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INTERANNUAL VARIABILITY OF SUMMER MONSOON RAINFALL OVER SOUTH PENINSULA

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Abstract

The Indian summer monsoon continues to have a significant impact on the overall economy of the country. There are many occurrences of 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 unexpected, results in substantial economic and social consequences. On the other hand, an accurate long-lead prediction of monsoon rainfall can improve planning to alleviate the adverse effects of the inter-annual variability of the monsoon. 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. This research study tries to establish pragmatic relationships between sea-surface temperature (SST) and summer monsoon rainfall over southern peninsular region, herein called as South Peninsula. The study identifies four pockets in the Indian Ocean which can be considered as precursors to the subsequent 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 over the South Peninsula homogeneous region. The study revealed that the relationship between the two variables has undergone phase-change, and has oscillated between inverse and direct correlation values. This study will therefore be helpful in further broadening the scope for researchers to evaluate the impact of coupled land-ocean and air interactions for different meteorological homogeneous regions of India.

Keywords: *Indian Ocean, sea-surface temperature, summer monsoon rainfall, meteorological homogeneous region, South Peninsula, lag correlation*

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1. Introduction

Since time immemorial, understanding and the prediction of the variability of the monsoon rainfall is extremely important. 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]. The Indian Summer Monsoon Rainfall (ISMR) plays an important role in affecting the agricultural production, particularly in the southern peninsular region, which depict the true character of the southwest monsoon system originating in the tropical waters. Thus, predicting the likely behaviour of the monsoon system and the resulting distribution of rainfall becomes unavoidable 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 [2]. 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 [3]. 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 [4].

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 [5-11]. 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 the homogeneous region of South Peninsula.

2. Study Area

The meteorological homogeneous region of Peninsular India as considered by India Meteorological Department (IMD) is taken as the study area for the present research, excluding the island regions of Andaman and Nicobar and Lakshadweep. Hence, it will be called as South Peninsula, hereafter. It consists of eight meteorological subdivisions, as shown in Figure 1. This region includes the meteorological subdivisions of Coastal Andhra Pradesh, Telangana, Rayalaseema, Tamil Nadu and Pondicherry, Coastal Karnataka, North and South Interior Karnataka and Kerala.

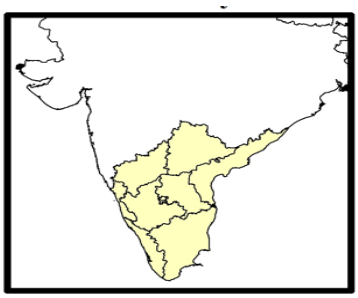


Figure 1. Study area (South Peninsula) with its meteorological subdivisions

The homogeneous region of South Peninsula experiences the typical tropical monsoon climate, characterized by moderate to high year-round temperatures and seasonally heavy rainfall. Agricultural production, mainly being rainfed, is heavily dependent on the summer monsoon rains in this region. Some of the regions, owing to its leeward location, also experience erratic rainfall pattern which makes it highly susceptible to frequent droughts, particularly the interior continental locations. 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 and summer monsoon rainfall over South Peninsula 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.

2. Data and Methodology

Monthly summer monsoon rainfall data over the meteorological subdivisions of South Peninsula 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 [12], 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 dataset 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. As the grid area was different for SST and wind stress, care was taken to superimpose both the data in such a way that a common region was delineated that represented both the characteristics of mean SST as well as mean wind variability.

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 both 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.

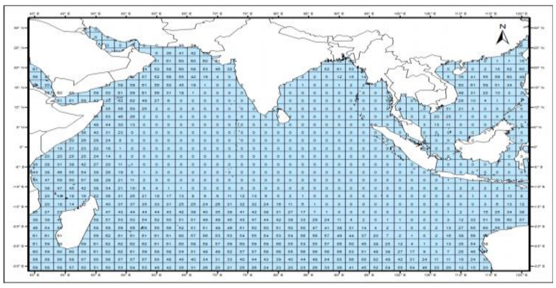


Figure 2. Frequencies of annual range (4° – 6° C) in SST anomalies

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 m^2/s^2, as shown in Figure 3. These values represented the minimum wind stress required for carrying the moisture from the oceans onto the landmasses, and hence was considered appropriate for the present study.

