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Hydroclimatic teleconnection between global sea surface temperature and rainfall over India at subdivisional monthly scale

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Abstract:

It is well established that sea surface temperature (SST) plays a significant role in the hydrologic cycle in which precipitation is the most important part. In this study, the influence of SST on Indian subdivisional monthly rainfall is investigated. Both spatial and temporal influences are investigated. The most influencing regions of sea surface are identified for different subdivisions and for different overlapping seasons in the year. The relative importance of SST, land surface temperature (LST) and ocean–land temperature contrast (OLTC) and their variation from subdivision to subdivision and from season to season are also studied. It is observed that LST does not show much similarity with rainfall series, but, in general, OLTC shows relatively higher influence in the pre-monsoon and early monsoon periods, whereas SST plays a more important role in late- and post-monsoon periods. The influence of OLTC is seen to be mostly confined to the Indian Ocean region, whereas the effect of SST indicates the climatic teleconnection between Indian regional rainfall and climate indices in Pacific and Atlantic Oceans. Copyright © 2006 John Wiley & Sons, Ltd.

KEY WORDS sea surface temperature (SST); temperature contrast; rainfall; hydroclimate; Euclidean distance

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INTRODUCTION

Sea surface temperature (SST), land surface temperature (LST) and their interaction play a significant role in the phenomenon of rainfall. The association between seasonal or annual rainfall and global SST has been investigated for different parts of world (Ogallo *et al*., 1988; Mason, 1995; Reason and Mulenga, 1999; Moron *et al*., 2001; Aldrian and Susanto, 2003). A significant influence of SST on Indian summer monsoon rainfall (ISMR; total rainfall during monsoon period, i.e. June–September (JJAS)) was reflected in earlier studies for the interannual scale (Shukla, 1975; Rao and Goswami, 1988; Chattopadhyay and Bhatla, 2002). The influence of SST from the El Niño region has been investigated widely for seasonal rainfall (Rasmusson and Carpenter, 1983). Li *et al*. (2001) have shown that the Indian Ocean SST, along with that of the Arabian Sea, plays a dominant role in the biennial oscillation of the Indian summer monsoon. Recently, Sahai *et al*. (2003) examined the relationship between SST and ISMR. Basically, the changes in SST influence the large-scale atmospheric circulation, which in turn influences the rainfall.

In other studies, the ocean–land temperature contrast (OLTC) is considered to be the basic mechanism for causing rainfall (Webster, 1987). Recent studies also show that the basic driving force of monsoon circulation is the OLTC (Li and Yanai, 1996; Liu and Yanai, 2001). According to Chao and Chen (2001):

> ... whether it (land–sea temperature contrast) really acts as the main driving force of the monsoon has not been tested in numerical experiments ... role played by land–sea contrast in the monsoon is basically equivalent to that played by SST contrast. Where land–sea contrast is important for the monsoon, the monsoon can still exist if the land is replaced by ocean of sufficiently high SST.

Thus, the temperature contrast between two locations (without considering whether land or ocean) has a role to play in causing rainfall. Robock *et al*. (2003) showed that a temperature anomaly over the land and ocean surface affects both the temperature gradient and the strength of monsoon.

However, most of the earlier studies on the influence of either SST or OLTC have investigated the spatially averaged all-India rainfall for the interannual or seasonal time-scale, whereas an analysis over a smaller spatio-temporal scale would be more useful for better management of water resources. The objective of this paper is to explore the relative influences of SST, LST and OLTC on the variability of rainfall over India for a subdivisional monthly scale, using a time-series similarity search approach. The Euclidean distance is taken as a measure of similarity (or closeness) of two time-series.

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STUDY AREA

India is spread over a large area with considerable spatial and temporal variations of rainfall characteristics in different regions. Considering this point, the Indian Meteorological Department has divided India into 35 meteorological subdivisions (Figure 1). Within a subdivision, rainfall characteristic as well as spatial variation is more or less uniform. Out of the 35 subdivisions, the following 13 subdivisions are suitably and uniformly selected from all over India: Gangetic West Bengal (6), Orissa (7), Jharkhand (8), Bihar (9), (East Uttar Pradesh (10), Punjab (14), Madhya Pradesh (19), Chattisgarh (20), Gujarat (21), Saurashtra, Kutch and Diu (22), Madhya Maharashtra (24), Vidarbha (26), and south interior Karnataka (33). The Indian Meteorological Department subdivision numbers are shown in parentheses.

DATA AND DATA TRANSFORMATION

The data for monthly global ocean surface temperature anomaly (Kaplan *et al*., 1998) for the period 1901–1990 was obtained from the website of the International Research Institute for Climate Prediction, Columbia University, USA (http://iridl.ldeo.columbia.edu). The entire globe is divided into 5° × 5° latitude–longitude grids and the SST anomaly data at the centre of each intersection point is considered.

Although a 5° × 5° resolution is coarse (compared with a 1° × 1° or 2·5° × 2·5° grid size), such a resolution is acceptable for the present study because the most influential regions of sea surface are identified for different subdivisions, as described later. It is also true that spatial variation of SST is not great when compared with rainfall. Thus, with respect to the globe, it is logically acceptable to consider a 5° × 5° region as the most influential sea surface region.

However, rainfall is far more variable in space than SST. Thus, rainfall data are used at the subdivisional scale, within which the spatial variation of rainfall is more or less uniform. Monthly rainfall data for the 13 subdivisions of India were obtained for the period 1871–2003. Maximum temperature data for (1) northeast India (2) north central India (3) northwest India (4) the interior peninsula (5) the east coast of India and (6) the west coast of India were obtained for the period 1901–1990. Both the rainfall and temperature data were obtained from the website of the Indian Institute of Tropical Meteorology (http://www.tropmet.res.in/data.html).

To investigate statistically significant relationships between two time-series, normalized monthly anomaly

