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July droughts over Homogeneous Indian Monsoon region and Indian Ocean dipole during El Niño events

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ABSTRACT: The monthly summer monsoon rainfall over the Homogeneous Indian Monsoon region (HI) that represents most of the variance of all-India monsoon rainfall is investigated using observational data from 1880 to 2002. Severe droughts in July occur mostly during El Niño events of the boreal summer monsoon season. They occurred frequently in the late 19th to early 20th century, rarely in the middle of the 20th century, and again occasionally occurred after the 1960s.

During El Niño events, severe droughts in July over HI are significantly associated with smaller sea surface temperature-(SST) based Indian Ocean Dipole mode index (SSTDMI) in May and July compared to the years without these outstanding events. The evolution of SSTDMI that usually starts around May/June during El Niño events tends to delay when July precipitation over HI is abnormally low. Niño3 values from May through October are not significantly associated with severe droughts over HI in July during El Niño events indicating that the strength of El Niño events is not related to the occurrences of severe droughts in July. Copyright © 2008 Royal Meteorological Society

KEY WORDS July Indian monsoon rainfall; severe droughts; Indian Ocean dipole mode

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1. Introduction

India receives most of the total annual rainfall during the summer monsoon season, June through September. The country is geographically and meteorologically divided into five regions (Parthasarathy *et al*., 1995): Northwest, West Central, Central Northeast, Northeast, and Peninsular India (Figure 1 obtained from the Indian Institute of Tropical Meteorology at http://www.tropmet.res.in/region-maps.html). Regional scale precipitation records are available from the middle of the 19th century to the present (Section 2, data descriptions).

The El Niño/Southern Oscillation (ENSO) phenomenon is known as one of the most important external forcings of the Indian summer monsoon rainfall variability. El Niño events (warmer than normal sea surface temperature (SST) in the eastern equatorial Pacific) are linked to a deficit in the all-India summer monsoon rainfall (Ihara *et al*., 2007 and see references therein). However, El Niño's influence on the monsoon is not always proportional to its strength. For example, in the year 2002, during a weak El Niño event, India experienced one of the severest droughts on record, a 19% overall deficit in rainfall during June through September (Rajeevan *et al*., 2004). All regions except for the Northeast experienced an extreme deficit of the total rainfall during the summer monsoon season in that year. However, a careful examination reveals that not all the months of the 2002 monsoon season display an outstanding rainfall deficit.

Figure 2 presents monthly precipitation from June to September in 2002 compared to the monthly mean precipitation derived from El Niño years between 1880 and 2002. Comparisons are shown over the so-called Homogeneous Indian Monsoon region (HI), defined by the Indian Institute of Tropical Meteorology to include both the Northwest Indian and West Central Indian regions (Figure 1), and over the region of Northeast India. Monthly precipitation over Northeast India in the year 2002 (the solid line in Figure 2(b)) was less than the mean precipitation derived from El Niño years (bars in Figure 2(b)) in June but exceeded this average in July, August and September. Monthly precipitation over homogeneous India in 2002 (the solid line in Figure 2(a)) was more compared to the mean precipitation derived from El Niño years (bars in Figure 2(a)) in June and August and slightly less in September. However, July precipitation there shows a strong deficit compared to the mean of El Niño years.

The monsoon rainfall is of great importance to India's economy and the total rainfall anomalies during June–September are linked to foodgrain production (Gadgil, 2003). Of the four summer monsoon months, July is the rainiest, however, the prediction of the summer monsoon rainfall in July 2002 was not successful and work particularly aiming to forecast July monsoon rainfall has just started (Rajeevan *et al*., 2004).

