Indian Ocean Decadal Variability: A Review

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INDIAN OCEAN DECADAL VARIABILITY

A Review

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Improved definition and understanding of decadal timescale variability in the Indian Ocean region will support climate prediction efforts and have the potential to benefit a large percentage of the world's population living in Indian Ocean rim countries and elsewhere around the globe.

Existing records of upper-ocean temperature exhibit clear fluctuations at time scales ranging from one to a few decades, which for simplicity we refer collectively to as "decadal variability" in this paper[1] (see Fig. 1). This variability includes a rising trend since the 1960s, which is attributed to anthropogenic greenhouse gas forcing, with about 90% of the excess heat input in the climate system stored in the ocean (Levitus et al. 2012). Overlying this trend are decadal fluctuations, part of which may be caused by natural external forcing, such as volcanic eruptions and variability in solar forcing (e.g., Domingues et al. 2008), and part of which is due to natural internal variability (e.g., Meehl et al. 1998; Alexander 2010; Liu 2012). In view of society's need for adapting to climate variability and change, understanding and predicting climate on decadal time scales emerge as pressing priorities in climate research today (Goddard et al. 2009; Hurrell et al. 2009; Meehl et al. 2009; Pohlmann et al. 2009; Doblas-Reyes et al. 2011). Preliminary

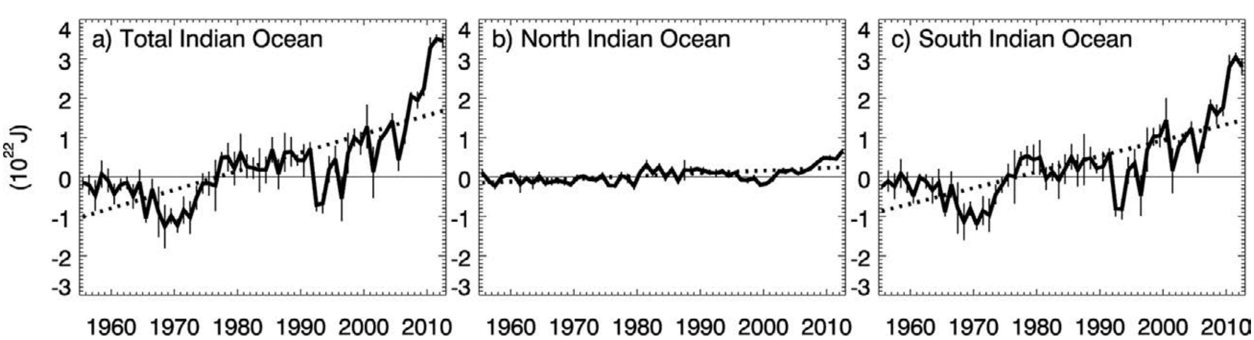

FIG. 1. Time series (1955–2012) of yearly, ocean heat content (10^{22} J) for the 0–700-m layer of the Indian Ocean (thick solid curves). One standard deviation errors (thin vertical lines) and linear trends (dotted lines) are shown in each panel. Data provided by Dr. John Antonov and replotted after Levitus et al. (2009).

[1] Unless specified otherwise in this review, "decadal" variability will refer broadly to variations on decadal to multidecadal time scales, spanning 10–100 yr.

decadal prediction experiments have been carried out and assessed recently (e.g., Collins 2002; Smith et al. 2007, 2013; Keenlyside et al. 2008; Hoerling et al. 2011; Corti et al. 2012). Defining the limits of decadal predictability and developing models capable of skillful decadal predictions, however, rely critically on our understanding of the causes of decadal variability, including contributions from both external forcing (greenhouse gases, aerosols, volcanoes, and solar forcing) and natural internal variations of the climate system (e.g., Hoerling et al. 2011; Solomon et al. 2011).

While natural modes of decadal climate variability have been identified and extensively studied in the Atlantic and Pacific Oceans [see reviews by Alexander (2010) and Liu (2012)], decadal variability of the Indian Ocean is much less understood. There is, however, considerable evidence showing that Indian Ocean decadal sea surface temperature (SST) variations have large climate impacts both regionally and globally.

Both observational and modeling studies have shown that decadal variability in Indian Ocean SST can influence the tropical and extratropical atmosphere via changes in the Walker and Hadley circulations (Wang and Mehta 2008) and in particular impact weather regimes and climate variability in the North Atlantic (Bader and Latif 2005; Hoerling et al. 2004; Hurrell et al. 2004; Latif et al. 2006; SanchezGomez et al. 2008; Schott et al. 2009) and North Pacific (e.g., Chen et al. 1992; Graham et al. 1994; Deser and Phillips 2006). Progressive warming of Indian Ocean SST also influences the tropical atmospheric circulation by strengthening the Pacific Walker circulation (Luo et al. 2012), which intensifies the easterly trade winds and thereby accelerates sea level rise in the western tropical Pacific Ocean (Han et al. 2014). Air–sea coupling over the tropical Indian Ocean can induce large-amplitude decadal modulations of El Niño–Southern Oscillation (ENSO; Yu et al. 2002; Yu 2008) and of the relationship between ENSO and the Indian monsoon (Ummenhofer et al. 2011). Decadal variations of Indian Ocean SST have led to an intensification of Arabian Sea premonsoon tropical cyclones in recent decades (Rao et al. 2008; Krishna 2009; Evan et al. 2011; Sriver 2011; Wang et al. 2012). The decadal trend in upper-ocean heat content in the southeast Indian Ocean combined with the strong 2010/11 La Niña forced an extraordinary surge of the Leeuwin Current off the west coast of Australia during austral summer 2011. This surge resulted in an unprecedented warming event (recently dubbed Ningaloo Niño) in February–March 2011 (Feng et al. 2013; Kataoka et al. 2013), which had devastating impacts on living marine resources in the region (Pearce and Feng 2013).

Tropical Indian Ocean SST variations have large climatic impacts over continents as well. Indian Ocean warming acted in concert with tropical Pacific cooling to force droughts over the United States, southern Europe, and southwest Asia during 1998–2002 (e.g., Hoerling and Kumar 2003; Lau et al. 2006). The Indian Ocean warming trend may have contributed to the increased frequency of Mediterranean winter drought during the past 20 yr (Hoerling et al. 2012), to the drying trend over West Sahel from the 1950s to the 1990s (Bader and Latif 2003, 2005; Giannini et al. 2003; Lu 2009; Mohino et al. 2011), and to the drier eastern Africa "long-rain" season since 1980 (Williams and Funk 2011). Indian Ocean SST also controls multidecadal variability in the hydroclimatic conditions of East Africa (Tierney et al. 2013). In addition, the reduced interhemispheric SST gradient associated with the aerosol loading of the atmosphere from South Asia since the 1950s acts to weaken the Indian summer monsoon rainfall (Chung and Ramanathan 2006; Meehl et al. 2008; Dash et al. 2009).

The Indian Ocean rim region is home to one-third of the world's population, mostly living in developing countries that are highly vulnerable to climate variability and change, especially in low-

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lying coastal areas. Indian Ocean island nations are likewise vulnerable to the vicissitudes of climate, including the likely increased incidence and/or magnitude of extreme high sea level events (Rhein et al. 2014). Consequently, there is a strong societal demand for improved understanding and prediction of decadal climate variability and sea level rise in the region (Milne et al. 2009; Church et al. 2011). Yet, our knowledge about Indian Ocean decadal variability remains primitive compared to the Pacific and Atlantic Oceans. The purpose of this review therefore is to summarize the observational basis for, and our current understanding of, decadal variability in the Indian Ocean. We will also identify outstanding scientific issues that need to be addressed and challenges we face in addressing them.

In the section titled "Indian Ocean circulation and interannual climate variations," we briefly review the mean circulation and interannual variability of the Indian Ocean, since these concepts are helpful for describing decadal variability in later sections. In the section titled "observed decadal variability

UNCERTAINTIES IN TRENDS OF THE INDO-PACIFIC WALKER CIRCULATION.

The Walker circulation is an equatorial zonal atmospheric circulation cell, driven by deep atmospheric convection over the Indo-Pacific warm pool (Fig. SB1). The lower branch of the Walker circulation is associated with easterlies in the Pacific Ocean and westerlies in the Indian Ocean that are important for driving decadal variations in the Indian Ocean (see the "observed decadal variability and its interpretation" section). There is, however, no consensus on decadal variations of the Walker circulation, as illustrated below.

Observational studies provide contrasting results regarding the long-term trends of the Walker circulation, depending on dataset and analysis technique. Some studies suggest enhanced trends in equatorial Pacific zonal SST gradients over the past century (Karnauskas et al. 2009), particularly after ENSO signals are removed (Solomon and Newman 2012). An enhanced Pacific Walker circulation since 1950 has also been suggested (L'Heureux et al. 2013; Newman 2013). However, there is no robust strengthening or weakening trends in Pacific Walker circulation for century-long records (Solomon and Newman 2012). By contrast, some observational studies have argued for a slowdown of the Pacific surface easterlies (Deser et al. 2010; Tokinaga et al. 2012a,b; Yasunaka and Kimoto 2013) and weakened zonal SST gradients (Deser et al. 2010). There is also no clear consensus on the long-term evolution of equatorial westerlies in the Indian Ocean. Atmospheric reanalysis products suggest a strengthening of the Indian Ocean Walker circulation since the 1950s and 1960s (Han et al. 2010; Yu and Zwiers 2010; Yasunaka and Kimoto 2013), while the bias-corrected observed winds indicate a weakening of equatorial Indian Ocean surface westerlies (Tokinaga and Xie 2011; Tokinaga et al. 2012a,b).

