Attribution of the summer warming since 1970s in Indian Ocean Basin to the inter-decadal change in the seasonal timing of El Niño decay phase

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[1] This paper reports that, on top of the general warming trend in the Indian Ocean Basin (IOB) SST in the past 140 years, there exists an additional multidecadal-scale warming in the period from late 1940s to early 2000s, and this warming in IOB is particularly stronger in summer than in other seasons. Our analysis indicates that, the seasonal timing of the decay phase of El Niño events during this period has been delayed from spring to early summer since 1970s, while the seasonal timing of La Niña decay phase remains in spring season. The direct effect of the later decay of El Niño events is the lengthening of the delayed warming effect of El Niño on IOB SST into summer, attributing to the stronger IOB warming in summer from the late 1940s to the early 2000s. **Citation:** Li, Q., R.-C. Ren, M. Cai, and G. X. Wu (2012), Attribution of the summer warming since 1970s in Indian Ocean Basin to the inter-decadal change in the seasonal timing of El Niño decay phase, *Geophys. Res. Lett.*, *39*, L12702, doi:10.1029/2012GL052150.

1. Introduction

[2] It is known that the inter-annual variation of the Indian Ocean Basin (IOB) Sea Surface Temperatures (SST) is closely related to the tropical eastern Pacific SST through the ENSO-induced “atmospheric bridge” processes [*Klein et al.*, 1999; *Lau and Nath*, 1996; *Alexander et al.*, 2002]. Specifically, following a warm ENSO peak in winter, the tropical IOB SST tends to be warmer than usual in spring season [*Chiu and Newell*, 1983; *Cadet*, 1985; *Nigam and Shen*, 1993; *Du et al.*, 2009]. Significant long-term warming trend is observed in IOB SST [*Lau and Weng*, 1999; *Terray and Dominiak*, 2005; *Ihara et al.*, 2008], while no companion warming trend is found in the tropical eastern Pacific associated with ENSO [*Lau and Weng*, 1999; *Kumar et al.*, 2010]. The long-term IOB SST warming has commonly been attributed to the anthropogenic effect associated with global warming [*Barnett et al.*, 2005; *Pierce et al.*, 2006]. Nevertheless, decadal changes over the Indian Ocean have been found closely related to ENSO [*Cole et al.*, 2000; *Allan et al.*, 1995; *Reason et al.*, 2000; *Xie et al.*, 2010; *Chowdary et al.*, 2012]. For example, *Allan et al.* [1995] suggested that the epochal changes in the mean condition over the south Indian Ocean are in-phase with ENSO-related correlation patterns. *Chowdary et al.* [2012] showed the epochal change in the persistency of the El Niño-induced warmer SST anomalies over the north Indian Ocean. This study will examine the interdecadal variation of the basin-wide SST in the Indian Ocean and provide evidence to show that, during the past 140 years, the most significant interdecadal IOB warming exists around 1970s, and it is intimately related to decadal changes of ENSO since 1970s. The result will help to advance our understanding of the cause of the decadal timescale variability of the IOB SST, and of the ENSO-IOB relationship in general.

2. Data and Method

[3] The monthly mean Sea Surface Temperature (SST) used in this study is derived from the Hadley Center's HadISST1 data set covering the period from 1870 to 2009 [*Rayner et al.*, 2003]. The monthly SST anomalies (SSTA) are obtained by removing the climatological annual cycle from the total SST fields. Following *Li et al.* [2010], we use the area mean SSTA in (40–110°E, 30°S–30°N) to define an IOB SSTA index (denoted as IOBI). The Niño3 index obtained by averaging the SSTA in the Niño3 region is used to represent the ENSO signal. To suppress the possible effect of the long-term warming trend of IOBI on our results, the linear trends in IOBI and in Niño3 are removed before the analysis.

[4] To test the statistical significance of the IOBI composites for ENSO and non-ENSO years, we apply a bootstrapping approach [*Efron and Tibshirani*, 1993] in which ten thousand bootstrap resamples are used to calculate the objective values of the changes in IOB SSTA, and the confidence intervals are determined from the statistical distribution of the objective values.