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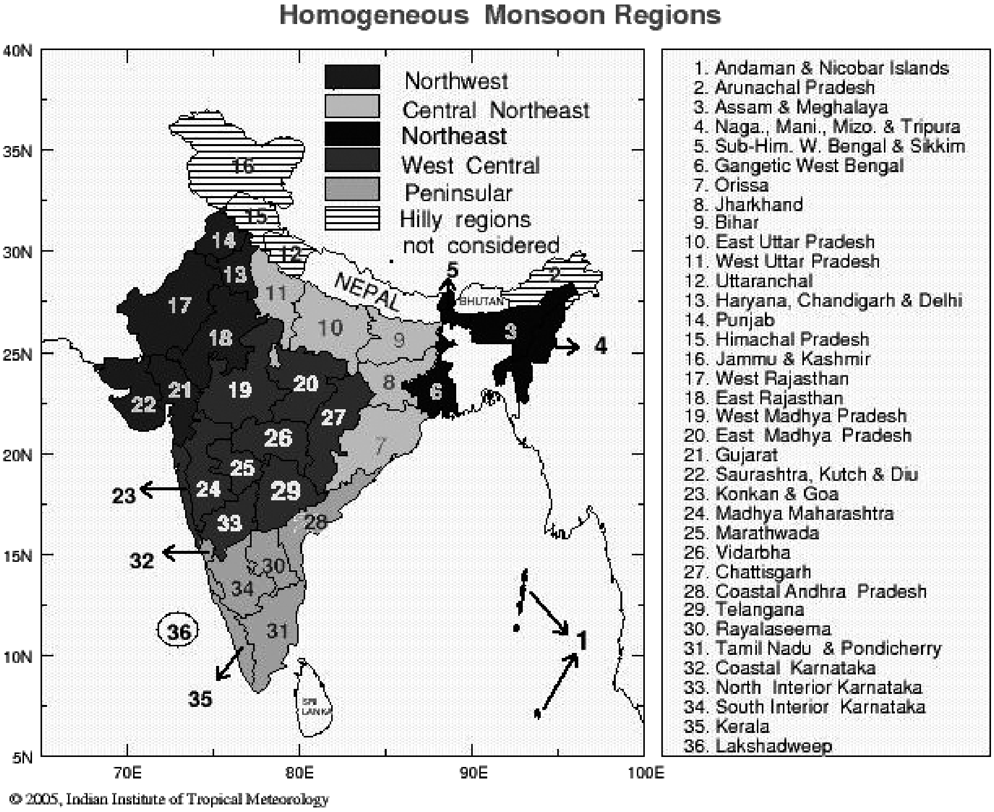

Figure 1. Map of India that displays the location of the five regions; Northwest, West Central, Central Northeast, Northeast and Peninsular India. The map was obtained from the Indian Institute of Tropical Meteorology at http://www.tropmet.res.in/region-maps.html.

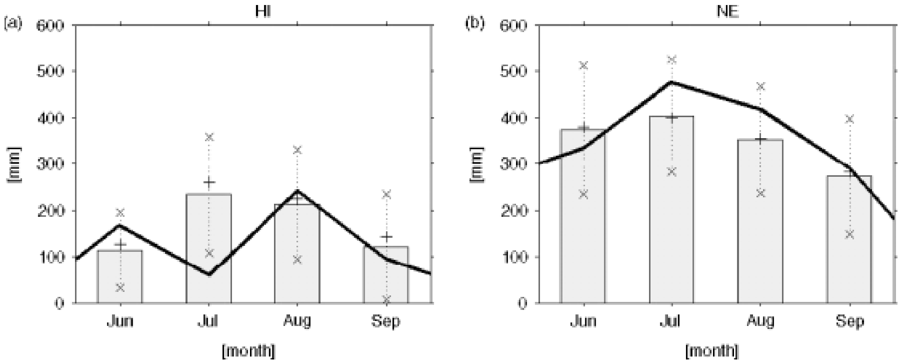

Figure 2. Monthly precipitation from June to September; (a) the Homogeneous Indian Monsoon region, and (b) the Northeast Indian region. The solid lines indicate the monthly precipitation in these regions in the year 2002, and the bars, the mean precipitation derived from El Niño years between 1880 and 2002. El Niño years are defined as years when the average June through September Niño3 values fall in the upper 33% of the distribution from 1880 to 2002. The dotted vertical lines ending with X indicate the range of two standard deviations above and below the monthly mean rainfall derived from El Niño years. + indicates the monthly mean rainfall derived from all years between 1880 to 2002.

