Increasing Trend of "Break-Monsoon" Conditions Over India—Role of Ocean–Atmosphere Processes in the Indian Ocean

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***Abstract*—Analysis of daily rainfall data over India during the period 1951–2007 reveal an increased propensity in the occurrence of "monsoon-breaks" over the subcontinent. The increasing trend is seen both in the duration and frequency of monsoon-breaks over the subcontinent, the causes for which are investigated using *in situ*, satellite, and reanalysis data products. While noting that the increasing trend of break-monsoon conditions is consistently related to changes in large-scale monsoon circulation and vertically integrated moisture transport; the findings also point to the role of sea surface temperature (SST) warming trend (0.015 °C · year^{-1}) in the tropical eastern Indian Ocean (IO) in inducing anomalous changes favorable for the increased propensity of monsoon-breaks. The results indicate that the SST warming in the tropical eastern IO has altered the ocean–atmosphere processes in a manner as to intensify the near-equatorial trough over the IO, but has led to a weakening of the southwest summer monsoon flow in recent decades into the Indian landmass.**

***Index Terms*—Equatorial Indian Ocean (IO) sea surface temperature (SST) warming trend, Indian monsoon, trends in "monsoon-breaks".**

I. Introduction

THE INDIAN subcontinent receives over 75% of the mean annual rainfall during the summer monsoon season (June–September), with July and August being the peak monsoon months which together contribute to about 61% of the mean monsoon seasonal rainfall [14] (hereafter referred as RU04). The summer monsoon low-level cross-equatorial flow [13], with its core at a height of about 1.5 km, brings in plenty of moisture from the south Indian Ocean (IO) into the Indian subcontinent [12]. The rainfall distribution is not continuous within the life cycle of a monsoon, but is associated with multiple spells of active and break monsoon phases. Prolonged breaks in the monsoon rainfall during July and August months can create drought conditions over the country, as witnessed recently in 2002—which incidentally had one of longest break spells of about 34 days [RU04]. In a recent study, Kalnay *et al.* [4] reported a weakening of the low-level summer monsoon flow through peninsular India during the past 50 years, based on National Centers for Environmental Prediction (NCEP)/National Center for Atmospheric Research (NCAR) reanalysis data [4].

Observations indicate that deep convection over the equatorial eastern IO tends to be enhanced during break-monsoon phases (e.g., [6]–[8], [15], and [20]). Krishnan *et al.* [8] pointed out that anomalous coupling between the monsoon winds and the IO dynamics on intraseasonal timescales can force prolonged monsoon-breaks leading to drought conditions over the subcontinent. This coupling involves a wind-thermocline feedback which maintains warmer-than-normal sea surface temperature (SST) and enhanced convection over eastern equatorial IO, so that the near-equatorial conditions can, in turn, weaken the monsoon flow and inhibit rainfall activity over the Indian landmass by inducing anomalous subsidence through the regional Hadley cell. By conducting general circulation model simulations, Krishnan *et al.* [7] further showed that persistently warmer-than-normal SST in the equatorial IO is effective in prolonging monsoon-breaks through changes in the regional Hadley circulation and regional rainfall distribution. If indeed the summer monsoon circulation has weakened in recent decades [3], it would be important to understand the associated changes in the incidence of monsoon-breaks in the last 50+ years, and gain insight into the physical mechanisms linked with the low-frequency interdecadal timescale variations/changes of the Indian summer monsoon. Keeping this in view, we have conduced detailed analyses of atmospheric and oceanic data sets for the period 1951–2007.

II. Data and Methodology

The recently released high-resolution daily gridded rainfall data set over India [11] is used in this letter. Only 1803 stations out of the possible 6329 stations had a minimum of 90% data availability for the study period 1951–2003, and the same have been used for the analysis of monsoon-breaks. More details regarding the data, its distribution, and quality can be found in [11]. Using the rainfall data for the period 1951–2007, we have identified monsoon-breaks during the peak months of July and August following the procedure described by RU04. Furthermore, we have classified monsoon-breaks into two different types depending upon their duration: 1) Type I (short-breaks, duration ≤ 7 days) and 2) Type II (long-breaks, duration > 7 days). Atmospheric winds and specific humidity at various pressure levels have been extracted from the NCEP/NCAR Reanalysis data set [4]. SST data are based on the extended reconstructed SST, which was constructed using the most recently

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TABLE I
DECADEWISE NUMBER OF BREAKS AND BREAK DAYS FOR JULY AND AUGUST MONTHS. *NOTE THAT THE DATA FOR 2001–2007 COVER A SEVEN-YEAR PERIOD

