Role of Indian Ocean in Influencing the Rainfall of Central India

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Abstract The Indian summer monsoon as a major component of the global climate system has received renewed attention in recent years. There are many instances of years with floods (strong monsoon) or drought (weak monsoon) during which India as a whole receives excess or deficient seasonal rainfall, respectively. Monsoon variations, particularly if they are unanticipated, impart significant economic and social consequences. On the other hand, an accurate long-lead prediction of monsoon rainfall can improve planning to mitigate the adverse effects of the inter-annual variability of the monsoon. One such attempt is made in this research to establish empirical relationships between sea-surface temperature (SST) and summer monsoon rainfall over Central India. India is surrounded by Indian Ocean and the annual cycle of SST in the Indian Ocean is crucially important in the distribution of precipitation over the Indian subcontinent. The study identifies four pockets in the Indian Ocean which can be considered as precursors to summer monsoon rainfall. Correlation analysis with lags in months was carried out to establish association between the SST over these pockets and summer monsoon rainfall. The study revealed that the relationship between the two variables has undergone phase-change, and has oscillated between inverse and direct correlation values. Besides, the study also reveals the relationship between SST and monsoon rainfall for different meteorological subdivisions of Central India, which further broadens the scope for researchers to evaluate the impact of coupled land-ocean and air interactions for different micro-spatial units of India.

Keywords: Indian Ocean, sea-surface temperature, summer monsoon rainfall, meteorological subdivisions, Central India, lag correlation

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1. Introduction

Since time immemorial, monsoon rains have been the bedrock of India’s food security and of the very survival of land and its people. Agricultural productivity is closely linked with the summer monsoon rainfall. Farmers have learnt to time their crop-seasons in order to get the best out of the monsoon rains. Almost half of the Indians still get their livelihood directly or indirectly from agriculture. However, the vulnerability of Indian agriculture, particularly rainfed agriculture, to the vagaries of monsoon is well-known and has been extensively documented [1,2,3]. The Indian Summer Monsoon Rainfall (ISMR) plays a vital role in affecting the agricultural production, particularly in Central India, which is predominantly rainfed. Thus, predicting the likely behaviour of the monsoon system and the resulting distribution of rainfall becomes inevitable in such a region. Monsoon prediction, therefore, becomes of great value in any efforts aimed at minimizing the agricultural risks and maximizing crop yields. However, predicting the likely physical behaviour of the complex monsoon system is an extremely challenging task. The monsoon is actually an extremely intricate combination of physical processes that operate not only in the atmosphere, but involve land and ocean as well. The ISMR shows variability on different time and spatial scales, varying from intra-seasonal to inter-annual scales. This suggests that a fundamental model to explain the variability of the Indian monsoon rainfall should consist of a linear combination of a large-scale persistent seasonal mean component causing inter-annual variations and a statistical average of intra-seasonal variations [4]. The inter-annual variability of the monsoon can be further influenced by the slowly varying forcings, such as sea-surface temperature (SST), soil moisture, sea ice and snow at the surface [5]. These global boundary forcings can modify the location and intensity of heat sources and atmospheric circulations such as the Hadley and the Walker Cells. Thus, the strength of the seasonal monsoon in a particular year may depend on the relative contributions from the internal dynamics and external forcings [6].
The role played by the ocean in the monsoon processes became more evident when systematic observations over the sea became available. India is located in the south-central part of the continent of Asia, surrounded by the Indian Ocean and its two arms extending in the form of Bay of Bengal and the Arabian Sea. Convection over these huge water-bodies plays a major role in the monsoon rainfall over India. Several studies demonstrate the significance of the sea surface temperature in influencing the monsoon [7-14]. These studies have demonstrated the feasibility of using SST as one of the important parameters having physical significance and inherent coupled association with the atmospheric circulation. However, the success what have been achieved in most empirical statistical models explaining monsoon variability is not adequate and still there is much to scope to improve the skill of monsoon prediction having sufficient lead time period. Keeping these aspects in the background, an attempt is made in the present study to explain the possible role of the Indian Ocean in causing the variability in the monsoon rainfall, particularly over Central India.

