

A new rain-based index for the Indian summer monsoon rainfall

SULOCHANA GADGIL, K. RAJENDRAN* and D. S. PAI**

Centre for Atmospheric and Oceanic Sciences, Indian Institute of Science, Bangalore – 560 012, India

*Multi-Scale Modelling Programme, CSIR Fourth Paradigm Institute, Bangalore – 560 037, India

**India Meteorological Department, Ministry of Earth Sciences, Pune – 411 005, India

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e mail :sulugadgil@gmail.com

सार - भारतीय ग्रीष्मकालीन मॉनसून वर्षा (ISMR) में पाई गई परिवर्तनशीलता, उसका पूर्वानुमान और उसके प्रभाव पर हुए अधिकांश अध्ययनों में पार्थसारथी (1995) व भारत मौसम विज्ञान विभाग की वेबसाइट पर उपलब्ध ग्रीष्म मॉनसून ऋतु के दौरान समूचे भारत की वर्षा के आँकड़ों से प्राप्त भारतीय ग्रीष्मकालीन मॉनसून वर्षा के इंडेक्स का विश्लेषण निहित रहता है। ये दोनों सूचकांक भारत के मौसम वैज्ञानिक उपखंडों में हुई औसत वर्षा के आधार पर हैं। 2006 में राजीवन ने भारतीय क्षेत्र के 1° के विभेदन पर ग्रिडेड वर्षा आँकड़ा समूह व्युत्पन्न किया और बाद में 2014 में पई ने उसी क्षेत्र के लिए वर्षा आँकड़ा समूह (0.25°) के विभेदन पर प्राप्त किया। इस समय मॉडल तैयार करने वाले काफी लोग इन आँकड़ा समूहों का इस्तेमाल कर रहे हैं। हालांकि विभिन्न अध्ययनों, विभिन्न क्षेत्रों का उपयोग भारतीय ग्रीष्म कालीन मॉनसून वर्षा (ISMR) के प्रेक्षण लेने हेतु ग्रिड डेटा के औसत के लिए किया गया। विभिन्न मॉडलों/वर्जनों द्वारा अनुकरण / पूर्वानुमान के कौशल का सही-सही मूल्यांकन और तुलना करने के लिए यह आवश्यक है कि हर मामले में भारतीय ग्रीष्मकालीन मॉनसून वर्षा के प्रेक्षण प्राप्त करने के लिए वर्षा का औसत निकालने के लिए उसी क्षेत्र का उपयोग किया जाए। यहाँ हम मॉनसूनी क्षेत्रों और भारतीय ग्रीष्म कालीन मॉनसून को वर्तमान में समझने को आधार मानते हुए व्युत्पन्न / ISMR 1° और 0.25° में औसत वर्षा के लिए उपयुक्त क्षेत्र समझते हैं। हमने ISMR की अतःवार्षिक परिवर्तनशीलता से (इस अध्ययन में क्षेत्रों औसत वर्षा का पता लगाया गया) व्युत्पन्न ग्रिडेड डेटा सेट अधिकांशतः पहले प्रयोग किए गए सूचकांकों में उपयोग किए गए उपखंडवार वर्षा आँकड़ों के क्षेत्रवार भारत सूचकांक काफी स्थिर हैं।

ABSTRACT. Most of the studies of the observed variability of the Indian summer monsoon rainfall (ISMR), its prediction and of its impact have involved analysis of an index for ISMR derived by Parthasarathy *et al.* (1995) or the all-India rainfall during the summer monsoon, available from the India Meteorological Department (IMD) website. Both these indices are based on the average rainfall over the meteorological subdivisions of India. Rajeevan *et al.* (2006) first derived a gridded rainfall data set for the Indian region which was at a resolution of 1° and subsequently, Pai *et al.* (2014) have derived a finer resolution (0.25°) rainfall data set for the same region. At present, these data sets are widely used by modelers to generate the ‘observed’ ISMR for assessment of the skill of their models. However, in different studies, different regions are used for averaging the grid data to obtain the ‘observed’ ISMR. For proper assessment and comparison of the skill of the simulations/predictions by different models/versions, it is important that the same region be used for averaging the rainfall to obtain the observed ISMR in each case. Here, we suggest what we consider as the appropriate regions for averaging the rainfall in terms of the 1° and 0.25° to derive/represent ISMR, on the basis of the present understanding of the monsoonal regions and the Indian summer monsoon. We show that the interannual variation of the ISMR thus derived (by averaging rainfall over the regions identified in this study) from gridded data sets is largely consistent with the indices derived as the area weighted sub-divisional rainfall data used in the indices used earlier.

Key words – Indian summer monsoon rainfall, Monsoonal region, ITCZ, Monsoon indices from gridded data.

1. Introduction

The monsoon was originally defined on the basis of seasonal variation of surface winds and circulation has always been considered as an important feature of the

monsoon system. Generally, models have better skill in simulating monsoon circulation than monsoon rainfall and several indices for the Indian/Asian monsoon have been proposed based on the circulation (Webster and Yang, 1992; Goswami *et al.*, 1999; Wang and Fan, 1999;

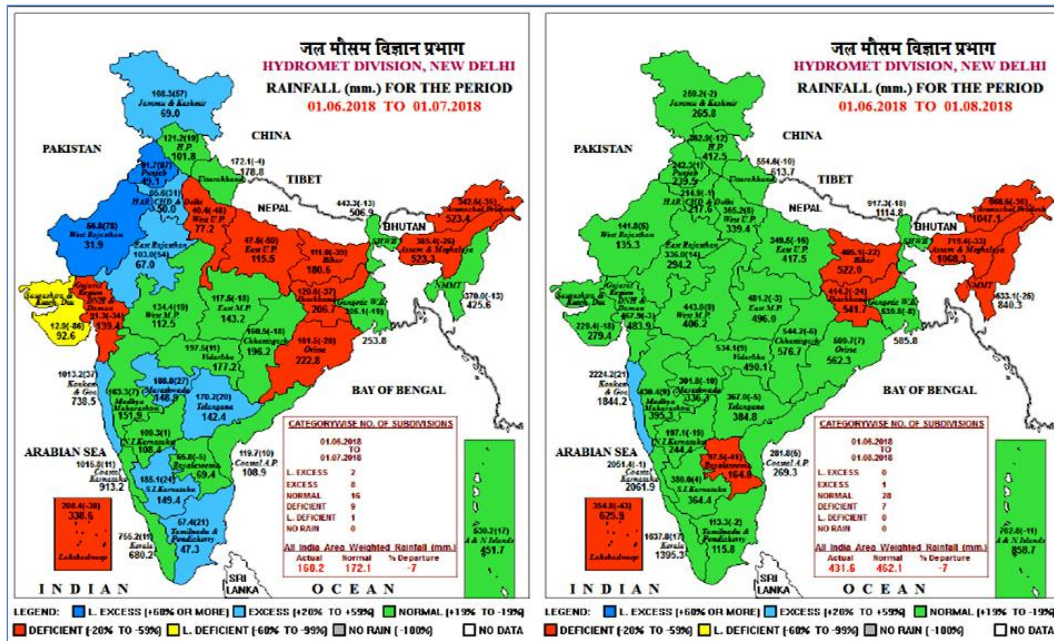
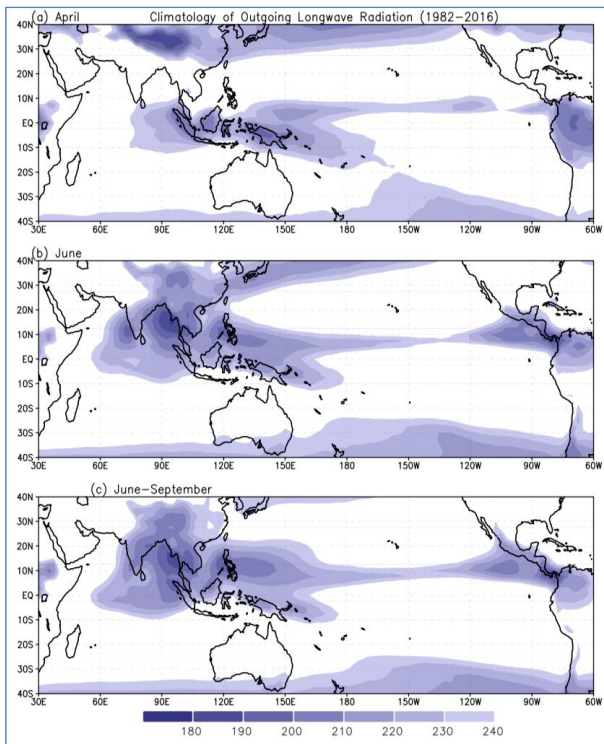


