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Thermocline spiciness variations in the tropical Indian Ocean observed during 2003–2014

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ABSTRACT

Spiciness variability in the thermocline is believed to be an important subsurface ocean process affecting sea surface temperature (SST) and climate variability over the tropical oceans. Analysis of in-situ observations during 2003–2014 reveals pronounced spiciness variations at interannual-to-decadal timescale within the thermocline of the tropical Indian Ocean (TIO). Isopycnal potential temperature and salinity anomalies between σ_θ=24.0–25.0 kg m^{-3} have typical magnitudes of 0.2 °C and 0.08 psu in the southeastern Arabian Sea and the southern TIO, comparable with those observed in the Pacific basin. In the southeastern Arabian Sea, spiciness variations are dominated by a decadal trend, showing positive (warm, salty) anomalies in 2003–2006 and negative (cold, fresh) anomalies in 2009–2013. The major cause is the mixed-layer property change in the northern Arabian Sea, which induces variation in both spiciness and amount of water detrained down to the thermocline. In the southern TIO, largest variations occur at two zonal spiciness fronts where different thermocline water masses converge. These signals are primarily produced by wind-driven geostrophic advection. Anomalies at the northern front (11–6°S) exhibit westward spreading tendency and quick diffusion, which reflect mainly the signatures of the 1st baroclinic mode Rossby waves. Anomalies at the southern front (18–13°S) move westward to the western TIO via the advection of the South Equatorial Current (SEC). These low-frequency subsurface spiciness variations can alter the background vertical thermal gradient in the thermocline ridge region (55–85°E, 12–4°S), although such impact on the SST variability is generally small.

1. Introduction

Potential temperature θ and salinity S of sea water at a given isopycnal surface are addressed as "spiciness" by oceanographers (e.g., Veronis, 1972; Munk, 1981; Flament, 2002; Huang, 2011). Correspondingly, density-compensated isopycnal θ and S variability is referred to as spiciness variability (e.g., Schneider, 2000). Positive (warm, salty) and negative (cold, fresh) subsurface spiciness anomalies are usually produced in the formation areas of thermocline water masses by air–sea interaction (Bindoff and McDougall, 1994), anomalous subduction (Johnson, 2006), and convective mixing (Yeager and Large, 2004). Otherwise, away from the outcropping region, anomalies can also be generated by subsurface isopycnal advection across spiciness fronts (Schneider, 2000; Kilpatrick et al., 2011; Li et al., 2012b). After generation, spiciness variations spread passively in the ocean via the wind-driven upper-ocean circulation. The important role of large-scale, low-frequency spiciness variations in the tropical climate modulations is drawing increasing attention. Especially, anomalies from the extra-tropics are brought equatorward by the lower branch of the shallow overturning cell (e.g., McCreary and Lu, 1994; Lee and Marotzke, 1998) and affect sea surface temperature (SST) variability through the equatorial upwelling (e.g., Schneider, 2004; O'Kane et al., 2014), which is believed to be one of the mechanisms responsible for the decadal climate variability (Latif and Barnett, 1996; Gu and Philander, 1997).

Descriptions of subsurface thermal variations in the Pacific basin based on historical hydrographic data have been available since the 1990s (Deser et al., 1996; Zhang et al., 1998; Schneider et al., 1999; Luo and Yamagata, 2001). Decadal timescale anomalies emerge at mid-latitudes of both hemispheres and propagate to the tropical Pacific along the mean geostrophic streamlines in the main thermocline. It was also pointed out that these anomalies undergo intensive diffusion along the pathways and have been greatly weakened as reaching the tropics (Schneider et al., 1999). Due to the shortage of subsurface conductivity measurements, it was difficult to separate spiciness signals from planetary wave signals in historical data. On the other hand, the connection between tropical and subtropical oceans through subsurface spiciness signal transmission were confirmed by many numerical modeling studies (e.g., Pierce et al., 2000; Nonaka and Xie, 2000;

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Schneider, 2000, 2004; Yeager and Large, 2004; Luo et al., 2005; Nonaka and Sasaki, 2007). Modeling researches also suggested that spiciness variations, especially those from the South Pacific, have a considerable impact on the decadal climate transitions (e.g., Giese et al., 2002; Yeager and Large, 2004; Luo et al., 2005; O'Kane et al., 2014).

The launch of Argo program (Roemmich et al., 2009) in the 2000s provides a powerful tool to routinely monitor the temperature and salinity variations below the sea surface. Analyses of Argo data have revealed robust spatial-temporal characteristics of regional and basin-scale spiciness variability (e.g., Johnson, 2006; Yeager and Large, 2007; Sasaki et al., 2010; Kolodziejczyk and Gaillard, 2012; Li et al., 2012a, 2012b; Katsura et al., 2013; Kolodziejczyk et al., 2014). Anomalies with large magnitudes are formed in the eastern Pacific basin in both hemispheres and communicated to the central equatorial Pacific by the interior equatorward flow (Johnson and McPhaden, 1999). Albeit intensively diffused along the pathways, arrivals of these signals are still sufficient to modify the background thermal structure of the equatorial region upon which SST evolves (e.g., Kolodziejczyk and Gaillard, 2012; Li et al., 2012a). These results provide observational support for the climatic importance of thermocline spiciness variations proposed by earlier modeling studies.

