The Curious Case of Indian Ocean Warming*,+

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ABSTRACT

Recent studies have pointed out an increased warming over the Indian Ocean warm pool (the central-eastern Indian Ocean characterized by sea surface temperatures greater than 28.0°C) during the past half-century, although the reasons behind this monotonous warming are still debated. The results here reveal a larger picture—namely, that the western tropical Indian Ocean has been warming for more than a century, at a rate faster than any other region of the tropical oceans, and turns out to be the largest contributor to the overall trend in the global mean sea surface temperature (SST). During 1901–2012, while the Indian Ocean warm pool went through an increase of 0.7°C, the western Indian Ocean experienced anomalous warming of 1.2°C in summer SSTs. The warming of the generally cool western Indian Ocean against the rest of the tropical warm pool region alters the zonal SST gradients, and has the potential to change the Asian monsoon circulation and rainfall, as well as alter the marine food webs in this biologically productive region. The current study using observations and global coupled ocean–atmosphere model simulations gives compelling evidence that, besides direct contribution from greenhouse warming, the long-term warming trend over the western Indian Ocean during summer is highly dependent on the asymmetry in the El Niño–Southern Oscillation (ENSO) teleconnection, and the positive SST skewness associated with ENSO during recent decades.

1. Introduction

A handful of studies have been devoted to the cause and effect of basinwide Indian Ocean warming (Alory et al. 2007; Chambers et al. 1999; Dong et al. 2014; Du and Xie 2008; Klein et al. 1999; Rao et al. 2012; Swapna et al. 2014), yet the reasons behind the steady and prominent warming remain ambiguous and are still debated. These studies have shown that the entire Indian Ocean has been warming throughout the past half century. A close examination of the sea surface temperatures (SSTs) over the Indian Ocean reveals a larger story—that the western Indian Ocean (WIO) has been warming for more than a century. Figure 1a shows the trend in summer SSTs, during 1901–2012. A striking feature is the absence of any trend in SST over the tropical Pacific, and the presence of a warming trend

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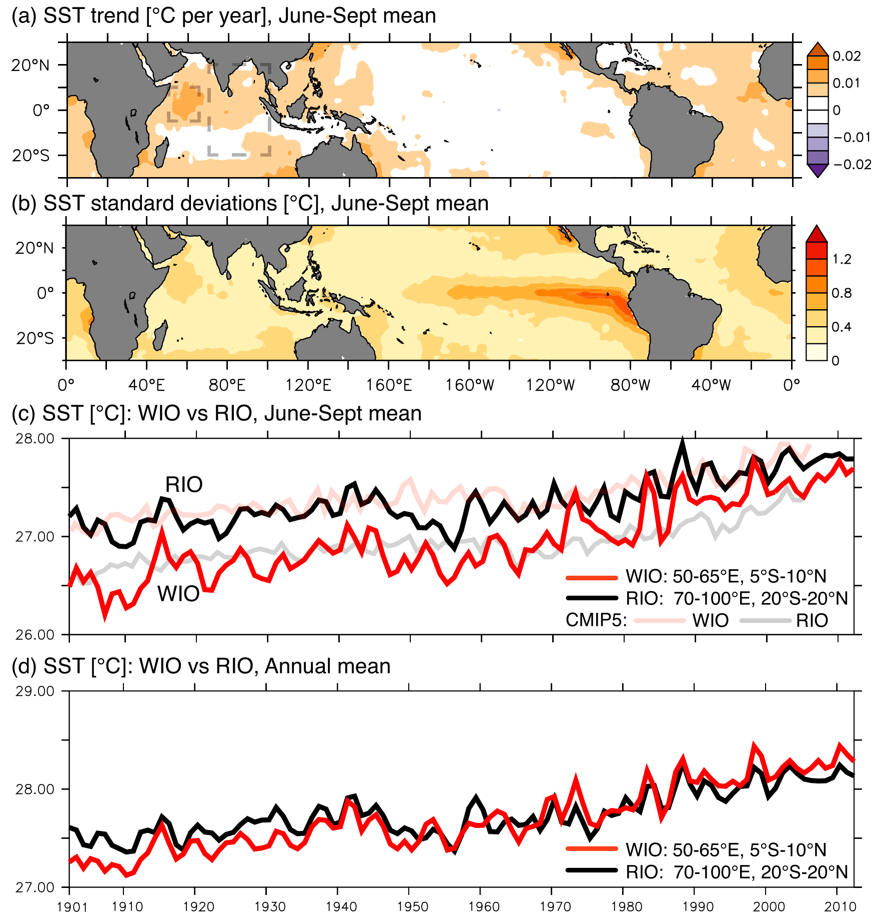