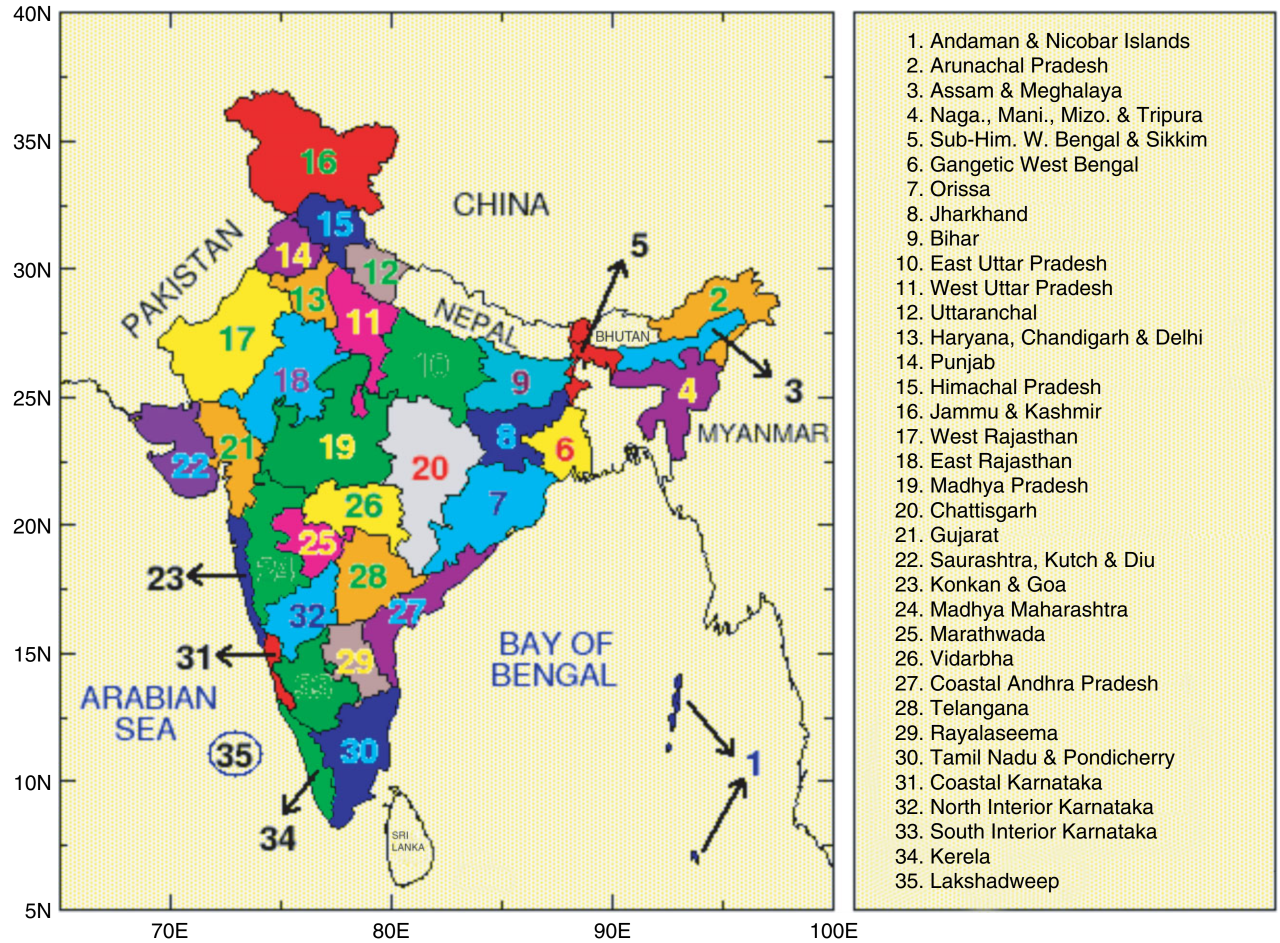

Figure 1. Location map of meteorological subdivisions in India. Source: website of the Indian Institute of Tropical Meteorology (http://www.tropmet.res.in)

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values were obtained. Month-wise anomaly values of rainfall and temperature are calculated from raw data series using

$$a_{i,j} = \frac{X_{i,j} - \overline{X_i}}{S_i} \quad (1)$$

where $a_{i,j}$ is the anomaly value for the ith month and jth year, $X_{i,j}$ is the observed value for the ith month and jth year, $\overline{X_i}$ is the mean value for the ith month calculated based on the available record and S_i is the standard deviation for the ith month calculated based on the available record.

IDENTIFICATION OF THE MOST INFLUENTIAL SEA SURFACE REGIONS

In this section, the influences of (1) SST anomaly, (2) LST anomaly and (3) OLTC on the regional rainfall over India are investigated by similarity measure. There are many methods available to measure the similarity between two time-series. The approach used most is to calculate the Euclidean distance between the two time-series, considering each to be a point in n-dimensional space, where n is the length of the time-series (Agrawal *et al*., 1993; Ma and Manjunath, 1996; Park *et al*., 1999). The Euclidean distance between two time-series X and Y is computed using

$$D_{\mathrm{E}}(X, Y) = \left[\sum_{i=1}^{n} (X_i - Y_i)^2\right]^{1/2} \quad (2)$$

The smaller the Euclidean distance, the closer the two time-series considered. In general, two-time series are considered to be similar if the Euclidean distance is less than some user-defined threshold value. A minor problem with this method is that the user has no means of measuring the similarity, other than by comparing with a threshold value. But, in this method, it is easy to identify a single time-series, from its group, that is most similar to the target time-series. For the present case, the time-series of monthly rainfall anomaly is the target series. Euclidean distances between rainfall anomaly and different cases of temperature anomaly time-series were calculated for all the grid points ($5^\circ \times 5^\circ$) throughout the globe on the basis of data for the period 1901–1990. A global contour plot was prepared based on the calculated Euclidean distances. The minimum value of Euclidean distance with its location on the sea surface (*most influential sea surface region*) were identified for each of the subdivisions and for different seasons of the year in order to investigate the spatio-temporal influences of SST and OLTC.

RESULTS AND DISCUSSIONS

Euclidean distances are calculated for three different cases of temperature anomaly. Calculation of Euclidean distances for the cases of SST only and LST only are straightforward. For the case of OLTC, the temperature anomaly difference is first obtained by deducting the SST anomaly series from the respective LST anomaly series. For example, in case of Orissa subdivision, OLTC is obtained for each grid point ($5^\circ \times 5^\circ$) by deducting SST anomaly series from the LST anomaly over the east coast of India. Thus, for each of the grid points over the sea surface, a new time-series is obtained that contains the information of temperature contrast between SST and LST. Then the Euclidean distances between the rainfall anomaly time-series and OLTC series are calculated for all the grid points throughout the globe. An analysis is performed for different overlapping seasons consisting of four consecutive months from each year.

The minimum values of Euclidean distances and their locations on the sea surface are tabulated, for all the three cases considered, in Tables I to XIII for the 13 subdivisions. In these tables, the values in italics indicate that their locations lie in the Indian Ocean region. Euclidean distances, in the case of OLTC, are in bold when they are smaller than those obtained in the case of SST only.

Table I. Results for Gangetic West Bengal subdivision[a]

Monthly sequence from each year	With SST only			With northeast India temperature			
				With LST only	With OLTC		
	Euclidean distance	Location		Euclidean distance	Euclidean distance	Location	
		Lat.	Long.			Lat.	Long.
JFMA	19·620	7·5 °S	92·5 °E	33·618	**17·921**	*17·5 °N*	*72·5 °E*
FMAM	18·708	*12·5 °N*	*52·5 °E*	34·286	**15·033**	*17·5 °N*	*62·5 °E*
MAMJ	19·440	12·5 °N	142·5 °E	34·925	**14·202**	*2·5 °N*	*62·5 °E*
AMJJ	19·552	12·5 °N	142·5 °E	34·325	**16·090**	*7·5 °N*	*87·5 °E*
MJJA	19·102	7·5 °S	27·5 °W	32·303	**18·086**	*2·5 °N*	*67·5 °E*
JJAS	19·158	32·5 °N	137·5 °E	31·384	19·602	*7·5 °N*	*72·5 °E*
JASO	18·683	62·5 °N	7·5 °W	30·659	20·429	*7·5 °N*	*97·5 °E*
ASON	18·530	32·5 °N	142·5 °E	30·273	20·378	2·5 °N	32·5 °W
SOND	18·020	2·5 °S	137·5 °E	29·648	20·435	*12·5 °N*	*87·5 °E*

[a] Italics indicate locations lie in the Indian Ocean region. OLTC Euclidean distances in bold are smaller than those obtained in the case of SST only.