3. The Inter-decadal Changes of the IOB SST

[5] Shown in Figure 1a is the temporal evolution of the monthly IOBI in the past 140 years from 1870 to 2009. As manifested by the dominance of cold anomalies of IOBI in the earlier years and warm anomalies in the later years after 1970s, the long-term warming trend of IOBI is apparent from a visual inspection of the time series. The warming rate is estimated as 0.0419°C/decade. After removing the long-term linear trend from the time series, we find that IOBI exhibits a pronounced inter-decadal variability signal (Figure 1b). To quantitatively detect the inter-decadal changes in the IOBI, we construct a statistic Z-value timeseries (solid curve in Figure 1b) which measures the temporal changes in IOBI at every time point, and then apply a moving t-test technique (MTT) on this timeseries [*Jiang and You*, 1996; *Xiao and Li*, 2007]. The temporal distribution of Z suggests four significant change points (maximum or minimum Z) over the 140-year time span,

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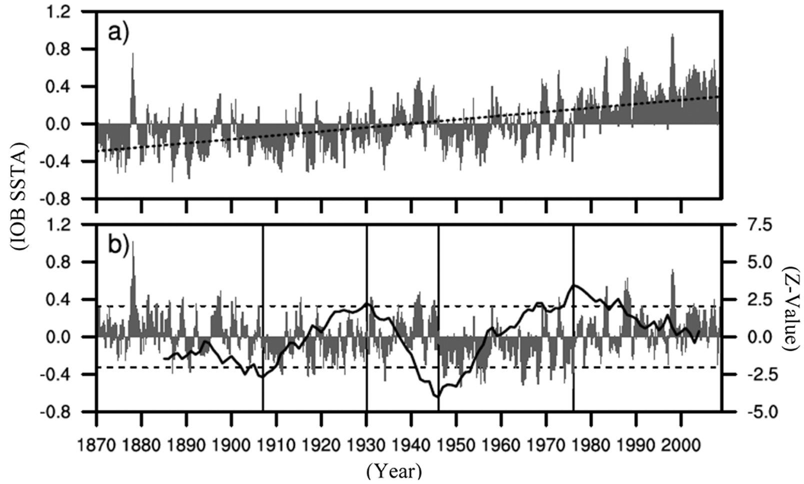

Figure 1. (a) Temporal evolution (bar) of the monthly IOBI (unit: °C) and (b) the detrended monthly IOBI (left ordinate) from 1870 to 2009. The dash line in Figure 1a denotes the linear trend of the IOBI. The solid curve in Figure 1b corresponds to the constructed statistic Z-values (right ordinate) of the IOBI and the horizontal dashed lines mark the 95% confidence level of Z for a 31-year moving t-test (MTT) [*Jiang and You*, 1996]. The vertical lines mark the statistically significant change points of the IOBI where Z values reach its maximum or minimum.

namely, 1907, 1930, 1946, and 1976. The four change points correspond respectively to the changes from increasing warming tendency to decreasing warming tendency of the IOBI around 1930 and 1976, and from increasing cooling tendency to decreasing cooling tendency around 1907 and 1946. Associated with these successive changes, persistent warming tendencies could be identified respectively from late 1900s to 1930s and from late 1940s to early 2000s. However, the earlier warming from late 1900s to 1930s is obviously much weaker (0.0420°C/decade) and with a much shorter duration relative to the recent warming from late 1940s to early 2000s (0.0687°C/decade). Next we will mainly focus on this stronger inter-decadal warming change in IOB SST occurred in recent decades.

