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Relationship between ocean mean temperatures and Indian summer monsoon rainfall

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Abstract

Besides improving the understanding of the physics of the challenging problem of monsoon prediction, it is necessary to evaluate the efficiency of the input parameters used in models. Sea-surface temperature (SST) is the only oceanographic parameter applied in most of the monsoon forecasting models, which many times do not represent the heat energy available to the atmosphere. We studied the impacts of ocean mean temperature (OMT), representing the heat energy of the upper ocean, and SST on the all India summer monsoon rainfall through a statistical relation during 1993–2013 and found that OMT has a better link than SST.

Keywords: ocean mean temperature; Indian summer monsoon rainfall; remote sensing; sea surface height anomaly

1. Introduction

Agricultural countries, such as India, have a great demand for accurate, long range forecast (LRF) of monsoon rainfall, which has always been a challenging problem. The India Meteorological Department (IMD) has been issuing the forecasts for the Indian summer monsoon rainfall (ISMR) for many years. Sadhuram (1997) and Sadhuram and Murthy (2001) used SST to predict monsoon rainfall. The variation of ISMR is 10% over its long-term (1941–1990) mean of 89 cm (Rajeevan *et al.*, 2006). Even this small variability (the maximum year-to-year amplitude) has shown to have devastating impacts on the agricultural sector in India. Many dynamical and statistical models, including the operational models of IMD, failed to predict the weak summer monsoon of 2002 and 2004 (Rajeevan *et al.*, 2006; Kumar *et al.*, 2012). However, an empirical statistical model (Rajeevan *et al.*, 2006) was able to provide the correct hindcast for the 2002 and 2004 ISMR. This model was developed using a new method of predictor selection. One of these predictors is the sea-surface temperature (SST) in the Indian Ocean spanning from 20–10°S to 100–120°E.

Three main types of approaches are currently used for the LRF of ISMR: (1) the statistical approaches, (2) the soft computing techniques and (3) the dynamical methods. The statistical methods use the relation between the ISMR and the atmospheric parameters (e.g. Delsole and Shukla, 2002; Rajeevan *et al.*, 2004, 2006; Pai and Rajeevan, 2006; and the references cited there in). Secondly, soft computing techniques use, time series of the past rainfall data without any predictors (Goswami and Srividya, 1996; Kishtawal *et al.*, 2003; Iyengar and Raghukanth, 2004). Thirdly, analytical methods use general circulation models of the atmosphere and the ocean based on fluid dynamics. Probably, due to the lack of perfect understanding of the physics coupled with imperfect initialization, the dynamical models have not shown at this moment the required skill to accurately predict the ISMR and its inter-annual variability (Krishnamurti *et al.*, 2000; Kang *et al.*, 2002; Gadgil *et al.*, 2005; Krishna Kumar *et al.*, 2005; Wang *et al.*, 2005).

