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Rapid Sea Level Rise in the Tropical Southwest Indian Ocean in the Recent Two Decades

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Key Points:

- Rapid sea level rise occurs in the tropical Southwest Indian Ocean (SWIO) since the early 2000s
- The ocean mass addition and the upper 2,000 m ocean warming contribute significantly to the total sea level rise
- The upper 2,000 m ocean warming is primarily attributed to thermal expansion below the thermocline associated with the spread of water masses

Supporting Information:

Supporting Information may be found in the online version of this article.

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Abstract

It has been reported that the sea level falls in the tropical Southwest Indian Ocean (SWIO) from the 1960s to the early 2000s. However, a rising trend of 4.05 ± 0.56 cm/decade has occurred during the recent two decades with our analysis showing that manometric sea level contributes 41% to this sea level rise. 30% of this rise is due to steric sea level (SSL) change in the upper 2,000 m with SSL rise in the upper 300 m of secondary importance. Conversely, thermal expansion below the thermocline (300–2,000 m), likely caused by water mass spread from the Southern Ocean, induces major contribution to SSL changes. Compared to existing studies demonstrating the contribution of thermal variations above the thermocline to sea level variability in the tropical SWIO, this study emphasizes the importance of ocean mass and deeper ocean changes in a warming climate.

Plain Language Summary

Global ocean sea level change is spatially and temporally nonuniform due to oceanic and atmospheric dynamics. The tropical Southwest Indian Ocean (SWIO) experienced a sea level fall from the 1960s to the early 2000s. However, a rapid sea level rise has occurred over the last two decades in the tropical SWIO that is faster than the global average. The ocean mass increase due to extra water input leads to an essential impact on sea level rise in the tropical SWIO. Compared to previous studies demonstrating the effect of thermal expansion in the upper 300 m, this study shows larger contributions from deeper ocean (300–2,000 m) warming over the past two decades. Overall, this study highlights the importance of ocean mass and deeper water thermal structure in regulating tropical SWIO sea level rise in a changing climate, as well as the need for observations and direct assessment of the abyssal ocean beneath 2,000 m.

1. Introduction

The Indian Ocean is one of the major sinks of excessive heat entering the Earth system during the recent hiatus period from 1998 to 2013 (S. K. Lee et al., 2015; Llovel & Terray, 2016; Nieves et al., 2015; Roemmich et al., 2015; Zhang et al., 2018). Especially, the ocean heat content (OHC) increase in the Indian Ocean accounts for more than 70% of global heat gain in the upper 700 m during 2003–2012 (S. K. Lee et al., 2015). In the Indian Ocean, the tropical Southwest Indian Ocean (SWIO) is a region with the largest interannual-to-decadal sea level and OHC variability (e.g., Han et al., 2018). Han et al. (2010) systematically investigated sea level fall in the tropical SWIO from the 1960s to the early 2000s under the warming background of the global ocean. Nevertheless, sea level trends in the subsequent decades have not been quantified, which serves as the motivation for the present study.

The South Indian Ocean (SIO) has shown an accelerated warming and sea-level rise during the recent hiatus, which are closely associated with the strengthening of Indonesian Throughflow (ITF) heat and freshwater transport (e.g., Jyoti et al., 2019; S. K. Lee et al., 2015; Li et al., 2017; Llovel & Lee, 2015; Zhang et al., 2018). The decade-long basin-wide warming and sea level rise in the SIO ended with an unprecedented drop 2014–2016, whereas it quickly recovered during 2017–2018 due to the anomalous wind-driven Ekman pumping associated with El Niño-Southern Oscillation (ENSO) variability (Volkov et al., 2020). These remarkable warming and sea level rise in the SIO are dominated by signals in the Southeast Indian Ocean (SEIO) and subtropical areas (Huang et al., 2020; Jyoti et al., 2019; Li et al., 2017; Y. Lu et al., 2022; Zhang et al., 2018), and have been well investigated. In contrast, sea level variability in the tropical SWIO during the recent two decades has received less attention. Unlike the SEIO and subtropical basins, which are strongly controlled by the ITF, sea level change

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in the tropical SWIO is primarily controlled by thermal expansion related to local forcing (e.g., Li & Han, 2015). Meanwhile, the salinity change can also regulate the SIO sea level variability (Llovel & Lee, 2015). Therefore, the controlling factors responsible for the sea level trend in the tropical SWIO during the recent two decades remain unclear.

