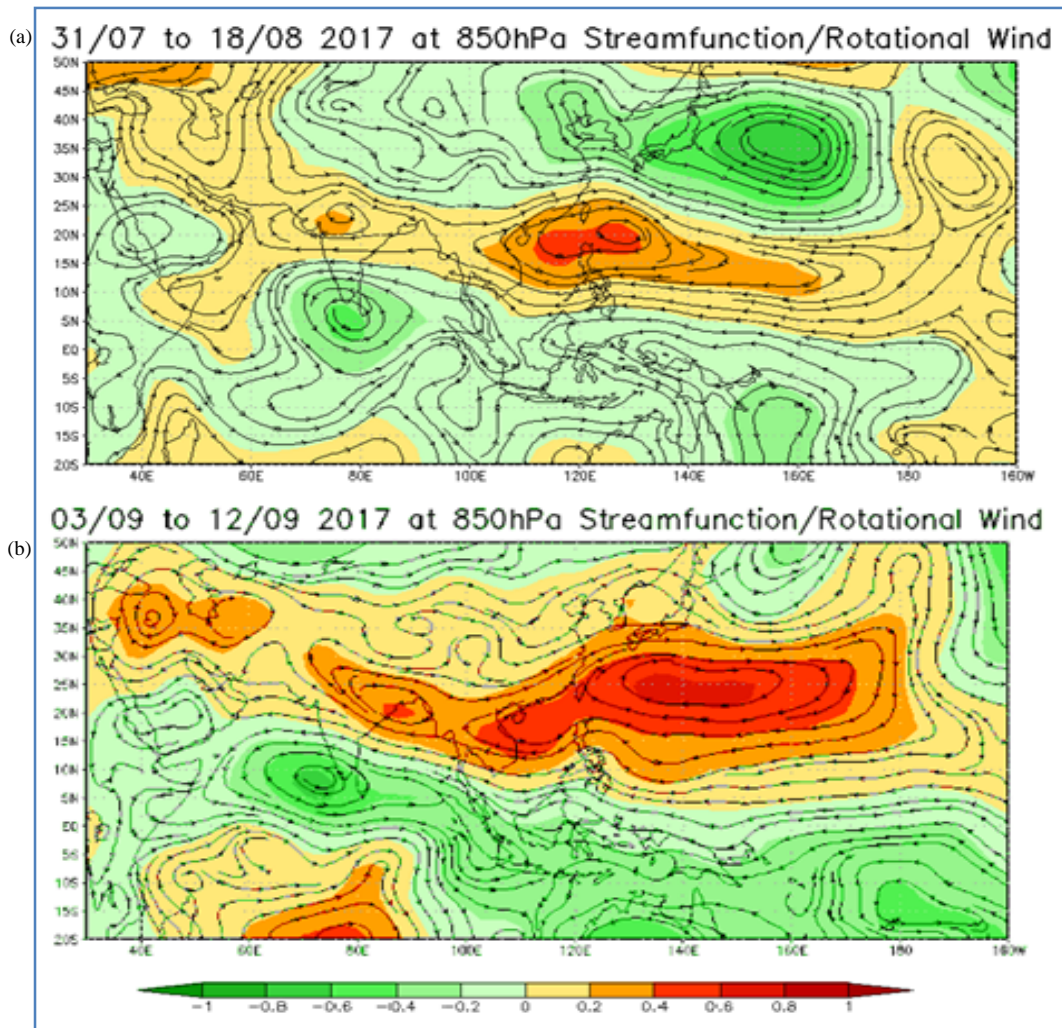
**Figs. 11(a-d).** Longitude Height Circulation Cross-section and Omega during (a) June, (b) July, (c) August and (d) September 2017. Pressure vertical velocity (Omega) is shaded. The anomalies are averaged over longitudes 15° N-25° N



**Fig. 12.** Time series of standardized Rainfall anomaly for core monsoon zone during the monsoon 2017

to 18<sup>th</sup> August, 3<sup>rd</sup> September to 12<sup>th</sup> September, 2017) because of which August and September months received below normal rainfall of the season. In order to understand large scale circulation during the rainfall deficiency period a composite analysis of stream function Figs. 13(a&b) is carried out. It is observed from the figure of composite analysis during the period 31<sup>st</sup> July, 2017 to 18<sup>th</sup> August,