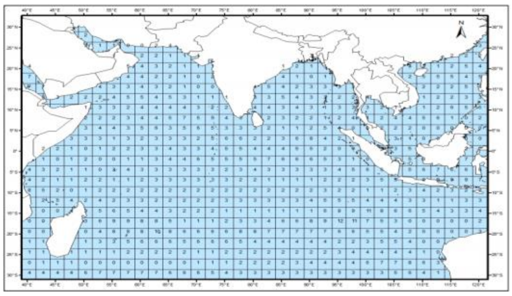


Figure 3. Frequencies for wind stress (20 – 40 m^2/s^2)

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.

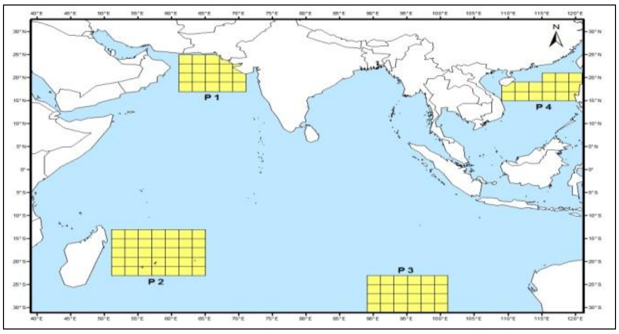


Figure 4. Four Pockets identified based on SST and Wind Stress

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

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

$$r = \frac{n(\sum xy)-(\sum x)(\sum y)}{\sqrt{\left[n\sum x^2-(\sum x)^2\right]\left[n\sum y^2-(\sum y\right.}} \qquad (1)$$

Where x = sea surface temperature anomalies

y = rainfall anomalies

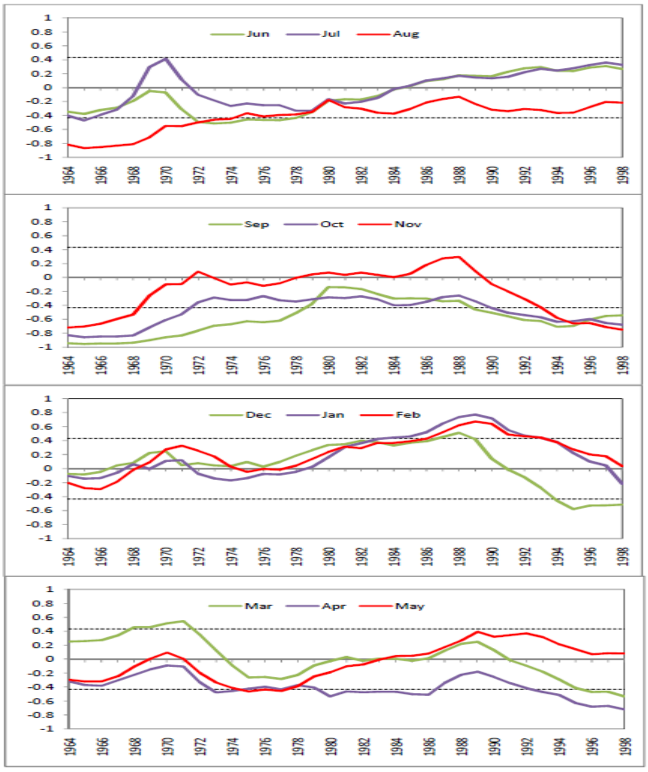
n = number of years

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 examined for the homogeneous region of South Peninsula, which helped in understanding the systematic changes over time in the relationship between the variables under consideration.

3. Analysis and Findings

3.1. Association of SST over Pocket 1 (P1) and Rainfall over South Peninsula

An attempt was done to find out the association between SSTs of each of these pockets and summer monsoon rainfall over South Peninsula on seasonal as well as monthly basis (Figure 5).



Note: X axis: Central year of sliding window

Y axis: Correlation coefficient

…….. Significant at 0.05 level

Figure 5. 21-year sliding CCs between SST of P1 and rainfall over South Peninsula

It is clear from the figure that the relationship between the above two variables have undergone phase change, in the month of June and July. The SSTs of August illustrates remarkable inverse linkage with rainfall of South Peninsula for a period of approximately 40 years (1951- 1989), and thereafter the relationship weakens but still maintains to remain in the negative phase.