Fig. 1. Actual rainfall and normal rainfall (in mm) and rainfall anomalies (as percentage departure from long term mean) for all the meteorological subdivisions for June 2018 (left) and June-July 2018 (right). The all-India rainfall anomaly for the two periods is also given as -7% and -7% (from IMD-Pune website)

Yim *et al.*, 2013). However, over the Indian region the most important facet of the summer monsoon is considered to be the rainfall since there is a large impact of the year-to-year variation of the summer monsoon (June-September) rainfall over the Indian region on the agriculture and economy of the country (Gadgil and Gadgil, 2006). Most of the studies of the observed variability of the Indian summer monsoon rainfall (ISMR), its prediction and of its impacts have involved analysis of an index for ISMR derived by Parthasarathy *et al.* (1995) or the all-India rainfall during the summer monsoon, available from the India Meteorological Department (IMD). It has been shown that the effect of what is commonly referred to as a drought, but now referred to as a deficient monsoon by IMD (*i.e.*, a monsoon season with the rainfall deficit over the Indian region larger than by 10% or more of the long-term mean) has remained between 2 to 5% of GDP since the 1950s, despite the rapidly decreasing contribution of agriculture to GDP. Not surprisingly, right from the time of the onset of the monsoon over Kerala in late May/early June, the progress of the summer monsoon is followed with keen interest by meteorologists and laymen alike. This has been facilitated by the IMD providing daily information about rainfall across the country. What is monitored closely is the rainfall over the country as a whole, the so-called all-India rainfall during the summer monsoon. In 2018, IMD had predicted that the all-India June-September rainfall would be a little below the average.

The season began well with the rainfall in June being normal (*i.e.*, between 80 and 120% of the long term mean of the subdivision) over a large number of subdivisions and more than 20% above the mean over eight subdivisions (Fig. 1). On the basis of real time data, at the end of the first half of the season, only Lakshadweep, the northeastern part and one subdivision over the peninsula experienced a large deficit (Fig. 1). Yet, the deficit of the all-India rainfall for June and June + July was not small, being 7% in each case. Hence with very large deficit in September, the seasonal deficit had reached around 10% by mid-September and a deficient monsoon seemed inevitable. However, fortunately reasonable rainfall was received in the rest of September and the season ended with a deficit of 9.4%, *i.e.*, not quite a deficient monsoon but close to one!

The IMD series of all-India rainfall is derived from the observed rainfall at more than 2000 stations (Guhathakurta, 2014), with the station network varying with time as stations get added and also from year to year due to the variation in the reporting stations. This series for the all-India rainfall is prepared by deriving district averages from the rainfall at the reporting stations, deriving average rainfall for each meteorological subdivision as the area-weighted averages of the districts in each subdivision and finally taking area-weighted averages of all the subdivisions of the country (Fig. 1). Thus, the IMD all India average rainfall is the average rainfall over the entire political India, including regions,



Figs. 2(a-c). Mean OLR for April (top), June (middle) and June-September (bottom) for the period 1982-2016

such as Jammu Kashmir, Himachal Pradesh etc. as well as the island subdivisions of Lakshadweep and Andaman. As such, it represents the average rainfall over the entire Indian region during the summer monsoon season of June-September. It turns out that while the June-September rainfall over a large part of the Indian region can be attributed to the monsoon system, there are some parts that cannot be considered monsoonal and hence the IMD all India rainfall cannot be considered as an index of the monsoon rainfall over the Indian region.

In this paper we seek an index of the monsoon rainfall over the Indian region based on the gridded rainfall data at 1° (Rajeevan *et al.*, 2010) and 0.25° (Pai *et al.*, 2014). As for the indices commonly used, *viz.*, all-India rainfall from IMD or ISMR derived by Parthasarathy, our index is also for the largest spatial scale of the country as a whole. Dwivedi *et al.* (2019) have defined two new indices on smaller spatial and temporal scales which are based on 0.25° rainfall data. It is expected that these indices will give better insight into intraseasonal variability. The seasonal average all-India rainfall derived by them is an average over the grids over the Indian landmass, obtained by excluding the mountainous regions of the Himalayas, which account for nearly 16% of the total number of grids and is thus average rainfall over a major part of the region considered

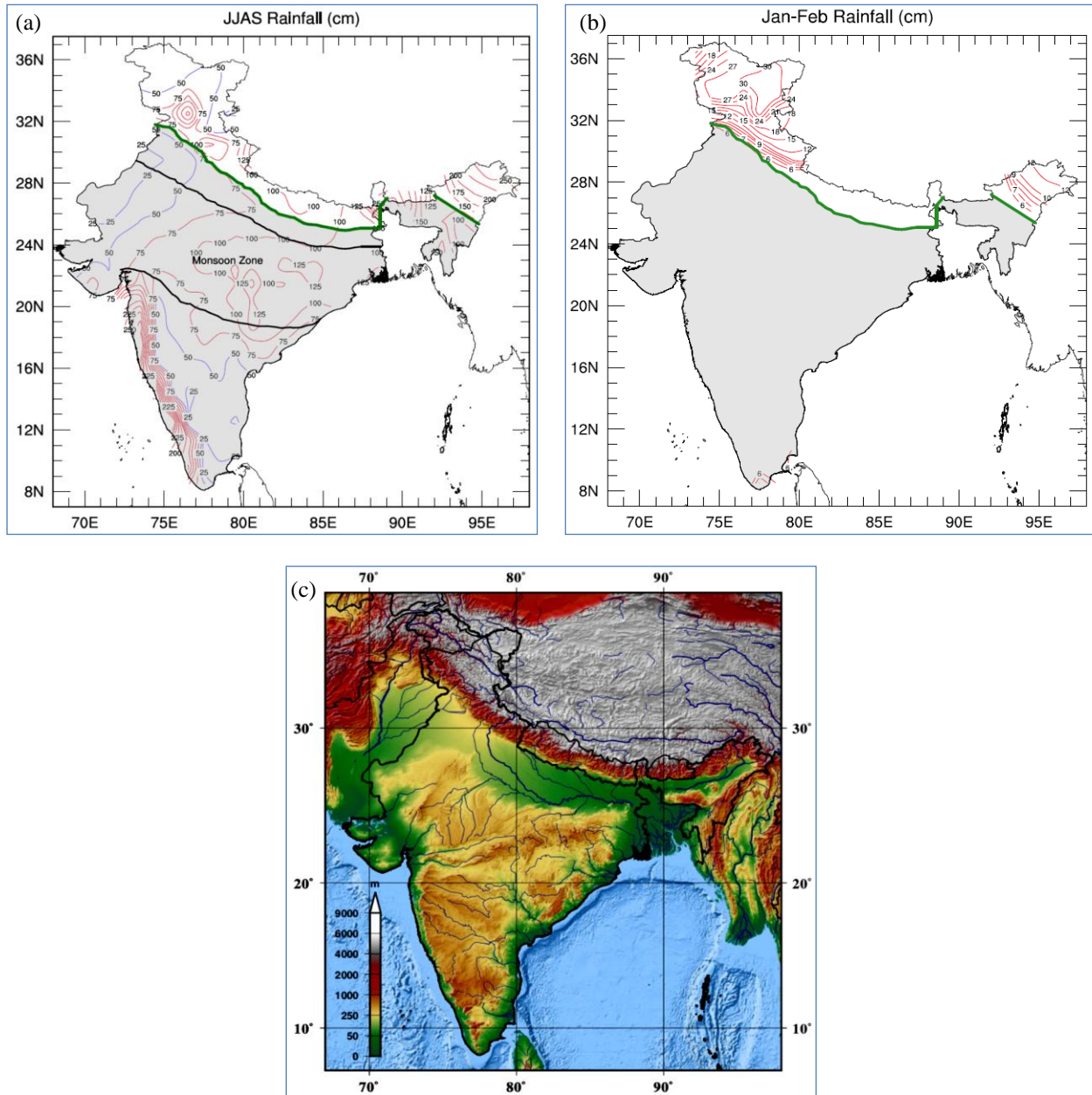
for the all-India rainfall of IMD. It is shown that the indices are in the same phase as the index for seasonal average all-India rainfall for deficit monsoon years and not for excess monsoon years. The implications of this in terms of the relationship between intraseasonal and interannual variability are yet to be understood. However, we restrict our attention to the largest spatial scale for this study.

In section 2 we consider the important features of the monsoonal region, on the basis of our present understanding of the basic system responsible for the monsoon. In section 3 we discuss how the ISMR series of Parthasarathy is derived from subdivisional rainfall and in section 4 discuss the importance of deriving an index for the Indian summer monsoon rainfall from gridded data sets, in the era of high demand from modelers for validation. What we consider as appropriate index for the Indian summer monsoon rainfall is derived in section 5 from the gridded data and compared with the indices used extensively at present, *i.e.*, all-India rainfall from IMD and ISMR from Parthasarathy. In section 6 the implications of the use of the new index for the monsoon season of 2018 are considered and concluding remarks are presented in the last section.