Decade	July		August	
	Breaks/Year	Break days/Year	Breaks/year	Break days/Year
1951-1960	1.9	9.5	2.4	13.1
1961-1970	1.6	8.7	1.9	13.7
1971-1980	1.5	7.1	2.4	13.5
1981-1990	1.8	9.9	2.5	15.5
1991-2000	1.6	10.1	2.7	14.8
2001-2007*	1.7	13.3	2.6	15.6
Mean	1.7	9.8	2.4	14.4

TABLE II
DECADEWISE DISTRIBUTION OF DIFFERENT TYPES BREAKS (SHORT DURATION BREAKS (TYPE I) AND LONG DURATION BREAKS (TYPE II), TOTAL NUMBER OF BREAKS AND PERCENT OF THE LONG DURATION BREAKS TO THE TOTAL NUMBER OF BREAKS FOR STUDY PERIOD. *NOTE THAT THE DATA FOR 2001–2007 COVER A SEVEN-YEAR PERIOD

Decade	Type I			Type II			Total Number of breaks	% of Type II breaks to the total number of breaks
	J	A	T	J	A	T		
1951-1960	15	21	36	3	4	7	43	16
1961-1970	14	12	26	3	6	9	35	26
1971-1980	14	18	32	2	5	7	39	18
1981-1990	15	19	34	3	6	9	43	21
1991-2000	9	20	29	7	7	14	43	33
2001-2007*	7	12	19	5	4	9	28	32

available International Comprehensive Ocean Atmosphere Data Set data and improved statistical methods [19].

III. RESULTS AND DISCUSSION

Table I gives a decadewise statistical summary of break-monsoon days and break-spells for July and August months during the period 1951–2007. It is important to note that data for 2001–2007 cover only seven years, while the remaining decades during 1951–2000 are based on ten years of data. Table II shows the decadewise distribution of short and long monsoon-breaks depending upon their duration. From Table I, it is seen that the mean break-spells and number of break-days are relatively higher in August as compared to July. However, it is interesting to note that the frequency of break-spells and the number of break-days during the period 1951–2007 show an increasing trend. In particular, the occurrence of long breaks (Type-II) during July and August are found to have increased in recent decades (Table II). Particularly, there has been a clear increase in the long breaks during the post mid-1970s as can be seen from the increase in the percentage of the Type II breaks to the total number of breaks (Table II).

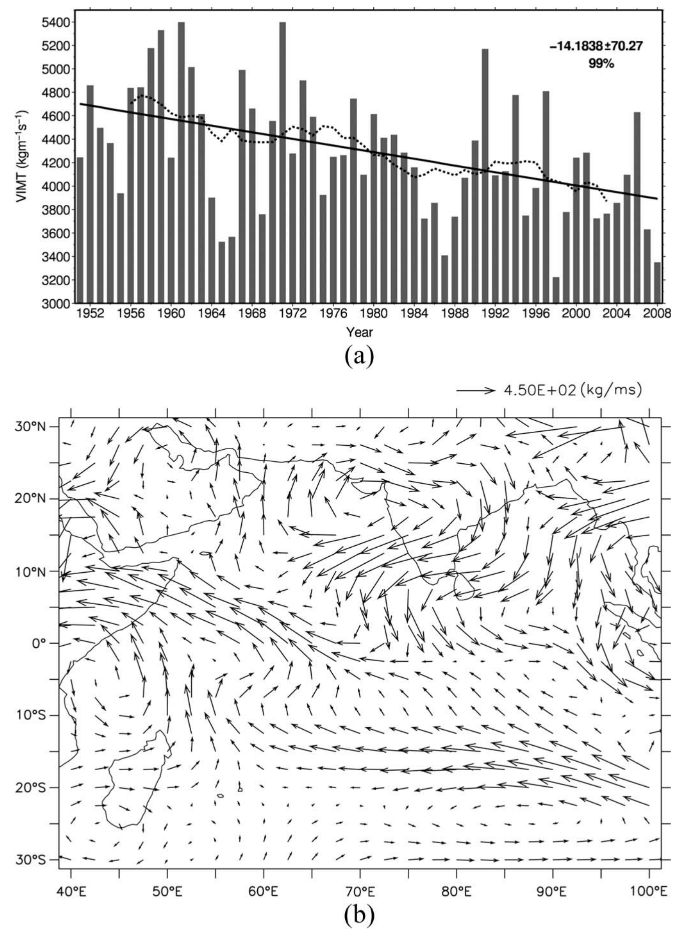

Fig. 1. (a) Time series of VIMT (in kilograms per meter per second) for the peak monsoon months (July–August) over the Indian region (8°–18° N; 70°–80° E) during the period 1951–2008. The dotted curve is the 11-year moving average, and the solid line is the fitted linear trend. (b) Difference in VIMT vector (in kilograms per meter per second), for the July–August months, between the post mid-1970s (1977 to 2008), and pre mid-1970s (1951 to 1976) epochs.