Analyses of the forecast failures of 2002 and 2004 concluded that operational forecast skill by IMD based on statistical methods has not improved despite the continued changes in the operational models (Gadgil *et al.*, 2005). One possible approach using statistical tools towards improving the forecasts is to introduce new parameters into one of the schemes. Recent studies suggest assessing the use of SST and upper ocean heat content for cyclone intensity prediction in the northern Indian Ocean (Ali *et al.*, 2013a, 2013b). Charney and Shukla (1981) hypothesize that tropical climate has a potential for long-term prediction because a significant part of its long-term variability is determined by slowly varying climate parameters like SST rather than by synoptic scale variability. However, the ability of SST to predict the seasonal mean monsoon has not been firmly established (Krishnamurthy and Kirtman, 2008). It has been shown that more than 50% of the north Indian Ocean tropical cyclone intensities have negative correlation with SST (Ali *et al.*, 2013b). Namias and Canyan (1981) concluded that patterns of lower atmospheric anomalies are more consistent with the upper ocean thermal structure than with SST alone. Sudden unexpected intensification of hurricane Opal, with its core pressure dropping from 965 to 916 hPa over a 14-h period (Shay *et al.,* 2000), is a classical example of the impact of upper ocean on an extreme weather phenomenon. Subsequently, a number of studies demonstrated the importance of sea surface height anomaly (SSHA) and oceanic eddies in cyclone intensity and track predictions (Goni and Trinanes, 2003; Ali *et al.,* 2007a, 2007b; Goni *et al.,* 2009; Lin *et al.,* 2009, 2012). As the atmosphere interacts with the thermal energy available in the upper ocean, which should be described in terms of the ocean heat content (OHC) rather than with SST alone, this parameter would be, in principle, a better predictor for long range monsoon forecasting. In these studies, it is hypothesized that OHC, rather SST alone, may serve as a predictor for cyclone studies because: (1) SSTs in the North Indian Ocean have large diurnal cycles in response to low wind speeds, low evaporation and strong insolation, and (2) the longer-term atmosphere interactions are with the upper layer of the ocean rather SST alone. Most of the studies refer to the role played by the OHC on cyclone intensities/tracks. However, no study has demonstrated, to-date, the importance of the OHC over SST for ISMR predictions. In this work, we introduce a new parameter referred as ocean mean temperature (OMT) to represent the OHC. For this purpose, we used the tropical cyclone heat potential (TCHP), estimated from the satellite altimeter-derived SSHA, as a proxy for OHC. As OMT and SST have the same units the replacement of the second parameter with the first in atmospheric models is convenient.

The objective of this work is to statistically show that OMT is a better link to ISMR than SST. Given that ISMR is mainly influenced by atmospheric parameters we do expect that neither SST nor OMT will be extremely well correlated with ISMR.

2. Data and methods

The ISMR is calculated as the area-weighted average (Rajeevan *et al.,* 2006) of the June–September rainfall data of all the 36 meteorological subdivisions in India during the time period 1993–2013. The ISMR time series is constructed from a network of more than 2000 rain gauges of IMD spread over India, including the hilly regions. Optimally interpolated monthly SST (following Reynolds, 1988) is obtained from the extended reconstructed SST (www.apdrc.soest.hawaii.edu). The TCHP data were estimated from altimeter-derived SSHA and SST following already established procedures (Goni *et al.,* 1996; Shay *et al.,* 2000). As the altimetry-derived SSHA fields are correlated with the available *in situ* hydrographic observations, synthetic temperature profiles are obtained to estimate the TCHP fields from satellite altimetry. TCHP and the depth of 26 °C isotherm fields were made available (www.aoml.noaa.gov) on weekly basis from 1993 to

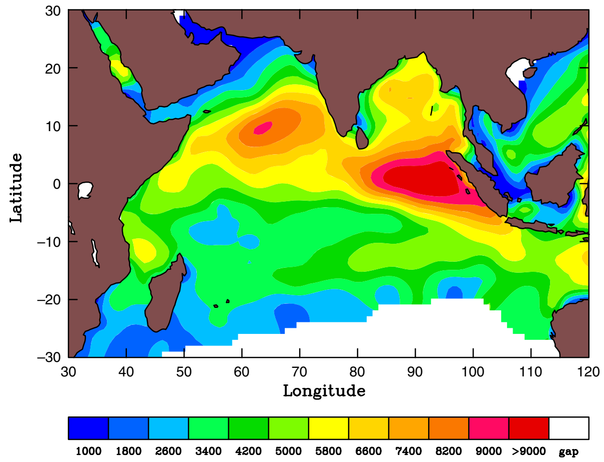

Figure 1. Annual mean depth of the 26 °C isotherm depth (cm).