2. Indian summer monsoon rainfall

The monsoon is a tropical system with a marked variation in winds and rainfall with season. Of particular importance is the seasonality of rainfall characterized by heavy summer rainy season versus a dry winter (Wang and Lin Ho, 2002). The Indian summer monsoon is believed to be a manifestation of the migration of the intertropical convergence zone (ITCZ) onto the heated subcontinent in the summer (Sikka and Gadgil, 1980; Gadgil, 2003 & 2018). The mean OLR of April and June [Figs. 2(a-c)] shows a planetary scale ITCZ extending from Indian longitudes eastward across the Pacific. Northward migration of the ITCZ over the Indian longitudes from April to June and to June-September is also clearly seen. A low OLR belt north of about 30° N, associated with extratropical systems across the region is clearly seen in all the three periods in Figs. 2(a-c), with the separation between this belt and the tropical ITCZ being maximum in April and minimum in June-September.

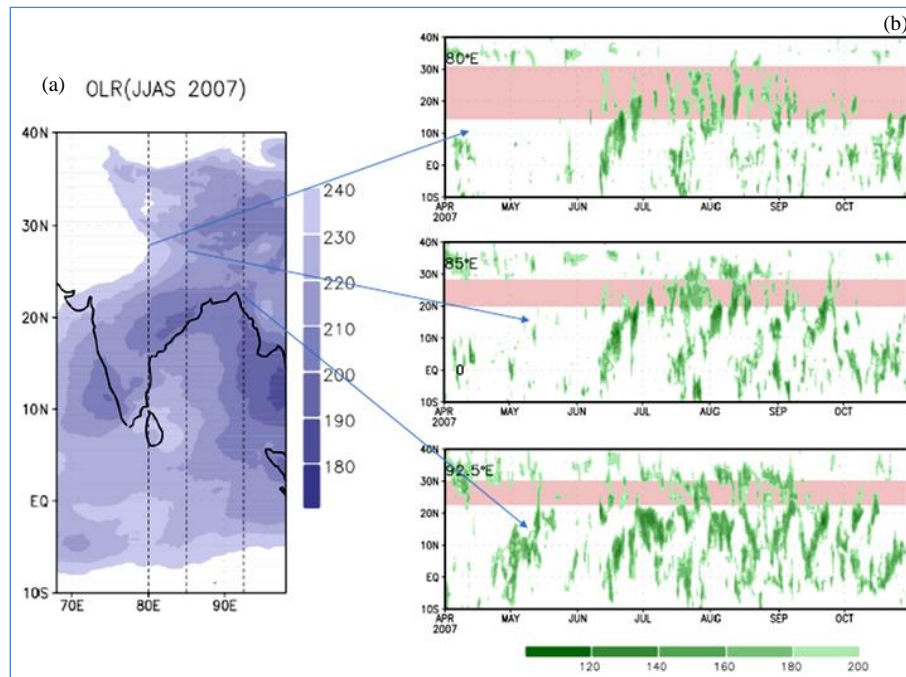
The mean June-September rainfall over the Indian landmass is shown in Fig. 3(a) and the mean January-February rainfall in Fig. 3(b). The basic system responsible for the large-scale rainfall during the summer monsoon is the ITCZ over the continent, *i.e.*, the Continental Tropical Convergence Zone (CTCZ). It is seen that, during June-September, there is a major rainbelt, centered around 23° N in the region called the



Figs. 3(a-c). Mean rainfall for (a) June-September, (b) January-February for 1951-2000 and (c) orography over the Indian region

monsoon zone and another rain belt along the northern boundary of the Indian region extending southward to the foothills region, with lower rainfall between these two rain-belts. In the peak monsoon months of July and August the CTCZ fluctuates primarily in the monsoon zone [Fig. 3(a)]. The onset phase commencing with the onset over Kerala culminates with the northward propagation of the ITCZ (in one or more spells) onto the monsoon zone and westward propagation of cloud systems generated over the Bay within the monsoon zone (Ding and Sikka, 2005). Thus, monsoon rainfall also

occurs over the peninsular region to the south of the monsoon zone. Just prior to the commencement of some breaks, the CTCZ/a monsoon disturbance propagates north of the monsoon zone towards the foothills, before disappearing. Hence the rainfall over the monsoon zone, the peninsular region to the south as well as the region just to the north of the monsoon zone, contribute to the Indian summer monsoon rainfall and this entire region can be considered to be monsoonal. We note that westward propagation of monsoon disturbances from the Bay of Bengal make a substantial contribution to the Indian



Figs. 4(a&b). (a) June-September OLR for 2007 (left) and (b) location of low OLR belt at 80° E (top), 85° E (middle) and 92.5° E (bottom). The latitudinal extent of the Indian land region for each of these longitudes is shaded

summer monsoon rainfall throughout the season. Northward propagations of the ITCZ, similar to those in the onset phase, occur at intervals of 2-6 weeks, throughout the season across all the Indian longitudes (Sikka and Gadgil, 1980) as seen in the summer monsoon season of 2007 in Fig. 4. At 80° E, the tropical region under the sway of the ITCZ is seen to be distinct from the region to the north of 30° N under the influence of the extratropical systems. At 92.5° E, *i.e.*, over the northeast, northward propagations of the ITCZ are seen to culminate over the northeastern subdivisions, particularly in late July and August, clearly showing the contribution of tropical systems to the rainfall over that region. Thus, the monsoonal region can be identified as the shaded region shown in Figs. 3(a&b).

It is seen from the mean rainfall of January and February [Fig. 3(b)] that this monsoonal region hardly gets rainfall in the winter. On the other hand, the region over which the northern belt is located during the summer monsoon, gets substantial rainfall in the winter because it is always under the sway of mid-latitude systems. The topography of the region also plays an important role in the rainfall over this region [Fig. 3(c)]. The mean pentad rainfall at two stations in the northernmost subdivision of Jammu and Kashmir (Fig. 5), demonstrate well the non-monsoonal character of this region.

There is some interaction between western disturbances which are extratropical systems and the summer monsoon. Some intense rainfall events such as over Uttarakhand in June 2013 and Pakistan in July 2010 have been attributed to direct interaction between extratropical and tropical systems (Houze *et al.*, 2011; Joseph *et al.*, 2014; Dube *et al.*, 2014; Kotal *et al.*, 2014; Krishnamurti *et al.*, 2016; Houze *et al.*, 2017; Priya *et al.*, 2017). There have been several studies of the impact of midlatitude systems on the monsoon. Mid-latitude disturbances during their eastward travel amplify, extend their influence to lower latitudes and interact with the CTCZ or even a monsoon low or depression if one happens to be present. During an interaction in the opposite phase, that is when the warm sector of the mid-latitude belt interacts with the cold sector of the tropical belt, the result is usually a weakening of the CTCZ. However, an interaction in the same phase leads to coupling and amplification of the disturbances (Saha and Saha, 1993). It has been shown mid-latitude systems can lead to (i) intensification or development of lower tropospheric low or trough, (ii) enhancement of rainfall in pre-existing systems, (iii) recurvature of depression and lows and (iv) onset of break conditions (Rao, 1976). Identifying the monsoonal region during the Indian summer monsoon season involves separating out the region over which the primary contribution of rainfall comes from extratropical systems, *i.e.*, the western

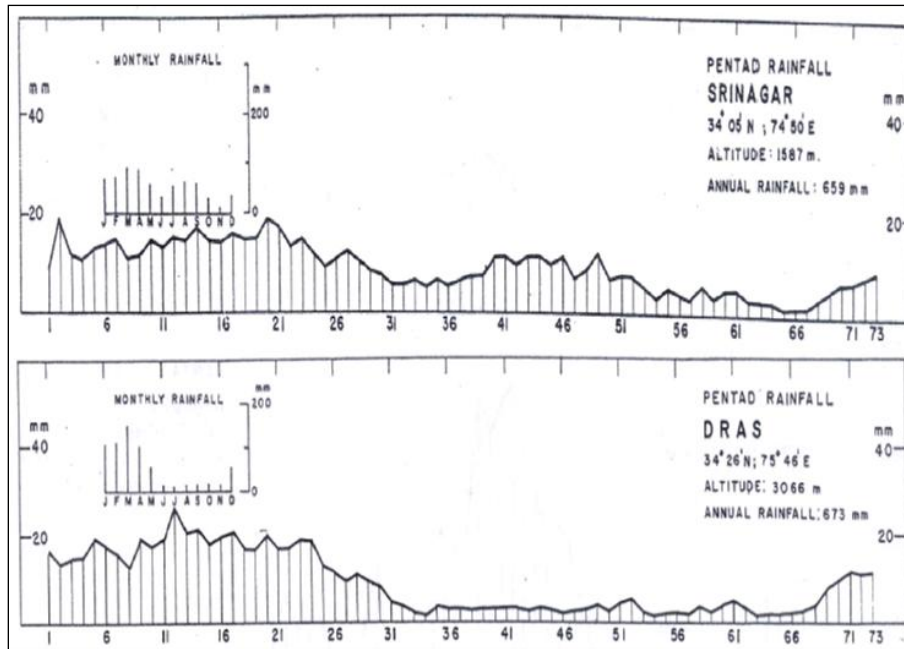


Fig. 5. Mean pentad rainfall (in mm) at Srinagar (top) and Dras (bottom) in Jammu and Kashmir subdivision (after Ananthakrishnan and Pathan, 1971)

disturbances. However, as yet, there is no quantitative assessment of the direct contribution of these extratropical systems to the rainfall over the different regions during the summer monsoon. Hence, the boundary of the monsoonal region has to be drawn subjectively as the northern limit of the region which gets substantial rainfall from tropical systems.