FIG. 1. (a) Observed trend in mean summer [June–September (JJAS)] SST (°C yr^{-1}) over the global tropics during 1901–2012. (b) Interannual standard deviation of SST (°C) for the same domain and time period. Time series of mean (c) summer and (d) annual SST (°C) over the WIO (red; 5°S–10°N, 50°–65°E) and rest of the Indian Ocean (RIO in black; 20°S–20°N, 70°–100°E). WIO and RIO are marked with dashed rectangles in (a). The CMIP5 ensemble means based on 25 climate models, averaged over the WIO (light red) and RIO (light gray), are also displayed in (c).

(>0.1°C $decade^{-1}$) over the western tropical Indian Ocean. A similar evolution is found in other seasons and other available SST datasets, although the trend is stronger during summer (see Fig. S1 in the supplemental material).

In comparison with the rest of the Indian Ocean, the western Indian Ocean generally has cooler mean SSTs in summer, owing to the strong monsoon winds and the resultant upwelling over the western Indian Ocean (Fig. 2). This creates a zonal SST gradient, which regulates the strength and flow of the moisture-laden winds toward the South Asian subcontinent (Izumo et al. 2008; Yang et al. 2007). In addition, the summer SSTs show that western region has the largest interannual variability (Fig. 1b). A warming trend in the mean SSTs over this region can in turn modify the monsoon interannual variability (Yang et al. 2007). The western Indian Ocean is also one of the most biologically productive regions during the summer because of the intense upwelling (Ryther and Menzel 1965). Hence a significant change in the SSTs of this region can also alter marine food webs (Behrenfeld et al. 2006). Besides localized responses, a warming in the Indian Ocean has remote influences too. It has been suggested that a warm Indian Ocean has the potential to weaken the El Niño during its developing and terminating phases (Annamalai et al. 2005; Kug and Kang 2006; Luo et al. 2012).

Although earlier studies have investigated the sustained warming over the Indian Ocean, the focus has been on the warm pool region (Dong et al. 2014; Du and Xie 2008; Rao et al. 2012; Swapna et al. 2014). These studies have implied local ocean–atmosphere coupled mechanisms for the continuous warming over the region, in addition to anthropogenic forcing. However,

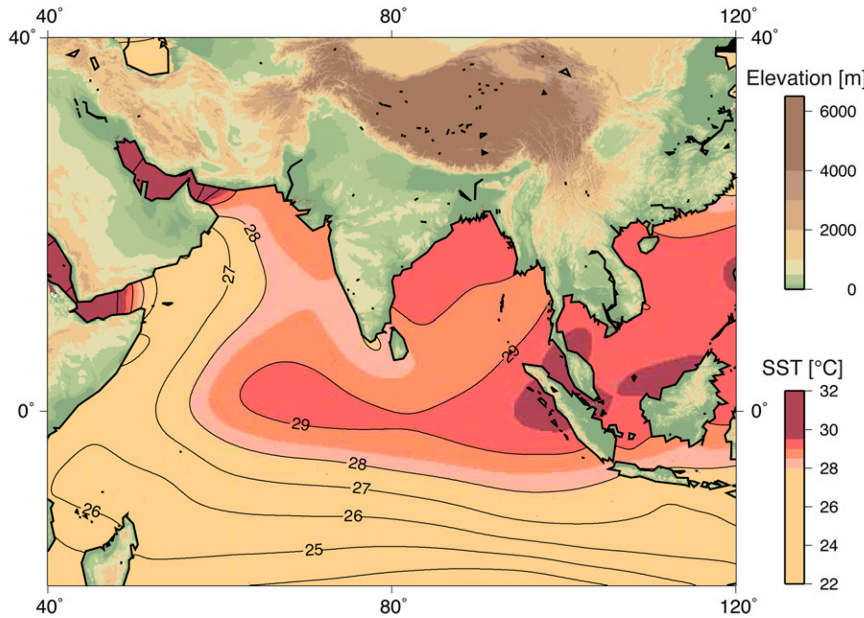

FIG. 2. Observed mean summer (JJAS) SST (°C) over the Indian Ocean. Warm pool region in the text refers to the highlighted region with SST > 28°C.

there is large uncertainty among these studies, presenting a chicken-and-egg problem as to the cause and effect of the warming. Some of these studies argue that the warming weakens the monsoon winds over the Indian Ocean, which further enhance the warming, while others suggest that weakened monsoon winds have accelerated the warming (Rao et al. 2012; Swapna et al. 2014).