Modeling studies also provide contrasting results. Coupled global climate models produce a robust slowdown of the tropical atmospheric circulation, including the Pacific Walker circulation (e.g., Vecchi et al. 2006; Vecchi and Soden 2007; Chadwick et al. 2013) and the Asian monsoon circulation (but with enhanced monsoon rainfall; Kitoh et al. 2013) in response to greenhouse gas forcing. Standalone atmospheric general circulation models produce contrasting changes in the Walker circulation depending on the SST forcing product (Tokinaga et al. 2012a; Meng et al. 2012). Using HadISST (Rayner et al. 2006) results in a strengthened Indo-Pacific Walker circulation for the twentieth century and for 1950–present. Using the extended reconstructed SST (Smith and Reynolds 2004) generates neutral response, and using Hadley Centre Sea Surface Temperature dataset, version 3 (HadSST3; Kennedy et al. 2011a,b) produces a weakened Walker circulation. If HadSST3 is the best dataset for detecting tropical Indo-Pacific SST changes, then the Indo-Pacific Walker circulation should be weakening. Without a careful investigation and comparison of data processing and analysis techniques for each dataset, however, we cannot judge which is superior.

The lack of consensus in these studies may arise from many factors, such as temporal heterogeneity of the observational datasets, differences in analysis methods, and systematic model errors. These inconsistencies point to our fundamental need for accurate, reliable, consistent, and decades-long data records for studying decadal climate variability. Models also need to be improved. Coupled climate models for example still have biases in simulating the mean state of the monsoons (e.g., Meehl et al. 2012), interannual variability (e.g., ENSO; Newman 2013), and the response to Indian Ocean warming (Meng et al. 2012). These shortcomings limit the ability of models to simulate decadal variability.

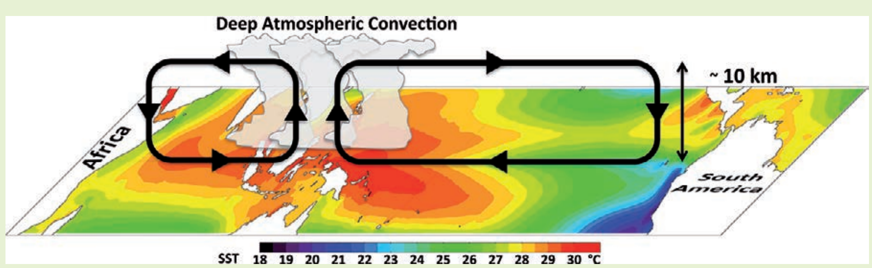

Fig. SB1. Schematic diagram of the Indo-Pacific Walker circulation. The ascending branch over warm water is associated with low surface pressure and the descending branches over cold water are associated with high surface pressure.

and its interpretation," we review the observations and current understanding of Indian Ocean decadal variability, delineating the effects of external forcing and internal climate variability whenever possible. In the final section, we briefly summarize the present state of our knowledge and list major issues that need to be resolved.

INDIAN OCEAN CIRCULATION AND INTERANNUAL CLIMATE VARIATIONS.

Here, we introduce the most important concepts that are essential for discussing decadal Indian Ocean variability. A detailed review of Indian Ocean circulation and climate variability can be found in Schott and McCreary (2001) and Schott et al. (2009).

Indian Ocean circulation. In contrast to the Pacific and Atlantic Oceans, the Indian Ocean is bounded to the north by the Asian landmass. As a result, the continental heating during boreal summer leads to a strong meridional pressure gradient that drives the southwest monsoon. The intense monsoon winds induce a strong northward Somali Current and coastal upwelling near the coasts of Somalia and Oman (Figs. 2b,d). During the winter monsoon, surface winds (Fig. 2a) and ocean circulation (Fig. 2c) reverse direction across the entire basin north of 10°S. By contrast, south of 10°S the South Equatorial Current (SEC) flows westward all year long under the influence of relatively steady trade wind forcing.

Warm water with SSTs > 28°C (the so-called warm pool) occupies a large portion of the tropical Indian Ocean north of 10°S, with cooler temperatures to the south and in the upwelling zones off Oman and the Horn of Africa (Figs. 2a,b). The north Indian Ocean gains heat on an annual average via air–sea fluxes and this heat gain is transported across the equator to the south within the wind-driven cross-equatorial cell

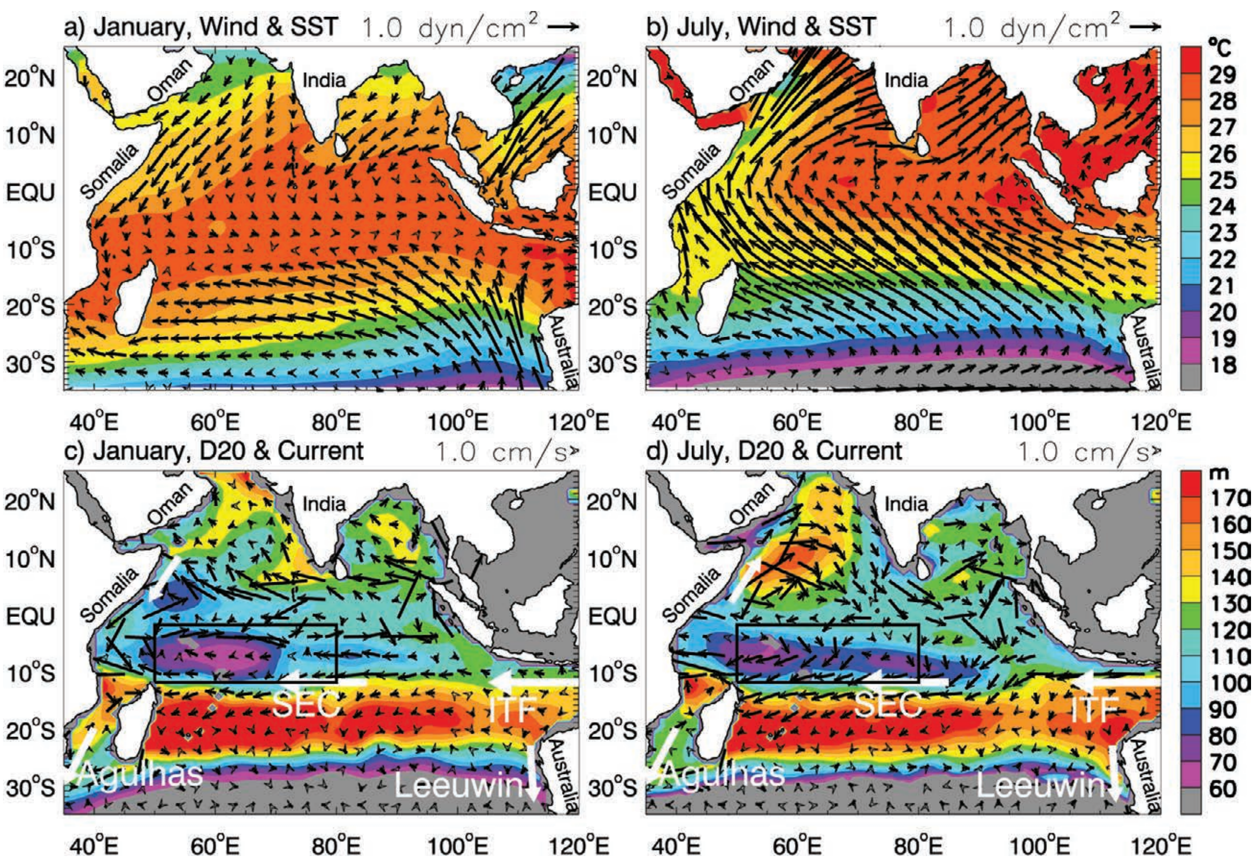

Fig. 2. (a) January and (b) July monthly SST climatology (color) and surface wind stress (arrows) from HadISST (Rayner et al. 2006) and ECMWF operational analysis/reanalysis winds (Balmaseda et al. 2008) for the 1960–2009 period; (c) January and (d) July depth of 20°C isotherm (D20; color) averaged for 2001–12 period based on in situ temperature data (Hosoda et al. 2008) and surface currents from Ocean Surface Current Analyses Real-Time (OSCAR) data (arrows; Bonjean and Lagerloef 2002) averaged for 1992–2012. Large bulk arrows identify the Leeuwin Current, Agulhas Current, ITF, SEC, and Somali Currents. The black boxes show the thermocline ridge region.

(CEC; Fig. 3). The surface branch of the CEC flows southward across the equator, while the subsurface branch is associated with cold thermocline water that flows northward within the Somali Current, upwelling near the coasts of Somali and Oman (Miyama et al. 2003; Lee 2004; Schott et al. 2004).

Unlike the prevailing easterly trades in the equatorial Pacific and Atlantic, annual-mean surface winds in the equatorial Indian Ocean are westerlies. In the tropical south Indian Ocean, wind stress curl associated with easterly trade winds south of ~10°S and the westerly winds farther north induce open-ocean upwelling in the western basin between 12° and 2°S (McCreary et al. 1993; Murtugudde and Busalacchi 1999). This upwelling causes the thermocline shoal in this latitude band, which is thus referred to as the thermocline ridge region (Hermes and Reason 2008; Yokoi et al. 2008, 2009; boxed areas of Figs. 2c,d). The existence of this upwelling induces a secondary overturning circulation referred to as the subtropical cell (STC; Miyama et al. 2003; Lee 2004; Schott et al. 2004; Fig. 3), which is fed in part by waters subducted (pumped down) into the thermocline in the southeastern Indian Ocean (e.g., Schott et al. 2009).

The Indian Ocean is fed to the east by water coming from the western Pacific via the Indonesian Throughflow (ITF). Part of the ITF feeds upwelling in the thermocline ridge region of the STC and some directly flows southward along the west coast of Australia in the Leeuwin Current. The majority of the ITF, however, flows westward across the Indian Ocean in the South Equatorial Current and southward through the Mozambique Channel to the Agulhas Current where part of it enters the Atlantic near the southern tip of Africa (Figs. 2c,d). The rest returns eastward around 25°S, where it feeds into the Leeuwin Current (e.g., Reid 2003; McCreary et al. 2007; Palastanga et al. 2007).