2017, a large scale anomalous cyclonic circulation over the West Pacific associated with above normal Typhoon activity over that region, may be the reason for the subdued rainfall activity over the Indian region during the period. In the month of September (during 3-12 September, 2017) above normal Typhoon activity continued and at the same time, southern hemispheric



**Figs. 13(a&b).** Composite of Stream function along with Rotational Winds at 850 hPa for the periods during (a) 31<sup>st</sup> July to 18<sup>th</sup> August, 2017 and (b) 3<sup>rd</sup> to 12<sup>th</sup> September, 2017

equatorial trough (SHET) was seen significantly active during the period. Due to these unfavorable conditions, the subdued rainfall activity prevailed in the months of August and September 2017.

### 8. Typhoon activity over west Pacific

As stated above, the west Pacific typhoon activity is also one of the important factors responsible for subdued rainfall activity over Indian Region. There are many previous studies which have discussed relationship between Indian summer monsoon rainfall and typhoon activity over west Pacific (Rajeevan *et al.*, 1993; Vinay Kumar and Krishnan, 2005; Pattanaik and Rajeevan, 2007). It may be noted that the typhoon activity over west Pacific Ocean had a slow start initially up to mid-July and increased drastically thereafter. There

were 17 Low pressure system formed over the west Pacific during the season, out of 7 systems became typhoon category. The tracks of the systems formed during first half and second half of season given in the Fig. 14.

It can be seen that most of systems were showing recurving tracks in west Pacific and formed east of 150° E which has negative impact on Indian summer monsoon rainfall. However, typhoon formed over south China Sea and moving westward has a positive impact on summer monsoon rainfall. Only two typhoons' remnants propagated westwards and induced genesis of monsoon lows over the Indian region during August & September, viz., Typhoons 'Hato' and 'Doksuri' which contributed to the re-invigoration of the monsoon trough during 27-30 August and 18-20 September respectively.

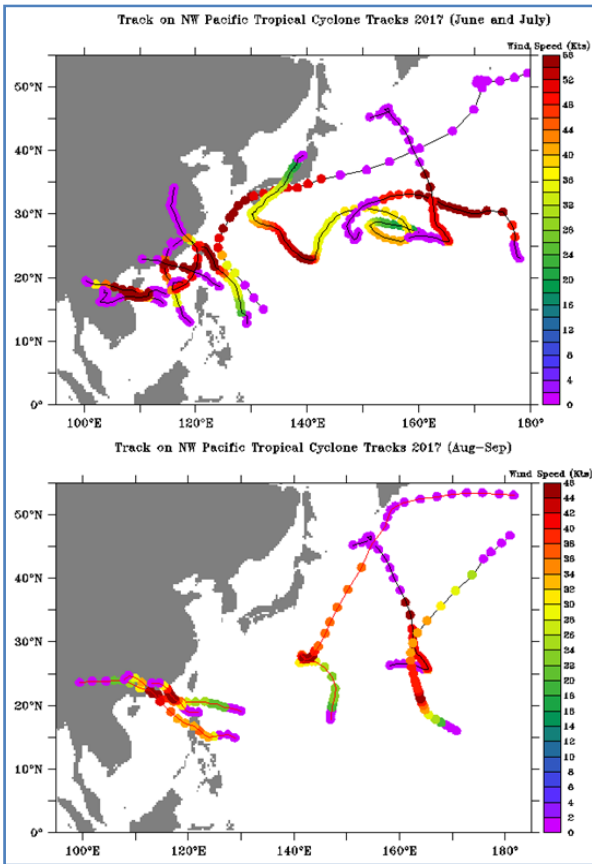


Fig. 14. Figure shows observed tracks of the Typhoons formed over North West Pacific during June to September months for the year 2017. (Data Source : Best track data JMA)