A few other studies have shown that the SSTs over the Indian Ocean are warmer 3–4 months after the mature phase of El Niño (Du et al. 2009; Lau and Nath 2003; Xie et al. 2009). Although a connection between individual El Niño and warm Indian Ocean events has been suggested (Cadet 1985; Murtugudde et al. 2000; Nicholson 1997; Tourre and White 1995; Xie et al. 2002; Yu and Rienecker 1999), no relationship has been demonstrated with respect to the long-term warming trends over the Indian Ocean, and hence its association with El Niño during summer is investigated here.

2. Data, model, and methods

Long-term warming trend and correlations are estimated using the Hadley Centre Sea Ice and Sea Surface Temperature, version 1 (HadISST1), dataset for the period 1901–2012 obtained from the Met Office Hadley Centre, and the robustness of these results are assessed using the extended reconstructed sea surface temperature (ERSST; Smith et al. 2008) and Hadley Centre nighttime Marine Air Temperature (HadMAT; Rayner et al. 2003) datasets. Data coverage in the tropical Indian Ocean is generally quite good since the late nineteenth century (Compo and Sardeshmukh 2010; Deser et al. 2010). To ascertain the role of greenhouse warming with regard to the Indian Ocean, SSTs from a suite of 25 climate models participating in phase 5 of the Coupled Model Intercomparison Project (CMIP5; Taylor et al. 2012) are used. For examining the atmospheric circulation, the wind and vertical velocity at different levels for the years 1979–2012 are obtained from the European Centre for Medium-Range Weather Forecasts (ECMWF) Interim Re-Analysis (ERA-Interim; Dee et al. 2011).

For the numerical model experiments a global coupled ocean–atmosphere model, the Scale Interaction Experiment–Frontier Research Center for Global Change (FRCGC) version 2 (SINTEX-F2) model, which has a realistic simulation of the ENSO–monsoon variability, is utilized (Masson et al. 2012; Terray et al. 2012). The oceanic and atmospheric components have 0.5° and 1.125° horizontal resolution respectively, with 31 levels in the vertical for both. The coupled configuration of SINTEX-F2 model is time integrated over a period of 300 yr and utilized as the reference run. In addition, a model sensitivity run is performed over a period of 110 yr, by suppressing the SST variability over the Pacific (25°S–25°N, 100°E–70°W). For this experiment, we used the standard configuration of the coupled model without any flux corrections, except in the Pacific where we applied a large feedback value ($-2400\,W\,m^{-2}\,K^{-1}$) to the surface heat flux. This value corresponds to the 1-day relaxation time for temperature in a 50-m mixed layer. The SST damping is applied toward a daily climatology computed from the reference run. This large correction suppresses the SST variability over the tropical Pacific. Difference between the control and sensitivity runs renders the role of ENSO variability on global climate variability, including its effects on the SST variability over the Indian Ocean.

The unbiased moment estimate of skewness is used to measure the asymmetry, and also the frequency and intensity of ENSO events. This statistic may be computed as

$$\text{Skewness} = nM_3/[(n-1)(n-2)\sigma^3],$$

where M_3 is $\sum(x_i - \overline{x})^3$, σ is the unbiased estimate of standard deviation, and n is the number of observations.

3. Results

It is observed that the western Indian Ocean (Fig. 1c; 5°S–10°N, 50°–65°E) shows continuous warming since the start of twentieth century (which attains an increased rate post-1950s), whereas for the rest of the Indian Ocean, including the warm pool (Fig. 2; SST > 28.0°C), the warming is prominent only after the 1950s. At the beginning of the twentieth century, the mean summer SST over the western Indian Ocean was around 26.5°C, which is cooler in comparison to the rest of the Indian Ocean at 27.2°C. The incessant warming for over a century has led to the western Indian Ocean SSTs reaching the high SST values (28.0°C) observed over the warm pool regions (Fig. 1c). During 1901–2012, the western Indian Ocean experienced anomalous warming of up to 1.2°C, while the warm pool warming was constrained to 0.7°C. This results in a 0.5°C difference in the warming, which is significant with respect to the Indian Ocean SSTs, and in turn the monsoon dynamics (Izumo et al. 2008; Yang et al. 2007). Apart from weakening the zonal SST gradient and changing the monsoon circulation, an SST increase from 26.5° to 28.0°C will also drastically change the convective response from shallow to deep convection (Gadgil et al. 1984; Roxy 2014; Roxy et al. 2013). The sustained warming over the western Indian Ocean against that of the warm pool is also stronger in the annual mean SSTs (Fig. 1d).