The tropical SWIO is characterized by a shallow mixed layer and thermocline, as well as strong air-sea interactions (e.g., Chowdary et al., 2009; Vialard et al., 2009; Xie et al., 2002). The local atmospheric circulation change plays a crucial role in modulating the decadal sea level variability with the dominant oscillation period of 15–20 years (T. Lee & McPhaden, 2008; Li & Han, 2015; Trenary & Han, 2013). Jin et al. (2018) further suggested that the decadal wind variability over the tropical SIO basin is mainly modulated by the inter-basin atmospheric teleconnections sourced from Interdecadal Pacific Oscillation, which is the leading Pacific climate mode defined as the first empirical orthogonal function mode of low-pass-filter sea surface temperature anomalies in the Pacific (Power et al., 1999).

Overall, the long-term sea level fall from the 1960s to the early 2000s and decadal sea level variability before the early 2010s in the tropical SWIO have been studied considerably (e.g., Deepa et al., 2019; Han et al., 2010; Jin et al., 2018). What remains unknown is the overall sea level trend in the recent two decades which includes both periods during and after the recent hiatus. It should be noted that most previous studies have focused on the essential effect of thermal expansion above the thermocline on the sea level variability in the tropical SWIO (e.g., Deepa et al., 2019; Li & Han, 2015; Zhuang et al., 2013). However, as global ocean warming penetrates into the deeper ocean and manometric sea level increase occurs due to the melting glacial and ice sheet in the polar region (e.g., Chen & Tung, 2014; Desbruyères et al., 2016; Llovel et al., 2014; Purkey et al., 2014; Trenberth & Fasullo, 2010), the regional variability of thermal expansion in the deeper ocean and mass change deserves further analysis to explore their contributions to sea level variability in the tropical SWIO.

Furthermore, up-to-date data sets have enabled a more deliberated investigation of sea level variability in recent decades. Since 1993, altimetry satellites have been constantly measuring global and regional sea level change with high precision. The Argo program, which began in the early 2000s, has provided temperature and salinity observations in the upper 2,000 m. Gravity Recovery and Climate Experiment (GRACE) satellites launched in 2002 have been estimating manometric sea level changes in the global oceans. Thus, we use multiple-sourced data sets to investigate the sea level budgets since 2000 in the tropical SWIO.

2. Data and Methodology

2.1. Data

2.1.1. Satellite Observations

This study utilizes the monthly satellite altimetry data from 1993 to 2021, which are provided by the Archiving, Validation, and Interpretation of Satellite Oceanographic (AVISO). Monthly changes in manometric sea level are observed by the GRACE/GRACE-FO (GRACE Follow-On) satellites. Here we use three GRACE data sets during 2002–2021 obtained from the RL06 Mascon solution from Jet Propulsion Laboratory, the RL06 Mascon solution from University of Texas, Center for Space Research, and RL06 Mascon solution from National Aeronautics and Space Administration, Goddard Space Flight Center (NASA GSFC), respectively.

2.1.2. In Situ Observations and Reanalysis Products

Three gridded observational temperature and salinity data sets are used in this study. The EN4.2.1 data set spanning the years 1940–2021 is obtained from the Met Office Hadley Center (Good et al., 2013). The Meteorological Research Institute provides grided ocean temperature and salinity data for the years 1955–2021 (referred to Ishii; Ishii et al., 2017). The Grid Point Value of the Monthly Objective Analysis using the Argo data (MOAA-GPV) for 2001–2021 is provided by the Japan Agency for Marine-Earth Science and Technology (Hosoda et al., 2008).

We use the Ocean Reanalysis System 4 (ORAS4) numerical assimilation outputs to examine sea level variability since the 1960s (Balmaseda et al., 2013). The variability of surface wind, heat flux, and freshwater flux in the SIO is investigated using monthly-mean JRA55 atmospheric reanalysis (Kobayashi et al., 2015).