**9. Important global and regional features that influenced the rainfall pattern over Indian region**

Out of the total 36 meteorological sub-divisions (Fig. 15), the season (June-September) rainfall was normal in 25 sub-divisions (65% of the total area of the country) and excess in 5 sub-divisions (18% of the total area of the country). However, the season rainfall was deficient in 6 sub-divisions constituting 17% of the total area of the country. Out of the 6 deficient sub-divisions, 4 sub-divisions were from Northwest India (West and East Uttar Pradesh, Punjab and Haryana, Chandigarh & Delhi) and 2 sub-divisions were from the Central India (East Madhya Pradesh and Vidarbha). Similarly, out of the 5 excess sub-divisions, 2 sub-divisions were from South Peninsula (Rayalaseema and Tamil Nadu & Pondicherry) and one each from Northwest India (west Rajasthan), Central India (Saurashtra & Kutch) and Northeast India [Nagaland, Manipur, Mizoram& Tripura (NMMT)].

In the month of June, 15 sub-divisions received excess rainfall, 14 sub-divisions received normal rainfall and 7 sub-divisions received deficient rainfall. Region wise, Northwest India received excess rainfall (52% of LPA). In July, 7 sub-divisions received excess rainfall, 14 sub-divisions received normal rainfall and 15 sub-divisions received deficient rainfall. In August, 8 sub-divisions were excess, 12 sub-divisions were deficient and 16 sub-divisions were normal. Most noticeable feature of rainfall distribution during the August was that, 6 of the 9 sub-divisions from Northwest India and 5 of the 10 sub-divisions from Central India were deficient resulting in large rainfall deficiencies in both the geographical regions (-33% of LPA in Northwest India and -24% of LPA in Central India). On the other hand, other two geographical regions received above normal rainfalls (15% and 16% of LPA respectively for East & Northeast and South Peninsula). In September, 9 sub-divisions were excess, 14 sub-divisions were deficient and 13 sub-divisions were normal. The region that mainly benefited during September was South Peninsula with 9 out of 10 sub-divisions from the region (except Telangana) receiving excess (6 sub-divisions) or normal rainfall resulting in excess rainfall (26% of LPA) over the region. In addition, 2 sub-divisions from Central India (Konkan & Goa and Madhya Maharashtra) and one sub-division from northeast (NMMT) also received excess rainfall. However, all the other 3 geographical regions experienced noticeable rainfall deficiency (-38% of LPA for Northwest India with deficient sub-divisions, -17% of LPA for East and Northeast India with 3 deficient sub-divisions and -14% of LPA for Central India with 5 deficient sub-divisions). It can be seen from the monthly rainfall distribution that during every months of season, not a single sub-division had received scanty monthly rainfall.

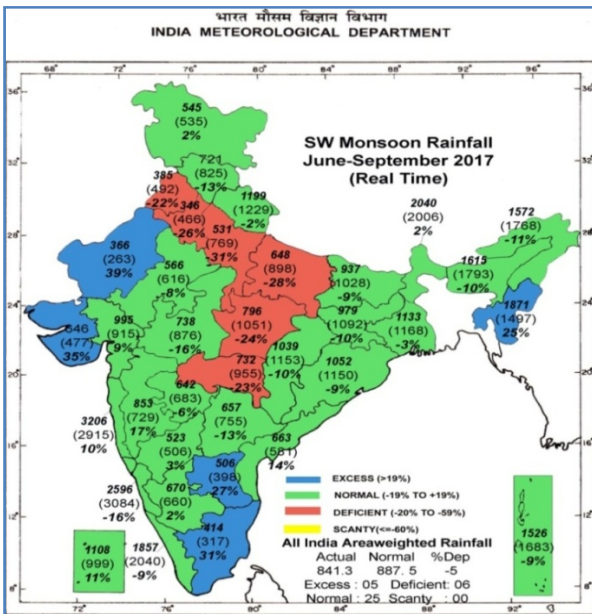
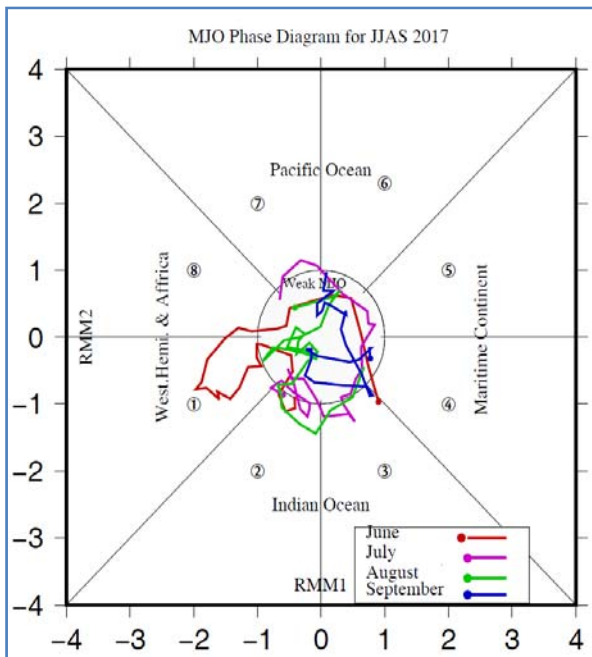