2. Study Area

The homogeneous region of Central India as considered by India Meteorological Department (IMD) is taken as the study area for the present research. It consists of ten meteorological subdivisions, as shown in Figure 1. This region extends across the states of Odisha, Chhattisgarh, Madhya Pradesh, Maharashtra, Gujarat and Goa.

Central India is considered as one of the biggest suppliers of cereals and pulses in the country. Agricultural production, mainly being rained, is heavily dependent on the summer monsoon rains in this region. The climate in Central India shows a wide variability ranging from semi-arid to humid tropical monsoon type. Some of the regions, owing to its leeward location, also experience erratic rainfall pattern which makes it highly susceptible to frequent droughts. So, it is obvious that a reasonably correct prediction of monsoon has become a significant stabilizing factor in a socio-economic milieu of such a large population inhabiting this region. The present study tries to discover the existence of significant empirical relationship between the sea surface temperatures of the Indian Ocean because it might provide some insight into the underlying physical process of the monsoon system, which in turn will help in improving the prediction of ISMR. The Indian Ocean extending between 40°E to 120°E longitudes and 30°N to 30°S latitudes has been considered for the present study. As monsoon is a part of the global system, the extent of Indian Ocean is not restricted only to the boundaries of India, but also includes the Southern Hemisphere as well.

Figure 1. Study area with its meteorological subdivisions
3. Data and Methodology

Summer monsoon rainfall data over Central India was collected for the period 1951 - 2012. The data was procured from National Data Centre of India Meteorological Department, located at Pune, India. Gridded monthly mean SST (2° x 2°) over the Indian Ocean was acquired from National Centers for Environmental Prediction (NCEP) reanalysis data for the same data period. As the variations of the horizontal wind shear at the 850 hPa level are directly related to the large-scale monsoon rainfall over the Indian region [15], the circulation pattern over the Indian Ocean were also taken into consideration for preliminary analysis in the present research. The gridded monthly mean zonal (u-component) and meridional (v-component) winds at 850 hPa datasets pertaining to wind anomalies is retrieved from the NCEP reanalysis. This data spanned from 1958 - 2012 and the grids covered an area of 2.5° x 2.5° latitude and longitude, resulting in 825 grid values for each month.

Monthly climatological mean of SST was calculated for the entire length of the study period. Wind stress was computed for each grid cell by adding the squares of the zonal wind data and meridional wind data values. Annual means and annual range of the anomalies were then computed for SST and wind stress. For SST, the annual range varied between 1°C to 12°C, with the median value between 4°C to 6°C. Accordingly, frequencies were worked out for those grids having median value of annual range, as depicted in Figure 2.

![Figure 2](image)

**Figure 2.** Frequencies of annual range (4° - 6° C) in SST anomalies

![Figure 3](image)

**Figure 3.** Frequencies for wind stress (20 - 40 m²/s²)
For wind stress, monthly climatology maps were prepared, where each grid represented 12 values of wind stress, corresponding to the twelve months of the year. Out of these 12 values, frequencies were worked out for those grids having wind stress between 20 to 40 m²/s², as shown in Figure 3.

The resultant two figures were superimposed over each other to identify the areas having both higher frequencies of median value of annual variation in SST anomalies as well as wind stress. The analysis produced four pockets fulfilling these criteria, as represented in Figure 4.

These pockets were taken as representative areas in the Indian Ocean, where the study of the relationship between SST and Indian summer monsoon rainfall was concentrated.

The latitudinal and longitudinal extent of all pockets is given in Table 1.

