Role of Regional Parameters in Inter-annual Variation of Indian Summer Monsoon Rainfall

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Abstract  The Indian summer monsoon affects almost all the facets of life in India. Variability in the onset and duration of monsoon has profound impacts on water resources, human life, agriculture, economics and ecosystems. That is why predictions of the monsoon behavior are eagerly watched by government planners and agronomists. However, every monsoon has its own unique characteristics, which makes it more enigmatic and complex. Predicting the likely physical behavior of the monsoon system and the resulting distribution of rainfall over different parts of India is an extremely challenging task. Sometimes, the necessity of producing long-range forecasts has compelled investigators to develop empirical relationships between different facets of the coupled atmosphere-ocean land system. The present study also presents some empirical evidence of relationships between summer monsoon rainfall and sea-surface temperature over the Indian Ocean. Sea surface temperatures exert significant control over the atmosphere, particularly over the monsoon circulation. The study has identified four pockets in the Indian Ocean, which can be used as potential predictor zones for summer monsoon rainfall (June to September) over India. To achieve this objective, correlation analysis with lags in months was carried out to establish association between the sea surface temperature over the four pockets and summer monsoon rainfall. Strong significant association can be found between the SST of these four pockets and Indian summer monsoon rainfall. The study also reveals a phase-change in the relationship between the sea surface temperature and Indian summer monsoon rainfall, particularly in the recent period.

Keywords: sea surface temperature, lag correlation, Indian summer monsoon rainfall (ISMR)

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1. Introduction

The Asian summer monsoon as a major component of the global climate system has received renewed attention in recent years. The fundamental driving mechanisms of the monsoon cycle are the cross-equatorial pressure gradients resulting from differential heating of land and ocean, modified by the rotation of the earth and the exchange of moisture between the ocean, atmosphere, and land [1]. The Himalayas and the Tibetan Plateau provide additional strong thermal forcing that produces a distinct asymmetry to the summer monsoons of the Northern and Southern Hemispheres [2,3]. Two remarkable features of the summer monsoon are its regular occurrence every year from June to September and the irregular variation in the amount of seasonal mean rainfall that it brings to India from one year to the other. There are many instances of years with flood (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 impacts of the inter-annual variability of the monsoon and to take advantage of beneficial conditions. Many attempts have been made to forecast the summer monsoon rainfall over India [4,5,6,7,8,9,10]. Empirical forecasting of Indian monsoon rainfall has been performed using combinations of climatic parameters, including atmospheric pressure, wind, snow cover and SST [11,12,13].

The large contribution from the Arabian Sea to the moisture supply for the Indian summer monsoon have been highlighted by Pisharothy, wherein he pointed out that small changes in sea surface temperature (SST) have profound influence on the amount of evaporation [14]. Thus, considering that the vast reservoir of heat in the ocean is important in relation to changes in the circulation patterns, the present study tries to explain the possible role of sea surface temperature observed over the Indian Ocean in causing the inter-annual variation in the monsoon rainfall.
2. Data Used

In this study, all-India monthly and seasonal (June - September) rainfall series provided by National Data Centre, India Meteorological Department (IMD) have been used, for a time span ranging from 1951 to 2012. These data sets have been prepared by IMD by considering each of the sub-divisional rainfall areas, with well-distributed rain-gauge stations throughout the country.

The Indian Ocean region (IO) extending between 40° E to 120° E longitudes and 30° N to 30° S latitudes has been considered for the present study. The monthly mean SST data on 2° grid mesh over IO were acquired from National Centers for Environmental Prediction (NCEP) reanalysis data, each consisting of 1271 grid values, for the same data period ranging from 1951 to 2012.

The circulation pattern over the IO has been examined by using monthly mean zonal (u - component) and meridional (v - component) winds at 850 hPa from the NCEP reanalysis dataset. 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 lower level winds were also taken into consideration for preliminary analysis in the present research. The dataset pertaining to wind anomalies spans from 1958 - 2012 and the grids cover an area of 2.5° X 2.5° latitude and longitude, resulting in 825 grid values for each month.

3. Methodology

The monthly climatological mean of each variable was calculated for the entire length of the respective dataset. Annual means for each grid point of SST were worked out for the study period of 62 years. Monthly anomalies were then computed by subtracting the climatological annual mean from the monthly means. The difference between the monthly maximum anomaly and the monthly minimum anomaly gave the values for annual range of the anomalies. Thus, each grid represented 62 values of annual range. 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 annual range between 4°C to 6°C during the study period of 62 years.