Thus, we need to find out phenomena that can explain the inter annual variability of July monsoon rainfall for its better prediction. Several studies propose that the Indian Ocean Dipole (IOD) mode (Saji *et al.*, 1999; Webster *et al.*, 1999) and the related phenomena explain unusual monsoon behaviour during El Niño (Ashok *et al.*, 2001, 2004; Gadgil *et al.*, 2003, 2004; Ihara *et al.*, 2007). Ihara *et al.* (2007) discussed an association between climate anomalies over the Indian Ocean, summer monsoon rainfall and El Niño, however, they did not find a statistically significant association between the all-India summer monsoon rainfall, area-weighted averaged total rainfall of the summer monsoon season obtained from the rain-gauge stations over entire India, and the June–September IOD-mode index based on SST anomalies from 1881 to 1998. In general, it is known that some parts of the Indian Ocean SSTs are influenced by both ENSO (Klein *et al.*, 1999 and many others) and the monsoon circulation (Shukla, 1987). The IOD itself is partly influenced by ENSO; positive IOD events tend to co-occur with El Niño events, and the negative IOD events with La Niña events. Anomalies of both positive and negative IOD events usually appear around the onset of the summer monsoon season, develop during and mature after

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the summer monsoon season. Thus, it is a complicated problem to find the simultaneous connection between the IOD-mode index and the summer monsoon rainfall over India when both indices are averaged over the 4-month summer monsoon season. This raises a question; in the monthly time scale: Does IOD influence the summer monsoon rainfall over India?

In this article, we focus on the monthly, regional scale summer monsoon rainfall over India and examine an association between the IOD-mode index based on SST anomalies and severe droughts over the Homogeneous Indian Monsoon region, using observational data records from 1880 to 2002. Motivated by the extreme rainfall deficiency of the July 2002 event, we particularly take July precipitation as the object of the study. Section 2 is devoted to data descriptions. In Section 3, we describe the link between regional scale summer monsoon rainfall over India and ENSO. In Section 4, the association between IOD and droughts occurring in July is investigated. Section 5 is devoted to summary and discussions.

2. Data descriptions

The following datasets are used in this study:

(1) Indian precipitation records: monthly precipitation records over five regions of India, i.e. Northwest, West Central, Central Northeast, Northeast, and Peninsular India, and the monthly area-weighted average precipitation record over the meteorological sub-divisions located in Northwest India and West Central India regions, i.e. the HI, from 1880 to 2002 are obtained from the Indian Institute of Tropical Meteorology Indian regional/sub-divisional Monthly Rainfall data set (http://www.tropmet.res.in). The total summer, June through September, rainfall in the regions of Northwest India and West Central India is highly correlated with each other. The correlation coefficient (c.c.) between them in the period from 1880 to 2002 is 0.68. Thus, the monsoon rainfall over these two regions is almost homogeneous. Neither of these regions shows a strong association with the total summer rainfall over Peninsular India, having c.c. ~0.4, or with the rest of the regions (c.c. less than 0.4). We use records of precipitation over the HI instead of using records relating to the Northwest and West Central India individually.

(2) Indian Ocean dipole mode index: the SST-based IOD-mode index represents SST anomalies averaged in the western box from 50 °E to 70 °E and from 10 °N to 10 °S minus SST anomalies averaged in the eastern box from 90 °E to 110 °E and from 10 °S to 0°. Monthly, gridded, SST anomaly data from 1880 to 2002 obtained from Smith and Reynolds (2004) (NOAA NCDC ERSST version 2) are used to calculate this index.

(3) ENSO index: Niño3 index representing SST anomalies in the box from 90 °W to 150 °W and from 5 °N to 5 °S obtained from Kaplan *et al*. (2003) is used to define the ENSO condition of the summer monsoon season.