### Table 1. Latitudinal and Longitudinal extent of the four pockets

| Pocket No. | Latitudinal extent | Longitudinal extent |
|------------|--------------------|---------------------|
| P1         | 17°N - 25°N        | 61°E - 71°E          |
| P2         | 13°S - 23°S        | 51°E - 65°E          |
| P3         | 23°S - 31°S        | 89°E - 101°E         |
| P4         | 15°N - 21°N        | 109°E - 121°E        |

Over these delineated pockets, anomalies of SST data are correlated with the anomalies of rainfall found over Central India. The Pearson’s correlation (symbolically written as ‘r’), which is a correlation coefficient (CC) commonly used in linear regression is employed in the present study, whose formula is given below:

\[
r = \frac{n(\sum xy) - (\sum x)(\sum y)}{\sqrt{n\sum x^2 - (\sum x)^2} \sqrt{n\sum y^2 - (\sum y)^2}}
\]

Where \(x\) = sea surface temperature anomalies
\(y\) = rainfall anomalies
\(n\) = number of years

Prior to this, very high frequency fluctuations in the SST dataset were removed by applying a 7-year moving average, as it was observed that SST dataset depicted a periodic cycle of 7 years. On similar lines, rainfall series were prepared by applying the technique of 7-year running mean. Both the series obtained were then associated with each other, and were subjected to a 21-year sliding window of correlation, taking lag of -1 (May) to -12 (preceding June) months. The relationship between SST and rainfall was further examined with reference to meteorological subdivisions of Central India, which helped in understanding the systematic changes over space in the relationship between the variables under consideration.

### 4. Analysis and Findings

#### 4.1. Association of SST over Pocket 1 (P1) and Rainfall over Central India

Figure 5 depicts that sea-surface temperature for the month of preceding July and August show inverse relationship with the rainfall over Central India, particularly from 1951 to 1980. While relation of July
SST became insignificant later, inverse relationship of August SSTs continued to persist till 1992. Thereafter, the relationship has weakened between SST and rainfall. There is a phase change in their relationship in the recent period, though not significant.

4.2. Association of SST over Pocket 2 (P2) and Rainfall over Central India

Figure 6 reveals the changing relationship between SST over Pocket 2 region and summer monsoon rainfall of Central India. Inverse relationships are observed for all the monsoon and post monsoon months during 1951-1982. Subsequently, the value of CCs undergoes phase change and become insignificantly positive.

December, January and February SST show fluctuations in their negative CCs till 1992. Thereafter, the relationship undergoes phase change for the months of January and February, while December continues to depict
significant negative CCs till 2005. However, the relationship almost nears zero for all the three winter months. Highly significant negative CCs are observed for the months of April and May during the period 1951 to 1983. Significant negative CCs are observed for March and April for a shorter duration (1963-1993). However, in the latter study period, the relationships remain insignificant for all the pre-monsoon months, after undergoing a phase change.

4.3. Association of SST over Pocket 3 (P3) and Rainfall over Central India

The graph depicting 21-year sliding window of correlation coefficients of SST over Pocket 3 region and rainfall of Central India is illustrated in Figure 7.

![Figure 7](image1)

Note: X axis: Central year of sliding window
Y axis: Correlation coefficient
…… Significant at 0.05 level

Significant negative relationships are observed during the monsoonal months during the period 1959 to 1990. Thereafter, all the months undergo phase change, highly significant only for August. Same pattern is replicated for the post-monsoonal months. SST of January and February exhibit highly significant positive CCs during the beginning part of the study period, but could not maintain the significant relationship in the latter part. Following pre-monsoon period witnessed more or less same trend, with 1963-93 showing significant negative CCs. The inclusion of the year 1994 drastically changes the association between the SSTs of pre-monsoon months and the rainfall over Central India.

4.4. Association of SST over Pocket 4(P4) and Rainfall over Central India

An overview of all the graphs of Figure 8 reveal that the SST over Pocket 4 region observed in all preceding
months is significantly inversely correlated with summer monsoon rainfall over Central India during recent period. The season-wise relationship is discussed in subsequent paragraphs.