In addition, it is well known that it is the air-sea momentum flux or wind stress, that actually drives the ocean circulation, wind stress was also computed for each grid cell. Due to difficulties of directly measuring the wind stress, different algorithms are used to relate the wind stress with wind velocity and other related variables. In the present study, wind stress is calculated by using the following formula:

\[
\text{Wind Stress} = u^2 + v^2
\]

Monthly climatology maps for wind stress were prepared, where each grid represented 12 values of wind stress. Out of these 12 values, frequencies were worked out for those grids having wind stress between 20 to 40m²/s², which is the minimum required value to drive any atmospheric circulation. The resultant grids were superimposed over each other to identify the area having both higher frequencies of annual variation in SST anomalies as well as windstress. The analysis produced four pockets fulfilling these criteria. The latitudinal and longitudinal extent of all pockets is given in Table 1.

| 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       |

Out of the four pockets, two pockets are located in the northern hemisphere (one each in eastern and western part), while remaining were positioned in the Southern hemisphere, thus representing the important regions of the Indian Ocean, as shown in Figure 1.

![Figure 1. Four Pockets identified based on SST and Wind Stress](image-url)
Over these delineated pockets, time series of SST were prepared. Further, correlations were computed between the above prepared SST and rainfall time series. 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:

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

Prior to this, very high frequency fluctuations in the SST dataset have been removed by applying a 7-year running mean in order to obtain more coherent results, as it was observed that SST has a periodic cycle of 7 years. On similar lines, rainfall series were prepared by applying the technique of 7-year running mean.

The series obtained by the 7-year moving averages were then subjected to a 21-year sliding window of correlation, taking lag of -1 (May) to -12 (preceding June) months. This procedure can, at least partially, consider the systematic changes in the relationship between the predictors and the predictand.

4. Analysis and Findings

An attempt was made to find out the association between SST of each of these pockets and ISMR on seasonal as well as monthly basis. A 21-year sliding window of correlation coefficients between gridded SST averages over the four pockets and summer monsoon rainfall have been prepared. The graphs were grouped according to different standard seasons (JJA, SON, DJF and MAM). The significance of the trends was found at 0.05 (represented by dotted line in the graphs) and 0.01 significance levels.

4.1. Association of SST over Pocket 1 (P1) and ISMR

The monthly graphs representing the association between rainfall and SST over Pocket 1 (with lag in months), are represented in Figure 2 and Figure 3. The graph of preceding June reveals significant negative relationship during a span of 27 years (1959 - 1987). The association remained negative till 1996. But, the addition of the SST for the year 1997 changed the phase of the relationship. Subsequently, positive correlation was observed and it became significant 1978 - 2006. However, the recent period, the association became insignificant. The period extending from 1951 - 1979 saw significant negative relationship between the SST’s of July and AISMR. This relationship changed its phase for a short time period during 1956 - 1984, and again reverted back to negative association, but not significant. The relationship again changed phase around the same period as of June and not only persisted in the same phase for nearly 40 years (1970-2011) but also became significantly associated during 1979 - 1994. In the preceding monsoon, linkage of August SST with ISMR stands out visibly with negative correlation at 0.01 level of significance for a longer period extending from 1951 - 1982. However, the relation between cooling in the month of August and ISMR gradually ebbed till 2002. In the recent period, this relation has again started assuming potential to develop into a significant negative correlation.

All the three months during the post monsoon season exhibits significant negative relationship from 1951 to 1982. The month of September continues to have negative association, but not significant till 2002. Amongst the three months, October is the most noticeable month having significant negative association throughout the study period. The month of November experienced a shift into the positive phase for a short duration and then again witnessed transformation of phase by inclusion of the SST for the year 2003, wherein the association between SST and ISMR dramatically became negatively significant, reaching its peak in recent period.

During the winter season, insignificant relationships are observed between the SST and ISMR from 1951 to 1999. However, a striking phase change in the relationship is observed in December by adding the SST for the year 2003. This replicates the period of phase change as observed in November, with similar significant negative correlation coefficients (CCs) even at 0.01 level of significance in the recent period. The graph also depicts significant positive relationship for the months of January and February, though extending for a shorter period (1973-2003). However, the relationship weakened thereafter.

The months of March and May show shift in the phase around 1985, though not achieving the significance level. The month of April remained in the negative phase but showed significant association (0.05 level of significance) from 1993 to 1998, and thereafter the relationship strengthened even at 0.01 level also. The graph depicts that SST for the month of March shows similar trend in CCs as observed in the month of April.
4.2. Association of SST over Pocket 2 (P2) and ISMR

Figure 4 depicts the relationship between SST observed over Pocket 2 and the monthly rainfall over India. In the initial period SST for the monsoon and post monsoon months show significant negative relationship from 1951 onwards to near about 1980, at 0.05 level of significance. Thereafter, the relationship undergoes phase change but not significant. The SST of August, September and October are significantly inversely related with ISMR during 1981 to 2011.