3. Indian summer monsoon rainfall: Time series based on subdivision data

An assessment of the Indian summer monsoon rainfall in any year has been made by Parthasarathy *et al.* (1995) as a weighted average of the rainfall over selected meteorological subdivisions of the country [Fig. 6(a)]. It is seen that the northern subdivisions which get substantial rain in winter have been omitted while deriving this index of the Indian summer monsoon rainfall. Furthermore, the subdivisions of Lakshadweep and Bay islands [which are considered to have a non typical monsoon rainfall pattern, Wang and Lin Ho (2002)] have also been omitted, for lack of contiguity with the mainland subdivisions. Thus, the region over which the average rainfall is calculated for deriving the Parthasarathy assessment comprises only the region recognized as monsoonal on the basis of the traditional definitions and our understanding of the monsoon system [shaded region in Figs. 3(a&b)] and we denote this estimate/assessment of the Indian summer monsoon rainfall as ISMR-Partha.

The ISMR-Partha estimate is based on the rainfall at 306 well distributed stations, one from each of the districts in the plains region of India spread across the retained subdivisions of the country. The sub-divisional average is taken as the area-weighted average of the rainfall of the districts within the subdivision and the all India average as the weighted average of the subdivisions. Thus, the methodology for deriving all-India rainfall by IMD and ISMR-Partha is the same. The differences are (i) the latter is based on much smaller but fixed number of stations and (ii) the latter considers only 90% of the area of India because of omitting of the northern hilly subdivisions and island subdivisions. Parthasarathy *et al.* (1995) have pointed out that the 306 stations on which their estimate is based, can be considered to be representative of the rainfall over the Indian region since the spatial maps of the mean rainfall derived from this network are very similar to those derived from a much larger network by IMD. We define an index of the ISMR-Partha series of any year as the ISMR-Partha anomaly, normalized by the standard deviation and IMD all-India index is similarly defined as the rainfall anomaly normalized by the standard deviation. In fact, the ISMR-Partha index is highly correlated with the IMD all-India index [Fig. 6(b)], suggesting that a large part of interannual variation is contributed by that over the monsoonal region. It is seen that of the 11 seasons with extreme deficits (*i.e.*, deficit larger than one standard deviation) of the IMD all-India index, 10 are also extreme deficits of ISMR-Partha index; of the 8 seasons with extreme positive anomalies of the

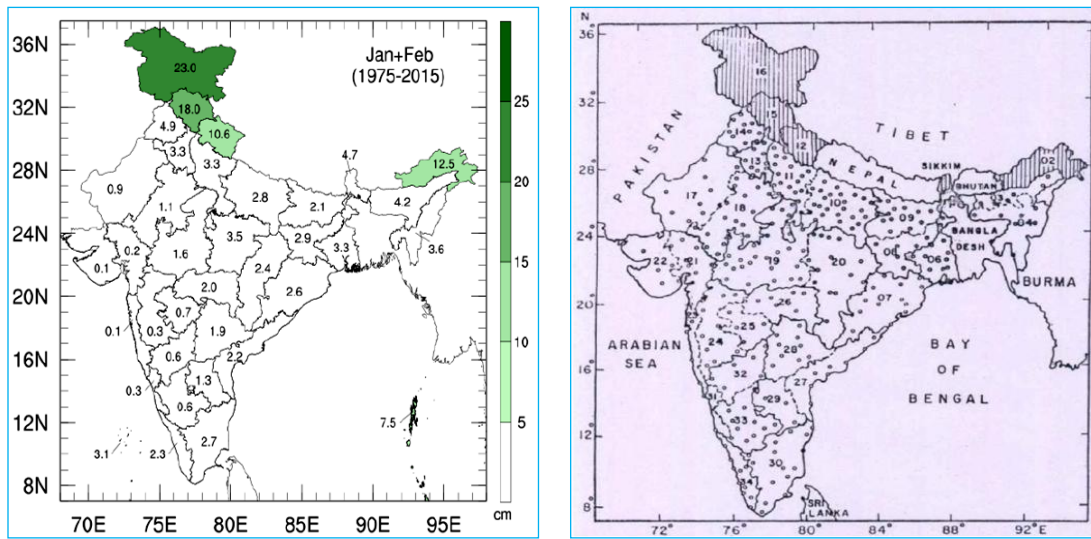


Fig. 6(a). (i) Mean January-February rainfall (in cm) for the period 1951-2000, over each meteorological subdivision (left) and (ii) the meteorological subdivisions of the country selected for deriving the ISMR index by Parthasarathy *et al.* (1995) with the location of the rain gauge stations (right), after Parthasarathy *et al.*, 1995

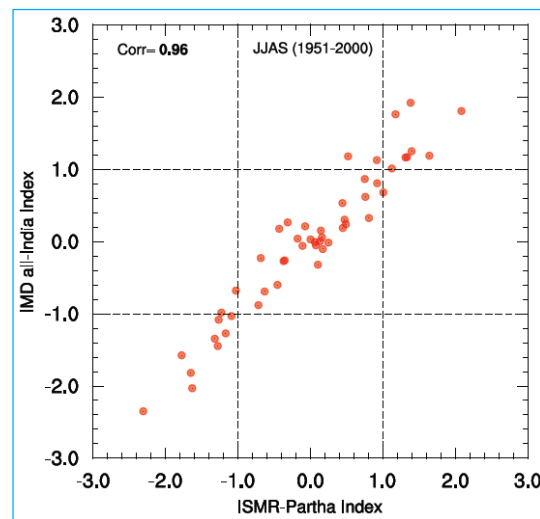


Fig. 6(b). Variation of the ISMR-Partha index with IMD All India Rainfall index for 1961-2000

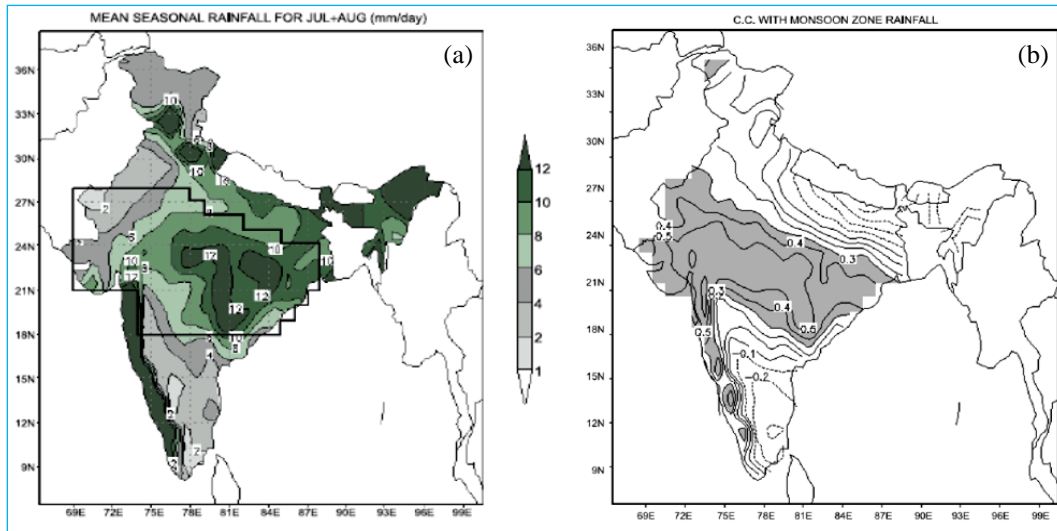
IMD all-India index, 7 are also positive extremes of ISMR-Partha index. Thus, the criteria for the extremes for ISMR-Partha are slightly more stringent than those for the extremes of IMD all-India rainfall.