Similar to other regions over the global oceans, anthropogenic forcing might be a major contributor to the observed warming over the Indian Ocean. However, the historical climate model simulations under CMIP5 using observed greenhouse gases forcing does not reproduce the zonal SST gradient or the pronounced warming over the western Indian Ocean (Fig. 1c). Instead, the western Indian Ocean warming trend in CMIP5 is similar to the warm pool trend. This could mean that, apart from the direct radiative forcing due to increased greenhouse gases, other unaccounted mechanisms in the simulations (e.g., modulation of ENSO skewness and associated teleconnections) may also have a role in contributing to the observed SST trends over the western Indian Ocean.

A simultaneous correlation analysis between the eastern Pacific and global summer mean SST anomalies, after removing the global warming trends, depicts significant positive correlation over the western Indian Ocean (Fig. 3a). Time series of these anomalies constructed over the eastern Pacific (5°S–5°N, 120°–80°W) and the western Indian Ocean also yield a high correlation ($r = 0.6$), significant at the 99% confidence level (Fig. 3b). This indicates that ENSO dominates the western tropical Indian Ocean variability during boreal summer through fast atmospheric teleconnections.

It is striking to notice that the number and intensity of El Niño events have significantly increased during the latter half of twentieth century (12 events), in comparison with the former half (7 events). During recent decades, SST skewness exhibits more positive values in the eastern Pacific, reflecting the fact that the amplitude and frequency of El Niño events have increased (Figs. 3b and 4). The rate of Indian Ocean warming has also increased during the last five decades, which saw some of the strongest El Niño events during the past century (Fig. 3b). It is however noted that the Indian Ocean SST anomalies associated with La Niña are relatively smaller in comparison with those associated with El Niño. One of the interesting facts is that, post-1950, a few warm events over the Indian Ocean have attained the threshold value for El Niño ($1\sigma = 0.77$°C; Fig. 3b). This places these warm events almost on par with El Niño in magnitude, although the peaks are not as high.

To ascertain whether the increasing number of warm events may contribute to the long-term warming trend, the skewness of the eastern Pacific detrended SST anomalies is contrasted along with the trend of the western Indian Ocean SST anomalies (Fig. 4c). The asymmetry between warm and cold events over eastern Pacific, with a skewness toward warm events throughout the time period is evident. This positive skewness of eastern Pacific SSTs is well correlated with the warming trend observed over the western Indian Ocean (Fig. 4c, $r = 0.76$ for annual values).

The asymmetry in ENSO forcing is substantiated by comparing the atmospheric circulation over the tropics during El Niño and La Niña years against the climatological Walker circulation (Fig. 5a). The El Niño composite shows an anomalous shift in the circulation over the tropics, with the ascending cell over the eastern Pacific and subsidence over the Maritime Continent, resulting in low-level easterly anomalies over the