The SST for the month of August show cyclicity in its relationship with rainfall, with highly significant negative CCs in the beginning of study period, followed by a phase change with subsequent significant positive CCs, and later undergoing another dramatic phase change leading again to significant negative CCs in 2012. It is observed from the graph that along with August, the month of July also witnessed significant inverse relationship between SSTs and rainfall.

The SST of post-monsoon months of October and November reflect significant inverse relationships with Central India rainfall in the first and last part of the study period. The relationship observed in the month of September, initially behaves in the same manner but later undergoes phase change leading to significant CCs during 1967-2001. Another phase change observed in the recent period in the month of September, carries the relationship to significant negative CCs.

The temporal fluctuations in relationships of SSTs of winter and pre-monsoon months with rainfall over Central India depict significant inverse relationship in the recent period.

4.5. Association of SST and Rainfall over Various Meteorological Subdivisions

It is evident from the above discussion that the relationship between the SST and rainfall has undergone phase changes in majority of months. In order to have a glimpse of the current spatial distribution of their association, maps showing CCs over the various meteorological subdivisions (MS) are prepared for the recent period.

4.5.1. Pocket 1

The various meteorological subdivisions of Central India depict all the three categories of relationships (negative CCs, insignificant CCs and positive CCs) during the recent period as revealed from Figure 9. Amongst the various months, preceding September to December and concurrent March-April stand out distinctly with large number of meteorological subdivisions having significant relationships. However, these MS do not fall in the same phase of relationship, as rainfall over East Madhya Pradesh (EMP), West Madhya Pradesh (WMP) and Chhattisgarh MS depicts highly significant inverse association with sea surface temperature over P1 region, while Saurashtra and Kutch, Gujarat, and Madhya Maharashtra MS reveals significant positive association.

4.5.2. Pocket 2

Figure 10 indicates a very good positive association between SST of Pocket 2 and rainfall over meteorological subdivisions of Odisha, North Interior Karnataka (NIK), Madhya Maharashtra, Gujarat, and Saurashtra and Kutch during all the months in the recent period. On the other hand, the rainfall over EMP catches the sight of the analyst with significant negative association with SST observed over Pocket 2 region.

Figure 9. CCs between SST of P1 and rainfall of meteorological subdivisions of Central India (with lags in months)
Rainfall of majority of MS shows positive association with SSTs of Pocket 3 during the earlier monsoon season, as seen from Figure 11. Significant positive relationship between rainfall over MS of Central India is prominently observed with SST of Pocket 3 during the preceding monsoon months of June, July and September. EMP and WMP MS exhibit significant negative relationships with Pocket 3 from October to January. However, these MS depict direct association in March, and then again reverting back to significant inverse association.

During March and April, rainfall over Madhya Maharashtra and Marathwada meteorological subdivisions is significantly inversely correlated with SST observed over Pocket 3 region during the preceding March and April months.

Figure 10. CCs between SST of P2 and rainfall of meteorological subdivisions of Central India (with lags in months)

Figure 11. CCs between SST of P3 and rainfall of meteorological subdivisions of Central India (with lags in months)
4.5.4. Pocket 4

This pocket behaves distinctly different as compared to all other pockets, as only significant negative relationships are seen over various MS. Rainfall over EMP, WMP, and Chhattisgarh depict significant negative association with SSTs of Pocket 4 during October, November and December. The relationship of different meteorological subdivisions with SST of pocket 4 (with lags in months) is represented in Figure 12.

5. Discussion and Conclusion

The inter-annual variation in the monsoon rainfall is controlled by a variety of factors. Among them, gradients of sea surface temperature (SST) are important in determining the position of precipitation over the tropics, including monsoon regions [16]. The present research study identifies four pockets over Indian Ocean, wherein the relationship of SST (with lag in months) was analysed with rainfall, by which they can be treated as potential indicators of succeeding monsoon rainfall. The summer monsoon rainfall of Central India, recognized as a homogeneous region, is taken for study. In addition, the spatial variation in the relationship between rainfall and sea surface temperature was also considered across the various meteorological subdivisions of Central India.