2007 and on a daily basis since 2008, which was the beginning of the high-resolution satellite altimetry products, at a grid spacing of 0.25 × 0.25 degree. Nagamani *et al.* (2012) compared these satellite-derived TCHP fields with those estimated from *in situ* hydrographic measurements and reported a root mean-square difference of 20.95 kJ cm^{-2}, with a coefficient of determination, R^2, of 0.65 and a bias of 11.27 kJ cm^{-2}. As TCHP cannot be used in place of SST in the numerical models, we converted TCHP to OMT using a few assumptions. As $\mathrm{TCHP}_{\mathrm{satellite}}$ and $\mathrm{TCHP}_{in\ situ}$ correlate well (and have a regression slope near one, and a y-intercept near zero), the Equation (1) is used to compute OMT from TCHP.

$$\mathrm{TCHP} = \rho C_{\mathrm{p}} \int_0^D 26\,(T-26)\,\mathrm{d}z \qquad (1)$$

where, ρ is the density of the sea water, C_{p} the specific heat capacity at constant pressure, T the temperature (°C) of each layer of dz thickness, and D_{26} the depth of 26 °C isotherm. This depth varies from 10 to 90 m (Figure 1). The depth of 26 °C isotherm is maximum (>90 m) near the eastern equatorial Indian Ocean. The southern Indian Ocean has lower values and the depth decreases to 10 m at around 30 N. The blank areas indicate that the SST around this region is less than 26 ° C. If we assume a mean temperature of the layer (from the surface to D_{26}) as OMT, the above equation can be simplified as:

$$\mathrm{TCHP} = \rho C_{\mathrm{p}}\,(\mathrm{OMT}-26)\,D_{26} \qquad (2)$$

From Equation (2), OMT can be estimated as

$$\mathrm{OMT} = \left(\mathrm{TCHP}/\rho C_{\mathrm{p}}\,D_{26}\right) + 26 \qquad (3)$$

The daily OMT values thus computed at a grid spacing of 0.25° have been averaged on monthly basis to a grid spacing of 1° × 1° using Cressman's (1959) technique with weighting function (WF) given by