Interannual climate variability. Until the late 1990s, the scientific community focused most of its efforts on the tropical Pacific, which hosts the powerful ENSO phenomenon [see McPhaden et al. (2006) for an introduction to this phenomenon]. Prior to that, no independent mode of interannual variability had been identified in the Indian Ocean. With the discovery of the Indian Ocean dipole (IOD; Saji et al. 1999; Webster et al. 1999), however, it was realized that ocean–atmosphere interactions in the Indian Ocean can also give rise to significant climate fluctuations. Like ENSO, the IOD varies on interannual time scales, sustained through positive feedbacks between equatorial winds and zonal SST gradients. A positive IOD is associated with a cold SST anomaly (SSTA) in the eastern tropical Indian Ocean and warm SSTA in the western tropical basin (Fig. 4), reaching peak amplitudes during boreal fall (September–November). Like ENSO, the IOD is linked to warm pool deep convection and the Indo-Pacific Walker circulation. It has also been suggested that the IOD is an integral component of the tropical biennial oscillation (Loschnigg et al. 2003; Meehl et al. 2003).

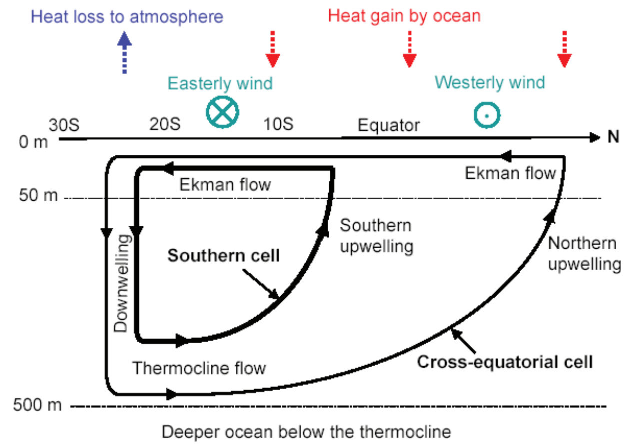

Fig. 3. Schematic diagram showing the zonal- and time-mean meridional overturning circulation of the upper Indian Ocean that consists of a STC and CEC. Adapted from Lee (2004).

Two other modes of interannual SST variability have also been identified: the Indian Ocean basin mode and the subtropical SST dipole. The basin mode features a basinwide warming (or cooling) pattern that primarily results from ENSO-induced changes in cloud cover and thus in shortwave radiation over the Indian Ocean (Klein et al. 1999). It is maintained beyond the termination of ENSO events by Indian Ocean air–sea interactions and ocean dynamics (Du et al. 2009). The subtropical SST dipole varies interannually with peak development in austral summer (Behera and Yamagata 2001; Suzuki et al. 2004). A positive phase is characterized by warm SSTA in the southwestern Indian Ocean south of Madagascar and cold SSTA in the eastern Indian Ocean off Australia. The Antarctic Circumpolar Wave (e.g., White and Peterson 1996) and air–sea interaction in the tropical Indo-Pacific basin may contribute to its generation (Morioka et al. 2012, 2013).

OBSERVED DECADAL VARIABILITY AND ITS INTERPRETATION.

Warming trends and decadal variations. Long-term trends. Upper-ocean heat content reveals a warming trend of the Indian Ocean since the 1950s (Levitus et al. 2009; Xue et al. 2012; Fig. 1). The Hadley Centre Sea Ice and Sea

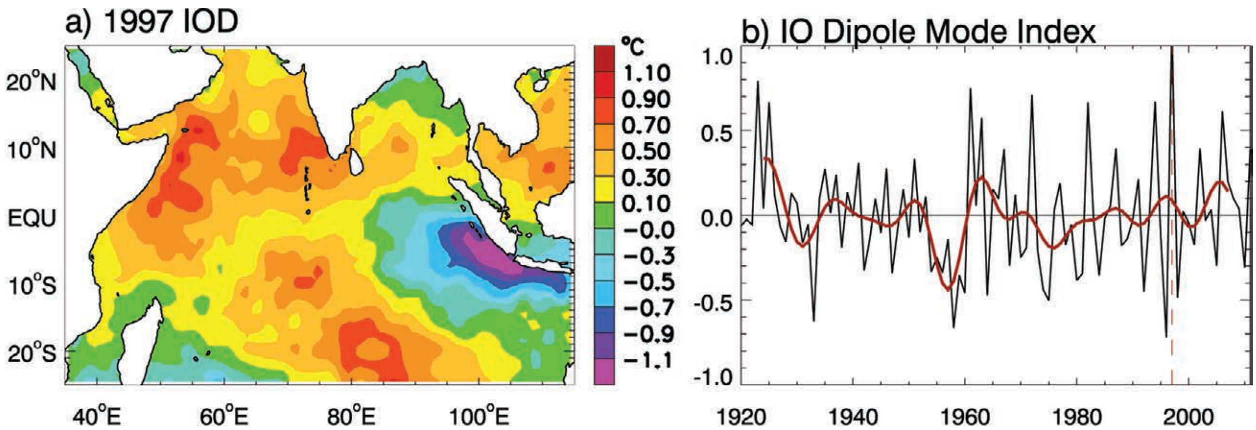

Fig. 4. (left) September, October, and November mean SSTA for the 1997 IOD event, based on the detrended and demeaned SST from 1920 to 2011; (right) dipole mode index (DMI; black) for each year, which is defined as the September, October, and November mean SSTA difference between the western pole (10°S–10°N, 50°–70°E) and eastern pole (10°S–0°, 90°–110°E); the red curve is 8-yr low-passed DMI, which shows decadal variability. The red dashed vertical line marks the 1997 IOD.

Surface Temperature dataset (HadISST; Rayner et al. 2003) suggests that the tropical Indian Ocean has generally warmed faster than most regions of the tropical Pacific and Atlantic since the 1950s, with an accelerated warming since the 1970s (Fig. 5; Hoerling et al. 2012). In all SST datasets, the northern Indian Ocean has slower warming rates than the equatorial zone, with warming signals that qualitatively agree among different datasets. However, there are apparent differences in the regional magnitudes and spatial structures of this warming, which underscore the uncertainty in quantifying regional warming rates.

Climate model simulations with and without anthropogenic greenhouse gases demonstrate that increases in these gases are the primary cause for the observed warming trends (e.g., Hansen et al. 2002; Reichert et al. 2002; Gent and Danabasoglu 2004; Gregory et al. 2004; Pierce et al. 2006; Hegerl et al. 2007; Gleckler et al. 2012). Attempts have been made by analyzing climate model simulations to understand the physical processes through which anthropogenic forcing causes the observed near-surface warming. Du and Xie (2008) argued that the steady warming of Indian Ocean SST since the 1950s results from greenhouse gas–induced increases in downward longwave radiation (see also Dong et al. 2014) amplified by the water vapor feedback and from weakened winds that suppress turbulent heat loss from the ocean. Reduced upwelling may also contribute to the surface warming over the thermocline ridge region (defined in Fig. 2; Alory and Meyers 2009). The weakened wind scenario proposed by Du and Xie (2008) from model studies, however, appears to contradict the observed trend toward increasing Indian Ocean surface wind speed from 1981 to 2005 (Yu and Weller 2007). This difference between models and observations may arise because the models could not properly simulate Indian Ocean regional convection and the atmospheric circulation response to warming (Meng et al. 2012). Alternatively, the observed wind trend over the period 1981–2005 may reflect internal decadal variability that is significantly damped in the ensemble means of climate model solutions.

Attempts have also been made to explain the slower warming rate in the north Indian Ocean (Figs. 1, 5). In this region, the effects of anthropogenic greenhouse warming are compensated by enhanced evaporative cooling and reduced solar radiation from South Asian aerosols (Chung and Ramanathan 2006). Despite the slow rate, the north Indian Ocean still exhibits "warming." This warming largely results from a spin down of the CEC since the 1950s and 1960s (Schoenefeldt and Schott 2006; Trenary and Han 2008). A weaker CEC reduces the southward transport of warm surface water from, and northward transport of cold thermocline water into, the north Indian Ocean. In the south Indian Ocean, both increased surface heat flux and lateral advection—likely from the Pacific Ocean—contribute to the observed warming (Pierce et al. 2006). It is unclear what the relative roles of anthropogenic forcing and natural variability play in causing the CEC change.

Indian Ocean warming exhibits a complex structure in the vertical: near-surface warming accompanies upper-thermocline cooling in the tropics and weaker warming beneath (Barnett et al. 2005; Pierce et al. 2006; Bindoff et al. 2007;