All the three months during the post monsoon season exhibits significant negative relationship from 1951 to 1982. Thereafter, the SST for the month of November experiences a phase change in its relationship with the summer monsoon rainfall over South Peninsula for a brief period. However, if we observe the recent period, the SST for the month of November has a very strong negative association with the subsequent rainfall over South Peninsula.

It is to be noted that all the three months of post monsoon season are currently depicting a significant association between the sea surface temperature of Pocket 2 and the summer monsoon rainfall of South Peninsula region. This significant relationship can be taken as a good indicator to predict the summer monsoon rainfall of the subsequent year over the meteorological homogeneous region of South Peninsula.

During the winter season, insignificant relationships are observed between the SST and summer monsoon rainfall over South Peninsula from 1951 to 1999. However, a striking phase change in the relationship is observed in December, January and February by adding the SSTs for the year 2003. The graph also depicts significant positive relationship for the months of January and February, though extending for a shorter period (1973-2003). In the recent period, it is seen that only sea surface temperatures in the previous December represents a significant negative relation with the summer monsoon rainfall of the South Peninsula region of the subsequent year.

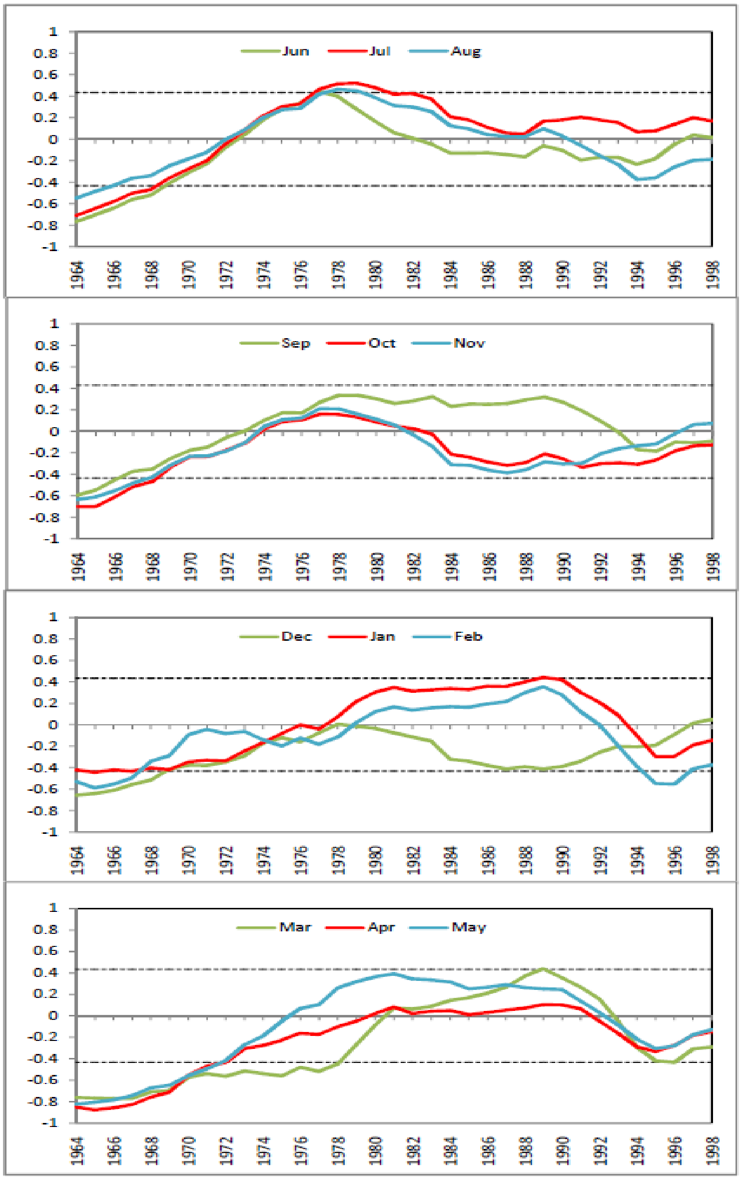
The months of pre-monsoon season (March, April and May) show a cyclic relationship between the SSTs observed during these months and summer monsoon rainfall of South Peninsula, wherein it switches between a positive correlation to a significant negative correlation between the variables considered.