$$\mathrm{WF} = \left(S^2 - D^2\right) / \left(S^2 + D^2\right) \qquad (4)$$

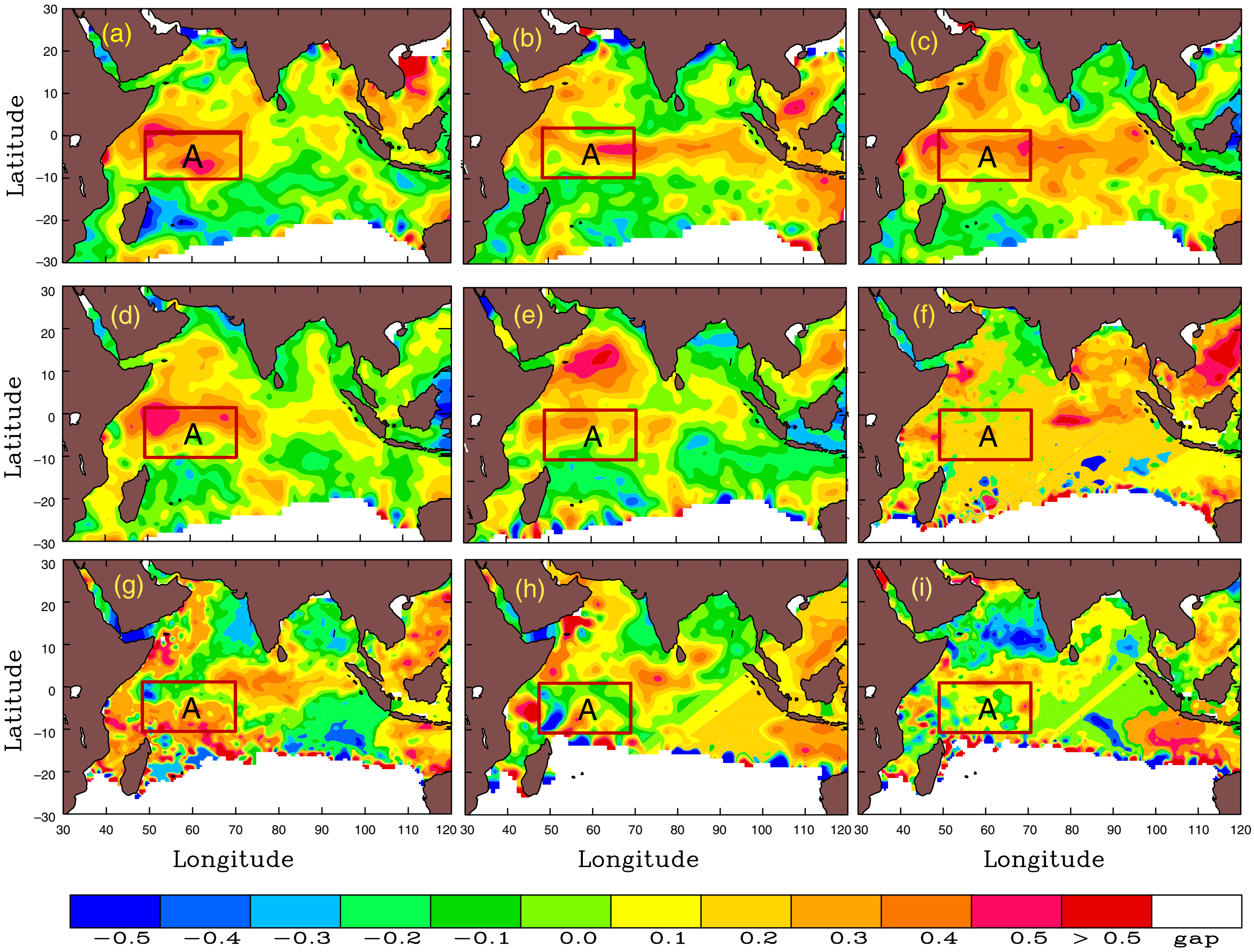

Figure 2. Pearson's correlation coefficient, r, between Indian summer monsoon rainfall and ocean mean temperature for (a) January, (b) February, (c) March, (d) April, (e) May, (f) June, (g) July, (h) August, and (i) September during 1993–2013.

where S is the search radius (1 degree in this case) and D is the distance between the center of the grid and the observation point. Then, the Pearson's correlation, r, was obtained from the ISMR and OMT time series based on all the months during 1993–2013 over 30°S to 30°N, and 30°E to 120°E. Similarly, r was computed between SST and ISMR for all the 12 months.

3. Results and discussions

The spatial distribution of r between OMT and ISMR from January to September during the study period (1993–2013) are shown in Figure 2 and those between SST and ISMR, in Figure 3. The correlations above 0.43 are significant at 98%. The OMT in the south western Arabian Sea, spanning from 10°S to 0°S and 50°E to 70°E (box A in Figure 2) has a better correlation with ISMR from January to April. This high correlation region has moved northward in May (5–20°N and 50–70°E) with an r of more than 0.5. As OMT represents the average temperature of the upper layer down to 26 °C isotherm depth, our results are in agreement with those of Dube *et al.* (1990), where, through numerical simulations, they reported that the interannual variability of the upper-layer thickness of the central Arabian Sea has a good correlation with ISMR. The entire Bay of Bengal has no significant correlation between ISMR and OMT from January to May indicating that the Arabian Sea may play a more prominent role in the variability of ISMR rather than Bay of Bengal. One reason for this could be that the southwest monsoon enters India through the Arabian Sea.

The r between SST and ISMR (Figure 3) is less than that between OMT and ISMR (Figure 2). IMD uses SST of February and March over the regions 20–10°S and 100–120°E (box B in Figure 3) for its current LRF of ISMR (Rajeevan *et al.,* 2006). From this figure, it is clear that the SST of the region A has a better correlation with ISMR than with that of region B. For further study, we computed r between ISMR versus OMT and SST of region A and that between ISMR and SST of region B (Table 1).