Fig. 15. Sub-divisional rainfall map of 2017 monsoon season



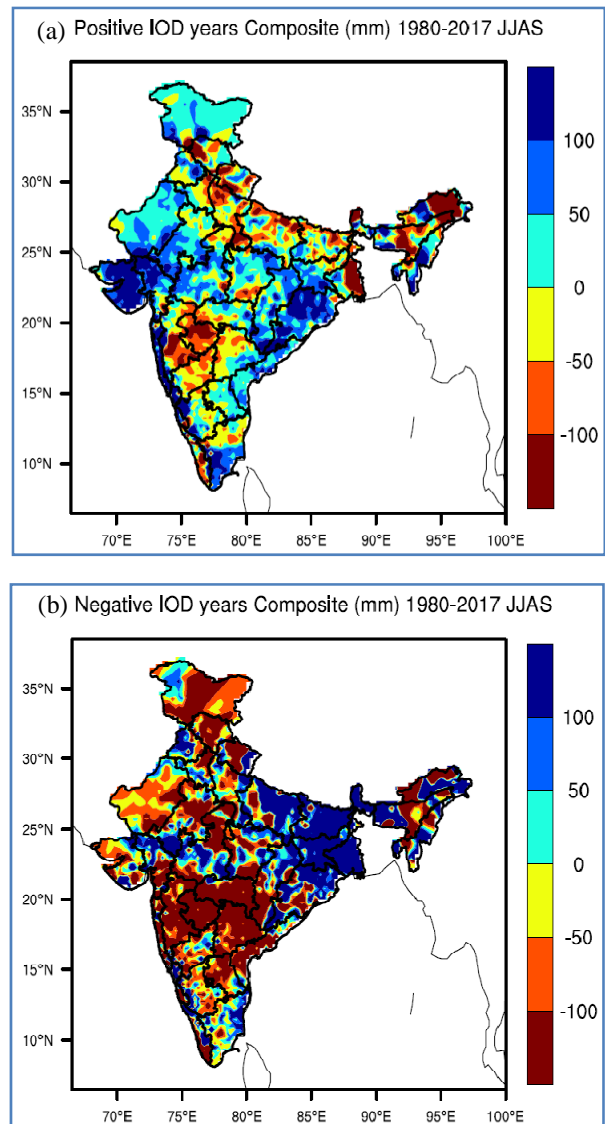
**Fig. 16.** The Phase-space diagram depicting MJO index during monsoon season 2017. The encircle number inside 8 sectors of the diagram represent 8 Phases of MJO in the diagram. Line in different colors for different months, June (red), July (magenta), August (green), September (blue)

There was also not a single sub-division that received deficient during all the four months. On the other hand, NMMT was the only sub-division which received excess rainfall during all the four months.