It should be noted that a lot of our present understanding of the nature of monsoon variability and its impact has come from studies based on analysis of the time-series of the index ISMR-Partha, which has been extended for later years by IITM. For example, studies of the links of the interannual variation with ENSO (Sikka, 1980 and many subsequent studies) and EQUINOO (Gadgil *et al.*, 2004) as well as the quantitative assessment of the impact of the monsoon rainfall over food-grain

production and GDP (Gadgil and Gadgil, 2006) are based on the ISMR-Partha index.

4. Indian summer monsoon rainfall from gridded data sets

Rapid developments of models in the eighties and nineties, led to a demand for gridded data for rainfall over the Indian region to facilitate validation of simulations and predictions. The first gridded daily rainfall data set for the Indian region was developed by Rajeevan *et al.* (2006) based on a fixed station network comprising 1803 stations. To improve the data quality over northern part of India, Rajeevan *et al.* (2010) reconstructed the data set of



Figs. 7(a&b). (a) Monsoon zone considered to identify the active and break events and (b) Correlation coefficient of 5-day average rainfall over the monsoon zone with rainfall at all grid points. Rainfall during only July and August months have been considered (after Rajeevan *et al.*, 2010)

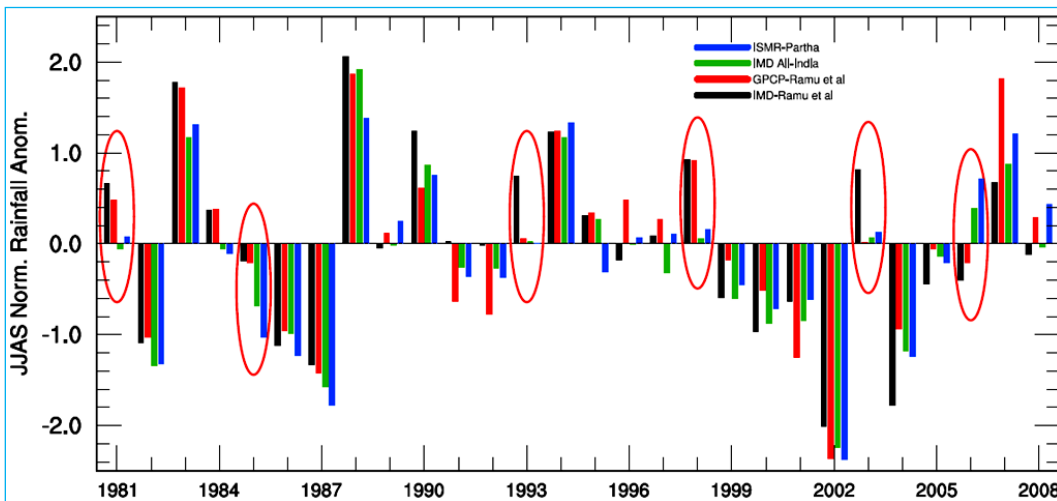


Fig. 8. ISMR-Partha index and the IMD all India rainfall index along with the all-India summer monsoon rainfall anomalies derived from GPCP and IMD data by Ramu *et al.* (2016) for the period 1981-2008

Rajeevan *et al.* (2006) using a fixed network of 2140 having minimum 90% data availability and the data period was extended up to present by IMD. Pai *et al.* (2014) have now developed a 0.25° data set using a varying station network of 6955 stations which is regularly used for deriving spatial patterns of monthly anomalies displayed on the IMD website.

Gridded data has enormous advantages because, rather than analyzing the average rainfall over fixed regions such as subdivisions, the region over which the rainfall is averaged can be chosen to be appropriate for the problem addressed. For example, to study the active-break cycles, Rajeevan *et al.* (2010) chose the average over the

monsoon zone, over which the intraseasonal variation is coherent and in opposite phase to the region to the north and south [Figs. 7(a&b)]. The gridded data are most often used for comparison with model simulations of the interannual variation of the ISMR. In the simulations of the rainfall over the Indian region, most of the models overestimate the rainfall over the northern part in which orography plays an important role (which is considered to be non-monsoonal), but underestimate the rainfall over the monsoon zone (Rajeevan *et al.*, 2010; Nanjundiah *et al.*, 2013; Sperber *et al.*, 2013). Hence if the area used for averaging the rainfall for deriving ISMR includes the northern region, the negative bias in the simulated ISMR is underestimated.

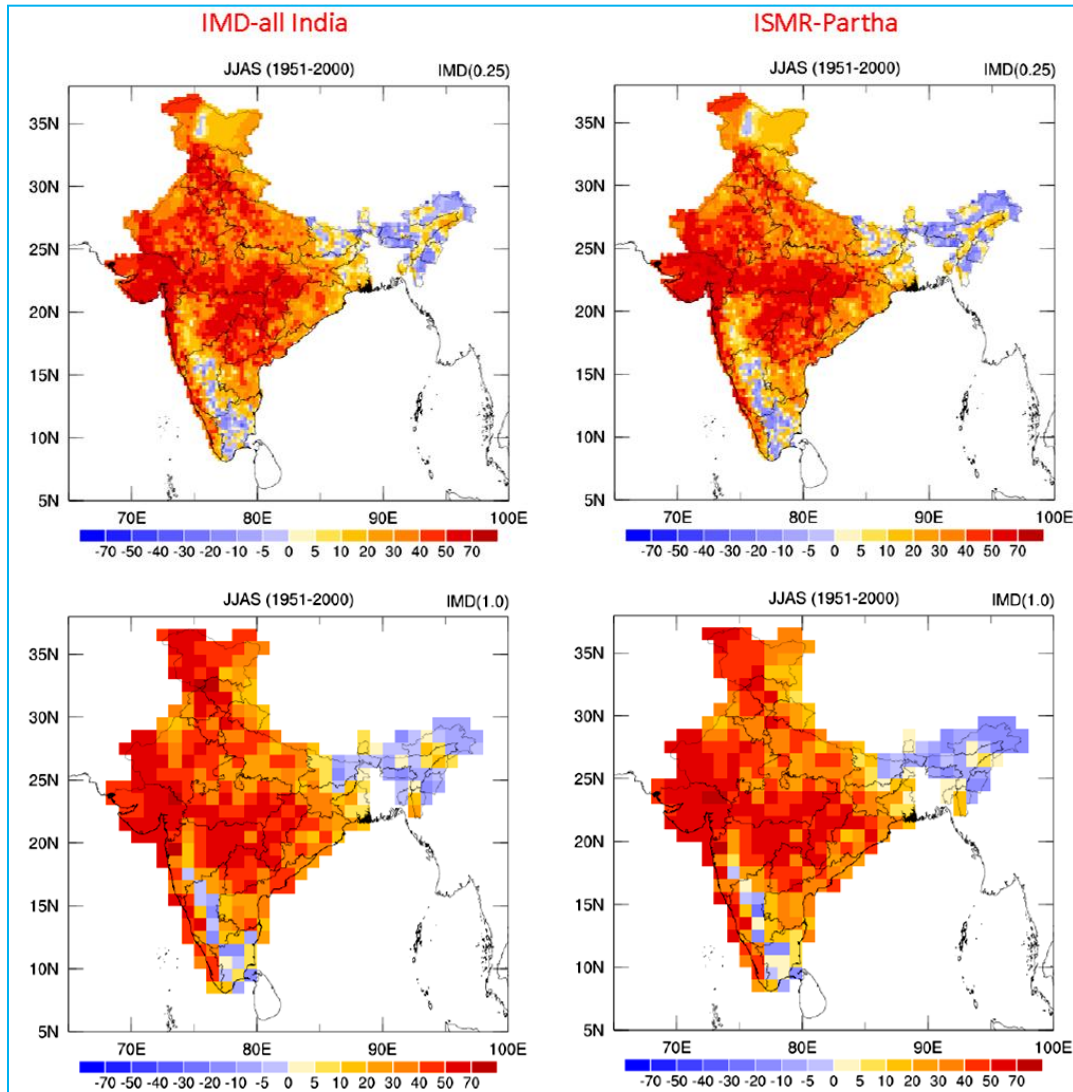


Fig. 9. Correlation coefficient of IMD All India index (left panels) and ISMR-Partha index (right panels) with IMD gridded rainfall data in 0.25° (top panels) and 1° (bottom panels) resolutions for June-September

At present, the region chosen for averaging June-September rainfall to derive the ISMR varies from one study to another and the ISMR and its variation thus derived can be rather different from the ISMR-Partha, on which almost all the studies of observed variation are based. For example, in the study of the impact of resolution of CFS on simulation of Indian monsoon rainfall by Ramu *et al.* (2016) the ISMR values they have derived from Rajeevan *et al.* (2006) data and GPCP rainfall data, are markedly different from ISMR-Partha or IMD all-India rainfall in several years such as 1981, 85, 93, 98, 2003, 06 (Fig. 8). It is clear that the region over which average rainfall is to be computed for deriving observed and simulated ISMR has to be fixed for a fair comparison of the skill of the different models in simulating the interannual variation of ISMR. The region

that can be considered as appropriate for deriving ISMR from gridded data sets of 1° and 0.25° has to be monsoonal and also one over which the interannual variation of the seasonal rainfall is coherent so that the regional average is a meaningful representation of the monsoon rainfall over parts of the region.