Considering all the values in the entire box A, OMT of January has a statistically significant correlation (at 98%) with ISMR ($r = 0.44$). However, there is a negative correlation of −0.45 between ISMR and SST in September, which means that lower temperature in box A is associated with greater rainfall explaining about

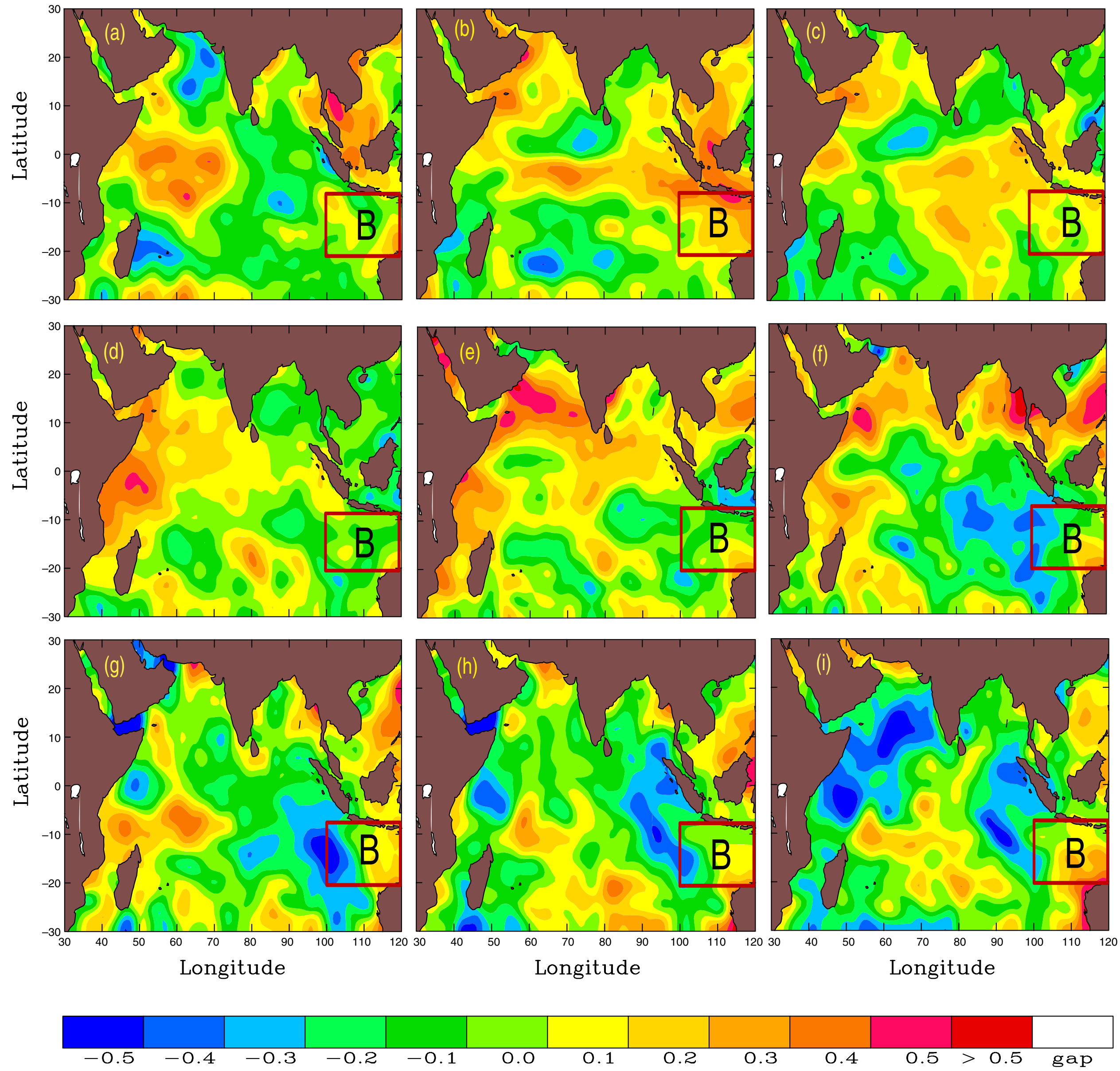

Figure 3. Pearson's correlation coefficient, *r*, between Indian summer monsoon rainfall and sea-surface temperature for (a) January, (b) February, (c) March, (d) April, (e) May, (f) June, (g) July, (h) August, and (i) September during 1993–2013.