Fig. 1(a) shows the time series of the magnitude of the vertically integrated moisture transport (VIMT) over the Indian region (8°–18° N; 70°–80° E), for the peak monsoon months (July–August), during the period 1951–2008. The VIMT has been computed following [1]. Since the monsoonal winds transport moisture from the IO to the subcontinent, our intention is to understand whether the increase in the occurrence of long-breaks in recent decades is related to changes in the moisture transport. The year-to-year variations of the VIMT time series in Fig. 1(a) basically correspond to the monsoon interannual variability (e.g., [2] and [21]). Additionally, it is important to note that the VIMT time series for the period 1951–2008 shows a significant decreasing trend of about $-14.2\ \mathrm{kg \cdot m^{-1} \cdot s^{-1} \cdot year^{-1}}$, which is statistically significant at the 99% confidence level. An interesting point in Fig. 1(a) is the decadal-like variability of VIMT. In particular, the low-frequency decadal-like variability is prominently discernible between the pre and post mid-1970s values; with the pre mid-1970s showing relatively higher values of VIMT as compared to the post mid-1970s. The same can be confirmed by computing the difference in the VIMT between the post mid-1970s (1977–2008) and the pre mid-1970s (1951–1976). Fig. 1(b) shows the map of the difference in the VIMT vector between the two epochs. Notice

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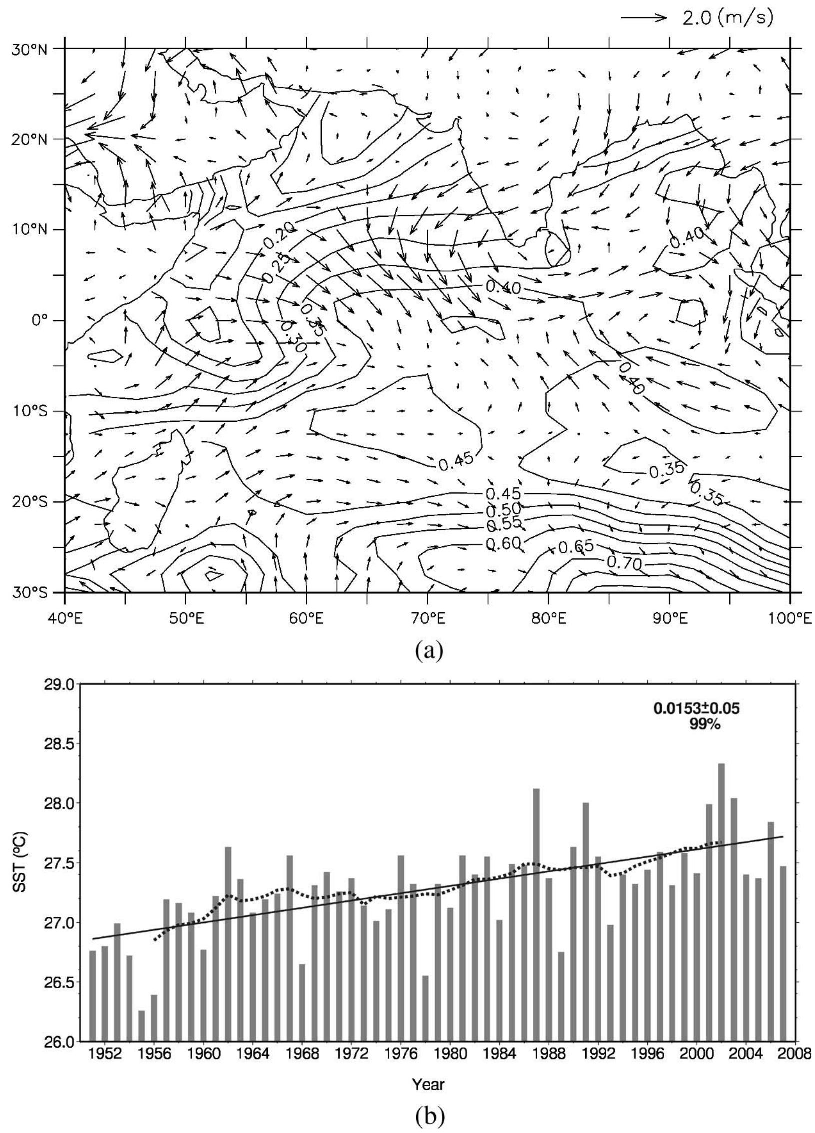