5. Appropriate index for Indian summer monsoon rainfall

The contribution of the rainfall during June-September over different parts of India to the IMD all-India index and the ISMR-Partha index can be gleaned from the correlation of these indices with series of the June-September rainfall over different parts of the Indian region depicted in Fig. 9. As expected, the correlation is

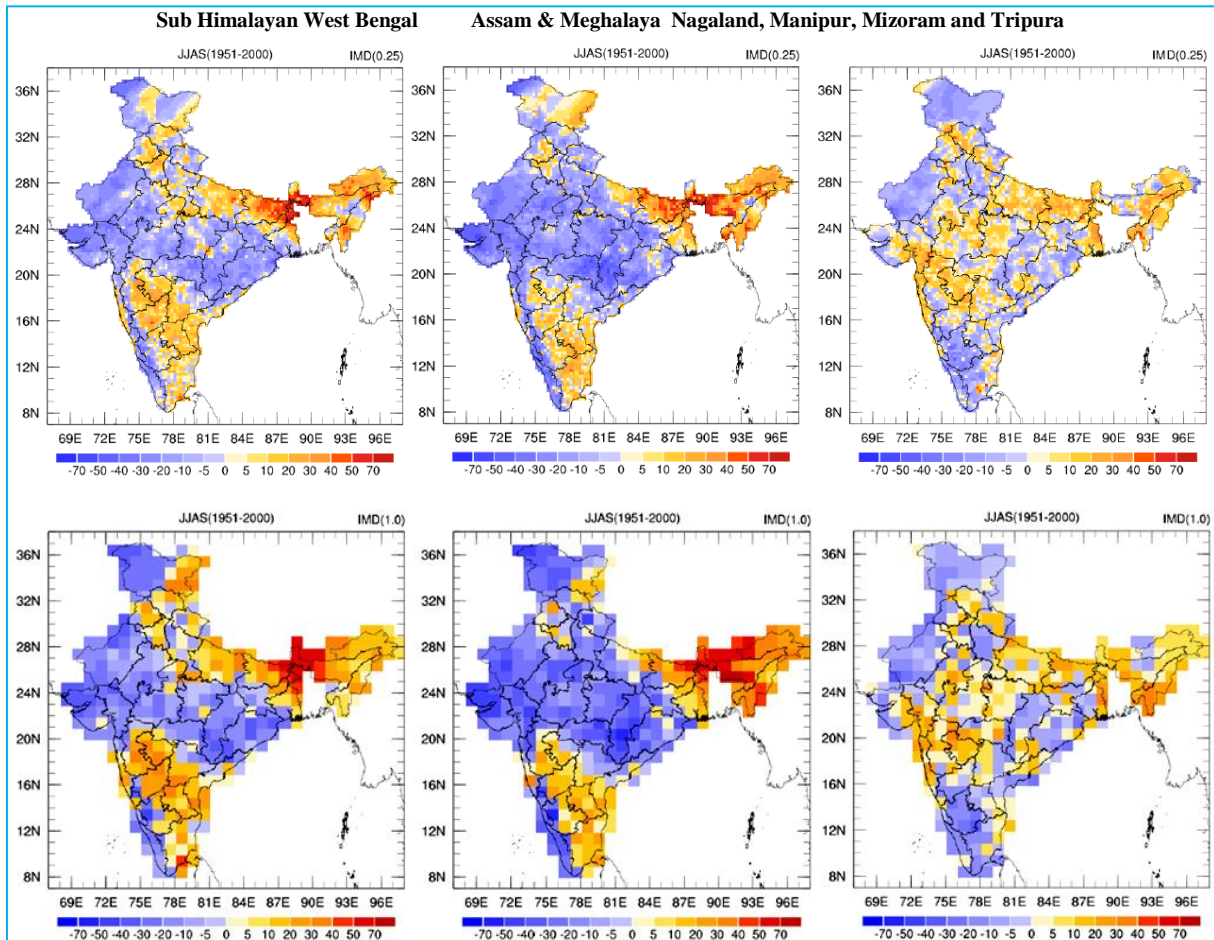
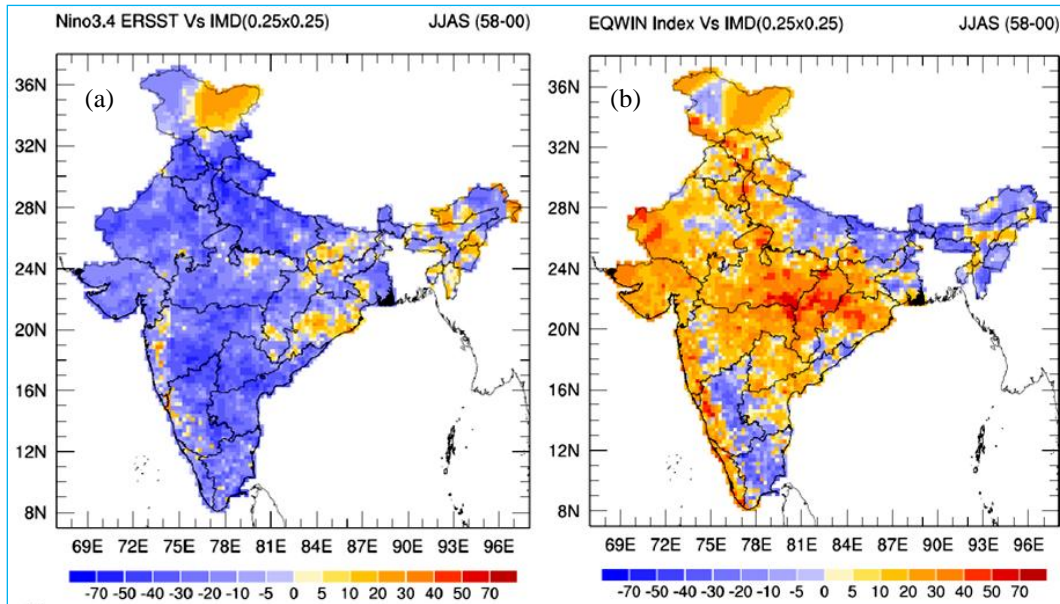


Fig. 10. Correlation coefficients of June-September rainfall of the subdivisions of sub-Himalayan West Bengal, Assam and Meghalaya and Nagaland, Manipur, Mizoram and Tripura with IMD gridded rainfall data in 0.25° (top panels) and 1° (bottom panels) resolutions

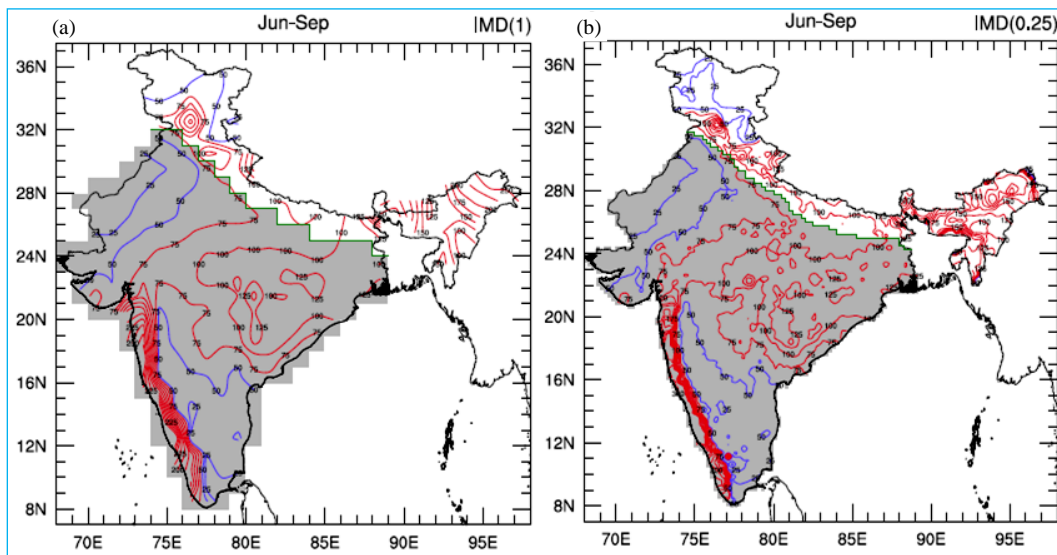
high over the monsoon zone and the west coast (which is known to be highly correlated with the rainfall over the monsoon zone as seen in Fig. 7). It is seen that the variation of the rainfall over parts of the northeast is in opposite phase with the rainfall over almost the entire monsoonal region. The correlation of the rainfall of the major subdivisions of the northeast (with the exception of Arunachal Pradesh which was omitted by Parthasarathy) with the rainfall over the entire Indian mainland is shown in Fig. 10. The correlation is seen to be highly negative over large parts of the monsoon zone.