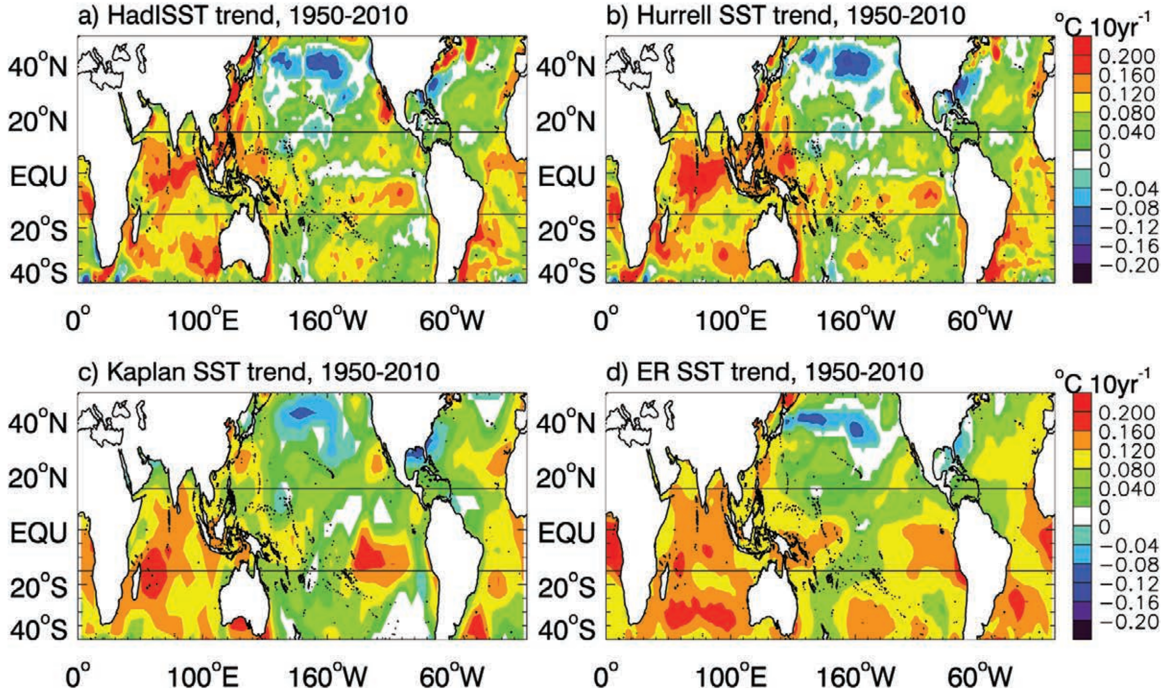

Fig. 5. (a) Linear trend of HadISST (Rayner et al. 2006) from 1950 to 2010; color (white) shading shows values that are above (below) 95% significance; (b)–(d) As in (a), but for SST from Hurrell et al. (2008), Kaplan et al. (1998), and Smith and Reynolds (2004) extended reconstructed (ER) data, respectively. The two horizontal lines show 15°S and 15°N latitudes. The tropical Indian Ocean warms faster than most regions of the tropical Pacific and Atlantic, except for a local area in the eastern Pacific south of the equator. This trend pattern also holds for median Hadley Centre Sea Surface Temperature dataset version 3 (HadSST3) data (Kennedy et al. 2011a,b) for the period of 1958–2006, even though the warming rate over the Indo-Pacific warm pool is slower (not shown). HadSST3 data are available until 2006 and have too many missing values in the tropical Pacific from 1950–57.

Fig. 6). This structure can only be reproduced when anthropogenic greenhouse gases are included in climate models (Barnett et al. 2005; Pierce et al. 2006). Han et al. (2006) and Trenary and Han (2008) suggested that long-term changes in tropical Indian Ocean winds are instrumental in causing the thermocline cooling. The increasing southeasterly trades strengthen the STC and the reduced wind stress curl on the equator weakens the CEC (see also Schoenefeldt and Schott 2006). These two effects combine to induce heat divergence and thus cool the upper thermocline over the thermocline ridge region (Trenary and Han 2008). In contrast, Alory et al. (2007) and Cai et al. (2008) suggested that in the third phase of the Coupled Model Intercomparison Project (CMIP3) climate models, the observed south Indian Ocean thermocline cooling results mainly from the shoaling thermocline in the western equatorial Pacific and wave transmission via the Indonesian archipelago, driven by the relaxation of the easterly trades in the Pacific (McPhaden and Zhang 2002). In agreement with this hypothesis, analysis of

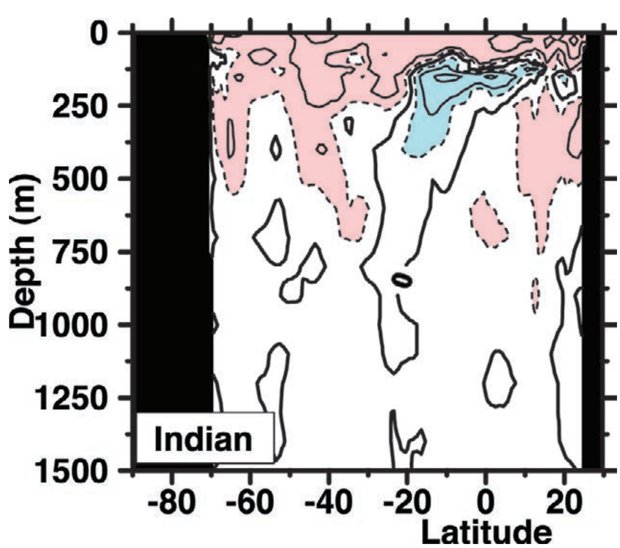

Fig. 6. Linear trend of zonal-mean temperature across the Indian Ocean in the upper 1500 m from 1955 to 2003. The contour interval is 0.05°C decade⁻¹, and the dark solid lines are zero contours. Pink shading indicates values ≥ 0.025°C decade⁻¹ and blue shading indicates values ≤ −0.025°C decade⁻¹. Adapted from Bindoff et al. (2007).

XBT data suggests a reduction of ITF transport by ~2.5 Sverdrups (Sv; 1 Sv ≡ 10^6 m^3 s^{-1}) after 1976/77 (Wainwright et al. 2008). This analysis, however, was based on temperature data in the upper 700 m only, without considering the effect of salinity and potential changes in transport below 700 m. Available multidecadal ocean data assimilation products do not show evidence of a significant reduction of total (top to bottom) ITF transport after 1976/77 as would be required for a net ITF-mediated loss of mass from the Indian Ocean basin (Lee et al. 2010). Schwarzkopf and Böning (2011) demonstrated in controlled ocean general circulation model (OGCM) experiments the role played by Indian Ocean winds in causing the complex, zonal-mean vertical temperature structure from 1960 to 1999, even though they emphasized the ITF effects on the thermocline cooling. Their solutions indeed produced stronger ITF effects on the cooling thermocline than that of Han et al. (2010). The causes for these differences are discussed further in the "sea level variability" section.

Decadal variations. Superimposed on these multidecadal trends, near-surface temperature and upper-ocean heat content exhibit large-amplitude decadal variations. Trenary and Han (2013) performed a hierarchy of OGCM experiments and showed that the observed complex vertical structures of zonal-mean temperature vary from decade to decade, with strong temperature variations generally occurring in the thermocline layer. Wind stress forcing over the Indian Ocean was primarily responsible for these variations, but the ITF made significant contributions after 1990. Near the surface, observations show significant decadal variations in basin-averaged upper-ocean heat content (Fig. 1). The century-long coral-based records in the southwest Indian Ocean show large-amplitude decadal variability of SST, which is apparently associated with the natural decadal variability of ENSO (Cole et al. 2000; Cobb et al. 2001; Allan et al. 2003; Zinke et al. 2004). Domingues et al. (2008) showed that volcanic eruptions induce significant decadal variability in global-mean temperature and sea level (also see Zanchettin et al. 2012), but they did not examine volcanic effects separately for the Indian Ocean.

Salinity variability. Long-term trends. Recent observational studies indicate that globally, sea surface salinity (SSS) has increased over the past few decades in regions where evaporation exceeds precipitation and decreased in regions of excess precipitation (e.g., Roemmich and Gilson 2009; von Schuckmann et al. 2009; Hosoda et al. 2009; Durack and Wijffels 2010; Helm et al. 2010). Regionally, SSS exhibits a decreasing trend in the equatorial Indian Ocean, Bay of Bengal, and Southern Ocean, but an increasing trend in the subtropical south Indian Ocean and the Arabian Sea (Fig. 7). This spatial pattern of SSS changes is consistent with the notion that saltier regions get saltier and fresher regions get fresher under global warning. The surface freshening at mid-to-high latitudes extends downward and equatorward to intermediate depths, primarily through subduction and advection of salinity anomalies in the thermocline by the mean flow (Wong et al. 1999; Bindoff and McDougall 2000; McDonagh et al. 2005; Bindoff et al. 2007; Böning et al. 2008; Roemmich and Gilson 2009; Durack and Wijffels 2010). Freshening in the abyssal southeastern Indian Ocean has also been observed (Johnson et al. 2008).

Climate model simulations with and without anthropogenic greenhouse gas forcing demonstrate that observed salinity changes cannot be explained by natural variability, either internal to the climate system or from external forcing via variations in solar output and volcanic eruptions (Durack et al. 2012; Terray et al. 2012; Pierce et al. 2012). The observed changes, however, are consistent with the changes expected due to the greenhouse gas–induced warming and the resultant amplification of the global hydrological cycle (Held and Soden 2006).

Decadal variations. In addition to the multidecadal trend since 1950 (Fig. 7), hydrographic data reveal decadal fluctuations in salinity. Freshening in the thermocline along 32°S before 1987 (Bindoff and McDougall 2000) is consistent with global warming (Joos et al. 2003). However, between 1987 and 2002, the trend reversed in the upper thermocline across the entire 32°S section, accompanied by an increased oxygen concentration (McDonagh et al. 2005). This signal appears to be associated with the natural decadal spinup of the south Indian Ocean subtropical gyre over that period, as evident from enhanced northward volume transport across 32°S (Palmer et al. 2004).

Variations in freshwater and heat transports in the southern Indian Ocean are tied to the variability in Agulhas Current transport (Bryden and Beal 2001), whose leakage to the Atlantic has increased during the past few decades as suggested by satellite observations (Rouault et al. 2009) and modeling studies [see Beal et al. (2011) for a review]. The increased leakage, however, is not supported by a recent analysis using along-track satellite altimeter data (Le Bars et al.