Because of the large uncertainty in the early record of SST anomaly data we begin our study in the year 1880 (Kaplan *et al*., 1998; Smith and Reynolds, 2003).

3. Regional scale monthly summer monsoon rainfall over India and ENSO

Figure 3 shows the composite of the monthly precipitation from June to September in El Niño years minus La Niña years; (a) over the HI, (b) over the Peninsular Indian (PI) region, (c) over the Central Northeast Indian region, and (d) over the Northeast Indian region (NE). Here, El Niño years are defined as years when the average June through September Niño3 values fall in the upper 33% of the distribution from 1880 to 2002, and La Niña years are defined as years when these averages fall in the lower 33% of the distribution. The shaded bars denote the months when the difference of the mean rainfall between El Niño years and La Niña years is significant at the 90% level and higher using two sample Student's t-test (The test statistics of the two sample Student's t-test are $(\mu_1 - \mu_2)/\sqrt{(s_1{}^2/n_1 + s_2{}^2/n_2)}$, where μ_1 and μ_2 are the means, s_1 and s_2 the standard deviations and n_1 and n_2 are the number of values in sample 1 and sample 2, respectively.). The monsoon rainfall over HI decreases significantly during El Niño years compared to La Niña years in all summer monsoon months, June, July, August and September. The monsoon rainfall over Peninsular India decreases significantly during El Niño years compared to La Niña years, in June, July and August, but not in September. The precipitation over the Central Northeast is very weakly related to ENSO conditions and the composite difference between El Niño years and La Niña years is significant only in June. The precipitation over the NE does not show the significant connection to ENSO in any of the summer monsoon months. Correlation coefficients between the total summer monsoon rainfall and June–September Niño3 including all years from 1880 to 2002 is significant at the 95% level over HI (c.c., −0.5), Peninsular India (c.c., −0.38) and Central Northeast India (c.c., −0.24), but not over the NE (c.c., −0.09).

4. The association between Indian Ocean dipole and severe droughts

4.1. Severe droughts over the Homogeneous Indian Monsoon region in July

Our main interest here is the droughts occurring in July over the HI region. We focus on the HI region because July precipitation explains about 80% of the total variance of inter-annual variability of the all-India July rainfall (c.c. between July precipitation over HI and July precipitation in all India is 0.91) and is significantly influenced by ENSO conditions. The relationship between