[6] Before exploring the possible contribution of ENSO to this warming change, we first show the monthly warming rates of IOBI during the period from late 1940s to early 2000s (Table 1). The statistical significance of the warming rates is evaluated by using the non-parametric Mann-Kendall statistical test (for details see *Mann* [1945] and *Kendall* [1975]). It is seen that the warming rates in all seasons are statistically significant, passing the statistical significance test at a 99% level. Furthermore, the warming rates in summer months are substantially larger than that in spring, and the maximum warming rates are found in August as 0.085°C/decade. In the next section, we will show that this inter-decadal warming in summer IOB is intimately related to decadal changes of ENSO.

4. Changes in the Seasonal Timing of ENSO Decay Phase and the Summer IOB Warming

[7] Shown in Figure 2a is the 21-year running lagged auto-correlation between the Niño3 index in winter (NDJ) and that from January to July of the following year as a function of calendar month and year from 1940s to 2000s. We use the lagged auto-correlation of 0.4 to define the timing of ENSO decay phase. It is seen that in the 1970s, there exists an abrupt increase in the lagged auto-correlation between the Niño3 in winter (NDJ) and that in the following summer. Specifically, before 1970s, the lagged auto-correlation decreases with time rapidly and reaches the value of 0.4 before April. After 1970s, the lagged auto-correlation decreases with time more slowly and is still above 0.4 in May or June. This indicates that on average, the seasonal timing of the decay phase of ENSO events has been delayed since 1970s. Comparison of the seasonal evolution of the lagged auto-correlation between the periods before 1976 (1946–1976, the line with asterisks in Figure 2b) and after 1976 (1977–2002, the line with close circles in Figure 2b) also confirms the delay of the timing of ENSO decay phase from April before 1976 to June after 1976. This finding is qualitatively consistent with that shown by *An and Wang* [2000] which also suggests that the period of ENSO has become longer in 1980–93 than that in 1962–1975.

[8] Note that the delay signal in the seasonal timing of the decay phase of ENSO events shown in Figure 2a could come equally from both El Niño and La Niña events, or mainly from El Niño or La Niña events. To sort this out, we have calculated the lagged auto-correlation separately for all El Niño (positive NDJ Niño3) and for all La Niña events (negative NDJ Niño3) during the two periods: 1946–1976 and 1977–2002. As indicated by the shading in Figure 2c, the lagged auto-correlation for El Niño events is significantly increased after 1970s relative to that before 1970s. However, the changes in the lagged auto-correlation for La

Table 1. Monthly Warming Rates in IOB SST From 1946 to 2002[a]

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Warming rate	**0.051**	**0.045**	**0.053**	**0.065**	**0.071**	**0.081**	**0.08**	**0.085**	**0.082**	**0.069**	**0.075**	**0.067**

[a]Units: °C/decade. Bold is statistically significant at 99% confidence level for a Mann-Kendall test.

