Chapter 10
Variability and Trends of Sea Surface Temperature and Circulation in the Indian Ocean

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1 Observations in the Indian Ocean

The history of the Indian Ocean observations stretches back approximately to the 1870s (Deser et al. 2010), and a large share of these measurements came from ships of opportunity, mostly linking Mediterranean through the Suez Canal to the maritime continent. Physical oceanographic expeditions were rare in the Indian Ocean until 1950s, with usually more than a couple of decades between two observations in the same region (Behrman 1981). It was only during 1959–1965 that a systematic recording of the Indian Ocean characteristics started with the International Indian Ocean Expedition (IIOE). This was later appended with large-scale sampling through regional programs such as MONEX, BOBMEX, JASMINE and ARMEX (Murakami 1979; Bhat et al. 2001; Webster et al. 2002; Shenoi et al. 2005) along with the use of Argo array profiling floats. Since the advent of satellite era, high-resolution satellite data at frequent intervals became available, helping scientists to decipher the spatiotemporal variability of the Indian Ocean even at finer scales (Bhat et al. 2004). Another major advancement in comprehending the Indian Ocean dynamics took place with the altimeter mission Topex/Poseidon. Understanding of the Indian Ocean sea surface temperature (SST) variability entered a new phase with the advent of microwave radiometer-based satellite observations from December 1997, especially during the cloudy period. Currently, the northern Indian Ocean has a reasonable observational coverage dating back to approximately 1870s (Deser et al. 2010) which supports a reliable analysis of Indian Ocean SST variability on both short and long timescales. The next section discusses the SST trends and variability over the tropical

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Indian Ocean, at annual, interannual and intraseasonal timescales and their impact on regional climate. Section 3 discusses the variability and trends in the Indian Ocean circulation.

2 Sea Surface Temperature (SST) Variability in the Indian Ocean

Among the tropical oceans, the Indian Ocean is the smallest and the warmest. The tropical Indian Ocean forms the major part of the largest warm pool (SST > 28 °C) among the global oceans. Tropical Indian Ocean SST plays a significant role in shaping climate as well as its variability on both regional (Chowdary et al. 2015) and global scales (Schott et al. 2009), and it is hence important to know the characteristics of Indian Ocean SST on spatial and temporal scales. Indian Ocean exhibits climate variability in several timescales, ranging from diurnal to interannual, and is strongly coupled to the seasonal cycle (Schott et al. 2009). The Indian Ocean also exhibits long-term trends in temperatures at both the surface (Roxy et al. 2014) and the subsurface (Lee et al. 2015), with an impact on the local monsoon Hadley circulation (Roxy et al. 2015), interannual variability (Chakravorty et al. 2014a) and the intraseasonal variability (Sabeerali et al. 2014).

The tropical ocean–atmosphere system exhibits marked variability in the intraseasonal timescales (Lau and Waliser 2012). Central to the intraseasonal variability is the Madden–Julian Oscillation (MJO), which was first discovered as an atmospheric phenomenon (Madden and Julian 1971, 1972, 1994) over the equatorial oceans. Subsequent experiments like the MONEX (see Murakami 1979) and BOBMEX revealed strong intraseasonal signals in the Bay of Bengal as well (Krishnamurti et al. 1988; Bhat et al. 2001). This intraseasonal variability in SST is closely associated with the atmospheric variability at similar scales (10–20 days and 30–90 days) and acts as a coupled phenomenon (Sengupta et al. 2001; Vecchi and Harrison 2002; Roxy and Tanimoto 2007; Vialard et al. 2012; Roxy et al. 2012). On the other hand, the intraseasonal SST variability in the Arabian Sea is forced by the oceanic processes (Vialard et al. 2012). A recent field campaign called the Dynamics of MJO/Cooperative Indian Ocean Experiment on Intraseasonal Variability in Year 2011 (DYNAMO/CINDY2011) traces the initiation of the MJO events to local ocean atmospheric processes over the Indian Ocean (Li et al. 2015). Several model studies addressed the intraseasonal SST variability associated with MJO and the associated processes (e.g. Jayakumar et al. 2011).