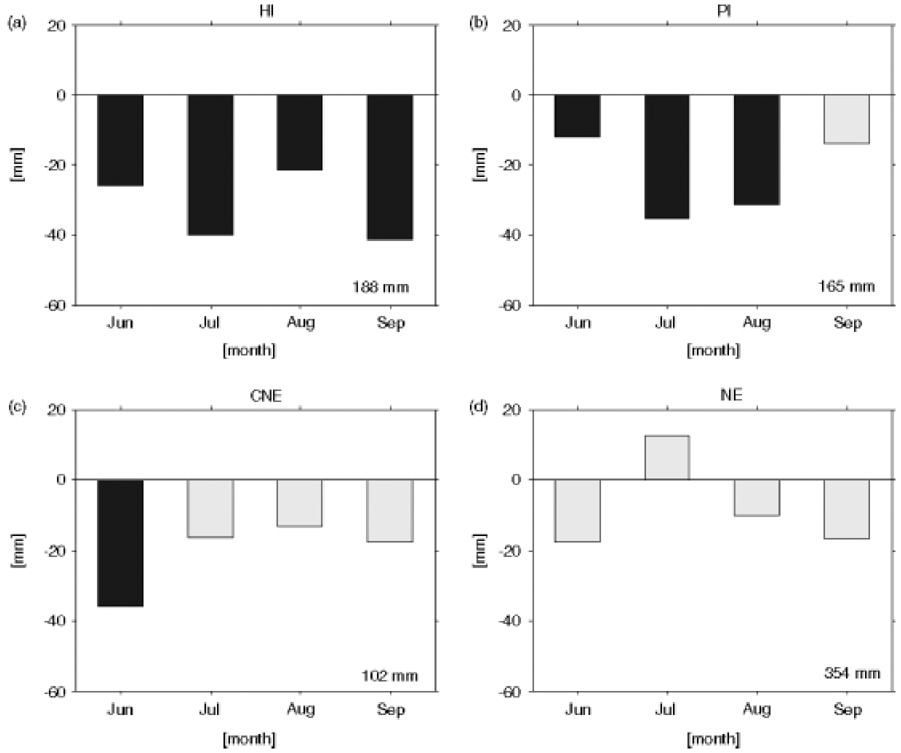

Figure 3. Composites of the monthly precipitation from June to September in El Niño years minus La Niña years; (a) HI, (b) the Peninsular Indian region (PI), (c) the Central Northeast region (CNE), and (d) NE. El Niño years are again defined as years when the average June through September Niño3 values fall in the upper 33% of the distribution from 1880 to 2002, and La Niña years are defined as years when these averages fall in the lower 33% of the distribution. The shaded bars denote the months when the difference of the mean between El Niño years and La Niña years is significant at the 90% level and higher using two sample Student's t-tests. The value of the monthly mean rainfall during June throughout September in each region is indicated at the bottom right of the respective figure.

June–September Niño3 and July precipitation over HI is shown in Figure 4. Severe droughts, defined as years having July precipitation over HI in the lowest 16% (The lowest 16th percentile corresponds to the value that is departed from the mean by one standard deviation in the normal distribution.) of the distribution, occur mostly during El Niño years. They sometimes occur even during neutral or La Niña years but they are less frequent and less intense. August is also an active monsoon month in HI, but the severe July drought years are related to a larger reduction of the total June–September HI rainfall than the severe August drought years. The mean of the total June–September rainfall over HI derived from all years between 1880 to 2002 is 752 mm, and the mean of the total June–September rainfall over HI derived from the severe July drought years is 563 mm. Whereas, the mean of the total June–September rainfall over HI is 590 mm when HI experiences severe droughts in August, and is slightly higher than the mean when HI experiences severe droughts in July.

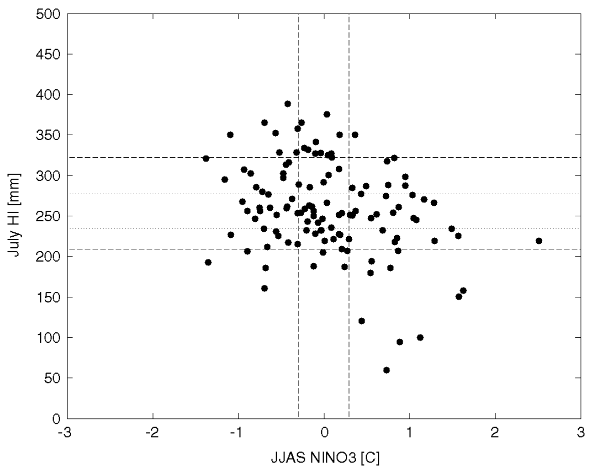

Figure 4. Scatterplot between June–September Niño3 and July precipitation over HI. The vertical dashed lines denote the lower/upper 33% values of June–September Niño3 respectively. The horizontal dotted lines denote the lower/upper 33% values of July precipitation over HI respectively. The horizontal dashed lines denote the lower/upper 16% value of July precipitation over HI respectively.

Of the ten severe droughts during El Niño events, five occurred between 1890 and 1920 and the other five occurred between 1960 and 2002 (see Table I left column for the individual years of severe droughts during El Niño events). None occurred between 1920 and 1960. Including all years regardless of ENSO conditions, nine severe droughts in July occurred between 1890 and 1920, and eight occurred between 1960 and 2002. Only two occurred between 1920 and 1960. Overall, the occurrence of severe droughts over HI in July exhibits decadal variability; droughts occurred very frequently in the late 19th century and early 20th century, but rarely in the middle of the 20th century, and again occasionally occurred after the 1960s.