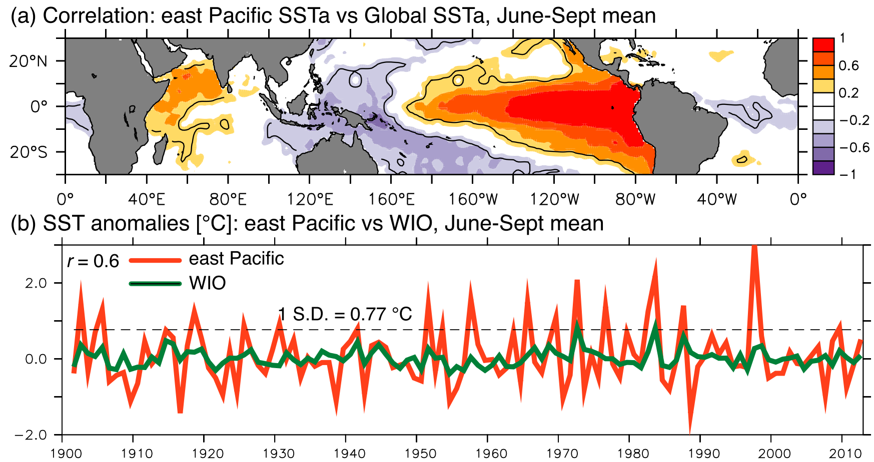

FIG. 3. (a) Observed correlation between mean summer (JJAS) SSTs (°C) over the eastern Pacific (5°S–5°N, 120°–80°W) and the global tropics during 1901–2012. Correlation coefficients have been computed from detrended data. Contours denote regions significant at the 99% confidence level. (b) Time series of mean summer SST anomalies (°C) over the eastern Pacific (red) and the WIO (green). Both time series have been detrended. Eastern Pacific SST anomalies, which rise above 1σ (0.77°C, horizontal dashed line) are considered as El Niño events.

western Indian Ocean (Fig. 5b). These easterly anomalies weaken the mean westerlies over the Indian Ocean, leading to the observed warming. On monthly time scale, the El Niño effect on warming during summer is simultaneous. This is different from the Indian Ocean warming during individual years, observed by other studies at 3–4 months lag (or more) after the mature phase of El Niño in winter (Du et al. 2009; Lau and Nath 2003; Xie et al. 2009). The anomalous circulation in the La Niña composite, meanwhile, does not show any significant change in the low-level winds and the vertical velocity over the Indian Ocean (Fig. 5c; 5°S–10°N, 20°–100°E). This might be a reason why the warm events over the western Indian Ocean are not interspersed by any significant cooling events despite of the ENSO variability (Fig. 3b). A composite of the summer SST anomalies during El Niño and La Niña years further demonstrates this asymmetry in forcing the Indian Ocean (Figs. 5e,f). While the El Niño composite exhibits significant warming over the western Indian Ocean, the La Niña composite does not show any significant negative anomalies over the region.

The fact that the SST anomalies do not show any long-term significant trend over the eastern Pacific, despite a globally warming environment and positive skewness in recent decades, is intriguing (Fig. 1a). Tropical Pacific variability oscillating between the warm and cool events might be a first reason. However, the fact that the Indian Ocean warming favors a faster transition from El Niño to La Niña conditions in the Pacific may also contribute significantly (Kug and Kang 2006; Luo et al. 2012). Also, a recent study shows that warming trend over the Atlantic results in La Niña–like conditions over the eastern Pacific, through a modification of the Walker circulation (Kucharski et al. 2011). These negative feedbacks due to enhanced warming over the Indian and Atlantic Oceans might explain why there are no robust long-term trends over the eastern Pacific. It may however be noted that unlike the Indian Ocean, data availability is relatively sparse over the Pacific, which makes it difficult for robust assessment of long-term trends over this region (Deser et al. 2010).

So where does all the heat go to? The results here indicate that a large share of the heat piles up in the Indian Ocean, consistent with earlier studies (Du et al. 2009; Xie et al. 2009). Figure 6a shows the SST difference between the post- and pre-1950s, and demonstrates the pronounced warming over the Indian Ocean in the recent decades. Apart from the direct radiative forcing due to increasing greenhouse gases, El Niño appears as an event through which the Pacific Ocean throws out its heat, which partially gets accumulated in the Indian Ocean. Indeed, Compo and Sardeshmukh (2010), using a decomposition of ENSO-related and ENSO-unrelated SST trends, demonstrated that ENSO explains up to 40% of long-term warming trends over the global oceans. Specifically, the following two factors might be helpful in explaining the sustained warming of Indian Ocean SST anomalies. One is the asymmetry in the ENSO teleconnection, from which El Niño induces warming over the western Indian Ocean, while the La Niña fails to induce any significant cooling. The second factor is the positive skewness in ENSO forcing during