The month of April remained in the negative phase but showed significant association (at 0.05 level of significance) only from 1993 to the recent period. The sea surface temperature observed in the month of March also has a negative association with the summer monsoon rainfall of South Peninsula region in the recent period. However, there was no significant association found between the previous May sea surface temperatures and the ensuing summer monsoon rainfall over South Peninsula.

From the above discussion, we can infer that among all the seasons, the sea surface temperatures experienced during the post-monsoon season of the previous year over the P1 region depicts a very good inverse relationship with the summer monsoon rainfall over South Peninsula meteorological homogeneous region. This can help to identify the precursors for predicting the rainfall over the study region.

3.2. Association of SST over Pocket 2 (P2) and Rainfall over South Peninsula

Similar analysis was performed for finding the association between SST over P2 (with lag in months) and summer monsoon rainfall over South Peninsula region.



Note: X axis: Central year of sliding window

Y axis: Correlation coefficient

…….. Significant at 0.05 level

Figure 6. 21-year sliding CCs between SST of P2 and rainfall over South Peninsula

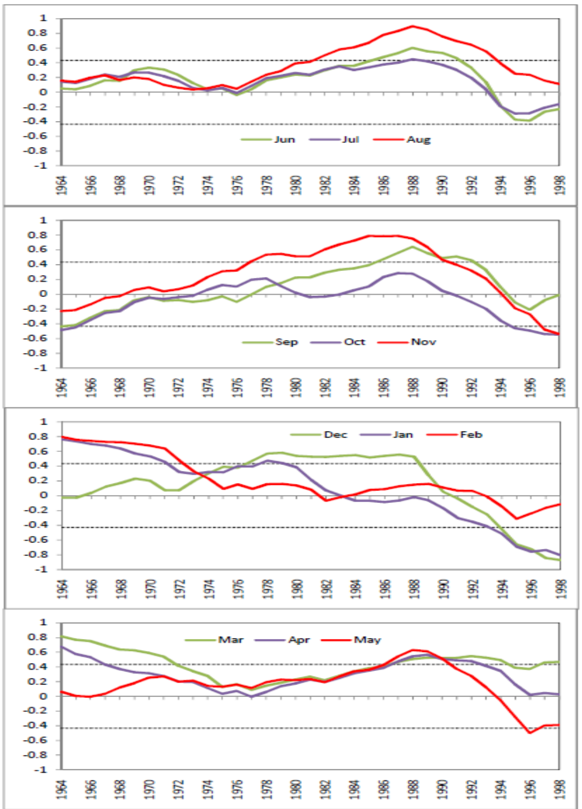
Figure 6 reveals that the sea surface temperatures over Pocket 2 for the previous monsoon season was strongly inversely associated with the subsequent summer monsoon rainfall over South Peninsula, during 1951 – 1981. However, the association started weakening and there was a phase-change observed in their relationship. Similar observations were seen for all the other months of post-monsoon, winter and pre-monsoon season.

In the recent period, there is no significant association between the sea surface temperatures observed over Pocket 2 region, experienced during the previous months and the summer monsoon rainfall over South Peninsula.

From the above discussion, we can infer that the sea surface temperatures over Pocket 2 had a strong association with the summer monsoon rainfall over South Peninsula in the past. However, there might have been changes in the circulation pattern, that has led to the weakening of this association.