Table I. Individual years of SDHI and DFHI. SDHI is defined as years when HI July precipitation is in the lower 16% of the distribution while having June–September Niño3 values in the upper tercile of the distribution. DFHI is defined as years when HI July precipitation is not in the lower 16% of the distribution while having June–September Niño3 values in the upper tercile of the distribution.

SDHI	DFHI
1899	1884
1904	1888
1911	1891
1915	1896
1918	1900
1963	1902
1972	1905
1979	1913
1987	1914
2002	1919
	1920
	1923
	1925
	1926
	1929
	1930
	1940
	1941
	1951
	1953
	1957
	1965
	1968
	1969
	1976
	1982
	1983
	1986
	1991
	1993
	1997

May–July SSTDMI also exhibits decadal to multi-decadal variability: nine-year running means of May–July SSTDMI indicate that they tend to be negative during the period 1880–1920 and in the 1950s, and positive during the period 1920–1950 and 1970–1980 (figure is not shown here). Frequent occurrences of severe July droughts over HI coincide with the negative phase of May–July SSTDMI in the early 20th century, however, the tendencies of May–July SSTDMI do not entirely explain the behaviour of the July precipitation over HI. In the 1950s, May–July SSTDMI tends to be negative, but July HI is relatively wet, and during the period of 1970–1980, vice versa.

4.2. SSTDMI and July droughts over HI during El Niños

The association between the IOD and severe droughts over HI occurring in July is investigated in this section. As mentioned in the Introduction, the IOD is influenced by the ENSO state. Figure 5 displays monthly evolutions of the mean SSTDMI from January to December during El Niño years and La Niña years respectively. El Niño years are again defined as years when the average June through September Niño3 values fall in the upper 33% of the distribution from 1880 to 2002, and La Niña years are defined as years when these averages fall in the lower 33% of the distribution. During El Niño years, SSTDMI tends to be in the positive phase, and during La Niña years, in the negative phase. In either case, an IOD event tends to start developing in May–June, peak in September–October and taper off in November–December. Since both HI precipitation and SSTDMI are influenced by ENSO, it simplifies the problem if we analyse the association between severe droughts over HI and SSTDMI separately by ENSO conditions. Severe droughts occurring during El Niño events are more frequent and intense than severe droughts during La Niña and neutral years (Figure 4), thus, we take El Niño years as the object of our statistical analysis.

Figure 6 demonstrates the evolutions of the composite means of various indices from May through October during El Niño years using the same definition as in Figure 5. The dashed lines correspond to the composites during El Niño years when HI July precipitation is in the lower 16% of the distribution (hereafter, these 10 years are referred to as severe drought HI during El Niño (SDHI)) and the solid lines correspond to the composites during El Niño years when HI July precipitation is not in the lower 16% of the distribution (hereafter, these 31 years are referred to as drought-free HI during El Niño (DFHI)). Individual years of SDHI and DFHI are summarized in Table I. The vertical solid lines denote the months when the difference of the means in SDHI and in DFHI is significant at the 90% level and higher using two sample Student's t-test.

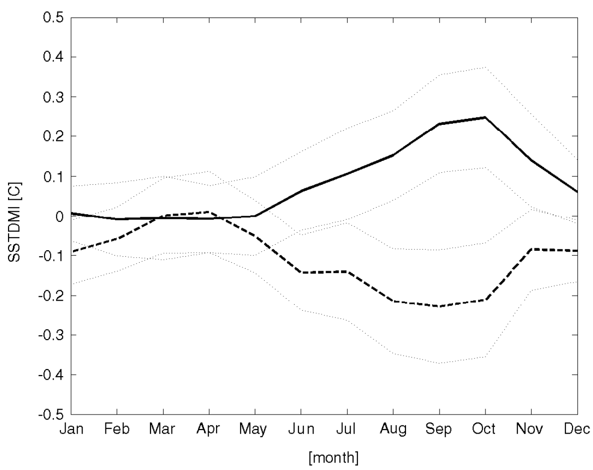

Figure 5. Monthly evolutions of the composite mean SSTDMI from January to December: the thick solid line corresponds to the composite mean during El Niño years, and the thick dashed line corresponds to the composite mean during La Niña years. The dotted lines represent 95% confidence intervals of the composite means during El Niño and La Niña years.