2.2. Methods

2.2.1. Sea Level Budget

To investigate the contributions of different components to the sea level variability in the tropical SWIO, a sea level budget analysis is diagnosed as follows (Volkov et al., 2017):

$$\mathrm{SSH_{total}} = \mathrm{SSH_{mass}} + \mathrm{SSL_{2000}} + \mathrm{SSL_{deep}} \tag{1}$$

$\mathrm{SSH_{total}}$ is the total sea surface height (SSH) observed by satellite altimetry and can be expressed as the sum of three terms on the right side. $\mathrm{SSH_{mass}}$ is the manometric sea-level component due to changes in ocean mass measured by GRACE satellites (Gregory et al., 2019). $\mathrm{SSL_{2000}}$ represents steric sea level (SSL) in the upper 2,000 m estimated using gridded ocean observations. SSL in the deep ocean below 2,000 m ($\mathrm{SSL_{deep}}$) is estimated as a residual. It should be noted that gaps exist in GRACE data due to battery issues late in the mission that required instruments to be turned off, as well as a year-long gap (2017–2018) between the end of the GRACE mission and the start of GRACE-FO (Bonin et al., 2018; Kornfeld et al., 2019). To ensure consistency, we estimate the linear trend with uncertainty for each sea level budget term using the months with data for all observations. For each data set, uncertainty of the linear trend is estimated by standard error at the 95% confidence interval. Meanwhile, the uncertainty of the averaged linear trend is assessed using the standard deviation of multiple data sets' respective linear trends. The monthly climatology over 2002–2021 is removed from all estimates presented in the sea level budget analysis.

2.2.2. Heave and Spice Decomposition

To investigate the driving mechanisms of ocean thermal expansion, temperature change can be decomposed into the spice and heave components as follows (Bindoff & Mcdougall, 1994):

$$\frac{d\theta}{dt}\Big|_z = \frac{d\theta}{dt}\Big|_{\rho_0} + \frac{d\theta}{dz}\frac{dz}{dt}\Big|_{\rho_0} + \mathrm{Residual} \tag{2}$$

Heave ($\frac{d\theta}{dz}\frac{dz}{dt}|_{\rho_0}$) refers to temperature variability due to vertical motions of isopycnal surfaces that are not subject to heat or salinity exchange with the environment (Häkkinen et al., 2016), whereas the spice component ($\frac{d\theta}{dt}|_{\rho_0}$) results from density-compensating variability along isopycnal surfaces and reflects the effect of anomalous water mass change (Bindoff & Mcdougall, 1994; McDougall & Krzysik, 2015).

3. Results

3.1. Sea Level Variability in the Tropical SWIO

To highlight sea level variability longer than the decadal scale, an 11-year low-pass-filter is applied to the sea level time series averaged in the tropical SWIO (50°E–80°E; 15°S–5°S) based on ORAS4 and AVISO data sets. Considering that global mean sea level in ORAS4 is solely due to global freshwater budget, Figure 1a only shows the regional sea level changes after removing the time series of the global averages from both ORAS4 and AVISO data sets. The result from ORAS4 shows a substantial sea level fall from the 1960s to 2000 (Figure 1a), similar to Han et al. (2010) based on model simulations and tide-gauge observations. However, as both data sets indicate, the long-term sea level fall ceased in 2000 and shifted to a noticeable sea level rise from 2000 to 2021 (Figure 1a).

The total sea level trends are not spatially uniform over the entire Indian Ocean (Figures 1b and 1c). In Particular, the tropical SWIO displays a prominent sea level fall from 1960 to 2000 (Figure 1b), which has been attributed to an anomalous cyclonic wind pattern associated with the combined contribution of Walker and Hadley circulations (Han et al., 2010). However, the total sea level shows a rising trend over the entire Indian Ocean from 2000 to 2021, with the strongest sea level rise located near 10°S in the tropical SWIO (Figure 1c). This phenomenon and related mechanisms have not been mentioned or investigated in previous studies.

3.2. Sea Level Budget

Since the GRACE mission began detecting global manometric sea level variations in 2002, here we conduct a sea level budget analysis from 2002 to 2021 to better understand the various contributors to sea level rise in the tropical SWIO. The AVISO product suggests a linear trend of SSH in tropical SWIO of 4. 05 ± 0.56 cm/decade