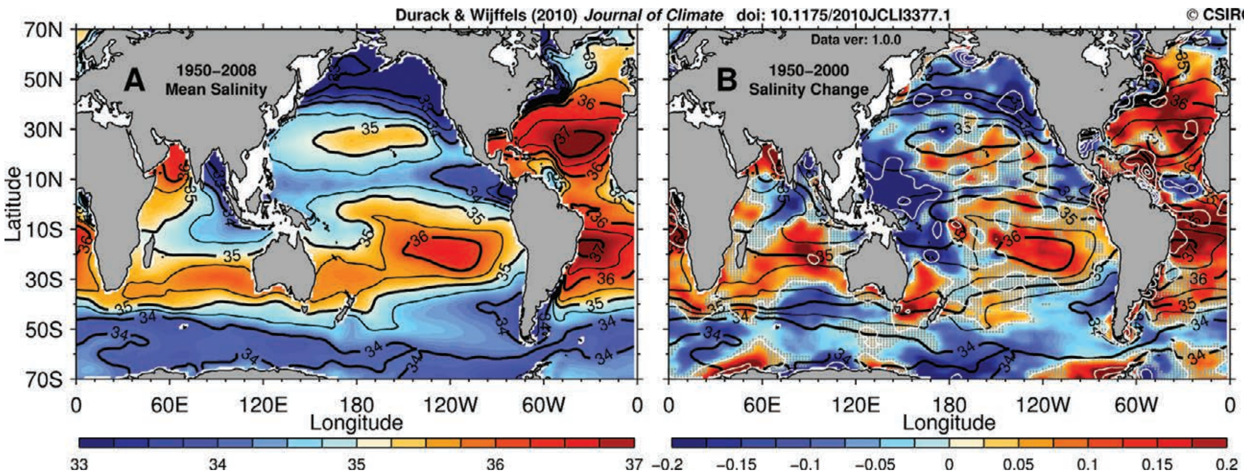

Fig. 7. (a) The 1950–2000 climatological-mean surface salinity. Contours every 0.5 on the practical salinity scale (PSS) are plotted in black. (b) The 50-yr linear surface salinity trend [PSS (50 yr)$^{-1}$]. Contours every 0.2 are plotted in white. Regions where the resolved linear trend is not significant at the 99% confidence level are stippled in gray. Adapted from Durack and Wijffels (2010).

2014). Thus, there remain uncertainties in detecting decadal variability in southern Indian Ocean freshwater and heat fluxes as well as their transports into the Atlantic Ocean.

Sea level variability. Tide gauge observations. Sea level rise has been detected by tide gauge observations at various locations along coasts bordering the Indian Ocean. In the northern Indian Ocean, sea level from tide gauge records longer than 40 yr yield average sea level rise rates of 1.06–1.75 mm yr^{-1} over the 1878–2004 period (Unnikrishnan and Shankar 2007). Overlying these trends, there is significant decadal variability. At Mumbai, the century-long record shows that decadal variations in sea level mimic that of rainfall over the Indian subcontinent, indicating the effect of salinity on sea level variability when freshwater from monsoon rainfall flows into the Indian Ocean (Shankar and Shetye 1999). This sea level/monsoon rainfall correlation may also reflect the effects of monsoon winds on sea level, which combine with freshwater input from monsoon rainfall and river discharge to force a large sea level response at Mumbai. Along the west coast of Australia, tide gauge and satellite altimeter data reveal large-amplitude decadal variability in sea level and in the Leeuwin Current, which are heavily influenced by decadal variability in the western tropical Pacific via the ITF (e.g., Lee 2004; Lee and McPhaden 2008; Feng et al. 2004, 2010, 2011).

Sea level trend patterns. The sea level trend and decadal variability along Indian Ocean coasts are in part associated with basinwide sea level patterns. Han et al. (2010) showed a distinct spatial pattern to the sea level trend since the 1960s, with sea level falling in the southwest tropical Indian Ocean and rising elsewhere. Similar patterns, evident in the thermosteric (i.e., temperature related) sea level derived from in situ observations for the upper 700 m (National Research Council 2012) and in reconstructed sea level data (Fig. 8) are well simulated by several ocean models (e.g., Timmermann et al. 2010; Schwarzkopf and Böning 2011; Dunne et al. 2012). The sea level fall in the southwest tropical Indian Ocean also agrees with the observed subsurface cooling associated with the shoaling thermocline in the same latitudinal band (Fig. 6).

Han et al. (2010) suggested that the sea level trend from 1961 to 2001 is primarily driven by changing surface winds associated with enhanced regional Walker and Hadley circulations (also see Yu and Zwiers 2010). On the other hand, Schwarzkopf and Böning (2011) suggested a considerably larger ITF influence. The divergence between these two studies, based primarily on model results, is probably due to the wind products that were used to force the ocean models. Han et al. (2010) used 40-yr European Centre for Medium-Range Weather Forecasts (ECMWF) Re-Analysis (ERA-40) winds that do not show an apparent reduction in easterly trades in the equatorial Pacific after 1977, while Schwarzkopf and Böning (2011) used National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) reanalysis winds that show an evident reduction of Pacific easterly trades near 1977 (e.g., Feng et al. 2011). These results stress the importance of long-term changes in the Indo-Pacific atmospheric circulation for describing and understanding decadal changes in the Indian Ocean; however, inconsistencies between different wind products, ocean reanalysis datasets, and the lack of reliable observations prior to the 1980s before the satellite era may cause significant uncertainties in detecting atmospheric circulation changes (see the side bar for Indo-Pacific Walker circulation change) and in quantifying their impacts on Indian Ocean sea level changes.

Decadal sea level variations. Basinwide sea level trend patterns also exhibit decadal variations. Lee and McPhaden (2008) detected in satellite observations substantial decadal reversals in basinwide sea surface height (SSH) trends in the Indo-Pacific region from 1993–2000 to 2000–06 associated with decadal changes in Indo-Pacific trade winds. Collectively, these wind and SSH changes imply opposite trends in the transports of the Pacific and Indian Ocean STCs (see also Zhuang et al. 2013). Lee and McPhaden (2008) suggested that the decadal changes in the Pacific and Indian Ocean STCs during this period were linked via the atmosphere through the Walker circulation and via the ocean through the ITF.

To understand the causes for Indian Ocean decadal sea level variability, Trenary and Han (2013) and Nidheesh et al. (2013) performed a hierarchy of OGCM experiments. The satellite observed basinwide SSH trend reversal from 1993–2000 to 2000–07 (Fig. 9) described in Lee and McPhaden (2008) was successfully simulated by the OGCMs (Figs. 10a,d). This pattern reversal resulted primarily from Indian Ocean wind forcing (Figs. 10b,e), with the effect of Pacific forcing transmitted through the Indonesian archipelago via the ITF contributing most significantly in the eastern basin (Figs. 10c,f). Nidheesh et al. (2013) showed that thermal variations dominate the decadal sea level variability, with sizeable salinity contributions in only a few regions. The large-amplitude decadal variations in sea level in the southwest Indian Ocean thermocline ridge region were primarily caused by local Ekman pumping velocity associated with wind stress curl and by westward-propagating Rossby waves generated by winds in the central and eastern basin (Trenary and Han 2013).

Since the early 1990s, however, the ITF has increased its contribution in the thermocline ridge region and along the west coast of Australia (Trenary and Han 2013). This increased Pacific influence is consistent with the decadal intensification of easterly trades and sea level in the western tropical Pacific (Merrifield 2011; Luo et al. 2012; Han et al. 2014), increased Makassar Strait transport (Susanto et al. 2012), and enhanced ITF and Leeuwin Current transports (Feng et al. 2011) since the early 1990s. Enhanced transmission of ENSO signals at thermocline depth into the Indian Ocean since 1980 has also been suggested (Shi et al. 2007). Trenary and Han (2013) also found that in the subtropics between 20° and 30°S, oceanic internal variability makes significant contributions to the decadal variability of sea level and thermocline depth.

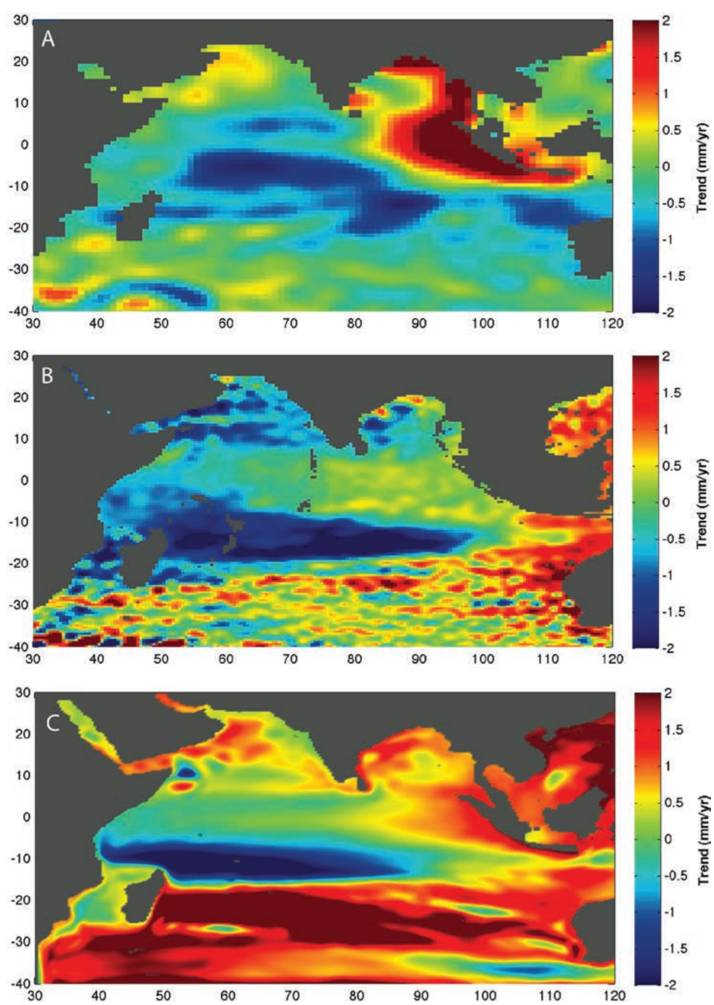

Fig. 8. Regional sea level trends for 1961–2001 computed from (a) the Church et al. (2004) reconstructed data, (b) the Hamlington et al. (2011) reconstructed data, and (c) a Hybrid Coordinate Ocean Model (HYCOM) simulation. Adapted from Hamlington et al. (2011).