Table II. Results for Orissa subdivision[a]

Monthly sequence from each year	With SST only			With northeast India temperature			
				With LST only	With OLTC		
	Euclidean distance	Location		Euclidean distance	Euclidean distance	Location	
		Lat.	Long.			Lat.	Long.
JFMA	19·124	*2·5°N*	*92·5°E*	31·963	19·310	*7·5°N*	*82·5°E*
FMAM	17·614	*2·5°N*	*92·5°E*	31·622	**17·053**	*7·5°N*	*82·5°E*
MAMJ	17·221	12·5°S	162·5°E	32·084	**15·059**	*2·5°N*	*62·5°E*
AMJJ	17·515	62·5°N	7·5°W	31·565	**16·850**	*12·5°N*	*82·5°E*
MJJA	17·715	62·5°N	7·5°W	30·811	18·872	7·5°N	112·5°W
JJAS	18·611	62·5°N	7·5°W	31·098	19·465	7·5°N	167·5°W
JASO	18·735	62·5°N	7·5°W	31·046	21·191	*12·5°S*	*32·5°W*
ASON	18·781	32·5°N	142·5°E	30·909	20·781	*2·5°N*	*57·5°E*
SOND	18·487	7·5°N	57·5°W	30·323	20·698	*2·5°N*	*62·5°E*

[a] Italics indicate locations lie in the Indian Ocean region. OLTC Euclidean distances in bold are smaller than those obtained in the case of SST only.

Table III. Results for Jharkhand subdivision[a]

Monthly sequence from each year	With SST only			With northeast India temperature			
				With LST only	With OLTC		
	Euclidean distance	Location		Euclidean distance	Euclidean distance	Location	
		Lat.	Long.			Lat.	Long.
JFMA	19·157	*2·5°N*	*92·5°E*	33·762	**16·817**	*7·5°N*	*92·5°E*
FMAM	18·698	*2·5°N*	*92·5°E*	34·240	**14·743**	*7·5°N*	*92·5°E*
MAMJ	18·762	12·5°S	162·5°E	34·434	**13·875**	*7·5°N*	*92·5°E*
AMJJ	19·508	12·5°S	162·5°E	33·701	**16·434**	*2·5°S*	*67·5°E*
MJJA	19·291	32·5°S	22·5°W	32·625	**18·103**	*2·5°S*	*67·5°E*
JJAS	19·862	32·5°N	137·5°E	32·414	**19·363**	*2·5°N*	*72·5°E*
JASO	19·801	32·5°N	72·5°W	32·093	20·133	*12·5°S*	*42·5°E*
ASON	19·885	32·5°N	142·5°E	32·399	**19·514**	*7·5°S*	*42·5°E*
SOND	19·172	27·5°N	142·5°E	31·477	19·205	*12·5°N*	*82·5°E*

[a] Italics indicate locations lie in the Indian Ocean region. OLTC Euclidean distances in bold are smaller than those obtained in the case of SST only.

Table IV. Results for Bihar subdivision[a]

Monthly sequence from each year	With SST only			With northeast India temperature			
				With LST only	With OLTC		
	Euclidean distance	Location		Euclidean distance	Euclidean distance	Location	
		Lat.	Long.			Lat.	Long.
JFMA	19·381	*7·5°N*	*92·5°E*	33·678	**17·534**	*7·5°N*	*92·5°E*
FMAM	18·705	*2·5°N*	*92·5°E*	33·720	**15·955**	*7·5°N*	*92·5°E*
MAMJ	18·972	12·5°N	147·5°E	34·407	**14·400**	*7·5°N*	*92·5°E*
AMJJ	18·707	12·5°N	147·5°E	34·089	**14·855**	*7·5°N*	*82·5°E*
MJJA	18·921	27·5°N	137·5°E	33·836	**14·896**	*7·5°N*	*82·5°E*
JJAS	19·255	27·5°N	137·5°E	33·959	**15·042**	*7·5°N*	*77·5°E*
JASO	19·136	12·5°S	37·5°W	33·389	**16·018**	*7·5°N*	*72·5°E*
ASON	19·620	*22·5°S*	*92·5°E*	32·801	**18·145**	*7·5°N*	*82·5°E*
SOND	18·328	7·5°S	27·5°W	30·929	18·706	*7·5°N*	*82·5°E*

[a] Italics indicate locations lie in the Indian Ocean region. OLTC Euclidean distances in bold are smaller than those obtained in the case of SST only.

Table V. Results for East Uttar Pradesh subdivision[a]

Monthly sequence from each year	With SST only			With northeast India temperature			
				With LST only	With OLTC		
	Euclidean distance	Location		Euclidean distance	Euclidean distance	Location	
		Lat.	Long.			Lat.	Long.
JFMA	19·610	*7·5°N*	*92·5°E*	33·512	**17·897**	*17·5°N*	*72·5°E*
FMAM	19·937	*7·5°N*	*92·5°E*	34·008	**17·673**	*22·5°N*	*67·5°E*
MAMJ	19·488	7·5°S	32·5°W	34·025	**16·255**	*17·5°N*	*67·5°E*
AMJJ	19·001	2·5°S	137·5°E	33·925	**16·338**	*17·5°N*	*67·5°E*
MJJA	18·242	12·5°S	162·5°E	33·446	**15·541**	*17·5°N*	*67·5°E*
JJAS	18·282	27·5°N	122·5°E	33·367	**16·312**	*12·5°N*	*62·5°E*
JASO	18·727	32·5°N	132·5°E	33·397	**16·578**	*12·5°N*	*62·5°E*
ASON	19·171	32·5°N	142·5°E	32·796	**17·358**	*17·5°N*	*67·5°E*
SOND	18·552	27·5°N	142·5°E	31·619	**17·747**	*12·5°N*	*57·5°E*

[a] Italics indicate locations lie in the Indian Ocean region. OLTC Euclidean distances in bold are smaller than those obtained in the case of SST only.

Table VI. Results for Punjab subdivision[a]

Monthly sequence from each year	With SST only			With northeast India temperature			
				With LST only	With OLTC		
	Euclidean distance	Location		Euclidean distance	Euclidean distance	Location	
		Lat.	Long.			Lat.	Long.
JFMA	19·200	7·5°S	42·5°E	32·446	19·374	*7·5°S*	*37·5°E*
FMAM	19·121	7·5°S	52·5°E	33·173	**18·387**	*7·5°S*	*42·5°E*
MAMJ	18·574	7·5°S	52·5°E	32·872	**17·180**	*7·5°S*	*42·5°E*
AMJJ	17·416	7·5°S	32·5°W	31·455	17·876	*7·5°N*	*72·5°E*
MJJA	16·857	7·5°S	32·5°W	30·211	18·162	7·5°N	112·5°E
JJAS	17·004	27·5°N	122·5°E	30·139	19·362	7·5°N	112·5°E
JASO	19·396	2·5°N	122·5°E	31·408	21·397	7·5°N	112·5°E
ASON	20·169	2·5°N	122·5°E	30·837	22·738	*17·5°N*	*67·5°E*
SOND	20·122	*7·5°S*	*87·5°E*	30·155	22·838	*17·5°N*	*62·5°E*

[a] Italics indicate locations lie in the Indian Ocean region. OLTC Euclidean distances in bold are smaller than those obtained in the case of SST only.