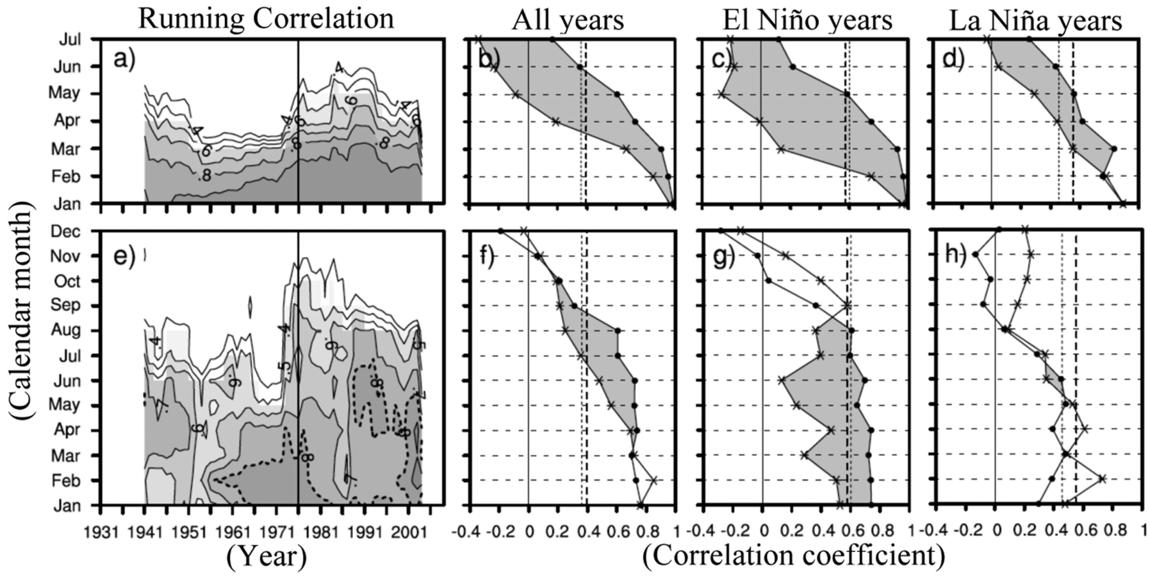

Figure 2. (a) The 21-year running lagged auto-correlation between the Niño3 in winter (NDJ) and that in each month of the following year as a function of year and calendar month, (b) the lagged auto-correlation as a function of calendar month and that (c) for El Niño years (NDJ Niño3 positive) and (d) for La Niña years (NDJ Niño3 negative) respectively during 1946–1976 (asterisks) and during 1977–2002 (close circles). The areas between the circled and the dotted curves in Figures 2b–2d are shaded. (e–h) Similar to Figures 2a–2d but for the running lagged cross-correlation between Niño3 in winter (NDJ) and the IOBI in each month of the following year. Dotted areas mark the 95% confidence level for the correlation in Figures 2a and 2d and the vertical line marks the significant change year as in Figure 1b. Thinner/thicker dash lines in Figures 2b–2d and 2f–2h mark the 95% confidence levels of the respective correlation in 1946–1976/1977–2002.

Niña events between the two periods are much weaker (Figure 2d), suggesting that the signal of the delay in the seasonal timing of the decay phase of ENSO is mainly from El Niño events. The slower decay of El Niño since 1970s identified here is consistent with the findings of *Xie et al.* [2010] with Niño3.4 index.

[9] As in Figure 2a, the 21-year running lagged cross-correlation between the winter (NDJ) Niño3 and the IOBI in months from January to December of the following year is displayed in Figure 2e. Consistently with the well-established fact that a warm/cold IOB tends to appear in the following spring after a warm/cold ENSO event in winter, large lagged correlation between winter Niño3 and the IOBI exists in the following spring persistently throughout the entire time span. In the 1970s, however, there also exists an abrupt increase in the lagged correlation between winter Niño3 and the IOBI in the following summer. Specifically, large values of lagged correlation (say 0.4 or greater) between the two indices are found mainly in the months before summer between 1940s and 1970s, but last into late summer or early fall after 1970s. The increase in the lagged correlation in summer months (MJJA) since 1970s is also clear in Figure 2f (shading). Moreover, the lengthening of the large lagged cross-correlation is found mainly for El Niño events (shadings in Figure 2g), and less noticeable for La Niña events (shadings in Figure 2h). This clearly suggests that the delayed decay of El Niño events after 1970s acts to extend the delayed warming effect of El Niño on IOB into summer, responsible for an enhanced warming in summer IOB since 1970s.

[10] Figure 3 shows the temporal evolution of the Niño3 (Figures 3a and 3b) and the IOBI (Figures 3c and 3d) in every ENSO decay year for large-amplitude of El Niño (Figures 3a and 3c) and La Niña (Figures 3b and 3d) events (NDJ Niño3 exceeds one standard deviation). To explicitly identify the changes since 1970s, the Niño3 and the IOBI before/after 1976 are plotted in blue/red. It is seen that the signal of El Niño events after 1976 (red in Figure 3a) tends to last substantially longer than that before 1976 (blue in Figure 3a) whereas the change in the average duration of the La Niña events is relatively less noticeable (blue vs. red in Figure 3b). Furthermore, the results shown in Figure 3c indicate that on top of the general warming changes in IOBI in all seasons since 1970s, the warming changes in summer season (JJAS) during El Niño decay years are stronger than that in other months (blue vs. red in Figure 3c). During La Niña decay years, however, the warming changes in summer are about the same as in other months (blue vs. red in Figure 3d). Therefore, the results shown in Figure 3 support the conjecture that the later decay of El Niño events after 1970s, which in turn lengthens the delayed warming effect of El Niño on IOB from spring to summer, may have resulted in the stronger warming in summer IOB since 1970s. It should be noted that the general warming in IOBI throughout the ENSO decay year (blue vs. red in Figures 3c and 3d) could also be related to the significant increase in the amplitudes of ENSO events since 1970s (Figure 3a).