While most of the existing researches were focused on the spiciness variations in the Pacific Ocean (e.g., Schneider et al., 1999; Schneider, 2000, 2004; Kessler, 1999; Yeager and Large, 2004; Luo et al., 2005; Sasaki et al., 2010; Kolodziejczyk and Gaillard, 2012, 2013) or the Atlantic Ocean (e.g., Lazar et al., 2001; Laurian et al., 2006, 2009; Kolodziejczyk et al., 2014), their counterpart in the Indian Ocean has never been examined before. However, the important role of the tropical Indian Ocean (TIO) in global climate has been increasingly recognized (e.g., Annamalai et al., 2007; Xie et al., 2009; Luo et al., 2010, 2012). Especially, the strong SST variance in the Seychelles–Chagos thermocline ridge (SCTR) (McCreary et al., 1993; Hermes and Reason, 2008) of the southwest TIO has profound local and remote impacts on the weather and climate (e.g., Xie et al., 2002; Annamalai et al., 2005; Duvel and Vialard, 2007; Izumo et al., 2010a, 2010b; Vialard et al., 2009; Li et al., 2013). Spiciness anomalies can travel in the complicated Indian Ocean overturning circulation (Lee and Marotzke, 1998; Schott et al., 2002; Lee, 2004) and modulate, directly or indirectly, the TIO SST variability associated with the important climate modes, such as the Madden–Julian oscillations (Madden and Julian, 1971) and the Indian Ocean dipole (IOD) (Saji et al., 1999). In this regard, knowledge of the thermocline spiciness variations in the TIO could contribute to our understanding of the tropical air–sea interaction.

In this study we attempt to investigate the low-frequency (interannual-to-decadal timescale) spiciness variability in the thermocline of the TIO. In-situ and satellite observational data (Section 2) are analyzed to reveal the spatial structure (Section 3.1) and temporal variability (Section 3.2) of the thermocline spiciness, explore the generation mechanism of low-frequency anomalies in important

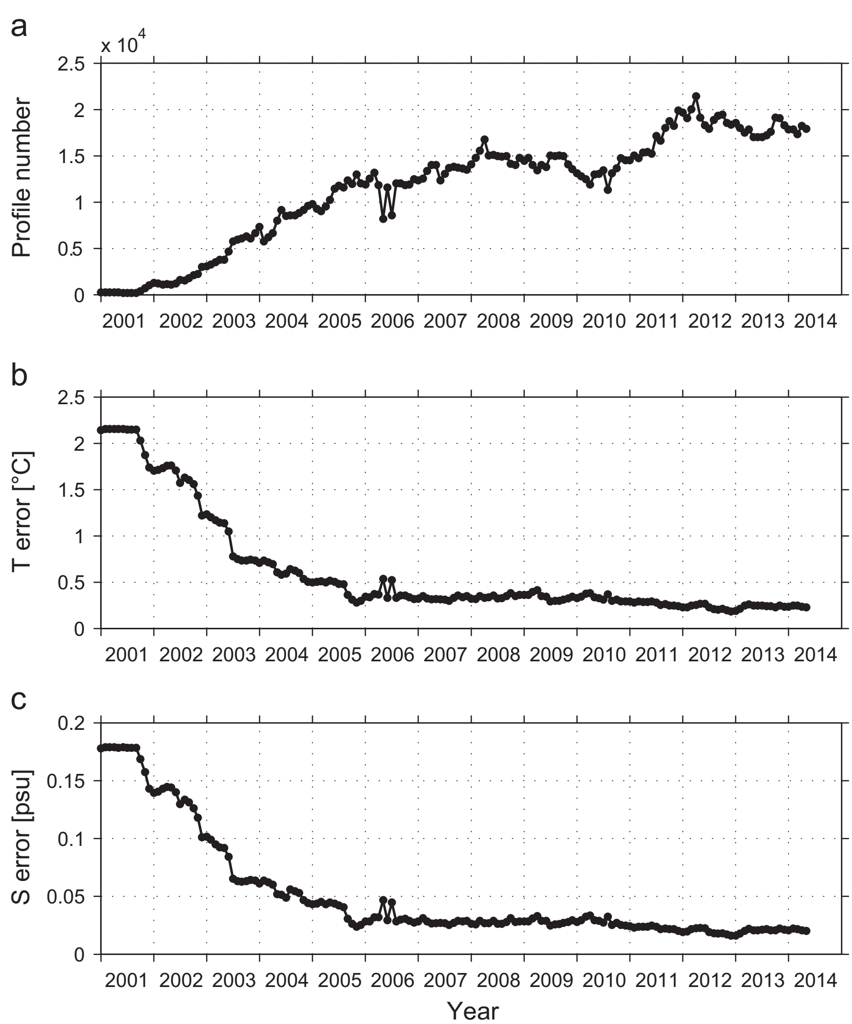

Fig. 1. (a) Number of monthly profile of the MOAA GPV dataset in the TIO (30–120°E, 20°S–20°N). (b) Mean interpolation errors of temperature between σ_θ= 24.0–25.0 kg m^{-3} of the MOAA GPV in the TIO. (c) is the same as (b) but for salinity.