Table VII. Results for Madhya Pradesh subdivision[a]

Monthly sequence from each year	With SST only			With northeast India temperature			
				With LST only	With OLTC		
	Euclidean distance	Location		Euclidean distance	Euclidean distance	Location	
		Lat.	Long.			Lat.	Long.
JFMA	19·700	*2·5°N*	*92·5°E*	32·402	20·061	*17·5°N*	*72·5°E*
FMAM	19·488	*7·5°S*	*97·5°E*	33·157	**18·698**	*17·5°N*	*67·5°E*
MAMJ	19·615	*7·5°S*	*97·5°E*	33·995	**16·852**	*17·5°N*	*67·5°E*
AMJJ	19·334	12·5°S	162·5°E	33·642	**16·949**	*17·5°N*	*62·5°E*
MJJA	19·077	7·5°S	32·5°W	32·563	**18·707**	*12·5°N*	*57·5°E*
JJAS	18·808	22·5°N	122·5°E	32·733	**18·146**	*12·5°N*	*72·5°E*
JASO	19·716	27·5°S	162·5°E	33·174	**19·065**	*12·5°N*	*52·5°E*
ASON	20·157	*12·5°S*	*97·5°E*	32·773	**19·946**	*12·5°N*	*67·5°E*
SOND	19·313	*12·5°S*	*92·5°E*	32·166	**19·009**	*17·5°N*	*72·5°E*

[a] Italics indicate locations lie in the Indian Ocean region. OLTC Euclidean distances in bold are smaller than those obtained in the case of SST only.

Table VIII. Results for Chattisgarh subdivision[a]

Monthly sequence from each year	With SST only			With northeast India temperature			
				With LST only	With OLTC		
	Euclidean distance	Location		Euclidean distance	Euclidean distance	Location	
		Lat.	Long.			Lat.	Long.
JFMA	19·590	*7·5°N*	*92·5°E*	33·000	**18·787**	*17·5°N*	*72·5°E*
FMAM	19·721	*7·5°N*	*92·5°E*	33·496	**18·149**	*17·5°N*	*67·5°E*
MAMJ	19·155	37·5°N	37·5°W	33·435	**16·684**	*17·5°N*	*62·5°E*
AMJJ	18·382	72·5°N	2·5°E	32·590	**16·680**	*22·5°N*	*57·5°E*
MJJA	18·420	62·5°N	7·5°W	32·251	**17·639**	12·5°N	82·5°W
JJAS	17·892	62·5°N	7·5°W	31·982	**17·436**	*12·5°N*	*72·5°E*
JASO	18·063	62·5°N	12·5°W	32·165	**18·023**	*12·5°N*	*67·5°E*
ASON	18·643	62·5°N	7·5°W	31·895	**18·191**	*12·5°N*	*67·5°E*
SOND	18·455	7·5°N	57·5°W	31·468	**18·355**	*17·5°N*	*72·5°E*

[a] Italics indicate locations lie in the Indian Ocean region. OLTC Euclidean distances in bold are smaller than those obtained in the case of SST only.

Table IX. Results for Gujarat subdivision[a]

Monthly sequence from each year	With SST only			With northeast India temperature			
				With LST only	With OLTC		
	Euclidean distance	Location		Euclidean distance	Euclidean distance	Location	
		Lat.	Long.			Lat.	Long.
JFMA	20·733	*7·5°S*	*42·5°E*	30·163	23·672	*17·5°N*	*72·5°E*
FMAM	20·768	*7·5°S*	*42·5°E*	31·041	22·781	*17·5°N*	*72·5°E*
MAMJ	21·211	7·5°N	152·5°E	31·966	21·971	*17·5°N*	*67·5°E*
AMJJ	20·269	12·5°N	147·5°E	32·399	**19·210**	*7·5°N*	*77·5°E*
MJJA	19·465	*7·5°N*	*92·5°E*	32·529	**17·230**	*7·5°N*	*77·5°E*
JJAS	18·412	22·5°N	122·5°E	32·818	**15·173**	*7·5°N*	*77·5°E*
JASO	19·278	*12·5°S*	*92·5°E*	33·422	**16·101**	*7·5°E*	*77·5°E*
ASON	19·905	*7·5°S*	*87·5°E*	32·756	**18·128**	*7·5°N*	*77·5°E*
SOND	20·425	*12·5°S*	*92·5°E*	31·741	20·807	*7·5°N*	*77·5°E*

[a] Italics indicate locations lie in the Indian Ocean region. OLTC Euclidean distances in bold are smaller than those obtained in the case of SST only.

Table X. Results for Saurashtra, Kutch and Diu subdivision[a]

Monthly sequence from each year	With SST only			With northeast India temperature			
				With LST only	With OLTC		
	Euclidean distance	Location		Euclidean distance	Euclidean distance	Location	
		Lat.	Long.			Lat.	Long.
JFMA	20·573	*12·5°S*	*42·5°E*	31·310	22·518	*17·5°N*	*62·5°E*
FMAM	20·330	*7·5°S*	*42·5°E*	31·579	21·452	*17·5°N*	*72·5°E*
MAMJ	20·123	7·5°N	122·5°E	31·470	20·733	*12·5°N*	*77·5°E*
AMJJ	19·023	12·5°N	132·5°E	31·204	**18·747**	*7·5°N*	*77·5°E*
MJJA	18·537	22·5°N	122·5°E	31·015	**18·163**	*7·5°N*	*77·5°E*
JJAS	18·611	22·5°N	122·5°E	31·704	**18·035**	*7·5°N*	*77·5°E*
JASO	19·440	32·5°N	132·5°E	32·520	**18·341**	*17·5°N*	*62·5°E*
ASON	19·917	*7·5°S*	*87·5°E*	31·665	20·069	*12·5°E*	*57·5°E*
SOND	20·594	*7·5°S*	*87·5°E*	32·076	20·459	*2·5°S*	*42·5°E*

[a] Italics indicate locations lie in the Indian Ocean region. OLTC Euclidean distances in bold are smaller than those obtained in the case of SST only.