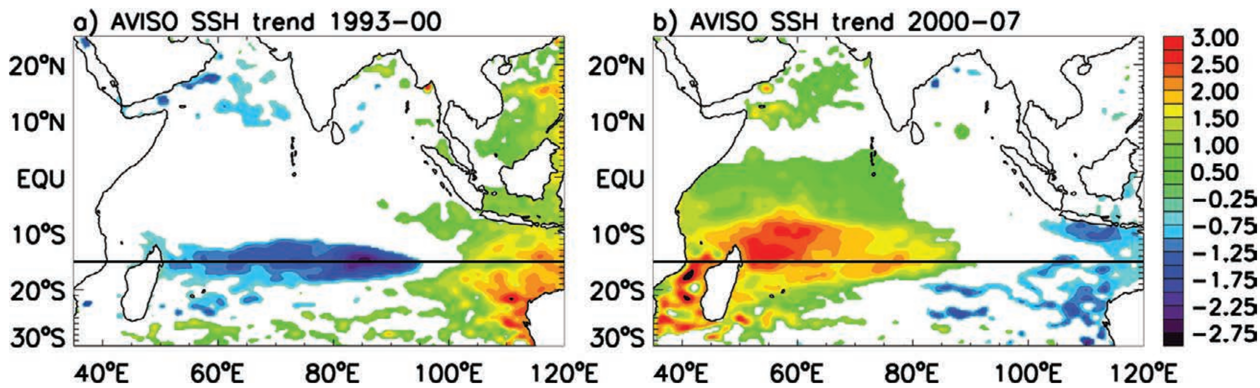

Fig. 9. (a) Linear trend of SSH anomaly (SSHA) from multisatellite merged French Archiving, Validation, and Interpretation of Satellite Oceanographic (AVISO) data (Ducet et al. 2000) for the 1993–2000 period; values exceeding 95% significance are shown; (b) As in (a), but for 2000–07. Units are centimeters per year. The horizontal line marks the latitude of 15°S.

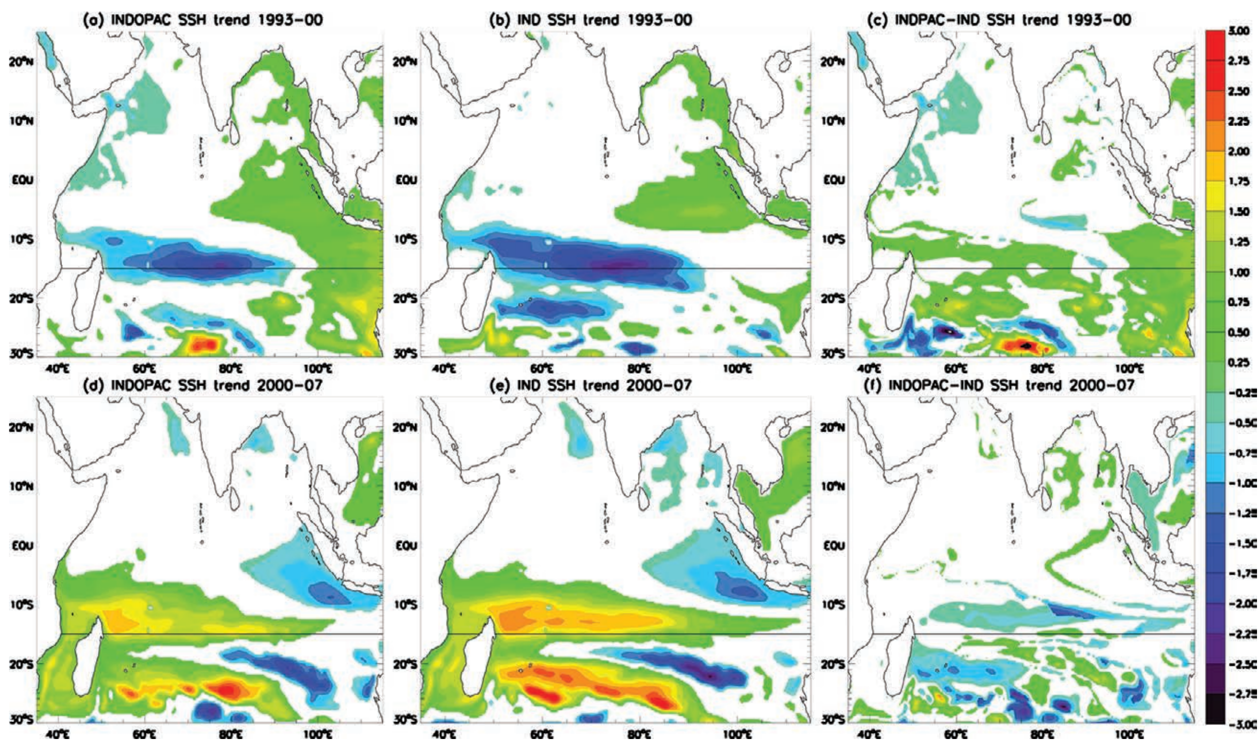

Fig. 10. Linear trends in SSHA for the period 1993–2000 for (a) HYCOM experiment with full forcing in both the Indian and Pacific Oceans (referred to as INDOPAC), (b) HYCOM experiment with variability of the Pacific forcing excluded (referred to as IND), and (c) DIFF = (INDOPAC – IND), which assesses the effect of Pacific forcing via the Indonesian Archipelago and also includes oceanic internal variability effect; (d)–(f) As in (a)–(c), but for the period of 2000–07. Values exceeding 95% significance are shown. Units are centimeters per year. Adapted from Trenary and Han (2013).

Finally, Nidheesh et al. (2013) and Lee and McPhaden (2008) are in basic agreement about the role of atmospheric teleconnections between the Pacific and southwestern Indian Ocean over the last 20 yr. These teleconnections, however, break down when considering the longer 1966–2007 period, during which large-amplitude decadal variations in Pacific SSH and winds do not correspond to large variability over the Indian Ocean (Fig. 11). This behavior is different from that on interannual time scales, when basin-scale winds and SSH associated with ENSO and IOD significantly covary. These conflicting results need to be reconciled, which may involve consideration of the possible varying relationship between the Pacific and Indian Oceans in different decades and the reliability of atmospheric reanalysis products in representing decadal variability, especially before the satellite era.

Decadal modulation of interannual variability. Abram et al. (2008) analyzed coral oxygen isotope records and showed an increasing trend in the frequency and strength of IOD events during the twentieth century. Analyses of historical SST datasets and ocean reanalysis products suggest that prior to 1920, negative IOD events dominated, whereas after 1950, positive IOD events prevailed (e.g., Kripalani and Kumar 2004; Ihara et al. 2008; Yuan et al. 2008; Cai et al. 2009). The upward trend of the IOD index (see Fig. 4b) in recent decades, however, appears in some SST datasets but not in others, highlighting the uncertainties in these trends (Cai et al. 2013). Zheng et al. (2010) examined the impact of greenhouse warming on IOD behavior [see Cai et al. (2013) for a review] and concluded that the increasing occurrence of positive IOD events in the past few decades results from a gradual increase in the mean west-minus-east SST gradient in the tropical Indian Ocean. As a result, the IOD index crosses the defined threshold more frequently near the end of the twentieth century. Climate model projections suggest that under greenhouse gas warming, the frequency of positive IOD events will increase by a factor of three near the end of the 21st century (Cai et al. 2014).

Overlying this trend, there are decadal fluctuations in the IOD index (e.g., Ashok et al. 2004; Ihara et al. 2008; red curve of Fig. 4; Figs. 12c,d,g,h) and decadal

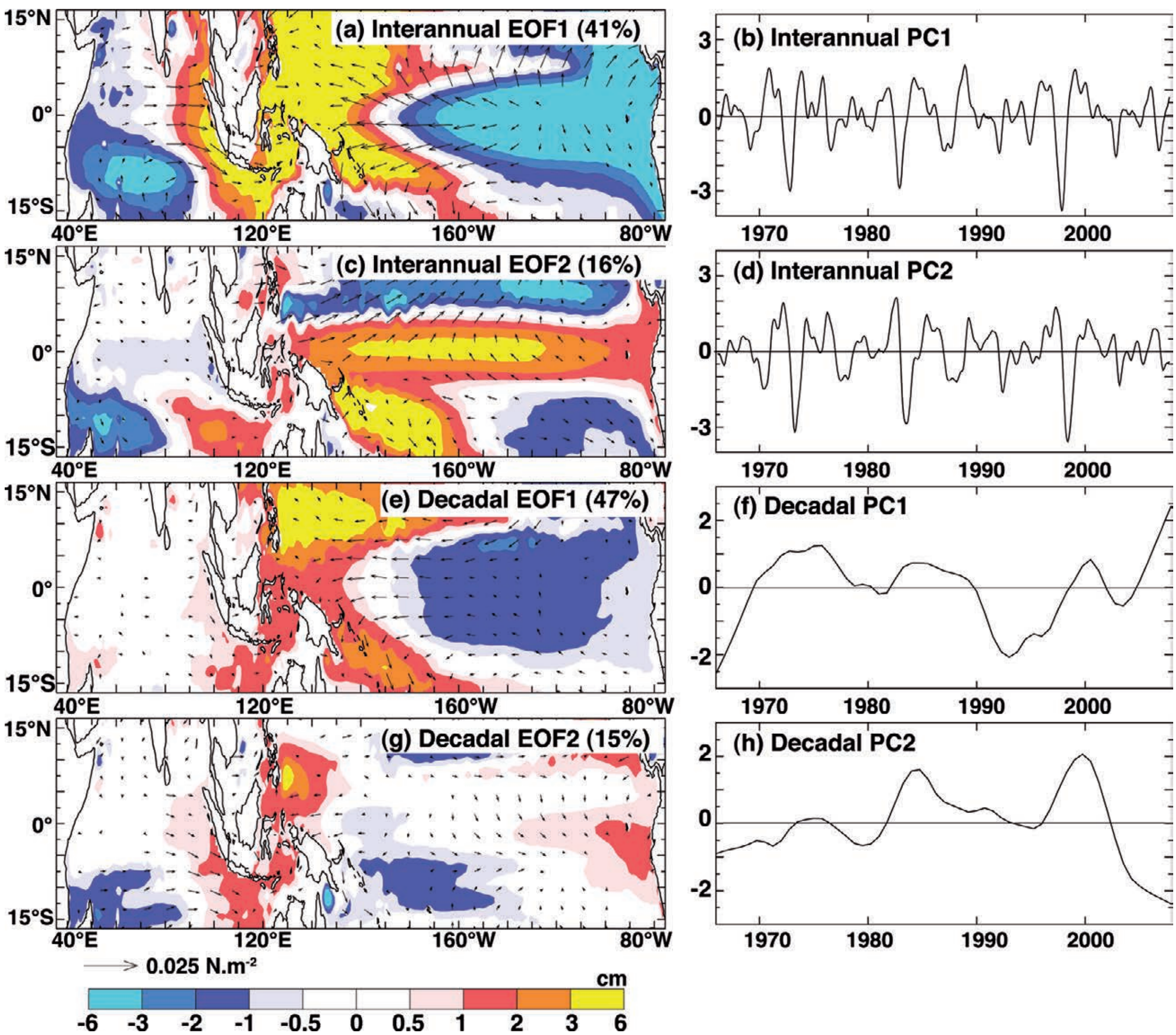

Fig. 11. The first two EOF patterns of steric sea level anomalies over the (left) Indo-Pacific sector and (right) their corresponding normalized PCs at decadal (7-yr low-passed) time scales from an OGCM experiment. Arrows are the wind stress components regressed onto each normalized PC. The percentage explained by each EOF is shown in parentheses. Adapted from Nidheesh et al. (2013).