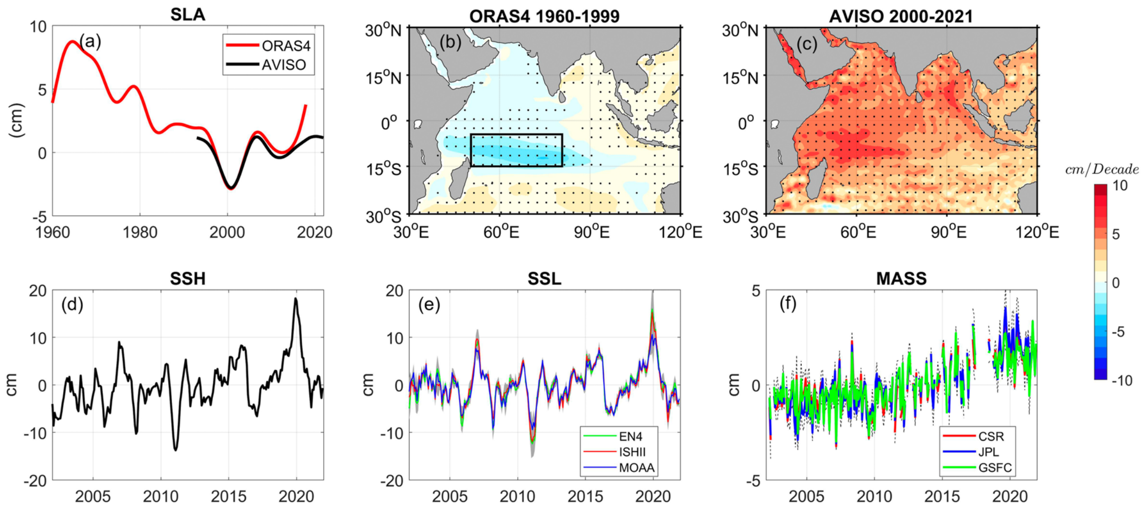

Figure 1. (a) Decadal regional sea level variability (unit: cm) in the tropical Southwest Indian Ocean (SWIO; 5°–15°S, 50°–80°E) after an 11-year low-pass filtering, derived from Ocean Reanalysis System 4 (ORAS4) and Archiving, Validation, and Interpretation of Satellite Oceanographic (AVISO) data sets. The sea level anomalies are the monthly anomalies relative to the mean pattern during 1993–2017. Sea level trends (cm/decade) in the Indian Ocean during (b) 1960–1999 and (c) 2000–2021. The black box in (b) indicates the tropical SWIO. Solid dots indicate values exceeding 95% statistical significance based on a Mann–Kendall test. (d) Monthly sea surface height observed by AVISO during 2002–2021. (e) Steric sea level (SSL) in the upper 2,000 m during 2002–2021 calculated from EN4, Ishii, and MOAA products. The shading indicates the 95% confidence intervals of the averaged values. (f) The manometric sea level change during 2002–2021 observed by the GRACE/GRACE-FO satellites (solid lines). The dashed lines indicate the 95% confidence intervals of the averaged manometric components from the three products. See (b) for the averaging box.

from 2002 to 2021 (Figure 1d), which is approximately 1.3 times the global mean sea level rise of 3.1 cm/decade (WCRP Global Sea Level Budget Group, 2018). Therein, the manometric component (SSH_{mass}) contributes with an increasing trend of 1. 65 ± 0.20 cm/decade (Table S1 in Supporting Information S1; Figure 1f), accounting for about 41% of the total sea level rise. SSL_{2000} estimated from the three observational data sets is 1. 20 ± 0.20 cm/decade (Figure 1e), contributing 30% of the total sea level rise observed by satellite altimeters. The sea level budget analysis presented here indicates that the combined effects of SSH_{mass} and SSL_{2000} explain about 71% of the total sea level rise from 2002 to 2021, reflecting their significant contributions to total sea level rise in the tropical SWIO.

By subtracting the SSH_{mass} and SSL_{2000} from altimetric SSH_{total}, the residual term of the budget equation exhibits an increasing trend of 1. 19 ± 0.24 cm/decade and explains about 29% of total sea level rise. This primarily reflects the effect of SSL change below 2,000 m depth (Llovel et al., 2014; Volkov et al., 2017).

3.3. Steric Sea Level and Ocean Heat Content

Given the important impact of SSL_{2000} on total sea level rise, we further investigate the relative contributions of thermosteric and halosteric components to the anomalous SSL rise during 2002–2021. Results based on the three observational data sets (EN4, Ishii, MOAA) suggest that the thermosteric sea level (TSL) and SSL_{2000} show similar amplitudes (Figures 2a, 2c, and 2e), indicating that SSL_{2000} rise is dominated by the thermosteric component, while the halosteric component's contribution can be neglected.