Table XI. Results for Madhya Maharashtra subdivision[a]

Monthly sequence from each year	With SST only			With northeast India temperature			
				With LST only	With OLTC		
	Euclidean distance	Location		Euclidean distance	Euclidean distance	Location	
		Lat.	Long.			Lat.	Long.
JFMA	18·578	*7·5°N*	*92·5°E*	31·251	19·309	*7·5°N*	*77·5°E*
FMAM	20·169	62·5°N	7·5°W	33·831	**18·450**	*7·5°N*	*67·5°E*
MAMJ	19·745	62·5°N	7·5°W	33·391	**18·161**	*12·5°N*	*77·5°E*
AMJJ	19·221	*7·5°N*	*92·5°E*	33·402	**16·808**	*12·5°N*	*77·5°E*
MJJA	18·388	22·5°N	122·5°E	32·913	**16·386**	*12·5°N*	*62·5°E*
JJAS	17·549	17·5°N	122·5°E	32·055	**17·081**	*12·5°N*	*62·5°E*
JASO	17·719	17·5°N	122·5°E	32·514	**16·496**	*12·5°N*	*57·5°E*
ASON	18·475	7·5°N	122·5°E	32·756	**17·271**	*12·5°N*	*62·5°E*
SOND	18·502	7·5°N	42·5°W	31·761	**18·491**	*2·5°N*	*77·5°E*

[a] Italics indicate locations lie in the Indian Ocean region. OLTC Euclidean distances in bold are smaller than those obtained in the case of SST only.

Table XII. Results for Vidarbha subdivision[a]

Monthly sequence from each year	With SST only			With northeast India temperature			
				With LST only	With OLTC		
	Euclidean distance	Location		Euclidean distance	Euclidean distance	Location	
		Lat.	Long.			Lat.	Long.
JFMA	18·854	*12·5°N*	*87·5°E*	32·259	**18·259**	*7·5°N*	*82·5°E*
FMAM	19·161	*7·5°N*	*92·5°E*	33·859	**15·887**	*7·5°N*	*77·5°E*
MAMJ	19·076	*7·5°N*	*92·5°E*	34·084	**15·031**	*7·5°N*	*72·5°E*
AMJJ	19·529	*2·5°N*	*97·5°E*	34·296	**15·651**	*7·5°N*	*77·5°E*
MJJA	18·746	2·5°S	137·5°E	33·797	**15·526**	*12·5°N*	*62·5°E*
JJAS	18·260	17·5°N	122·5°E	33·369	**15·585**	*12·5°N*	*62·5°E*
JASO	18·086	17·5°N	132·5°E	33·117	**15·886**	*12·5°N*	*57·5°E*
ASON	18·744	27·5°S	152·5°E	33·107	**16·682**	*7·5°N*	*62·5°E*
SOND	18·450	*12·5°S*	*92·5°E*	31·276	18·899	*2·5°N*	*62·5°E*

[a] Italics indicate locations lie in the Indian Ocean region. OLTC Euclidean distances in bold are smaller than those obtained in the case of SST only.

Table XIII. Results for south interior Karnataka subdivision[a]

Monthly sequence from each year	With SST only			With northeast India temperature			
				With LST only	With OLTC		
	Euclidean distance	Location		Euclidean distance	Euclidean distance	Location	
		Lat.	Long.			Lat.	Long.
JFMA	18·716	*12·5°N*	*87·5°E*	31·536	19·258	*12·5°N*	*82·5°E*
FMAM	19·998	*12·5°N*	*87·5°E*	33·236	**19·147**	*12·5°N*	*82·5°E*
MAMJ	18·944	*7·5°N*	*92·5°E*	31·071	20·209	*12·5°N*	*72·5°E*
AMJJ	18·557	*22·5°N*	*62·5°E*	30·852	19·825	*12·5°N*	*62·5°E*
MJJA	18·441	17·5°N	122·5°E	30·461	20·882	*12·5°N*	*62·5°E*
JJAS	17·774	17·5°N	122·5°E	28·442	22·419	*12·5°N*	*57·5°E*
JASO	18·280	12·5°N	127·5°E	29·948	21·620	*12·5°N*	*57·5°E*
ASON	18·177	12·5°N	122·5°E	29·635	21·971	*12·5°N*	*57·5°E*
SOND	18·640	*17·5°N*	*87·5°E*	29·576	21·890	12·5°S	112·5°W

[a] Italics indicate locations lie in the Indian Ocean region. OLTC Euclidean distances in bold are smaller than those obtained in the case of SST only.

Large Euclidean distances between the rainfall anomaly and the LST anomaly, compared with the other two cases (SST and OLTC), indicate that LST does not play a very important role on rainfall, compared with the role played by SST and OLTC. It is interesting to note that, in general, the most influential sea surface regions, in the case of OLTC, are located in the Indian Ocean region (including the Arabian Sea and the Bay of Bengal). This indicates that the OLTC is a local influential factor for the rainfall phenomenon. The most influential sea surface regions, in the case of the SST anomaly only, are generally located in the eastern and western parts of the Pacific Ocean or in the Atlantic Ocean. This may be due to the well-established climatic teleconnection between different global climate indices and ISMR (Rasmusson and Carpenter, 1983; Kane, 1998; Ashok *et al*., 2001; Sahai *et al*., 2003).

It is also observed that, during the early monsoon period, the Euclidean distance between the rainfall anomaly and OLTC is lower than that between the rainfall anomaly and just the SST for the subdivisions located in the eastern part of India, namely Gangetic West Bengal, Orissa, Jharkhand, Bihar, and Chattisgarh. On the other hand, for subdivisions located in the western part of India, namely Gujarat, Saurashtra, Kutch and Diu, Madhya Maharashtra, Vidarbha, etc., the Euclidean distance between the rainfall anomaly and OLTC also remains lower during the late monsoon period. This observation is reflected when calculating the correlation coefficient between them during different seasons, as discussed later.

Contour maps can be plotted with the global Euclidean distances for all the subdivisions. However, such contour maps are presented only for two subdivisions, namely Gangetic West Bengal and Gujarat (Figures 2 and 3 respectively) on the basis of Euclidean distances between rainfall anomaly and OLTC for the season JJAS. The approximate locations of Gangetic West Bengal and Gujarat are indicated by circles (however, the reader should refer to Figure 1 for their exact locations) and the location of global minimum Euclidean distance is shown by an asterisk. It can be interpreted that the SST anomaly data from these regions (region marked with asterisk) on the sea surface produce the best OLTC series similar to the rainfall anomaly time-series for the respective land surface regions.

The reason behind a particular region over the sea surface being the most influential for a particular subdivision is that India is a vast area and the rainfall pattern varies significantly in the spatial dimension. Thus, the reasons for rainfall over Gujarat and that over Gangetic West Bengal, for example, are different. It depends on how the effect of change in SST is transmitted by the oceanic–atmospheric teleconnection. Thus, a change in SST at a particular location in the sea may cause disturbances in the atmosphere, which may cause rainfall