3.3. Association of SST over Pocket 3 (P3) and Rainfall over South Peninsula

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



Note: X axis: Central year of sliding window

Y axis: Correlation coefficient

…….. Significant at 0.05 level

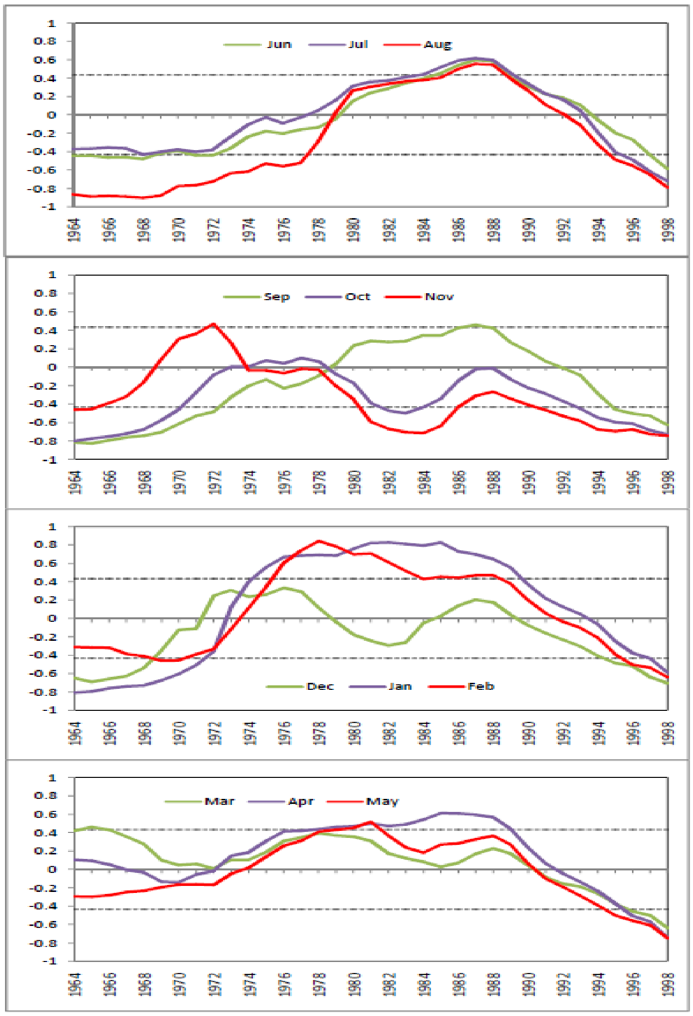
Figure 7. 21-year sliding CCs between SST of P3 and rainfall over South Peninsula

During 1970 - 2000, SSTs over Pocket 3 observed during the previous monsoon months were directly associated with the following summer monsoon rainfall over South Peninsula. However, this relationship has weakened in the recent period.

Amongst the post monsoon months, SSTs of November during the period (1964-2003) show highly significant positive CCs. However, this month experiences phase change, leading to significant negative CCs along with October in the recent period.

For the winter season, SSTs of January depict a noticeable change in their relationship with summer monsoon rainfall of South Peninsula during the beginning and latter part of the study period. SSTs during March and April show highly significant association during the period (1951-1983) and later the CCs become insignificant.

3.4. Association of SST over Pocket 4(P4) and Rainfall over South Peninsula



Note: X axis: Central year of sliding window

Y axis: Correlation coefficient

…….. Significant at 0.05 level

Figure 8. 21-year sliding CCs between SST of P4 and rainfall over South Peninsula

An overview of all the graphs of Figure 8 reveal that the SST over Pocket 4 region have undergone a phase-change in its relationship with summer monsoon rainfall over South Peninsula during the study period.

Although the SSTs of all the three months of preceding monsoon season show a shift from significant negative CCs to significant positive CCs and then again reverting back to significant negative CCs, the month of August depicts the most dramatic transformations.

SSTs for the post-monsoon months reveal significant negative CCs in the initial and latter part of the study period. Both SSTs for September and November experiences phase changes in their relationships, although at different points of time.

It is to be noted that the sea surface temperatures for all the previous winter and pre-monsoon months exhibit a significant inverse relationship with the subsequent summer monsoon rainfall over South Peninsula. Thus, the sea surface temperatures observed over this pocket can be effectively used to predict the summer monsoon rainfall of the following year over the South Peninsula region.

4. 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 [13]. 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 South Peninsula, recognized as a homogeneous region, is taken for study.

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 [14].

From the result and findings enlisted above, it can be concluded that relationships between SST (with lag in months) and summer monsoon rainfall over South Peninsula 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, wherein such climatic shifts have been interpreted by some as a manifestation of global climate change [15-16]. 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.

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 most of the previous months.

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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