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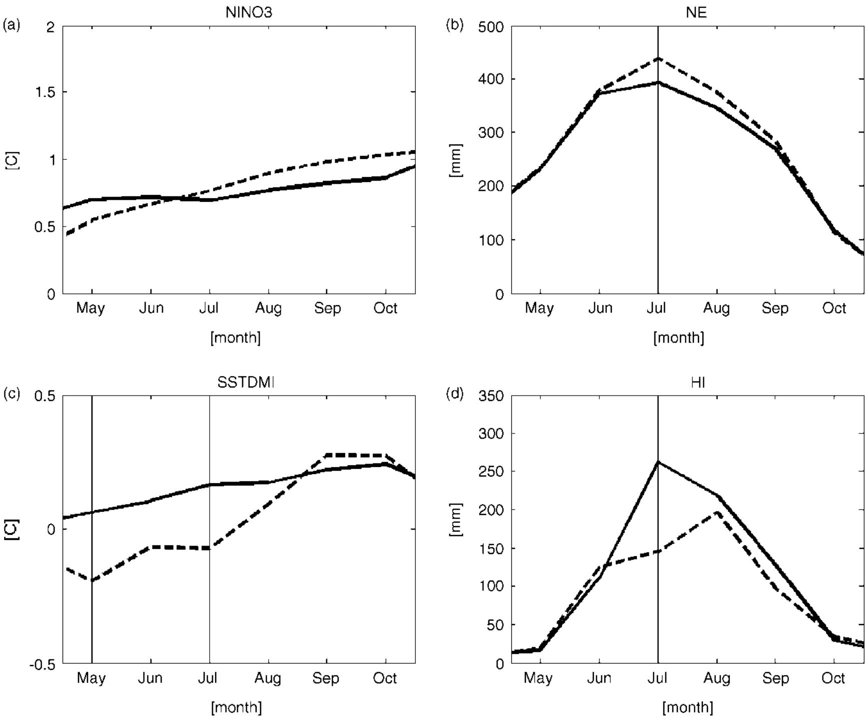

Figure 6. Evolutions of the composite means based on various indices from May through October during El Niño years; (a) Niño3, (b) precipitation over the NE, (c) SSTDMI and (d) precipitation over HI. The dashed lines correspond to the composite mean during El Niño years when HI July precipitation is in the lower 16% of the distribution ('SDHI') and the solid lines correspond to the composite mean during El Niño years when HI July precipitation is not in the lower 16% of the distribution ('DFHI'). The vertical solid lines denote the months when the difference of the mean between these two cases is significant at the 90% level, and higher, using two sample Student's t-tests.

Severe droughts in July over HI are not associated with significant decrease or increase of the precipitation in other months of the summer monsoon season (Figure 6(d)). The precipitation over the NE in July is negatively associated with precipitation over HI in July and is significantly lower in DFHI than in SDHI (Figure 6(b)). Niño3 seems to start developing a few months earlier in DFHI compared to SDHI (Figure 6(a)). But the difference in the mean Niño3 values between DFHI and SDHI is not significant from May through October. This implies that the strength of El Niño does not significantly affect the July rainfall over HI during El Niño events of the summer monsoon season. However, the evolution of SSTDMI differs between DFHI and SDHI. In SDHI, SSTDMI does not tend to start developing in May, the month when SSTDMI usually begins to develop during El Niño years, and the composite mean becomes positive only after July (Figure 6(c)). The difference of the mean SSTDMIs between DFHI and SDHI is significant in May and July at the 90% level and higher. We confirm this result with seasonal mean SSTDMI and Niño3 values. The SSTDMI values averaged over May, June and July are significantly smaller in SDHI than in DFHI (p-value, 0.03) but the difference in May–July Niño3 values between these cases is not significant at the 90% level. Neither the August–October SSTDMI values nor August–October Niño3 values in DFHI are significantly different from those in SDHI.