Fig. 2. (a) Difference maps of SST (in degrees Celsius) and surface winds (in meters per second), for the July–August monsoon months, between the post mid-1970s (1977 to 2007) and pre mid-1970s (1951 to 1976) epochs. (b) Time series of the SST (in degrees Celsius), for the July–August monsoon months, in the equatorial eastern IO (0°–10° S; 70°E–90° E) for the period 1951–2007. The dotted line gives the 11-year moving average, and the solid line is the fitted linear trend.

that the anticyclonic anomaly of VIMT over the Indian landmass and adjoining area indicates a decrease in the moisture transport into the Indian monsoon region; whereas a cyclonic shear zone of the VIMT anomaly can be seen over the eastern tropical IO.

Past studies have drawn attention to SST warming trends in the tropical eastern IO following the mid-1970s (e.g., [10] and [22]). Here, we shall try to understand the circulation changes over the tropical IO in the context of the regional SST warming in recent decades. Fig. 2(a) shows the difference in SST between the two epochs, post mid-1970s and pre mid-1970s. Superposed on the SST difference map is the difference of surface winds between the post mid-1970s (1977–2007) and the pre mid-1970s (1951–1976) epochs. A pattern of anomalous SST warming can be clearly seen in the eastern tropical IO, together with anomalous westerly winds along the equator. An anticyclonic anomaly can be seen over the Indian landmass and the Arabian Sea which is indicative of a weak monsoon low-level flow, while the anomalous equatorial westerlies are associated with the formation of a cyclonic shear zone over the eastern tropical IO. In short, the pattern of SST warming in the eastern IO is associated with an intensified equatorial shear-zone or an equatorial trough [Fig. 2(a)].

It is known that during weak-monsoon phases, the monsoon cross-equatorial flow acquires a southward curvature in a manner as to avoid blowing into the Indian subcontinent [16]. Krishnan *et al.* [8] noted that the anomalous equatorial westerly winds, during weak-monsoon phases, tend to deepen the thermocline in the eastern equatorial IO and thereby maintain warmer-than-normal SST in the region. They further pointed out that the positive SST gradient along the equator, which results from the anomalous warming of the eastern IO, can help sustain anomalous equatorial westerly winds through a Bjerknes-type wind-thermocline feedback mechanism. It can

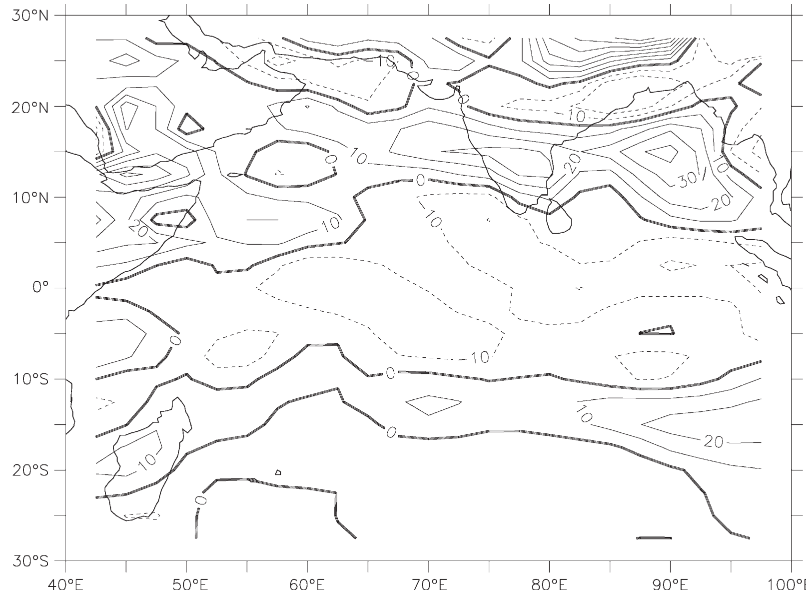

Fig. 3. Difference map of divergence ($\times\ 10^{-5}\ \mathrm{kg \cdot m^{-2} \cdot s^{-1}}$) of the VIMT vector, for the July–August monsoon months, between the post mid-1970s (1977 to 2008) and pre mid-1970s (1951 to 1976) epochs.