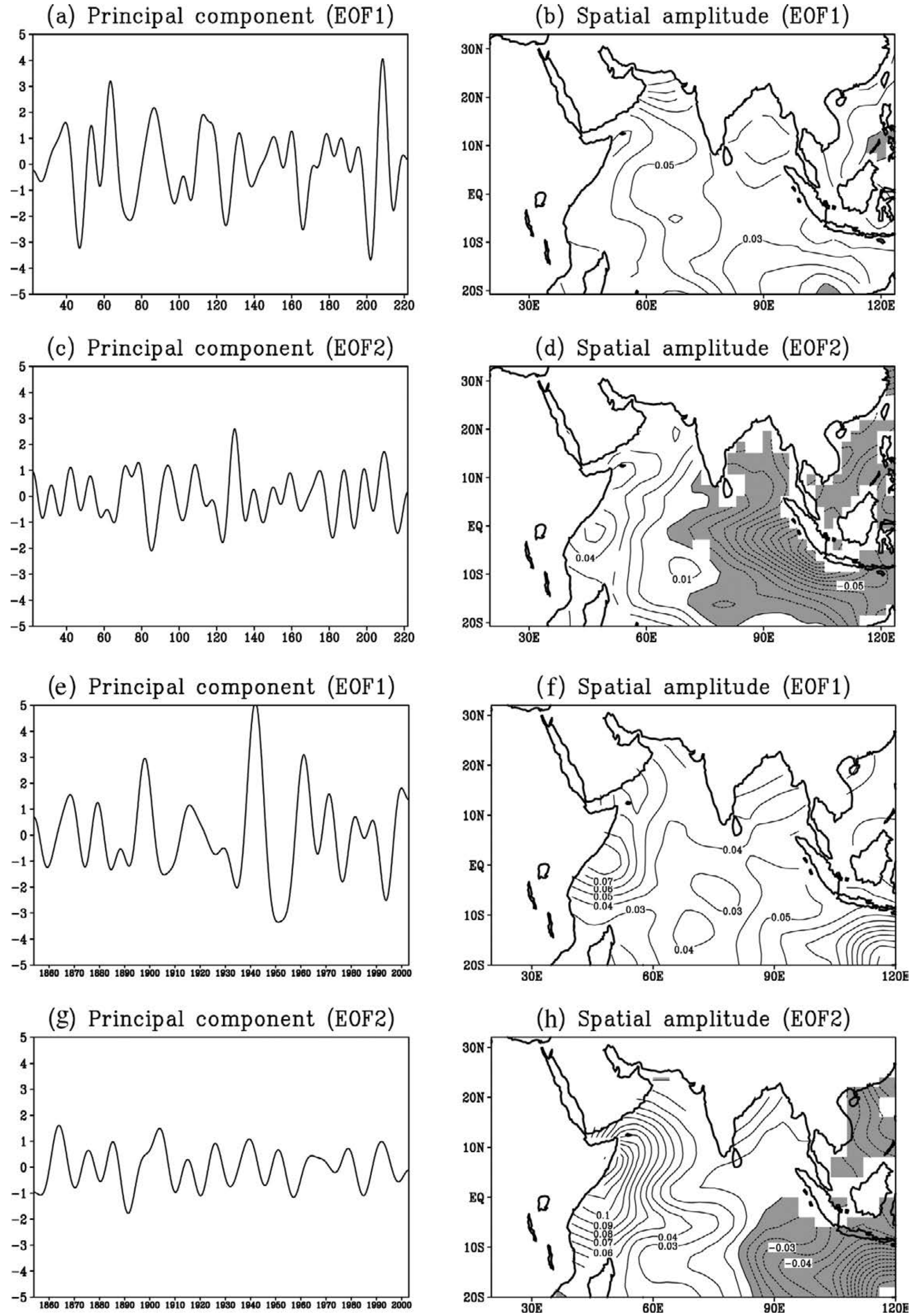

Fig. 12. (a),(c) PCs and (b),(d) spatial amplitudes of the first and second EOF modes of the simulated decadal (9–35-yr bandpass) SSTA by a global coupled model control run. (e)–(h) As in (a)–(d), but for the observed decadal (9–35-yr bandpass) SSTA from extended reconstructed data of Smith and Reynolds (2004). Contour interval is 0.01°C and negative anomalies are shaded for the spatial amplitude (from Tozuka et al. 2007).

changes in the Indian Ocean SST–ENSO (Annamalai et al. 2005) and IOD–ENSO–monsoon relationship before and after 1976/77 (e.g., Allan et al. 2003; Clark et al. 2003; Meehl and Arblaster 2011, 2012). Decadal fluctuations of IOD index are not well correlated with decadal variations in the Niño-3 index—the SSTA averaged over 5°S–5°N and 90°–150°W in the Pacific and an indicator of ENSO variability (Ashok et al. 2004; Song et al. 2007; Tozuka et al. 2007). They are, however, highly correlated with Indian Ocean thermocline depth and equatorial zonal wind anomalies (Ashok et al. 2004), suggesting that ocean dynamics are involved. Since the time for low-latitude Rossby waves to cross the tropical Indian Ocean is too short to account for decadal time scale variability, Tozuka et al. (2007) concluded that decadal variations in the IOD are due to the skewness (asymmetry) of positive and negative IOD events.

Meehl and Arblaster (2011, 2012) suggested that interdecadal Pacific oscillation (IPO; Power et al. 1999; Fig. 13) can significantly modulate the relationship between the Asian–Australian monsoon, ENSO, and IOD. Given that the IPO index—the principle component (PC) of the leading empirical orthogonal function (EOF) of Pacific decadal SSTA—is highly correlated with ENSO indices (Han et al. 2014), the low IOD–ENSO correlation on decadal time scales discussed above requires an explanation. It is possible that the IOD possesses a component independent of IPO, even though IPO can modulate its variability.

In addition to the IOD, the Indian Ocean basin mode ("interannual climate variability" section) shows pronounced interdecadal modulation in its variance and correlation with ENSO, strengthening when ENSO variance is high and weakening when it is low (Chowdary et al. 2012). This decadal modulation has large impacts on atmospheric variability over the northwest Pacific (Xie et al. 2010; Chowdary et al. 2012). The Indian Ocean subtropical dipole ("interannual climate variability" section) also undergoes decadal variations. In particular, its amplitude weakened but its correlation with ENSO was enhanced after 1979/80 (Yan et al. 2013). The reasons for this decadal variability in the subtropical dipole are not clear.

Decadal variability generated by processes internal to the Indian Ocean. On decadal time scales, a basinwide warming/cooling pattern dominates Indian Ocean SSTAs and explains 54% variance using HadISST (Fig. 13a). We dub this fluctuation the "decadal Indian Ocean basin mode" by analogy with the basin mode that is evident on interannual time scales. While this basin mode is positively correlated with the IPO before 1985, analogous to ENSO impact on the interannual Indian Ocean basin mode ("interannual climate variability" section), the correlation reverses to negative after 1985 (Fig. 13c). Causes for this change in character remain unclear. It may indicate that the Indian Ocean plays an increasingly important role in shaping Indo-Pacific decadal climate under global warming (Han et al. 2014) or that it is due to natural variability (forced or internally generated) in the climate system.

To understand the effect of air–sea interaction in the Indian Ocean in generating decadal variability, Allan et al. (1995) and Reason and Lutjeharms (2000) analyzed detrended observational datasets and identified decadal variations in SST, sea level pressure (SLP) and surface winds during austral summer and for the annual mean for four epochs: 1900–20, 1921–41, 1942–62, and 1963–83 (also see Jones and Allan 1998; Reason et al. 1998). The first two epochs showed relatively weak south Indian Ocean SLP and anticyclonic

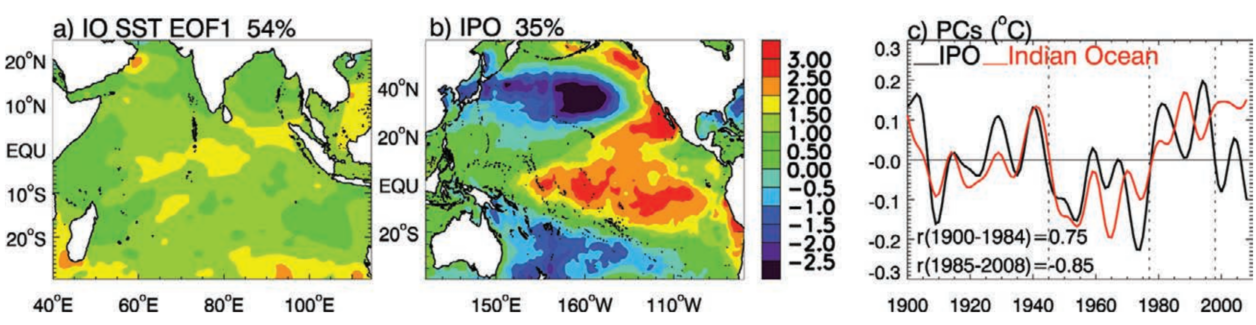

Fig. 13. (a) The leading EOF of SST for the Indian Ocean, based on 8-yr low-pass filtered monthly HadISST from 1900 to 2008, which explains 54% variance. The monthly SST data from 1870 to 2012 are first detrended and demeaned and then the Lanczos low-pass filter with half power point placed at 8-yr period is applied. The filtered SST from 1900 to 2008 is chosen to perform the EOF analysis. (b) As in (a), but for the Pacific SST, which represents the IPO spatial pattern and explains 35% variance. (c) The leading PC (PC1) of 8-yr low-passed SST for the Pacific (black curve) and Indian Ocean (red). Adapted from Han et al. (2014).

surface winds, which were associated with cold SSTAs across the midlatitudes (south of 30°S) and weaker, warm SSTAs in the subtropical south Indian Ocean. The last epoch shows a significant intensification of the anticyclone, which was associated with warm SSTAs in the midlatitudes and weaker, cold SSTAs in the tropics. During 1942–62 (the third epoch), the atmospheric circulation underwent a transition between the first two epochs and the last.