On interannual and decadal timescales, the Indian Ocean SSTs are influenced by two prominent modes of variability, namely El Niño Southern Oscillation (Rasmusson and Carpenter 1982; ENSO) and the Indian Ocean Dipole (IOD; Saji et al. 1999; Webster et al. 1999; Murtugudde et al. 2000).

2.1 Response of Indian Ocean to El Niño Southern Oscillation (ENSO)

ENSO is characterized by quasi-periodical events of warm and cool SST anomalies in the east equatorial Pacific. The large-scale shift in convection during an ENSO event alters the atmospheric circulation over both the tropics and extra-tropics. Tropical Indian Ocean (TIO) climate is strongly influenced by El Niño through an atmospheric bridge (e.g. Alexander et al. 2002) and ocean bridge such as pathways of Indonesian throughflow (ITF, e.g. Vaid et al. 2007; Sprintall et al. 2014). The basin-wide warming or cooling is found to be the first leading mode of the interannual SST variability in the Indian Ocean (Klein et al. 1999; Alexander et al. 2002; Chowdary and Gnanaseelan 2007; Yang et al. 2007; Du et al. 2009; Schott et al. 2009; Chowdary et al. 2015) and is induced by El Niño (La Niña) in boreal winter (Klein et al. 1999; Alexander et al. 2002; Chowdary and Gnanaseelan 2007). Ekman divergence/convergence-induced Rossby waves and El Niño-related subsidence-induced variations in heat flux play crucial roles in inducing TIO basin-wide warming (e.g. Chowdary and Gnanaseelan 2007; Du et al. 2009; Chowdary et al. 2015). This TIO warming persists until the following boreal summer (Xie et al. 2009; Chakravorty et al. 2014b), especially during the recent years (e.g. Chakravorty et al. 2014a), whereas El Niño-related warm SST anomalies in the eastern Pacific weakens or terminates by the following spring (e.g. Xie et al. 2010).

2.2 Indian Ocean Dipole (IOD)

IOD events are characterized by cool SST anomalies in the south-eastern equatorial Indian Ocean and warm SST anomalies in the western equatorial Indian Ocean (Saji et al. 1999; Webster et al. 1999; Vinayachandran et al. 1999; Murtugudde et al. 2000). The SST dipole is accompanied by a similar dipole in the precipitation anomalies, with suppressed precipitation in the east and enhanced precipitation in the western Indian Ocean. They are also closely associated with the equatorial Indian Ocean wind anomalies (e.g. Gadgil et al. 2004). Dipole events are generally initiated during June–August, but the events peak during September–November. The magnitude of any given event is represented by a normalized time series of the difference between west and south-east equatorial Indian Ocean anomalies known as the Dipole Mode Index (DMI). Positive IOD events often coincide with El Niño or El Niño-like events (Drbohlav et al. 2007; Roxy et al. 2014). Good Asian summer monsoon may also trigger IOD events (Ashok et al. 2003; Krishnan and Swapna 2009; Cai et al. 2013). Sayantani et al. (2014) showed the evolution of premonsoon Arabian Sea warming as a trigger for pure IOD events. A few studies indicate that the decadal variability in the Indian Ocean and the IOD is associated with the Pacific Decadal Oscillation (PDO) of the North Pacific SST (Crueger et al. 2008; Krishnamurthy and Krishnamurthy 2016). IOD has significant impact on Indian Ocean circulation, and interbasin mass and salt transport (Thompson et al. 2006; Jensen 2007) as well as the climate of the adjoining region. The east African fall rainfall variability is strongly affected by the developing phase of IOD, and significant impact on the Indian summer monsoon is observed only during strong IOD years (Deshpande et al. 2014). In addition to the surface dipole variability, Rao et al. (2002) and Sayantani and Gnanaseelan (2015) reported, respectively, the east–west and north–south dipole variability in the subsurface temperature (thermocline).