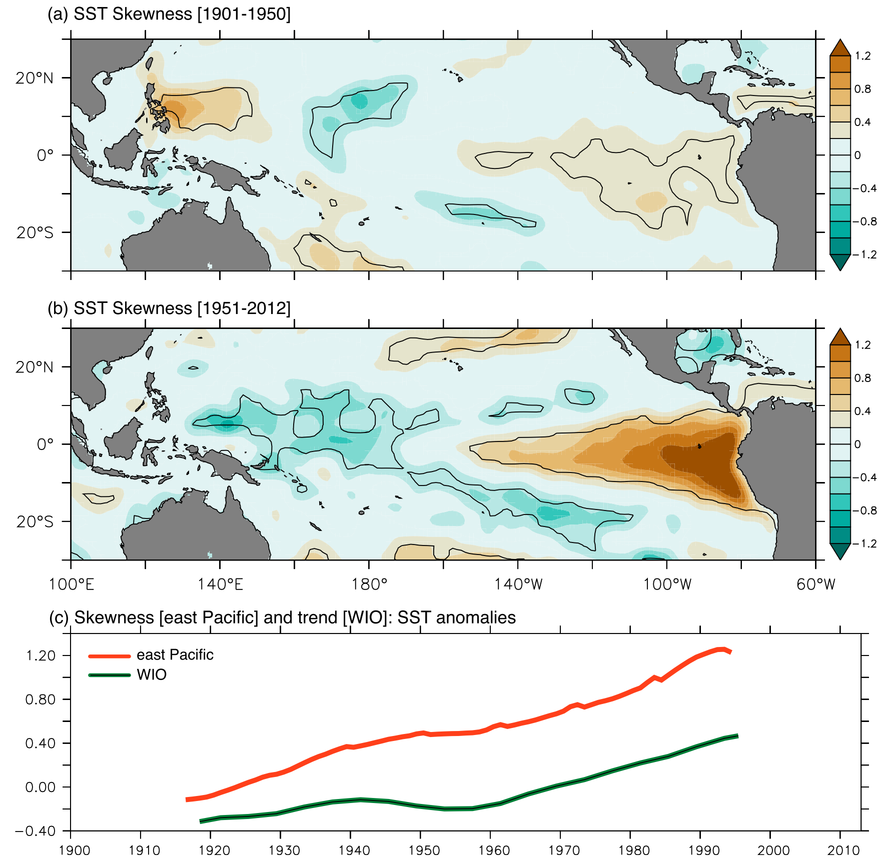

FIG. 4. SST skewness estimated for detrended monthly SST anomalies during the periods (a) 1901–50 and (b) 1951–2012. Contours denote regions significant at the 99% confidence level. (c) Time series of skewness computed from detrended SST anomalies over the eastern Pacific (red) and of SST trend (green) over the WIO estimated over 31-yr sliding periods, for the NH summer. The two time series have also been smoothed with a 31-yr moving average, for display only. The annual values of the two time series are highly correlated ($r = 0.76$).

recent decades, which aggravates the warming in the recent period.

The hypothesis of ENSO forcing on the western Indian Ocean warming trend during summer is tested with sensitivity experiments using a state-of-the-art global coupled ocean–atmosphere model with a realistic ENSO variability (Fig. S2 in the supplemental material). Numerical simulations are compared for a tropical Pacific in which ENSO variability is suppressed against a Pacific where ENSO variations are free to evolve. Figure 6b shows the SST anomalies over the Indian Ocean resulting from ENSO variability in the simulations. During boreal summer, the SST anomalies show a significant warming over the western Indian Ocean. Despite the fact that our coupled model has difficulties in representing the positive skewness associated with ENSO (Fig. S3), it is found that El Niño events have a stronger impact on warming than La Niña events on cooling the Indian Ocean. The model experiment brings out an interesting fact: that the long-term warming over the western Indian Ocean, although at magnitudes lower than those observed, may exist even without increasing greenhouse gases, because of a decadal modulation of the ENSO variability.

A consequence to the western Indian Ocean warming and ENSO is probably a tendency toward more Indian Ocean dipole (IOD) events during recent decades. IOD events manifest as patterns of anomalously warm SST in the western Indian Ocean, along with cool SST in the southeastern Indian Ocean (Murtugudde et al. 1998; Saji et al. 1999; Webster et al. 1999). These dipole events tend to develop during the months of June–August (JJA) and peak during September–November (SON). Positive IOD events generally coincide with El Niño or El Niño–like events (Roxy et al. 2011). In fact, the SST anomalies over the Indian Ocean in Fig. 3a is indicative of an IOD-like response to the ENSO at the interannual time scale, but our trend analysis of the observations and