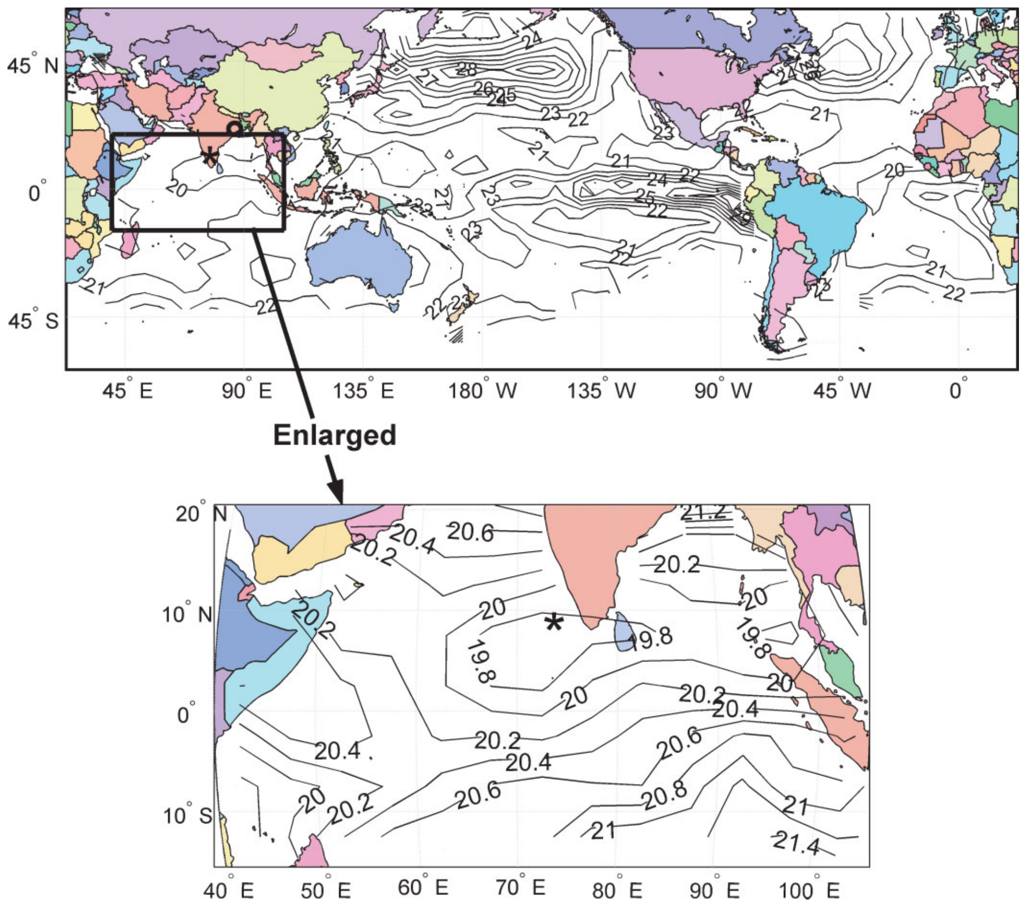

Figure 2. Contour map showing Euclidean distances between rainfall anomaly series and OLTC for Gangetic West Bengal for the JJAS season

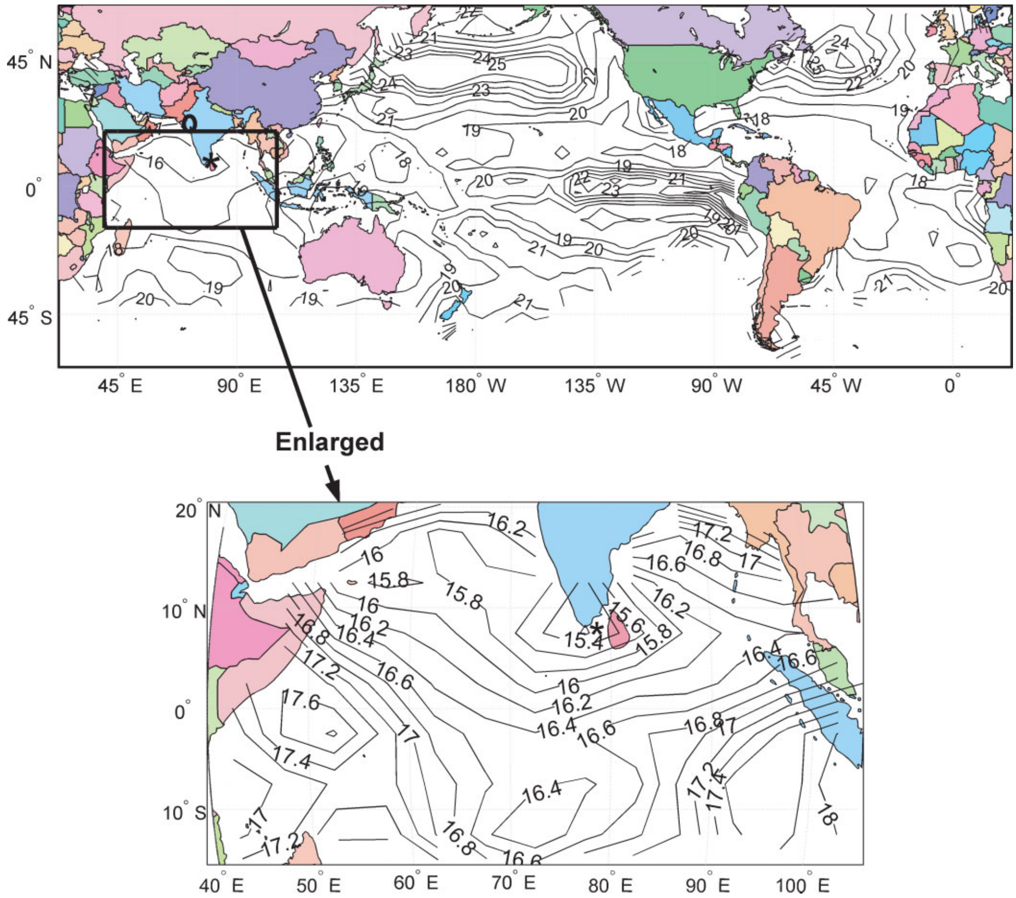

Figure 3. Contour map showing Euclidean distances between rainfall anomaly and OLTC for Gujarat for the JJAS season

in some other region through an atmospheric–oceanic teleconnection.

It is observed that the most influential regions are located in and around the western part of the tropical Indian Ocean region. To check this observation further, an anomalous OLTC series was prepared by taking the average SST anomaly from this region (specifically equator–10°N and 60–70 °E). The scatter plots between rainfall anomaly and anomalous OLTC for different monthly sequences are shown in Figures 4 and 5. Correlation coefficients are also mentioned in these scatter plots which are highly significant (significant correlation coefficient at the 95% confidence level is 0·1). From these values, it can be concluded that the two series are significantly associated with each other. Similar observations were also made for other subdivisions (figures not shown). Correlation coefficients are higher in the early monsoon period for the subdivisions located in the eastern part of the country. On the other hand, higher correlations were obtained for the late-monsoon period than for the early monsoon period for the subdivisions located in the western part of the country.

Euclidean distances between these two series were obtained for individual months (Table XIV). From these values of Euclidean distances, it can be noted that the two series for the early monsoon period are very close to each other in the case of Gangetic West Bengal, whereas in the case of Gujarat they also remain close to each other during the late-monsoon period. The reason behind this observation is that, in general, OLTC is better correlated with the rainfall anomaly for the early monsoon, as it creates the basic driving force of monsoon circulation (Li and Yanai, 1996; Liu and Yanai, 2001), which is considered to be the basic mechanism for causing rainfall (Webster, 1987). However, as rainfall over the land surface starts, the temperature of the land surface decreases rapidly; as a result, the temperature contrast between the ocean and the land surface also decreases. Thus, in the late-monsoon period, the rainfall anomaly is better associated with SST than with OLTC for most of the subdivisions located in the eastern part of India. However, during the late-monsoon period, OLTC remains as good as during the early monsoon period for the subdivisions located in the western part of India. This may be due to two reasons. First, rainfall over the subdivisions located in the western part of India (except coastal subdivisions) is lower than that over subdivisions located in the eastern part (Parthasarathy *et al*., 1995). This low rainfall causes the subdivisions over the western part of India to be warmer even after the monsoon starts, which helps the continuous existence of the temperature contrast between the ocean and land surface. Second, the SST of the Arabian Sea is in a cooling phase during the summer monsoon period (Vinayachandran, 2004), which also helps in sustaining the ocean–land temperature contrast.