2.3 Indian Ocean Warming

The global oceans account for approximately 93 % of the warming of the earth system that has occurred since 1955. Indian Ocean exhibits enhanced warming in the surface and subsurface. Observations indicate a substantial surface warming of the Indian Ocean during the past half-century (Alory et al. 2007; Ihara et al. 2008; Alory and Meyers 2009; Swapna et al. 2014; Roxy et al. 2015). These studies indicate a basin-wide surface warming in the Indian Ocean (Du and Xie 2008; Hoerling et al. 2004), with an expansion of the warm pool region (Fig. 1a). The peak surface warming is displayed over the central equatorial region. This is favourable for weakening the monsoon Hadley cell. Ihara et al. (2008), using observed data, indicated that the western and the eastern regions of the Indian Ocean display significant warming trends since 1950. Over the past 60 years, the Indian Ocean warmed two to three times faster than the tropical Pacific (Williams and Funk 2011). Radiative forcing due to increased greenhouse gases has been given as an obvious cause of the warming (Du and Xie 2008), but that does not explain the enhanced warming in the Indian Ocean relative to the other tropical regions, especially with the decreasing trends in the net heat flux (Rahul and Gnanaseelan 2013). A few of these studies

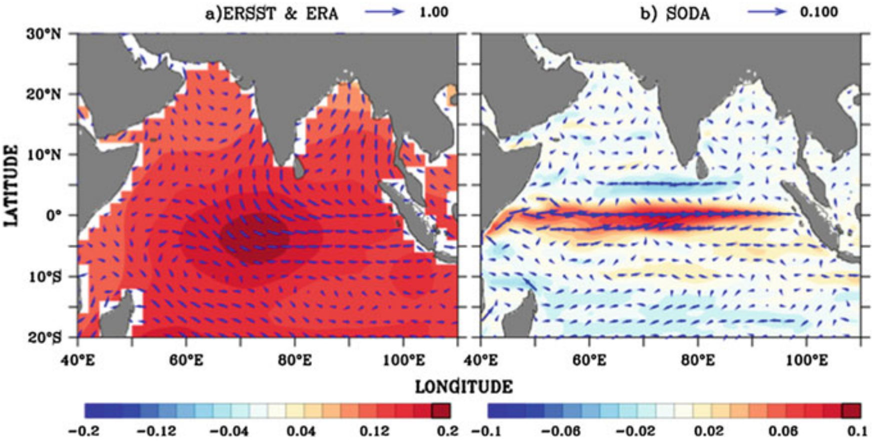

Fig. 1 **a** Trend in annual SST (*shaded*, per decade) superimposed with trend in ERA 10 m annual winds (*vectors*, per decade) for the period of 1958–2015, **b** trend in annual zonal current (per decade) superimposed with linear trend in current (vectors, per decade) for the period of 1958 to 2008

suggest that warm SSTs in this region trigger a local air–sea coupled interaction (Lau and Nath 2000; Du et al. 2009), which raises the warm pool temperature further. Meanwhile, other studies (Swapna et al. 2014) suggest that the weakening monsoon winds are responsible for the increasing surface warming over the Indian Ocean during the monsoon season. Roxy et al. (2014) point out that the western Indian Ocean has been warming consistently in summer during the past century and links the warming to the asymmetry and skewness in the ENSO forcing. They suggest that the increase in the frequency and magnitude of El Niño events in the recent years has resulted in a warming of the western Indian Ocean during summer, which persists for several months due to local air–sea interactions (Du et al. 2009) and ocean dynamics (Chowdary and Gnanaseelan 2007).

Though the century-long warming indicates large warming trend in the western Indian Ocean, SST trends during 1958–2015 display a basin-scale warming with peaks in the central equatorial Indian Ocean (Fig. 1a). The basin-scale warming is the leading mode of tropical Indian Ocean SST variability on interannual timescales and hence known as the Indian Ocean Basin (IOB) mode (e.g. Chowdary and Gnanaseelan 2007). It is also the prominent feature of the interdecadal SST trend in the recent decades. The IOB mode and Nino indices are highly correlated (Klein et al. 1999; Saji et al. 2006) though part of the SST variability is attributed to ocean dynamic processes and local air–sea interaction in the TIO (Lau and Nath 2000; Chowdary and Gnanaseelan 2007; Du et al. 2009).