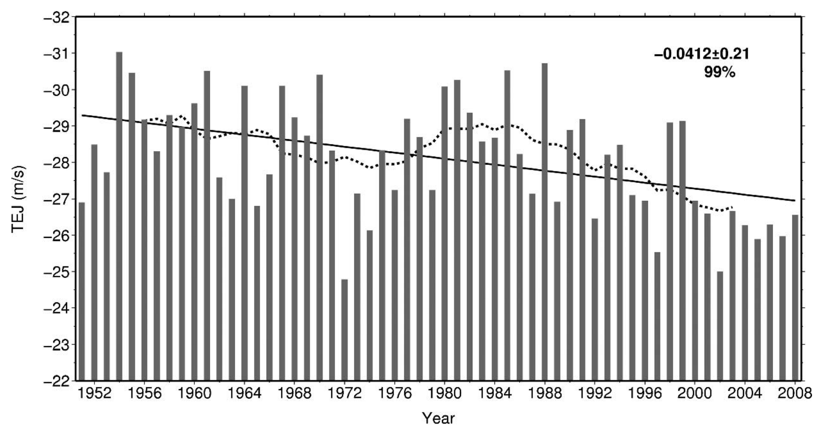

Fig. 4. Time series of the zonal wind (in meters per second) at 150 hPa, for the July–August monsoon months, averaged over the region (5°–20° N; 40°–100° E) during the period 1951 to 2008. The dotted line is the 11-year moving average, and the solid line is the linear trend.

be noted from Fig. 2(a) that the SST warming is more pronounced in the eastern tropical IO as compared to the western IO, which is consistent with the strengthening of equatorial westerly winds. The warming trend in the tropical eastern IO is also evidenced in the SST time series (1951–2007) shown in Fig. 2(b); moreover, it is noted that the rate of SST warming is about 0.015 $^\circ\mathrm{C} \cdot \mathrm{year}^{-1}$ which is statistically significant at 99% level.

If indeed the equatorial westerly winds and the zonal gradient of SST have strengthened in recent decades, then the moisture convergence over the tropical eastern IO is expected to enhance in response to the intensified SST gradient (e.g., [8] and [9]). Fig. 3 shows the difference map of the divergence of the VIMT vector between the post mid-1970s (1977–2008) and pre mid-1970s (1951–1976) epochs. The positive anomalies over the Indian landmass indicate anomalous divergence of moisture, while the negative anomalies over the tropical eastern IO indicate increased moisture convergence conducive for enhancement of moist-convection over the equatorial region. While the above results bring out the ocean–atmosphere coupled processes associated with the SST warming in the eastern IO in recent decades, the enhancement of convection over the equatorial eastern IO can induce anomalous subsidence and inhibit the monsoon convection activity over the Indian subcontinent [8]. In fact, the suppression of monsoon convection over the Indian region in recent decades can be noticed from the weakening trend of the upper tropospheric easterly winds (Fig. 4). Basically, the upper level circulation features during the boreal summer monsoon season are dominated by the Tibetan anticyclone and the tropical easterly jet (TEJ) which are strongly coupled to the monsoon convection over the subcontinent [5]. Fig. 4 shows the time series of the zonal winds at 150 hPa over the Indian region for the period 1951–2008. It can be noticed from Fig. 4 that the strength of the TEJ shows a significant weakening trend (and the same has been confirmed in an independent study by [17]. In addition to the aforementioned changes in the large-scale monsoon circulation, studies have reported an overall decrease in the frequency of transient monsoon rain-producing synoptic disturbances like lows and depressions in recent decades [18]. All these points are consistent with the observed increase in the occurrence of break-monsoon conditions during recent decades.

IV. Conclusion

Examination of daily rainfall over India for the period 1951–2007 reveals that there has been a significant increase in the incidence of prolonged monsoon-breaks, during the core monsoon rainy months of July and August, over the subcontinent in the recent decades. Based on analyses of *in situ*, satellite, and reanalysis data products, an attempt has been made to understand this problem. The present findings point to the role of SST warming trends in the tropical eastern IO in altering the large-scale ocean–atmosphere processes in a manner as to intensify the near-equatorial trough and moisture convergence over the eastern IO, but have led to weakened southwest summer monsoon flow, decreased moisture transport from the tropical IO into the subcontinent, and suppressed monsoon rainfall over the Indian landmass since the post mid-1970s. The decadal timescale changes are consistently corroborated by various atmosphere and ocean parameters. While it is concluded that the increasing trend of break-monsoon conditions over India is related to changes in the monsoon and tropical IO coupled system in the recent decades, further studies will be needed to unravel and fully comprehend the causative mechanisms that have led to the aforementioned alterations of the ocean–atmosphere coupled system.

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