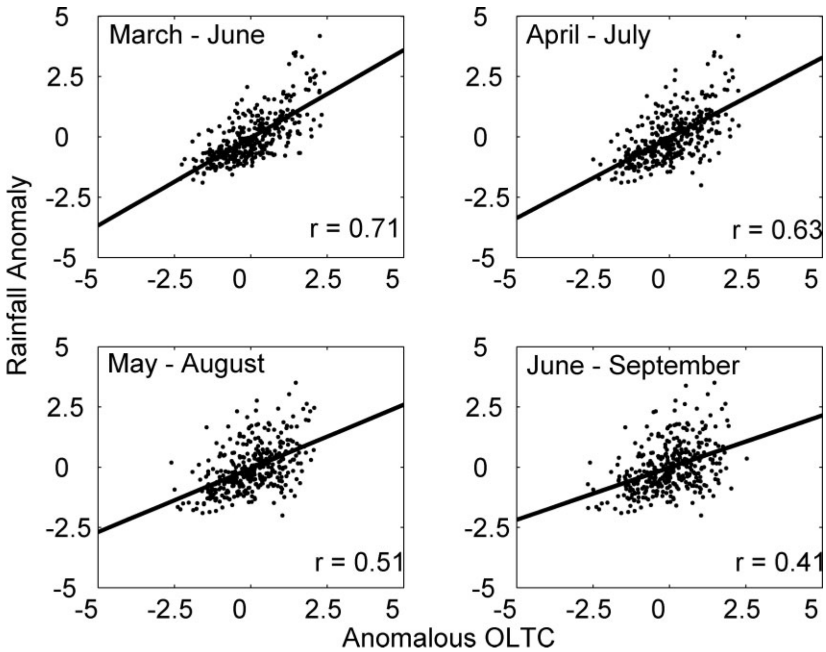

Figure 4. Scatter plot between anomalous OLTC and rainfall anomaly for different monthly sequences for Gangetic West Bengal

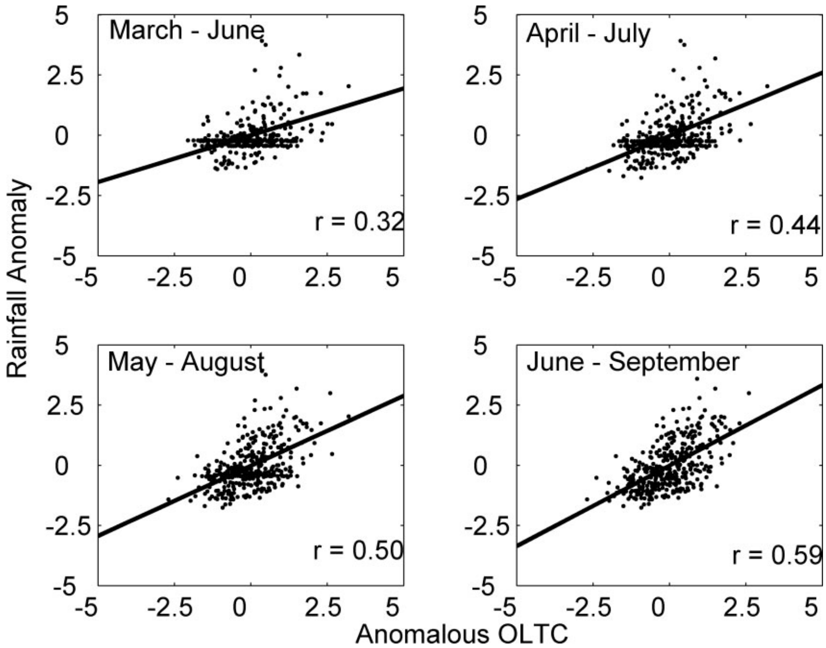

Figure 5. Scatter plot between anomalous OLTC and rainfall anomaly for different monthly sequences for Gujarat

Table XIV. Euclidean distances between rainfall anomaly and OLTC for Gangetic West Bengal and Gujarat

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Gangetic West Bengal	12·153	8·651	7·295	7·568	6·732	7·076	10·443	11·061	10·557	9·961	10·810	11·103
Gujarat	12·774	10·121	13·643	11·643	10·853	7·521	8·424	8·854	7·161	8·597	11·836	13·494

Analysis of the results in this study indicates a link between subdivisional rainfall and the recently identified Indian Ocean dipole (IOD) mode. The IOD mode is a pattern of internal variability with anomalously low SST off Sumatra and high SST in the western Indian Ocean (Saji *et al*., 1999; Webster *et al*., 1999). Saji *et al*. (1999) identified a dipole mode index that describes the difference in SST anomaly between the tropical western

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Indian Ocean (50–70 °E, 10 °S–10°N) and the tropical eastern Indian Ocean (90–110 °E, 10 °S–equator). Its impact on the Indian monsoon is still being investigated (Ashok *et al*., 2001; Gadgil *et al*., 2003, 2004). In this study, it has been shown that the most influential sea surface regions, in the case of anomalous OLTC, are located in and around the western part of the tropical Indian Ocean region (equator–10°N and 60–70 °E) and that the anomalous OLTC series obtained from this region correspond very well with the rainfall anomaly series. Thus, a link between the IOD and subdivisional rainfall over India is observed in this study. However, further investigations are necessary to corroborate this link.

CONCLUSIONS

In this study, the global influence of SST, LST and OLTC on Indian subdivisional monthly rainfall is investigated by similarity search. The most influential sea surface regions for different subdivisions of India are identified for different cases and for different overlapping seasons. The following observations are made from this study.

SST plays a more important causative role in the rainfall phenomenon than that played by just LST. But OLTC is observed to play a still more significant role for the subdivisional and monthly scale. The influence of OLTC is very prominent for the subdivisions of Gangetic West Bengal, Orissa, Jharkhand, Bihar, Chattisgarh, Vidarbha and Madhya Pradesh, particularly for the early monsoon period. It is also observed that the effect of OLTC declines for the late- and post-monsoon season.

In the case of just the SST anomaly, the most significant sea surface zones are located mostly in the tropical eastern Pacific Ocean. This is expected due to the climatic teleconnection between ISMR and different climate indices like El Niño, etc.

On the other hand, the association of the rainfall anomaly with anomalous OLTC is highly significant for monthly variation of subdivisional rainfall. The location of the most significant sea surface region is observed to be around the Indian Ocean region for this case. This indicates that OLTC is a local factor behind the rainfall mechanism, compared with other climatic teleconnections like that with the El Niño–southern oscillation. It is also observed that the most significant sea surface zones for different subdivisions are located in and around the western part of the Indian Ocean region. The anomalous OLTC, obtained from the tropical western part of Indian Ocean (equator–10°N, 60–70 °E), is significantly associated with the rainfall anomaly.