The trend in the heat absorbed by the oceans contributes significantly to the variability at different depths (Levitus et al. 2012). About 60 % of the variability in the upper Pacific Ocean (top 1000 m) and Atlantic Ocean (top 1500 m) is contributed by linear trends (Levitus et al. 2012). The scenario is so complex in the Indian Ocean with the significant variance contributed by the linear trend observed in the 0–100 m, 200–500 m and 1100–1500 m layers (Levitus et al. 2012). Previous studies indicate the prominent subsurface warming of the Indian Ocean. Increase in the heat content of the upper 700 m of the southern Indian Ocean is reported by Levitus et al. (2012). According to Pierce et al. (2006), most of the tropical Indian Ocean warming is trapped in the top 125 m. Lee et al. (2015) reported an increase in the heat transport from the Pacific to the Indian Ocean during the recent decade through the Indonesian pathways. They pointed out that this heat gain in the past decade is more than 70 % of the global ocean heat gain in the upper 700 m. These studies indicate the growing importance of Indian Ocean as a heat reservoir in a warming world.

Figure 2a, b shows the trends in the upper ocean heat content, respectively, from SODA (Carton and Giese 2008) during 1958–2008 and Hadley centre EN4.0.2 (Good et al. 2013) during 1958–2015. Both products show warming trends in the north Indian Ocean, especially over the eastern equatorial Indian Ocean, Bay of Bengal and Arabian Sea. The warming pattern is similar for both the products in the upper 100 m, whereas they display some differences below 100 m, especially over the western Bay of Bengal. Figure 2c shows the increasing trend in the north Indian Ocean heat content of the upper 700 m from SODA and EN4. Both the products show similar trends though they display some differences in the interannual variability. Figure 2d shows the evolution of the annual mean over the north Indian Ocean and its linear