Based on spatial and temporal rainfall anomaly figures, seasonal rainfall pattern can be summarized as;

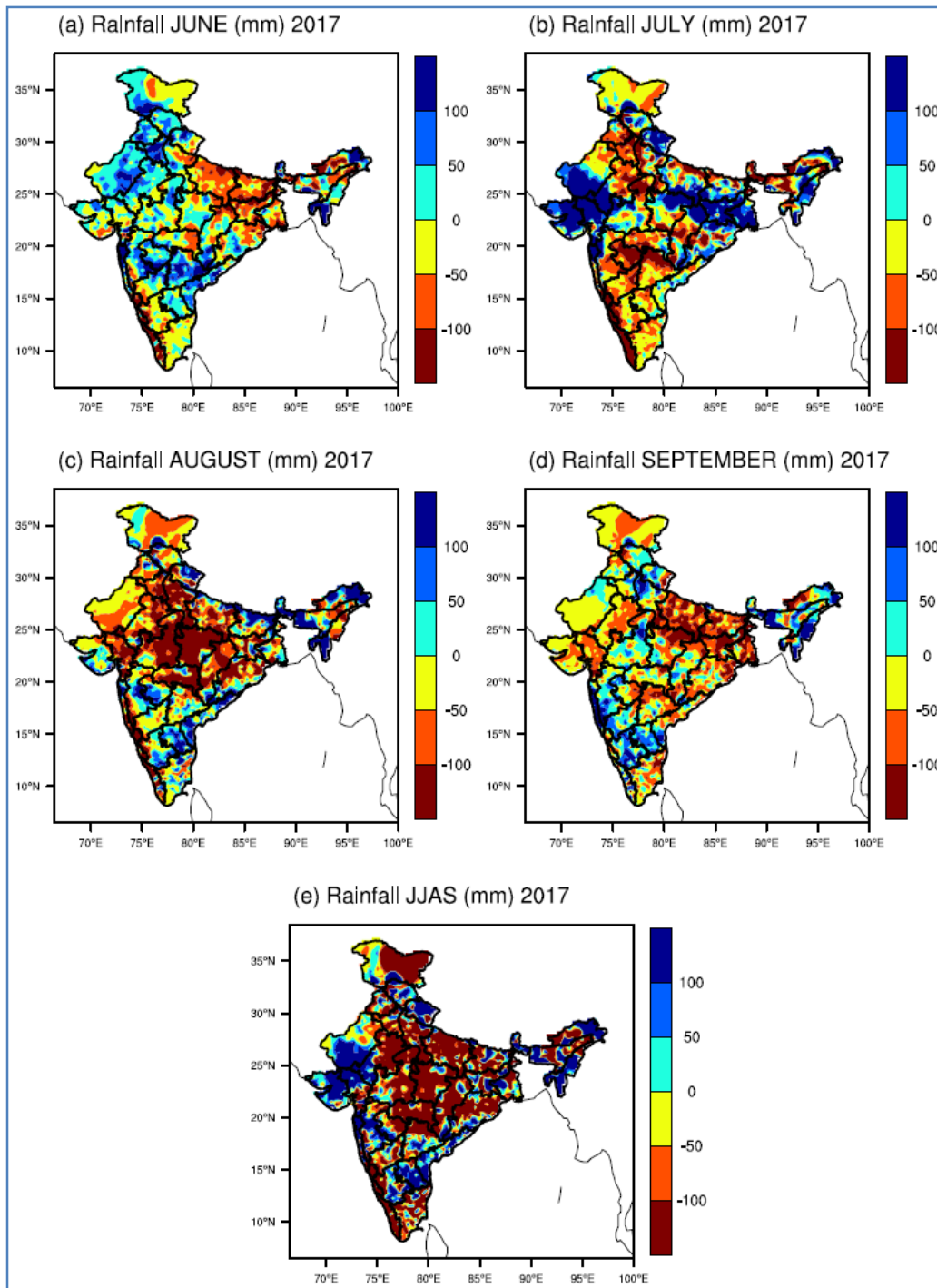
- (i) The season rainfall was normal/excess over most part of the country except 6 sub-divisions.
- (ii) The seasonal rainfall was normal/excess over 83% of the total area of the country.
- (iii) There were intra seasonal fluctuations contributed by synoptic systems observed during the monsoon season.
- (iv) The spatial rainfall distribution was fairly well distributed during the monsoon season.
- (v) The rainfall deficiency was more during the second half of the season than the first.