To test the sensitivity of the results to the categorization, we further compare the SDHI to the years when July HI rainfall is normal and above normal during El Niño events. The same results are obtained: the severe drought years tend to be associated with smaller SSTDMI values prior to July compared to normal and above normal July HI rainfall years but the significant association between the severe July droughts and Niño3 values is not found in any of the monsoon months.

May–July SSTDMI values in SDHI after 1960 are not always smaller than those in DFHI during interval of 1890–1920 due to the decadal variability of May–July SSTDMI. However, during each interval of 1890–1920 and 1960–2002, the mean May–July SSTDMI in SDHI (−0.35 in 1890–1920 and 0.12 in 1960–2002) is smaller than the mean May–July SSTDMI in DFHI (0.05 in 1890–1920 and 0.21 in 1960–2002), although we do not perform a statistical test separately in these two periods because the sample numbers are too small to assess the robustness. We test the significance of the association between the May–July SSTDMI from which low frequency variability is removed by subtracting 9-year running means of May–July SSTDMI, and severe droughts in July over HI. The same result as found with the SSTDMI including low frequency variability is obtained: May–July SSTDMI values tend to be smaller in SDHI than in DFHI (p-value, 0.03).

5. Summary and discussions

The monthly, regional scale summer monsoon rainfall, mainly the rainfall over the HI that represents most of the variance of the all-India monsoon rainfall, is investigated using observational data from 1880 to 2002. The monthly summer monsoon rainfall over HI is significantly negatively related to ENSO conditions during all summer monsoon months. In contrast, the summer monsoon precipitation over Northeast India is not significantly connected to ENSO in any of the summer monsoon months.

July precipitation over HI demonstrates decadal variability, and occurrences of severe droughts in that month are rare between 1920 and 1960. May–July SSTDMI also shows decadal variability that is somewhat related to the decadal variability of July precipitation over HI in the early 20th century, however, it does not entirely explain the decadal variability of July precipitation over HI, particularly, in some decades after the 1950s. During El Niño events, the severe droughts in July over HI tend to be associated with smaller SSTDMI values in May and July compared to the years without these outstanding events. However, SSTDMI values after July are the same regardless of the amount of July precipitation. Thus, it seems that the evolution of SSTDMI during El Niño is important. Specifically, the evolution of the IOD-mode events, which usually starts around May, is delayed when July precipitation over HI is abnormally low. There is no significant difference of Niño3 values in DFHI and in SDHI from May through October.

Ashok *et al.* (2004) suggested that the anomalous convergence over the western pole of IOD induced by positive dipole events, led to circulation towards India and thus increased precipitation over India. At the same time, the anomalous divergence over the eastern pole induced by positive dipole mode events, decreased the effect of El Niño-induced subsidence over India. Our findings indicate that when HI experiences severe droughts in July, the development of the SSTDMI during El Niño events is delayed and the IOD tends to be anomalously negative in July compared to the drought-free years during El Niño events. This can be connected to Ashok *et al.* (2004) and it is speculated that the conditions over either or both poles of the dipole induced by the anomalous negative IOD can influence the monsoon rainfall over India in the opposite condition as explained in their hypothesis.

Since the occurrences of severe July droughts are rare during La Niña and neutral ENSO conditions, the same analysis we have done with El Niño cases cannot be applied to La Niña or neutral ENSO conditions. Our findings only focus on the severe droughts occurring during El Niño, but since most of the severe droughts occur during El Niño events and El Niño during the summer monsoon season could be predicted in advance using statistical and dynamical models (e.g. Cane *et al.*, 1986 and many others), it is concluded that in the premonsoon season, particularly May, SSTDMI values can be one of the explanatory variables for severe droughts in July over HI.

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