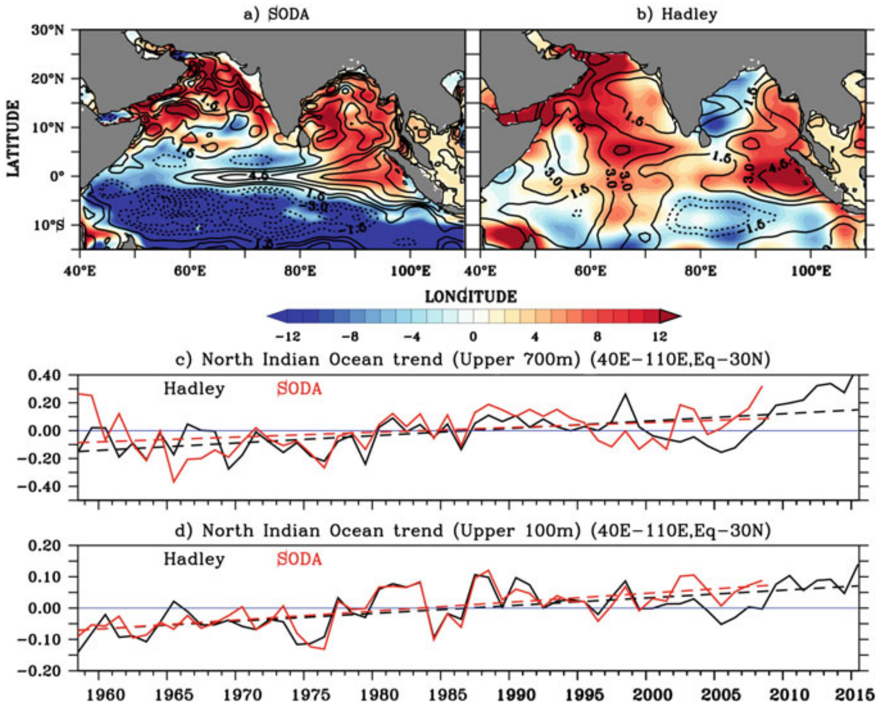

Fig. 2 *Upper* 700 m ocean heat content trend per decade (*shaded*, $\times 10^{-7}$) superimposed with upper 100 m heat content trend per decade (contour, $\times 10^{-7}$) from **a** SODA (for the period of 1958–2008), **b** Hadley centre EN4 (for the period of 1958–2015), **c** annual upper 700 m heat content anomaly over north Indian Ocean basin (40°E–110°E, Eq-30°N) (*solid*) superimposed with its trend (*dash*) from SODA (*red*) (for the period of 1958–2008) and Hadley centre EN4 (*black*) (for the period of 1958–2015), **d** is same as **c** but the upper 100 m heat content anomaly and its trend (color figure online)

trend. The correspondence between SODA and EN4 is better for 100 m heat content compared to that of 700 m. Both the products show steady warming of north Indian Ocean.

2.4 Local and Remote Impacts of Indian Ocean Warming

The Indian Ocean warming has local and remote impacts on regional climate change. Observations and model simulations indicate that the enhanced warming in the Indian Ocean increases rainfall over the Indian Ocean, but results in subdued convection over the Indian subcontinent via a weakened local Hadley circulation (Mishra et al. 2012; Kulkarni 2012; Saha et al. 2014; Roxy et al. 2015). Associated with the warming, the weak south-westerly winds during summer (Fig. 1a) and the coupled ocean–atmosphere interaction keep the surface ocean warm. Sabeerali et al. (2014) indicate that the SST warming in the Indian Ocean during the recent decades has changed the space–time characteristics of the northward-propagating monsoon intraseasonal oscillations. They found that the excess warming during the recent years triggers stationary convection over the equatorial Indian Ocean, stalling the northward propagation. Additionally, the warming trend has the potential to influence the Australian precipitation (Ashok et al. 2003) and the East Asian monsoon circulation (Li et al. 2010).

Model simulations indicate that the Indian Ocean warming plays a significant role on the African and Sahel droughts (Bader and Latif 2003; Giannini et al. 2003; Hoerling et al. 2006). According to Hoerling and Kumar (2003), widespread drying over the mid-latitudes are due to warm SST anomalies over the tropical Indian and the western Pacific oceans.

Several studies suggest that a warmer Indian Ocean may modulate the tropical Pacific variability. Terray et al. (2015), using model sensitivity experiments, showed that positive SST anomalies in the Indian Ocean dampen the magnitude of ENSO and also shorten its life cycle. This involves modulations of wind-induced eastward-propagating oceanic Kelvin waves by altering the thermocline. Luo et al. (2012) indicate that enhanced tropical Indian Ocean warming is favourable for the strengthening of trade winds in the western Pacific through atmospheric processes, contributing to La Niña-like conditions in the Pacific, as observed in the recent decades. Their analysis based on historical and future projections suggests that the Indian Ocean warming is modulating the Pacific climate in the twentieth and twenty-first centuries.

The rapid ocean warming has also resulted in increased surface stratification over the Indian Ocean. Increasingly stratified ocean waters suppress the upwelling of nutrients from the subsurface waters and reduce the marine primary production (Roxy et al. 2016). Future climate projections suggest the possibility of further warming of the Indian Ocean, which may affect the marine productivity further, which, combined with the fishing pressure, can deprive this region from its enhanced biological productivity.

Another contributing factor in the modulation of SST is the heat and mass transport carried by currents. Indian Ocean currents are dominated by the strong seasonal cycle of winds and also exhibit intraseasonal and interannual variability. The details of Indian Ocean circulation and its variability and trends are discussed in the following sections.