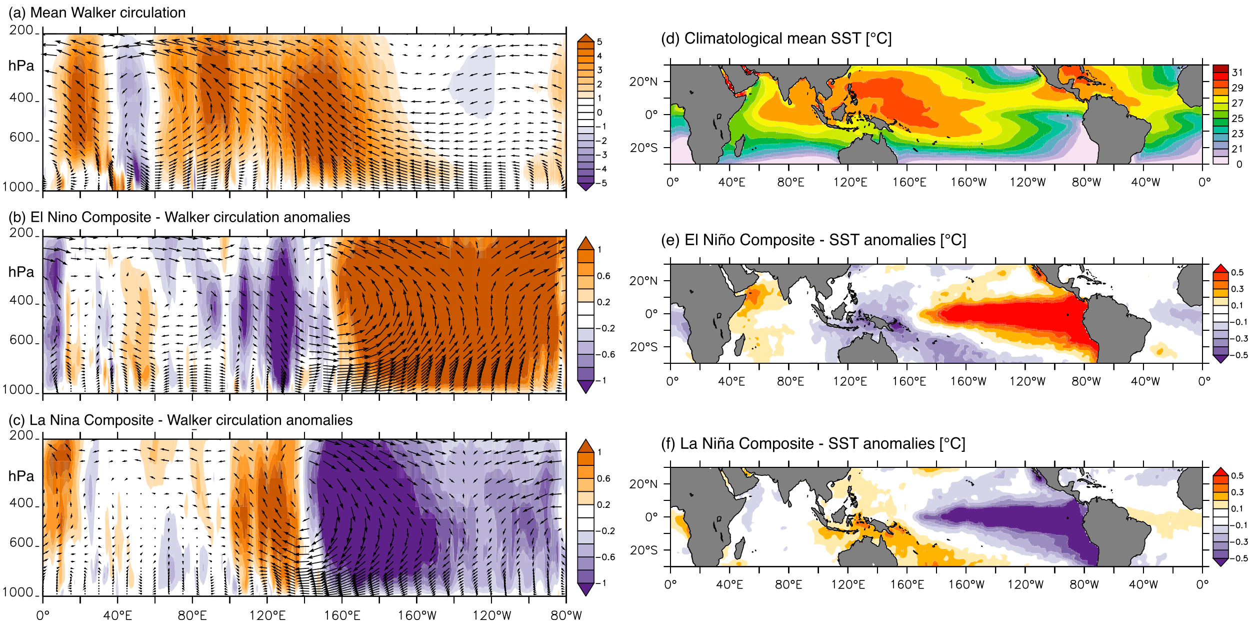

FIG. 5. Zonal atmospheric circulation for boreal summer over the equator (5°S–10°N) during (a) climatological mean conditions, and anomalies during (b) El Niño years and (c) La Niña years. The winds (vectors; m s^{-1}) and the vertical velocity (colors; Pa s^{-1}) indicate the zonal and vertical motion (positive upward) of air, respectively. Similarly, SST (°C) during (d) climatological mean conditions, and anomalies during (e) El Niño years and (f) La Niña years. The composites are estimated from detrended monthly SST anomalies.

model simulations do not corroborate the hypothesis that the western Indian Ocean warming is tightly linked to IOD frequency changes (Fig. 6). Besides ENSO, other drivers such as the Asian monsoon variability can also trigger IOD events (Ashok et al. 2003; Cai et al. 2013). The focus of the current study is not to separate and examine the IOD events due to ENSO and other drivers, but to address whether the increasing warm events and the long-term trend over the western Indian Ocean are a consequence of El Niño.

4. Summary and discussion

Recent studies have shown that the Indian Ocean warm pool has been warming for the past half-century. The current study, using SST trends computed over the past century, indicates a long-term warming trend over the western Indian Ocean that surpasses that over the warm pool in both magnitude and period (Fig. 1c). The results from the study point out the asymmetry in the ENSO teleconnection as one of the reasons whereby El Niño events induce anomalous warming over the western Indian Ocean and La Niña events fail to do the inverse. A second, prominent reason is the positive SST skewness associated with ENSO, as the frequency of El Niño events has increased during recent decades.