Standalone OGCM experiments show that the observed decadal SSTA pattern in the southern Indian Ocean is well reproduced by the Indian Ocean surface forcing primarily through surface heat fluxes (Reason 2000). By contrast, when forced by idealized SSTAs prescribed in the southern Indian Ocean where the observed SSTAs are large in amplitude, the AGCM could not reproduce the observed winds and SLP (Reason and Lutjeharms 2000). The authors concluded that the decadal SSTAs in the southern Indian Ocean might be forced by a global atmospheric mode, with Indian Ocean air–sea interaction providing some regional feedback. The caveat for this experiment was that the SSTAs were prescribed only in the midlatitudes of the southern Indian Ocean. SSTAs have smaller amplitudes in the equatorial and northern Indian Ocean basins, but their effects on convection can be large there because they are superimposed on high mean SSTs (Fig. 2). Given the nonlinear dependence of convection on SST, tropical variability can affect the extratropics via atmospheric teleconnections, an issue that was not explored in Reason and Lutjeharms (2000). Krishnamurthy and Goswami (2000) analyzed the NCEP–NCAR reanalysis and suggested that SST and SLP patterns over the Indian Ocean, Pacific, and Atlantic regressed onto an 11-yr running-mean Indian summer monsoon rainfall index that resembles those regressed onto an 11-yr running-mean Niño-3 index. They argued that these results support a hypothesis that decadal variations of the Indian summer monsoon and tropical SST are parts of a tropical coupled ocean–atmosphere mode that is connected by the Walker and Hadley circulations (also see Meehl et al. 1998).

Trenary and Han (2013) showed that variability internal to the Indian Ocean can generate decadal SST variations in the southern Indian Ocean. Similarly, Compo and Sardeshmukh (2010) showed that the Indian Ocean SST trend pattern from 1949 to 2006 is dominated by variability unrelated to ENSO. In addition, they found that for 1871–2006, Indian Ocean SST variability related to ENSO and that not related to ENSO have comparable amplitudes. Just what role does the Indian Ocean air–sea interaction play in generating Indian Ocean decadal SSTAs? What are the effects in the Indian Ocean of stochastic atmospheric forcing, which has been shown to be important for generating Pacific decadal variability? What is the relative importance of external forcing (greenhouse gases, aerosols, solar forcing, and volcanoes) versus natural internal variability in generating decadal Indian Ocean variability? These are important unanswered questions.

SUMMARY, ISSUES, AND CHALLENGES.

In situ and satellite observations, ocean–atmosphere reanalysis products, and reconstructed datasets show multidecadal trends in upper Indian Ocean heat content, temperature, salinity, and sea level since the 1950s. Model experiments suggest that all the observed trends are associated with anthropogenic forcing to some degree. While basinwide warming is attributed to forcing by anthropogenic greenhouse gases, the slower warming rate over the north Indian Ocean results from reduced solar radiation caused by the loading of the atmosphere with anthropogenic aerosols of South Asian origin. The basin-scale near-surface warming accompanies thermocline cooling and falling sea level over the tropical–subtropical south Indian Ocean. The distinct spatial structures of temperature and sea level can largely be explained by the changing wind patterns, which are partly driven by the Indo-Pacific warming. On the other hand, there is no consensus on the contribution to these trends from the Pacific via the ITF. The SSS trend has a spatial pattern resembling that of the mean SSS, which is consistent with an enhanced hydrological cycle associated with global warming. There is an apparent upward trend of positive IOD occurrence since the 1950s, which is attributed to the mean state change associated with global warming.

It is important to understand decadal changes of the Indo-Pacific winds and Walker circulation because they largely drive the spatial structures of Indian Ocean sea level and thermocline changes. There is, however, no consensus on trends in equatorial Indian Ocean westerly winds and the Indo-Pacific Walker circulation over the past 50–100 yr. Some observational analyses indicate that Indo-Pacific Walker circulation is weakening while others indicate it is strengthening. AGCMs forced by different SST products produce divergent results. Hence, further research is needed to resolve these issues.

Superimposed on these long-term trends are decadal time scale fluctuations. The observed decadal variability in the Indian Ocean basinwide sea level, salinity, and thermal structure results primarily from forcing by Indian Ocean winds, with a significant contribution from the ITF in the interior of the south Indian Ocean after 1990. Near the coasts, salinity variability due to the river discharge may also contribute to decadal sea level fluctuations. Decadal modulation of the interannual Indian Ocean basin mode, the IOD, and subtropical dipole are observed. While decadal variability of the interannual basin mode is tied to decadal variability in ENSO, decadal modulations of the subtropical dipole and IOD are not well understood. Some studies suggest that decadal fluctuations of the IOD are not correlated with the decadal variability of ENSO or the IPO, while some climate model studies suggest that the IPO can modulate the IOD via changes in the Walker circulation. Thus, the relative importance of variability internal to the Indian Ocean versus Pacific forcing of the IOD at decadal time scales remains an open question.

Basinwide patterns of decadal covariability in SST, SLP, and surface winds have been detected for the past century. Data analyses, together with dynamical model experiments, suggest that the observed decadal variability in Indian Ocean SST results from atmospheric forcing associated with global-scale variations in circulation, with Indian Ocean SST providing only a weak local feedback to the atmosphere. Recent studies show that large-amplitude decadal SST variability over the Indian Ocean unrelated to ENSO is comparable in magnitude to that which is related to ENSO. The dominant pattern of decadal SST variability, which we dub the decadal Indian Ocean basin mode, also appears to be partially independent from the IPO and to have impacts on tropical Pacific variability particularly since the mid-1980s. What are the processes internal to the Indian Ocean in generating the observed decadal variability? Ocean modeling results suggest that oceanic instabilities contribute to decadal SST variability in the extratropical south Indian Ocean. While the role of stochastic atmospheric forcing in generating decadal variability has been investigated in detail in the Pacific and Atlantic Oceans, it has not been carefully studied for the Indian Ocean. What are the effects of stochastic forcing and oceanic Rossby waves in causing Indian Ocean decadal variability, and what is the relative importance of forcing that is external to the Indian Ocean (natural and anthropogenic forcing plus the influence of ENSO) versus processes internal to the Indian Ocean in generating Indian Ocean decadal variability? These are outstanding questions that need to be addressed.

Efforts to predict the evolution of climate over the next several decades have recently begun, taking into account both forced climate change and natural decadal-scale climate variability. Most of these efforts have adopted a global perspective, but with emphasis on variations in the Atlantic and Pacific. There are recent studies showing predictive skill in the Indian Ocean at interannual time scales, such as for the 2006 and 2007 IOD (Luo et al. 2008); also there is evidence of predictive skill for Indian Ocean SST at 2–9-yr lead times, which is attributed to variations in radiative forcing, volcanic aerosols, and the long-term warming trend (Corti et al. 2012; Guemas et al. 2013). The predictive skill for Indian Ocean SST on 10-30-yr time scales and the effect of Indian Ocean SST variability on regional and global decadal climate prediction, however, remain largely unexplored.

From an oceanographic perspective, the generation of decadal time scale variability in the Indian Ocean involves processes operating both at and below the air–sea interface. Subsurface oceanic processes in particular provide the memory of the system because of the vast thermal inertia of the interior ocean. Development of successful decadal prediction schemes will rely critically on our understanding of the origins and mechanisms of Indian Ocean decadal variability. Advancing our understanding of that variability will require reliable, long-term surface and subsurface oceanic observations. Continuous progress is being made to quality control existing historical datasets for climate research applications (e.g., Gouretski and Koltermann 2007; Wijffels et al. 2008; Ishii and Kimoto 2009; Levitus et al. 2009; Willis et al. 2009; Gouretski and Reseghetti 2010), but there remains an imperative for sustained in situ and satellite observations into the future as well. Recent advances in observing system development, most notably with the implementation of the Indian Ocean Observing System (IndOOS), have significantly enhanced our capability to conduct Indian Ocean research. IndOOS includes the Research Moored Array for African–Asian–Australian Monsoon Analysis and Prediction (McPhaden et al. 2009); the Argo network (www.argo.ucsd.edu); and other elements designed to complement satellite observations of wind stress, SST, sea level, and gravity. Collectively, these satellite and in situ measurements systems are providing indispensable observational resources for studies of decadal variability and predictability in the Indian Ocean region. Recent advances in salinity remote sensing from Soil Moisture Ocean Salinity (SMOS; www.esa.int/Our_Activities/Observing_the_Earth/SMOS) and *Aquarius/Satelite de Aplicaciones Cientificas-D* (*SAC-D*; http://aquarius.nasa.gov) missions are broadening the frontiers of the Indian Ocean research further. Sustaining and enhancing these in situ and satellite-observing systems are essential to ensure future progress in our ability to describe, understand and predict decadal time scale variability in the Indian Ocean.

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