3 Indian Ocean Surface Circulation

Ocean currents transport mass and energy from one region to another around the world. The large movement of heat and salt associated with these currents makes the ocean current one of the primary drivers of global climate. The ocean circulation stabilizes the global atmospheric circulation and regulates the local weather and temperature extrema. Unlike the other tropical oceans, the atmospheric circulation over the tropical Indian Ocean is characterized by the seasonally reversing cross-equatorial flow. The circulation of the northern Indian Ocean is therefore strongly influenced by the reversing monsoon winds. The most prominent current systems in the northern Indian Ocean are the seasonally reversing Somali current, the west and east India coastal currents and semi-annual equatorial jets or Wyrtki jets. In addition to the seasonality in these current systems, they undergo large interannual and intraseasonal variability. Several studies in the recent years have addressed the Indian Ocean currents to a large extent, but more focused long-term observations are needed for better understanding of the Indian Ocean circulation (Schott and McCreary 2001; Shankar et al. 2002). Satellite-derived surface current products and the observations based on moored buoy array (e.g. RAMA) provide some relief despite their limitations. Rahul and Gnanaseelan (2016) reported decadal changes in the large-scale circulation over Indian Ocean contributing to surface temperature trends and variability.

3.1 Seasonal Mean Circulation in the Indian Ocean

The Somali current, monsoon currents (coastal currents), Wyrtki jets and ITF are the major current systems affecting the north Indian Ocean. Somali current is closely associated with the Findlater jet and the resultant coastal upwelling. The strong upwelling brings down the seasonal mean SST to below 26 °C off Somalia and the Arabian Peninsula. This further undergoes significant intraseasonal (Roxy and Tanimoto, 2007; Vialard et al. 2012) and interannual (Schott et al. 2009) variability, making it an important process in this part of the Indian Ocean. The monsoon currents are the pathways for the interbasin mass transport between Arabian Sea and Bay of Bengal. This plays an important role in the salt balance in the Bay of Bengal and Arabian Sea. This interbasin mass and salt transport displays strong interannual variability through changes in the circulation patterns of Bay of Bengal (e.g. Thompson et al. 2006; Jensen 2007). The equatorial Indian Ocean is characterized by strong eastward surface currents (Wyrtki jets, Wyrtki 1973) during boreal spring and fall, driven by the prevailing westerlies. The Wyrtki jets are closely related to the heat budget of the tropical Indian Ocean. They deepen the thermocline in the east and raise it in the west (Wyrtki 1973), inducing an east–west thermocline (and temperature) gradient (Gnanaseelan et al. 2012). The ITF links Pacific and Indian Oceans by providing a pathway and modifies the stratification within each of these oceans. In addition to the heat and freshwater balance in the Indian Ocean, ITF plays a significant role in the global circulation (Godfrey and Golding 1981). ITF also displays intraseasonal to decadal variability (Valsala et al. 2010).

3.2 Intraseasonal Variability in the Indian Ocean Circulation

Intraseasonal variability in SST over the Indian Ocean is very important in the air–sea interaction associated with MJO and monsoon intraseasonal oscillation (Lau and Waliser 2012). Intraseasonal variability in the ocean currents has a major role in the evolution of intraseasonal SST over Indian Ocean, especially over the Arabian Sea (Vialard et al. 2012). So we provide a brief review of intraseasonal oscillations in current over the Indian Ocean. Reppin et al. (1999) reported small-scale variability in currents near Sri Lanka. Sengupta et al. (2007) showed that both spring and fall Wyrtki jets are modulated on intraseasonal timescale. They showed that the spring Wyrtki jet is modulated by a single intraseasonal event, whereas the fall Wyrtki jet is modulated by two to three intraseasonal events. In addition to the intraseasonal variability in the spring and fall Wyrtki jets, Senan et al. (2003) reported intraseasonal jets during the summer monsoon season. Vialard et al. (2009) reported intraseasonal variability in the west India coastal current from ADCP observations off Goa coast. Mukherjee et al. (2014) reported intraseasonal variability in the east India coastal current. Shenoi (2010) provided a review on the evidences of intraseasonal variability of the coastal currents around India.