Statistically significant correlations were observed with the SST of preceding months and the succeeding summer monsoon rainfall, highlighting the importance of Indian Ocean in influencing the temporal variability of the distribution of precipitation. In this connection, reference is invited to Weare, who performed an Empirical Orthogonal Functional analysis of Indian Ocean SST data for a period of 1949-1972 and established an association of warmer Arabian Sea or Indian Ocean in the preceding months with decreased rainfall over much of the Indian sub-continent [17].

From the result and findings enlisted above, it can be concluded that relationships between SST (with lag in months) and summer monsoon rainfall over Central India undergo phase change in the recent period. This phase change in their relationship can be explained with the help of various analyses pertaining to Indian Ocean [18,19,20], wherein such climatic shifts have been interpreted by some as a manifestation of global climate change [21,22]. These studies have shown that the tropical Indian Ocean has experienced rapid basin-wide sea surface temperature warming, with an average rise of 1.0°C (0.15°C/decade). The SST warming is spatially non-uniform and about 90% of the warming is attributed to anthropogenic emissions in the recent period. It favours deep atmospheric convection [23] and energizes the global atmospheric circulation, particularly the Hadley circulation and the Walker circulation, thereby modulating the major elements of global climate such as the Indian monsoon. In view of these climatic shifts in atmospheric circulations, the phase-change observed in the present analysis may be taken as a hint towards the modification of the different components of the atmosphere-land-ocean system.

Furthermore, rainfall over different meteorological subdivisions of Central India portray opposite associations with SST for Pocket 1, 2 and 3. The CCs between summer monsoon rainfall and SST over the aforesaid pocket regions, do not exhibit a systematic evolution, as described above, for all the meteorological subdivisions of the same homogeneous region of Central India. MS of Saurashtra and Kutch, Gujarat, and Madhya Maharashtra
mostly follow the same pattern of positive relationships, while EMP, WMP, and Chhattisgarh form another group having significant inverse relationships. This incongruous mode in relationships calls for a more micro-level spatial association of monsoon parameters, as against a more regional approach. This analysis supports the suggestion given by Ghosh et al., wherein they urge the researchers to study the Indian summer monsoon rainfall at a more local scale [24]. According to them, macro-scale study of monsoon rainfall may eclipse the impact of local changes that affect the rainfall.

It is to be noted that none of the meteorological subdivisions of Central India are significantly correlated with SST of preceding January (for P1) and SST of preceding February (for P3). Though the reason is unclear, but the warming of North Indian Ocean since 1950s might have weakened the meridional SST gradient, which in turn might have resulted in altering the relationship between SST and summer monsoon rainfall in the preceding winter months. [25].

The authors would also like to highlight the robustness of present analysis, wherein it is found that the remote influence of the SST of Pocket 4 region in the preceding months can be taken as a significant signal influencing the rainfall in the succeeding months. Pocket 4 portrays more optimistic results, wherein only negative association is found for various MS. It is found in the present analysis that Pocket 4 has recently started assuming significant inverse association with rainfall of Central India. The location of Pocket 4 assumes importance, as it is situated in the vicinity of one of the ascending branches of Walker Cell that completes the Southern Oscillation [26]. Many studies have shown and proved that the ascending currents of the Walker Cell in the preceding months favour heavy rainfall over the Indian region [27,28,29]. But the present analysis depicts that the direct relationship had transformed to an indirect association in the recent period. Here, reference can be given of the studies which showed that there has been an eastward shift in the Walker circulation, a change that has been observed in response to a warmer climate [30]. Observations have also shown that the Hadley circulation has also widened in response to the recent global warming, which in turn has generated regional climatic effects, particularly affecting the precipitation trends [31].

The present study thus becomes essential to understand the changing monsoon-SST relationship, and correctly representing this phase-change in their relationship in future climate projections of the Indian monsoon.

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