[11] To further support our conjecture that the stronger IOB warming in summer in recent decades is mainly due to the later seasonal timing of El Niño decay phase since 1970s, we have separately calculated the composite changes of IOBI from the period 1946–1976 to the period 1977–2002 in all ENSO decay years (NDJ Niño3 exceeds one standard deviation, Figure 4a) and in all other years (referred to as non-ENSO years, Figure 4b). To highlight the stronger

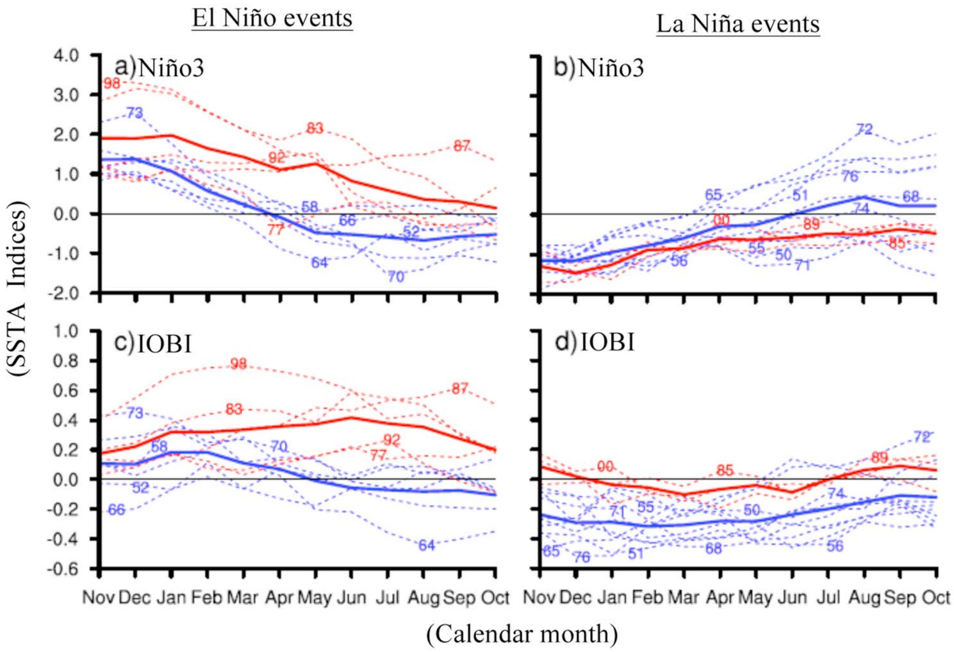

Figure 3. Temporal evolutions of the (a, b) Niño3 and (c, d) IOBI SST anomalies in all (left) El Niño and (right) La Niña decay years (dashes) from 1946 to 2002 when NDJ Niño3 exceeds one standard deviation, and the average evolutions (thicker lines) for the ENSO events during 1946–1976 (blue) and during 1977–2002 (red).