SST of December depict significant inverse association with ISMR from 1972 to 2003. Later, the relationship weakens. However, after a few years, the association of SST in the preceding December with the summer monsoon rainfall start strengthening and becomes nearly significantly inversely correlated. SST for the months of January and February indicate inverse relationship with ISMR during the period 1951 to 1980. During the period 1961 to 2004 the SST for the month Jan and Feb indicates direct association with that of rainfall but not significant. In the recent period, the SST for the month of January and February again revert back to significant negative CCs.

The SST for the month of March, April and May shows highly significant inverse relationship with ISMR during the earlier (1951-1984) and latter (1981-2011) part of the study period. During all the 3 months, the relationships between SST and summer monsoon rainfall weakens in the central part of study period. The SST for the month of May depict significant positive CCs from 1975 to 2003.
4.3. Association of SST over Pocket 3(P3) and ISMR

Figure 5 indicates that the monsoon months undergo a phase change from significant positive CCs (1971-2003) to significant negative CCs (1982-2011), with the exception of August which cannot achieve significant negative CC in the recent decade. The post monsoon months reveal more or less similar pattern with the preceding months. SST for the month of December indicates conspicuous shift in their relationship, reaching highly significant negative CCs in the latter study period. SST for January depict a noticeable change in their relationship with ISMR during the beginning and latter part of the study period. Fluctuations in the positive CCs of pre-monsoon months are clearly visible throughout the study period. Amongst them, the March SST stands out predominantly having statistically significant positive CCs.
during majority of the period. There is a phase change in the relationship of May SST, due to which significant positive CCs are altered to significant negative CCs, particularly in the recent period.

4.4. Association of SST over Pocket 4(P4) and ISMR

The relationship between SST over Pocket 4 and monthly rainfall is depicted in Figure 6. The graph of preceding June reveals significant negative relationship during a span of 27 years (1959 - 1987). The SST for the month of August show cyclicity in its relationship with rainfall, with highly significant negative CCs in the beginning 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 the recent period. The SST of post-monsoon months reflect significant inverse relationships with succeeding summer monsoon rainfall till around 1983. The SST of all the post-monsoon months exemplify significant negative CCs with All-India rainfall in the recent period, reverting back to the tendency observed in the initial study period. The SST of December and January show significant negative association with AISMR in the initial part of the study period. The SST for the months of January and February undergo change in the phase of their relationships with rainfall around the same point in time. They depict prolonged period (1962 to 2001) of highly significant positive association with rainfall, then reverting to negative associations in the recent period. The SST of pre-monsoon months stand out as an exception with all other months in the sense that they do not show negative association in the beginning study period, but become significantly negatively correlated in the recent period.

5. Discussion and Conclusions

Monsoon inter-annual variations are influenced by a wide variety of processes. Among them, gradients of sea surface temperature (SST) are important in determining the position of precipitation over the tropics, including monsoon regions [16]. Along with SST, the surface wind stress play an important role in the variability of sea surface temperatures and moisture fluxes [17]. As the present paper tries to understand the thermodynamics over the Indian Ocean associated with change in the Indian summer monsoon circulation, four pockets were identified in the Indian Ocean based on SST and wind stress criteria. 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.

Correlation analysis with lags in months depicted that the sea surface temperatures of the previous months can become a crucial predictor of the ensuing monsoon rainfall. Statistically significant correlations were observed with the preceding months SST 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 [18].

The present study also highlighted the fact that relationships between SSTs (with lag in months) and summer monsoon rainfall have undergone phase change for almost all the pockets during all the four seasons, particularly in the recent period. This phase change in their relationship can be explained with the help of various analyses pertaining to Indian Ocean [19,20,21], wherein such climatic shifts have been interpreted by some as a manifestation of global climate change [22,23]. These studies have shown that the tropical Indian Ocean has experienced rapid basin-wide sea surface temperature (SST) 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 [24] 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.

Observations have shown that the Hadley circulation has widened in response to the recent global warming, which in turn has generated regional climatic effects, particularly affecting the precipitation trends [25]. Simulations have demonstrated that increasing greenhouse gases and SST variations are contributors to the observed widening trends of the Hadley circulation. In addition, studies have also shown that there has been an eastward shift in the Walker circulation, a change that has been observed in response to a warmer climate [26]. In view of these climatic shifts in atmospheric circulations, the phase-change may be taken as a hint towards the modification of the different components of the atmosphere-land-ocean system. The present study thus becomes essential to understand the monsoon-SST relationship, and correctly representing this phase-change in their relationship in future climate projections of the Indian monsoon.

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