Table 1. Pearson's correlation between ISMR and the predictors: OMT and SST in box A and SST alone in box B from January to September during 1993–2013. Level of significance in % is shown in parenthesis, and if not shown it is below 75%.

	Months								
Parameters	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**
OMT (box A)	0.44 (98%)	0.32 (90%)	0.23 (80%)	−0.03	0.00	0.28 (85%)	0.39 (90%)	0.27 (85%)	0.03
SST (box A)	0.28 (85%)	0.20 (80%)	−0.13	−0.05	−0.08	0.18	0.36 (90%)	0.18	−0.45 (98%)
SST (box B)	0.01	0.14	−0.04	−0.14	0.08	0.27 (80%)	0.32 (90%)	0.10	0.33 (90%)

20% of the variance in rainfall with September SSTs in box A region. However, the September correlation does not have a predictive value as this is the last month of the Indian summer monsoon season. That the correlation is very likely an effect of the monsoon variability (e.g. a shorter monsoon season), rather than related to a cause (Anonyms Referee, 2014, pers. comm.). Only the correlation between ISMR and OMT for January and ISMR and SST for September are significant at 98% confidence level, although other correlations are significant at 75, 80, 85 and 90% confidence levels. While there are statistically significant correlations between OMT and ISMR as well as SST and ISMR in box A, the correlation and confidence levels are greater for OMT than SST. The significant correlations between SST and ISMR in box B starts only after June (after the onset of the southwest monsoon). The correlations between SST and ISMR of both boxes A and B are less than those between OMT and ISMR for January through March, July and August. As OMT in box A in January itself has a significant correlation with ISMR this value can be used in place of SST of box B in the statistical prediction model of ISMR. As SST in box A is also significant, although less than that of OMT, a combination of using OMT and SST of this region is another possibility; however, these variables are not independent, therefore they cannot be used together without additional considerations. A question that could arise from this study is, how can the Indian rainfall be influenced by a region that is quite far and 6 months in advance. Winds from the south of the equatorial Indian Ocean pass through this region before reaching the Indian coast. As OHC of this place is a useful indicator of the long-term transfer of energy and moisture to the atmosphere, it helps to understand the atmospheric circulation pattern and perhaps the amount of water vapour associated with the circulation of the monsoon.

4. Summary and conclusions

India, being an agricultural country, has a demand for accurate long-range forecast of the monsoon rainfall. Besides attempting to understand the physics of the monsoon problem it is also valuable to assess new parameters that can be used as predictor to improve forecasts. The atmosphere interacts with the upper layer of the ocean rather with the sea-surface skin represented by SST alone. Although the atmosphere does respond to SSTs, the evolution of SST patterns depends much on OHC. Such an impact of the heat energy available in the deeper layers of the ocean is shown for cyclone studies. For the first time, we computed a new parameter called OMT, which represents the heat available in the ocean layer to the depth of the 26 °C isotherm. The OMT is estimated from TCHP that was computed from satellite altimeter observations. A suite of different regions and months were selected to carry out this study and to assess the impact of this parameter on ISMR. While there are statistically significant correlations between OMT and ISMR as well as SST and ISMR in box A, the correlation and confidence levels are greater for OMT than SST. The significant correlations between SST and ISMR in box B start in June, after the onset of the southwest monsoon. As the OMT in January has a better significant correlation with ISMR with a predictive value the capability to forecast ISMR in January itself is another advantage of using OMT of box A.

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