warming in summer months in ENSO decay years, the total annual mean change (about 0.24°C) of IOBI for all years between the two periods have been removed from the composite results shown in Figure 4. It is seen that, on top of the annual mean warming change, there exists additional warming year around in ENSO decay years. And this additional warming is the strongest in summer months. The bootstrapping significance test indicates that the average IOB warming in summer (MJJA) of ENSO decay years is statistically significant. It is estimated that the annual mean of the additional warming in ENSO decay years is about 0.09°C. In contrast, the composite changes of IOBI for all non-ENSO years are mostly negative (Figure 4b), indicating that the IOB SST changes between the two periods in non-ENSO years are mostly less than the total (for all years) mean warming change. The annual mean in Figure 4b is about −0.06°C. Therefore, the annual mean IOB warming between the two periods in ENSO decay years is 0.33°C, about 0.15°C larger than that in non-ENSO years. This implies that the changes in ENSO years contribute to about one quarter (0.06°C) of the total warming (0.24°C) in IOB SST between 1946–1976 and 1977–2002. As indicated in Figure 4a, the strengthening of the general warming in IOB SST between the two periods mostly comes from the summer months.

5. Summary

[12] Analysis of the long-term variations of the basin-wide SSTA in the Indian Ocean in the past 140 years indicates that, on top of the general long-term warming trend in the last century, the IOB SSTA exhibits significant inter-decadal variability. Particularly, there exists an additional multidecadal-scale warming in the period from late 1940s to early 2000s. Furthermore, the strongest warming during this period is

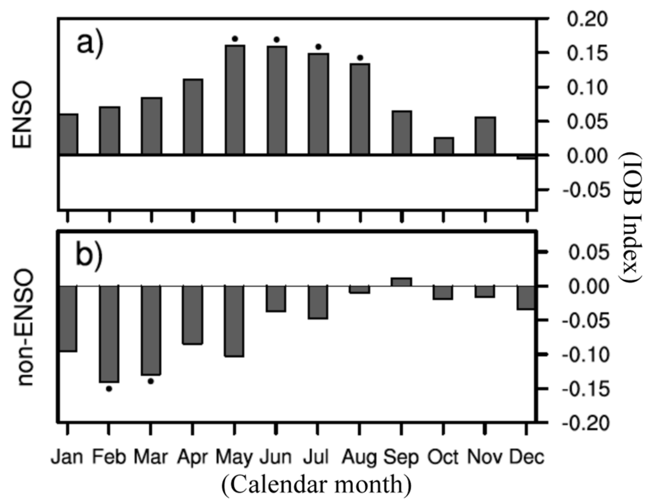

Figure 4. Composites of the changes in IOBI (units: °C, bar) from the period of 1946–1976 to the period of 1977–2002 (a) for ENSO (NDJ Niño3 exceeds one standard deviation) years and (b) for non-ENSO years. Dots over bars indicate that the changes are statistically significant above 95% confidence level based on a bootstrapping resampling test. The changes in the annual mean IOBI in all years between the two periods has been removed. The number of ENSO years during 1946–1976 is 16 and that during 1977–2002 is 8. We note here that should the number of years and the number of ENSO years be the same between the two periods, the sum of the annual means of Figures 4a and 4b would be exactly zero.

found in summer months. The evidence presented here indicates that, this stronger summer warming can be attributed to a significant delay in seasonal timing of El Niño decay phase since 1970s. The direct effect of the later decay of El Niño events is a lengthening of the delayed warming effect of El Niño on IOB into summer months, thus responsible for the additional warming in summer IOB. Composite changes of the IOBI for all ENSO decay years from late 1940s to early 2000s reproduce the stronger IOB warming in summer months, confirming that the additional warming in summer IOB since 1970s is mainly resulted from the interdecadal changes of ENSO events. The ENSO-induced additional warming contributes about one quarter of the total IOB warming since 1970s. Our findings further support the notion that the multi-decadal variability over IOB is part of the decadal variability in the North Pacific, or the Pacific Decadal Oscillation (PDO) through the ENSO-IOB relationship, as reported by *Krishnan and Sugi* [2003], *Terray and Dominiak* [2005], and *D'Arrigo and Wilson* [2006]. The well-known 1976 abrupt climate shift that is a main feature of this variability also echoes in the Indian Ocean.

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