During the 2017 southwest monsoon season, the ENSO conditions were mainly neutral with warm ENSO neutral conditions observed in the first half and cool ENSO neutral conditions observed in the second half of the



**Figs. 17(a&b).** (a) Positive and (b) Negative IOD years rainfall anomaly composite for period 1980 to 2017 during June to September period

season. However, positive IOD conditions prevailed during most part of the monsoon season except in September when the conditions weakened sharply to neutral IOD conditions. The Madden Julian Oscillation (MJO) (Wheeler & Hendon, 2004), which has significant influence on the monsoon intra-seasonal variability (Pai *et al.*, 2009), was in the weak phase during most part of the monsoon season except in the mid-June (Fig. 16) when it was in the favorable phase for stronger than normal monsoon activity over monsoon trough region. Thus while the influence on the monsoon from ENSO (Pacific Ocean) and MJO was nearly absent, that of positive IOD prevailed during most part of the season, particularly in the first half of the season.



**Figs. 18(a-e).** Spatial pattern of monthly rainfall anomalies during (a) June, (b) July, (c) August, (d) September and Southwest Monsoon season (JJAS) 2017 (*Data Source* : 0.25 by 0.25 Rainfall data, IMD)

To further understand the influence of IOD on the monsoon, rainfall anomaly composite of positive (1982, 1983, 1991, 1994, 1997, 2003, 2007, 2008, 2011, 2012, 2015 and 2017) and negative (1984, 1985, 1992, 1996,

1998 and 2016) IOD years was prepared and shown in Figs. 17(a&b) respectively. From Fig. 17(a), it is seen that during positive IOD years, in general, areas along the monsoon trough region from northwest India to Orissa

and northern parts of the west coast receive above normal rainfall. On the other hand, the region close to Himalayas & northern parts of Peninsula receive below normal rainfall. This above normal rainfall along monsoon trough region and below normal rainfall along the Himalayas to some extent also can be seen in the rainfall pattern over India during first half of the 2017 southwest monsoon season [Figs. 18(a&b)].

The rainfall activity over monsoon trough zone including central India and neighboring northwest India has a robust positive (negative) relationship with the number of low pressure systems (lows and depressions) formed over the Indian monsoon region as well as the above normal typhoon activity over northwest Pacific (Mooley and Shukla, 1989). During the season there were 2 depressions and 1 deep depression formed over the Indian monsoon region. This year, 11 low pressure areas formed in the first half of the season with 3 of them intensifying into depressions. On the other hand, during the second half of the season, only 3 low pressure systems formed in the Indian monsoon region with none of them intensified into depressions. Similarly, the activity of low pressure systems (with intensity of depression and above) over the northwest Pacific was normal during the first half and above normal during the second half of the season. This resulted in above normal convective activity over the northwest Pacific and below normal convective activity across the entire intertropical convergence zone including the monsoon trough zone over the India during the second half of the season. The below normal rainfall over the central and northwest India during the second half of the season [Figs. 18(c&d)] was also attributed to the above normal convective activity over southern hemispheric equatorial trough (SHET), which was below normal during the first half of the season. Thus the rainfall activity over Indian main land during this season [Fig. 18(e)] was significantly linked to the activity of the low pressure systems formed over Indian monsoon region as well as over northwest Pacific Ocean.

## 10. Summary

During the Monsoon season, 2017, ENSO conditions were mainly neutral with warm ENSO neutral conditions observed in the first half and cool ENSO neutral conditions observed in the second half. As a result, influence on the monsoon from the large scale SST forcing from Pacific Ocean was nearly absent during the season. However, Positive IOD conditions over the Indian Ocean during the monsoon season, particularly during first half of the monsoon were prominent. In this year monsoon season has observed more intra-seasonal

variations associated with Northwest Pacific typhoon activity and formation of monsoon low pressure systems. One of the major tropical intra-seasonal variations associated with the MJO, was weak during the entire monsoon season except few days in the month of June, so the influence of MJO was less. The rainfall during the second half of the season was mainly affected by the formation of less number of low-pressure systems over Indian region as well as the above normal Typhoon activity over the Northwest Pacific. The below normal rainfall over the central and northwest India during the second half of the season was also attributed to the above normal convective activity over southern hemispheric equatorial trough (SHET), which was below normal during the first half of the season. Thus, the rainfall deficiency was more during the second half of the season than the first. However, the spatial rainfall distribution was fairly well distributed during the monsoon season.

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