The Intergovernmental Panel on Climate Change Fifth Assessment Report (IPCC AR5) points out that 90% of the heat resulting from global warming during the last four decades has been accumulated in the oceans (Rhein et al. 2014). The periodic occurrence of El Niño acts as a vent to exchange this heat from the ocean to the atmosphere. It is this heat that is partially transferred to the Indian Ocean via a modified Walker circulation, and is reflected in the warming trend over the region. It is interesting to note that the warming trend over the Indian Ocean is a major contributor, and largely in phase with the overall trend in the global mean SST (Fig. 7). Although the frequency of El Niño events has increased in the recent decades, a strong warm event has not been recorded since 1997/98 (Fig. 3b), and correspondingly the Pacific and Indian Ocean SST anomalies show a slight dampening (Figs. 1c). This could add up as a reason for the recent hiatus in the global surface warming (Kosaka and Xie 2013). Again, the recent cool conditions over the eastern Pacific might be due to the feedback from a warmer Indian Ocean, bringing the sequence of events to a vicious cycle, which requires further extensive research. As noted by several other studies (Kucharski et al. 2011; Kug and Kang 2006; Luo et al. 2012), the warming trends over the Indian and Atlantic Oceans lead to La Niña–like conditions over the Pacific.

In the recent decades, anomalous warm events, though of weaker amplitude, have occasionally shown prominence over the central Pacific (El Niño Modoki; Ashok

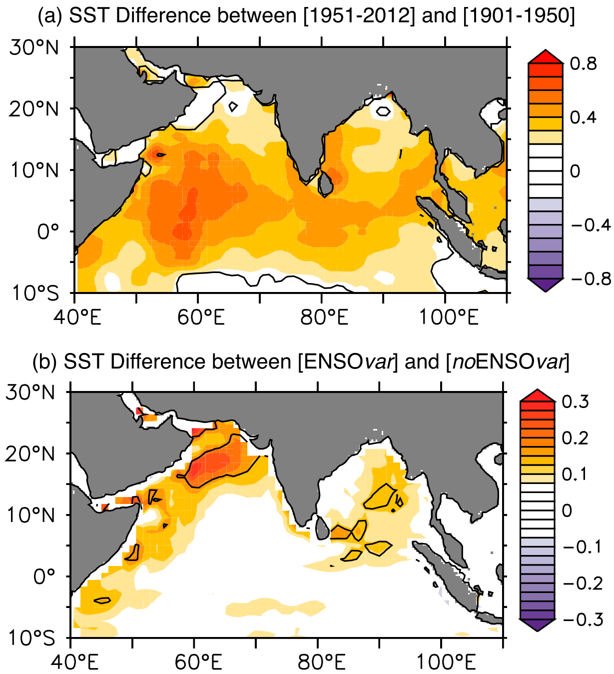

FIG. 6. (a) Difference in the SST (°C) over the Indian Ocean, for the periods 1951–2012 and 1901–50, for the NH summer. (b) Model simulated mean SST anomalies (°C) during NH summer, in response to ENSO variability in the model. The model simulated SST variability due to ENSO is estimated from the SST anomalies in the control run (ENSOvar). These SST anomalies are defined with respect to a monthly climatology computed from the sensitivity experiment without ENSO variability (noENSOvar). The role of ENSO skewness is depicted in (a) and that of ENSO asymmetry is depicted in (b), on the Indian Ocean. Contours denote regions significant at the 99% confidence level estimated from a resampling method.

and Yamagata 2009) and even the entire Pacific basin (Ashok et al. 2012), and the dynamics of the Indian Ocean warming may reflect these changes as well. It was noted earlier that, post-1950, the warm summer SST anomalies over the western Indian Ocean have occasionally attained the El Niño threshold value (0.77°C). Supplementing the long-term persistence of these events, the warming scenario over the Indian Ocean and related climate dynamics is a factor to be vigilant about while assessing long-term climate change and variability.

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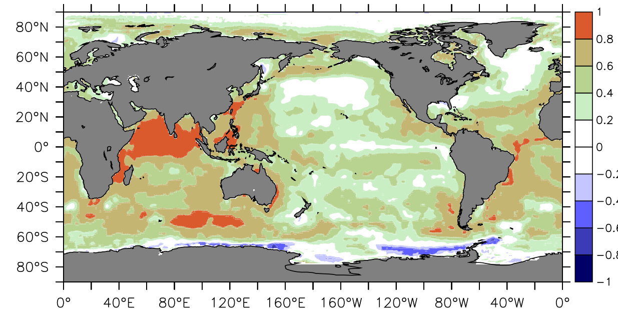

FIG. 7. Observed correlation between annual global mean SST and the annual SST at each grid, during 1901–2012. Color shading denotes correlation coefficients significant at the 99% confidence.

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