Analysis of the interannual variation of the spatial pattern of June-September rainfall shows that the first EOF is of the same sign over most of the Indian region and opposite sign over the northeast (Shukla, 1987; Krishnamurthy and Shukla, 2000). Thus, the phase of variation of the seasonal rainfall over the northeast tends to be opposite to that over most of the Indian region. If the rainfall over the northeast as well as the rest of the Indian

mainland region is averaged to derive the ISMR, the average will not be a meaningful representation of all the sub-regions. Hence the appropriate region for deriving the average seasonal rainfall is the large coherent part of the monsoonal region, *i.e.*, the monsoonal region without the northeast. We suggest that ISMR should be derived as the average summer monsoon rainfall over the Indian monsoonal region after omitting the northeast. The link of the seasonal rainfall with ENSO plays an important part in the predictions of by statistical as well as dynamical models. It should also be noted that the correlation of the rainfall over the northeast with ENSO as well as EQUINO, the two modes which have strong links with the interannual variation of the summer monsoon rainfall over the Indian region (Gadgil *et al.*, 2007) is also poor and in places of opposite sign to that over the monsoon zone [Fig. 11(a&b)]. Thus, not including the northeast in the region over which rainfall is averaged to derive ISMR, should lead to better predictions.



Figs. 11(a&b). Correlation coefficient for June-September IMD 0.25° grid data with (a) Nino3.4 SST and (b) with EQUINOO Index, EQWIN



Figs. 12(a&b). June-September rainfall with the region (a) MR (1° grid) and (b) MRHR (0.25°) shaded

The mean June-September rainfall from the two gridded data sets is shown in Figs. 12(a&b). The boundaries of the Indian monsoonal region over which most of the June-September rainfall can be attributed to the large scale and synoptic scale tropical systems, *i.e.*, CTCZ, monsoon disturbances and mesoscale systems (Fig. 3), from which the northeast region is omitted, is shown as shaded in Figs. 12(a&b). We suggest that this region (shown as grid fill maps of 0.25° and 1° grids, which we refer to henceforth as monsoonal region (MR)

and monsoonal region with high resolution grid (MRHR) respectively) be used for deriving the Indian summer monsoon rainfall. It is interesting that Rajeevan *et al.* (2006) derived the Indian June-September rainfall from their grid data, after omitting the north eastern region, for comparison with a global gridded rainfall data set from a joint climate research project named Variability Analysis of Surface Climate Observations (VASClimo), carried out by German Weather Service and Johann Wolfgang Goethe-University, Frankfurt.

TABLE 1

The mean and standard deviation of the IMD all-India rainfall, ISMR -Partha series and the ISMR derived from the Monsoonal Regions (MR) defined for 1° grids and MRHR for 0.25° grids

	June (1951-2000)		June-July (1951-2000)		June-August (1951-2000)		JJAS (1951-2000)	
	Mean (mm)	Std Dev (mm)	Mean (mm)	Std Dev (mm)	Mean (mm)	Std Dev (mm)	Mean (mm)	Std Dev (mm)
IMD-All-India	166.2	27.6	457.3	50.8	720.6	68.1	892.2	90.5
ISMR-Partha	157.5	29.6	428.1	47.4	676.8	62.9	845.8	83.7
MR (1.0°)	153.5	34.0	431.1	58.9	678.4	75.5	837.1	101.3
MRHR (0.25°)	139.3	32.5	405.8	57.3	650.5	74.9	807.6	99.0

TABLE 2

The indices for IMD (real time) all-India rainfall and MR and MRHR rainfall for 2018

	June		June-July		June-August		JJAS	
	Anom. (mm)	Norm. Anom.	Anom. (mm)	Norm. Anom.	Anom. (mm)	Norm. Anom.	Anom. (mm)	Norm. Anom.
IMD - All - India	-8.3	-0.30	-25.1	-0.49	-45.0	-0.66	-83.5	-0.92
MR (1.0°)	+12.0	+0.35	+14.5	+0.25	-10.1	-0.13	-57.7	-0.57
MRHR (0.25°)	+0.4	+0.01	+1.1	+0.02	-20.4	-0.27	-67.0	-0.68

The mean and standard deviation of the IMD all-India rainfall, ISMR-Partha series and the ISMR derived from MR and MRHR are given in Table 1 for June, June-July, June-August and June-September. Note that the mean values of the rainfall for all these periods are highest for the 1-degree gridded data, probably because parts of the Arabian Sea get included in the grids along with that over the west coast. Since the coefficient of variation varies across these four indices, it would be more appropriate to use the anomaly normalized by the standard deviation rather than as a percentage of the mean for identifying extremes and other categories of ISMR.

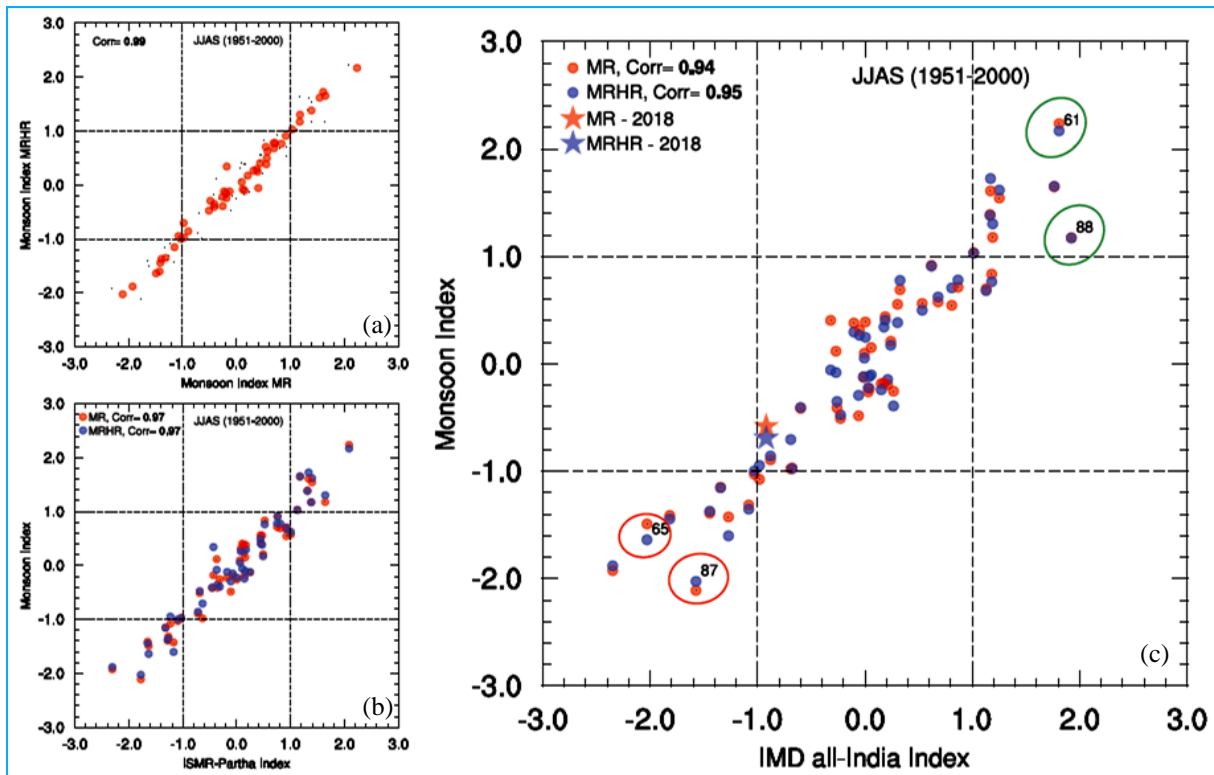
It should be noted that the two monsoon indices, *i.e.*, June-September rainfall anomalies over MR and MRHR, normalized with standard deviation, are highly correlated with each other [Fig. 13(a)]. The relationships of these indices anomalies with ISMR-Partha and IMD all India rainfall indices [Figs. 13(b&c)] show that the ISMR from gridded data are largely consistent in identification of large deficits/excess. We should note that some difference between the value of the index derived from grid data *vis a vis* that derived from subdivision data can arise even if the station network used is identical. This is

because while the index derived from grid data is a simple average of the grid rainfall over the selected area, the IMD index based on subdivisions is derived by first deriving the district average from stations, then taking weighted average of districts in each subdivision to get subdivisional rainfall and finally the index as a weighted average of the subdivisions. In addition, differences arise because the all-India data of IMD includes rainfall over the islands in the Arabian Sea and Bay of Bengal whereas the gridded data sets are only for the mainland. The relative contribution of each of these factors needs to be investigated.