3.3 Interannual Variability in the Indian Ocean Circulation

Interannual variability over the equatorial Indian Ocean is dominated by Wyrtki jet variability. Interannual wind variability in winds associated with IOD and El Niño is primarily responsible for the Wyrtki jets variability. Anomalous westward currents in response to the easterly wind anomalies during the 1997 IOD event are reported by Grodsky et al. (2001). Thompson et al. (2006) also analysed the anomalous circulation associated with IOD. Reppin et al. (1999) from ship drift observations speculated that the El Niño is primarily responsible for the interannual variability of the Wyrtki jets. Recent studies have attributed this interannual variability mainly to IOD forcing (Chowdary and Gnanaseelan 2007; Nagura and McPhaden 2010; Gnanaseelan et al. 2012). The coastal region of the western Indian Ocean is a relatively unexplored area but displays strong variability in currents. Modelling studies on the formation and interannual variability of Great Whirl are few, but have shown that the Great Whirl variability is primarily dominated by its internal processes rather than the wind field (Schott and McCreary 2001). The Somali current as well as the coastal currents in both Arabian Sea and Bay of Bengal are studied by Schott and McCreary (2001) extensively using observations as well as models. The mean clockwise Bay of Bengal circulation is intensified during El Niño and IOD years (Thompson et al. 2006; Jensen 2007) resulting in excess transport of high saline Arabian Sea water to Bay of Bengal. On the other hand, the transport of Arabian Sea water to Bay of Bengal reduces during the La Niña years (Jensen 2007). Tropical Indian Ocean climate is strongly influenced by ITF (e.g. Sprintall et al. 2014). ITF displays strong interannual and intraseasonal variability and is dominated by El Niño. There is a large reduction in ITF transport during El Niño years (e.g. Valsala et al. 2010). Lee et al. (2015) suggest an increase in the heat transport from the Pacific Ocean to the Indian Ocean by ITF during the recent decade.

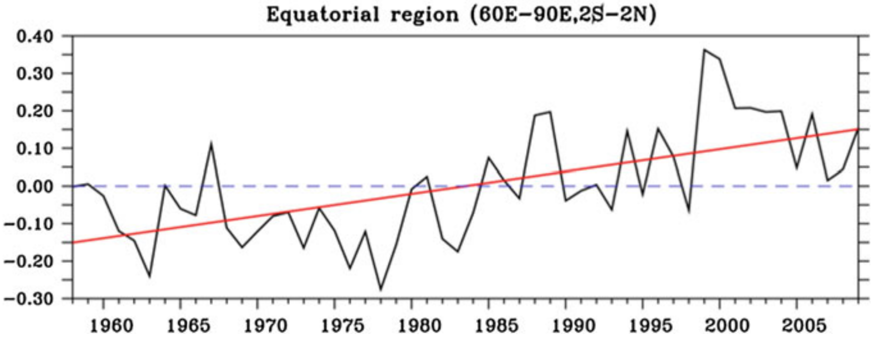

Fig. 3 Annual zonal current anomaly averaged over the region 60–90°E, 2°S–2°N (*black*) superimposed with its linear trend during 1958–2008 (*red*) (color figure online)

3.4 Trends in Indian Ocean Circulation

The Indian Ocean warming and the associated wind changes have strong impact on the Indian Ocean currents. Rahul and Gnanaseelan (2016) showed the existence of coupled feedback between Indian Ocean warming trends and circulation changes. It is important to note that there is a strengthening of mean westerly winds over the equatorial Indian Ocean (Fig. 1a) in the recent years (1958–2015). These westerlies force eastward surface currents along the equator. The trends in Indian Ocean surface circulation are shown in Fig. 1b. The trends in major currents over the Indian Ocean are evident. The most significant features are strengthening of the mean eastward currents along the equator and westward currents along 5°N. There is a significant increasing trend in the equatorial Indian Ocean currents (Fig. 3) and weak (and insignificant) reduction in the Somali current (figure not shown) during 1958–2008. The significant increasing trend in the equatorial currents or Wyrtki jets in turn increases eastward heat transport. These have tremendous consequences on the heat content of Bay of Bengal and the eastern Indian Ocean.

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