Finally, a visible link between the IOD and subdivisional rainfall over India is observed in this study. It is noted that such a link between the atmospheric part of the IOD (equatorial Indian Ocean oscillation) and ISMR has been established in some recent studies (Gadgil *et al*., 2004; Maity and Nagesh Kumar, 2006). However, to our knowledge, such a link for subdivisional rainfall is yet to be established. More investigation is necessary in this direction to corroborate this link further.

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REFERENCES

Agrawal R, Faloutsos C, Swami A. 1993. Efficient similarity search in sequence databases. In *Foundations of Data Organization and Algorithms: 4th International Conference, FODO '93 Chicago, Illinois, USA, October 13–15, 1993 Proceedings*, Lomet DB (ed.). *Lecture Notes in Computer Science*, No. 730. Springer Verlag: Berlin; 69–84.

Aldrian E, Susanto RD. 2003. Identification of three dominant rainfall regions within Indonesia and their relationship to sea surface temperature. *International Journal of Climatology* **23**: 1435–1452. DOI: 10.1002/joc.950.

Ashok K, Guan Z, Yamagata T. 2001. Impact of Indian Ocean dipole on the relationship between the Indian monsoon rainfall and ENSO. *Geophysical Research Letters* **28**: 4499–4502.

Chao WC, Chen B. 2001. The origin of monsoons. *Journal of the Atmospheric Sciences* **58**: 3497–3507.

Chattopadhyay J, Bhatla R. 2002. Possible influence of QBO on teleconnections relating Indian summer monsoon rainfall and sea-surface temperature anomalies across the equatorial pacific. *International Journal of Climatology* **22**: 121–127. DOI: 10.1002/joc.661.

Gadgil S, Vinayachandran PN, Francis PA. 2003. Drought of the Indian summer monsoon: role of clouds over Indian Ocean. *Current Science* **85**: 1713–1719.

Gadgil S, Vinayachandran PN, Francis PA, Gadgil S. 2004. Extremes of the Indian summer monsoon rainfall, ENSO and equatorial Indian Ocean oscillation. *Geophysical Research Letters* **31**: L12213. DOI: 10.1029/2004GL019733.

Kane RP. 1998. Extremes of the ENSO phenomenon and Indian summer monsoon rainfall. *International Journal of Climatology* **18**: 775–791.

Kaplan A, Cane M, Kushnir Y, Clement A, Blumenthal M, Rajagopalan B. 1998. Analyses of global sea surface temperature 1856–1991. *Geophysical Research Letters* **103**: 18 567–18 589.

Li C, Yanai M. 1996. The onset and interannual variability of the Asian summer monsoon in relation to land–sea thermal contrast. *Journal of Climate* **9**: 358–375.

Li T, Zhang YS, Chang CP, Wang B. 2001. On the relationship between Indian Ocean sea surface temperature and Asian summer monsoon. *Geophysical Research Letters* **28**: 2843–2846.

Liu X, Yanai M. 2001. Relationship between the Indian monsoon rainfall and the tropospheric temperature over the Eurasian continent. *Quarterly Journal of the Royal Meteorological Society* **127**: 909–937.

Ma WY, Manjunath BS. 1996. Texture features and learning similarity. In *Proceedings of the 1996 Conference on Computer Vision and Pattern Recognition (CVPR '96)*. IEEE Computer Society: Washington, DC; 425–430.

Maity R, Nagesh Kumar D. 2006. Bayesian dynamic modeling for monthly Indian summer monsoon rainfall using ENSO and EQUINOO. *Journal of Geophysical Research* **111**(D07104): 1–12. DOI: 10.1029/2005JD006539.

Mason SJ. 1995. Sea-surface temperature–South African rainfall associations, 1910–1989. *International Journal of Climatology* **15**: 119–135.

Moron V, Ward MN, Navarra A. 2001. Observed and SST-forced seasonal rainfall variability across tropical America. *International Journal of Climatology* **21**: 1467–1501. DOI: 10.1002/joc.690.

Ogallo LJ, Janowiak JE, Halpert MS. 1988. Teleconnection between seasonal rainfall over East Africa and global sea surface temperature anomalies. *Journal of the Meteorological Society of Japan* **66**: 807–822.

Park S, Lee D, Chu WW. 1999. Fast retrieval of similar subsequences in long sequence databases. In *3rd IEEE Knowledge and Data Engineering Exchange Workshop*, Chicago, USA.

Parthasarathy B, Munot AA, Kothawale DR. 1995. *Monthly and seasonal rainfall series for all-India homogeneous regions and meteorological subdivisions: 1871–1994*. Contributions from Indian Institute of Tropical Meteorology, Research Report RR-065, August 1995, Pune, India.

Rao KG, Goswami BN. 1988. Interannual variations of sea surface temperature over the Arabian Sea and the Indian summer monsoon:

a new perspective. *Monthly Weather Review* **116**: 558–568. DOI: 10.1175/1520-0493(1988)116<0558:IVOSST>2.0.CO;2.

Rasmusson EM, Carpenter TH. 1983. The relationship between eastern equatorial Pacific Sea surface temperature and rainfall over India and Sri Lanka. *Monthly Weather Review* **111**: 517–528.

Reason CJC, Mulenga H. 1999. Relationships between South African rainfall and SST anomalies in the southwest Indian Ocean. *International Journal of Climatology* **19**: 1651–1673. DOI: 10.1002/(SICI)-1097-0088(199912)19 : 15<1651::AID-JOC439>3.0.CO;2-U.

Robock A, Mu M, Vinnikov K, Robinson D. 2003. Land surface conditions over Eurasia and Indian summer monsoon rainfall. *Journal of Geophysical Research* **108**: 4131–4147. DOI: 10.1029/2002JD002286.

Sahai AK, Grimm AM, Satyan V, Pant GB. 2003. Long-lead prediction of Indian summer monsoon rainfall from global SST evolution. *Climate Dynamics* **20**: 855–863. DOI: 10.1007/s00382-003-0306-8.

Saji NH, Goswami BN, Vinayachandran PN, Yamagata T. 1999. A dipole mode in the tropical Indian Ocean. *Nature* **401**: 360–363.

Shukla J. 1975. Effect of Arabian Sea surface temperature anomaly on Indian summer monsoon: a numerical experiment with GFDL model. *Journal of the Atmospheric Sciences* **32**: 503–511.

Vinayachandran PN. 2004. Summer cooling of the Arabian Sea during contrasting monsoons. *Journal of Geophysical Research* **31**: L13306. DOI: 10.1029/2004GL019961.

Webster PJ. 1987. The elementary monsoon. In *Monsoons*, Fein JS, Stephens PL (eds). Wiley: New York; 3–32.

Webster PJ, Moore AM, Loschnigg JP, Leben RR. 1999. Coupled oceanic–atmospheric dynamics in the Indian Ocean during 1997–98. *Nature* **401**: 356–360.