Note that the scatter in the MR and MRHR indices is higher for the extremes for IMD-all-India index (magnitude of anomaly exceeding one standard deviation), than that for extremes of ISMR-Partha.

6. Implications for Monsoon rainfall of 2018

The indices for 2018 June, June-July, June-August and June-September rainfall are given in Table 2. Note that the normalized anomalies are smaller in magnitude for the rainfall derived from gridded data than those from the all-India IMD data for all the periods. In fact, there is a



Figs. 13(a-c). (a) The relationship between the two monsoon indices for June-September, (b) Relationship between the two monsoon indices and ISMR-Partha index for June-September and (c) Relationship between the two monsoon indices and the IMD All India Rainfall index for June-September

difference in the sign of the anomalies for June and June-July, between the all-India IMD index and the monsoonal region indices based on grid (1° as well as 0.25°) data defined here. Consistent with our impression from Fig. 1, that the rainfall was not deficit over most of the country, anomalies are positive in both cases being somewhat higher for MR than for MRHR. Thus, the large deficits in the rainfall over the northeast and the Lakshadweep islands appear to have made a major contribution to the IMD all-India rainfall for June and June + July being 7% of the mean, which led to considerable anxiety about the monsoon of 2018. It is important to analyze the contribution of these regions to the first half of the summer monsoon season of 2018. For June-August and June-September the anomalies are negative for all the three indices. But note that the magnitude of the monsoon indices MR and MRHR is smaller than for the all-India index.

Substantial differences between the IMD all-India index and the values of the monsoon indices can arise from the differences in the spatial patterns of the anomalies. Comparison of the anomaly patterns of two excess monsoon seasons of 1961, 1988 (Fig. 14) with comparable values of the IMD all-India index shows that

the monsoon indices largely reflect the anomalies over the monsoon zone, whereas the rainfall anomalies over the northeast and Arabian Sea and Bay islands play an important role in determining the IMD index. The important role of the anomalies over the northeast in the IMD all-India index is also brought out by a comparison of the two deficient monsoon seasons of 1965 and 1987 (Fig. 14). The points for 2018 are marked as stars in Fig. 13(c). In 2018 also, large negative anomalies over the northeast and Arabian Sea and the Bay islands appear to have contributed to the larger negative value of the IMD all-India index than the monsoonal indices.

We have noted that for the summer monsoon of 2018, whereas the seasonal deficit for IMD all-India rainfall is close to one standard deviation, *i.e.*, close to that of a deficient monsoon season/drought, the monsoon indices suggest substantial deficit (-0.57 for MR and -0.68 for MRHR), but cannot be considered close to an extreme. Hence, we suggest that, in addition to the IMD all-India rainfall, information on the progress of ISMR, derived as the average over MRHR, be made available on IMD website. Then people would know that the Indian summer monsoon rainfall was not deficit in the first half of the season and while large deficit in the second half led to a

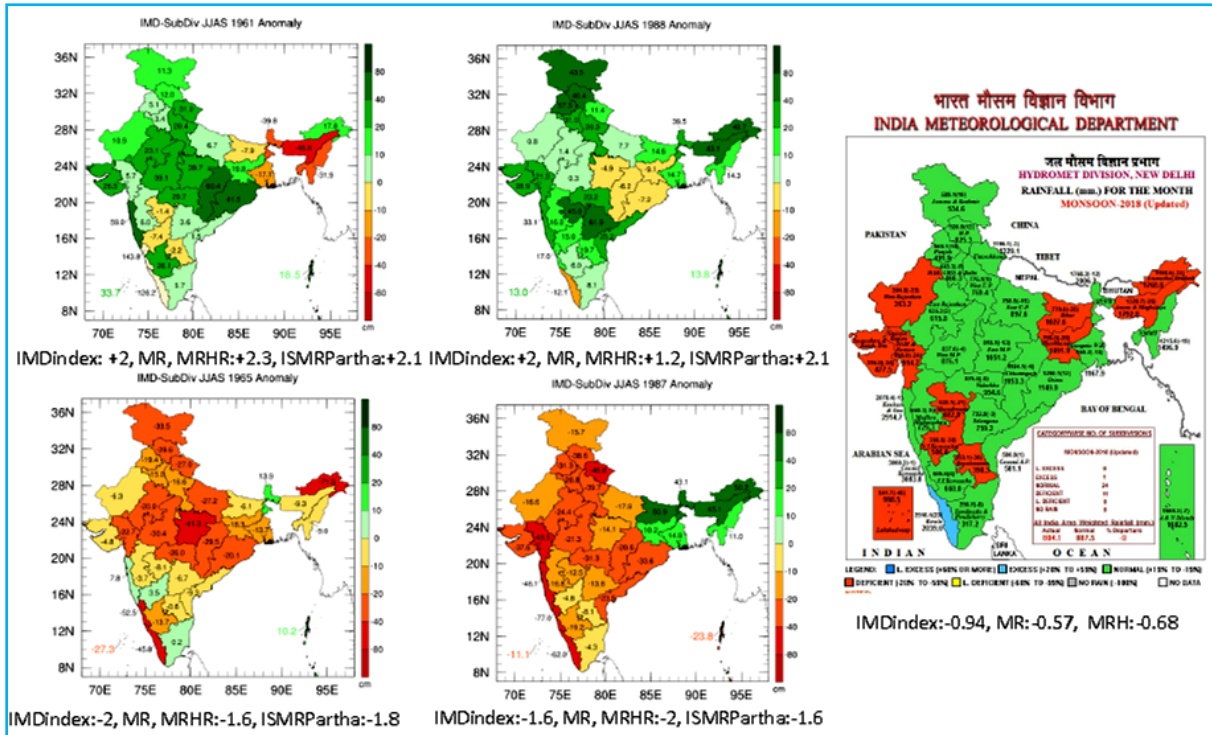


Fig. 14. Sub-divisional June-September rainfall anomalies for 1961, 1988, 1965, 1987 and 2018. The values of the IMD - All India and monsoonal indices are also mentioned.

substantial deficit in the seasonal rainfall, the situation was not close to a drought as suggested by the deficit of IMD all-India rainfall.

7. Concluding remarks

We have identified the region over which most of the rainfall occurs from tropical systems comprising the CTCZ, synoptic and mesoscale disturbances during June-September as the monsoonal region. This can be called the Indian monsoonal region and is rather similar to the region chosen by Parthasarathy *et al.* (1995) for deriving what they consider as all-India monsoon rainfall.

The hilly region to the north of this core region, is under the sway of mid-latitude systems, gets substantial rainfall in the winter also and cannot be considered as monsoonal. It turns out that the northeast is not well correlated with the rest of this Indian monsoonal region. Furthermore, the well - known teleconnections of the Indian summer monsoon with ENSO and EQUINO are also relatively weak (or of opposite sign over parts) for the northeast. Hence, we have suggested that the main monsoonal region which is coherent with respect to the summer monsoon rainfall (*i.e.*, the entire monsoonal region from which northeast region is removed), as the appropriate region for deriving Indian summer monsoon

rainfall. We have delineated the boundaries at grid scales of 1° and 0.25° for which rainfall data are available. In 2018, whereas the IMD all-India index was close to the value for a deficient monsoon season, the index for the ISMR suggested here suggested a substantial deficit but which was not close to the value associated of the deficient season, but only just above half of that value.

We suggest that average rainfall over the main monsoonal region we have identified is the appropriate index of the Indian summer monsoon rainfall (ISMR) for validation of simulation and prediction of the models. We recommend that the other part of the Indian monsoonal region, *viz.*, the northeast, should be considered separately and attempts should be made for developing methods of prediction of the northeast rainfall. The northern hilly regions which cannot be considered monsoonal because it gets a lot of rain in the winter and is often under the sway of mid-latitude systems should also be considered as a separate region. If considered important, the islands over the Arabian Sea and Bay of Bengal could be the fourth region.

The country could thus be divided into four regions; main monsoon region, northeast region, northern hilly region and islands region. At present, information is

readily available from IMD on daily, monthly and seasonal scales of the rainfall averaged over the country as a whole. We suggest that such information should also be provided separately on the monsoon rainfall over the above four regions (derived as average over each of the four regions suggested here), in order to assess the progress of the summer monsoon rains as well as the rains over other important parts of the country.

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