Due to the dominant contribution of thermosteric components to SSL_{2000} variability, OHC in the upper 2,000 m is further calculated. It should be noted that previous studies primarily focused on decadal and multidecadal OHC variations above the thermocline (upper 300 m) where the vertical temperature gradient is strongest and thus generally shows the dominant contributions to the OHC variations in the upper 2,000 m (Jin et al., 2018; Trenary & Han, 2013). In this study, we further examine OHC variability in the layer of 300–2,000 m of the tropical SWIO. Similar to the TSL variability, OHC in the upper 2,000 m exhibits an increasing trend from 2002 to 2021 (Figures 2b, 2d, and 2f), in which the OHC increase in the upper 300 m accounts for approximately 33% (Table S2 in Supporting Information S1). The remanent 67% is contributed by the 300–2,000 m OHC (Figures 2b, 2d, and 2f), leading to a significant TSL rise and accounting for 74% of the TSL increase in the upper 2,000 m, as well as 22% of the total sea level rise. These indicate the crucial role of thermal expansion in the deeper ocean in the

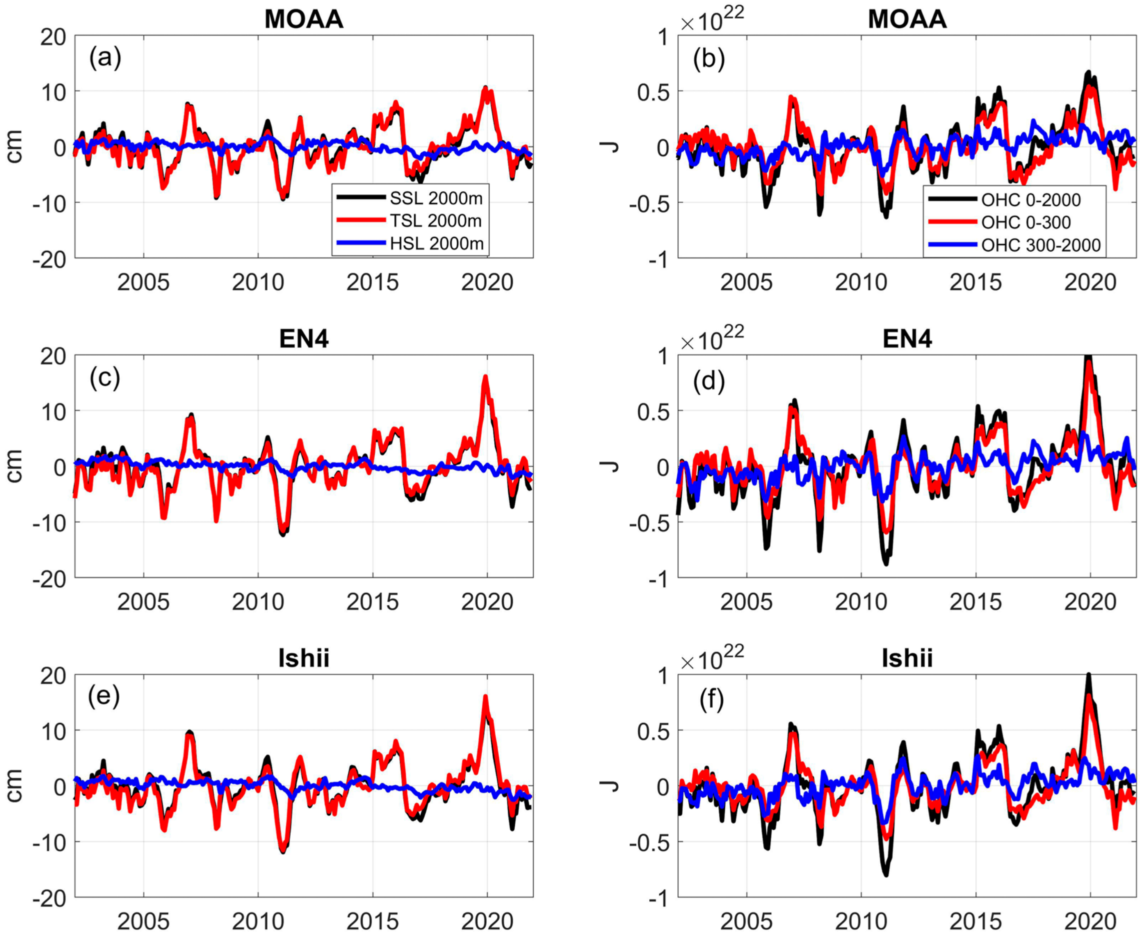

Figure 2. (a) The steric sea level (SSL), thermosteric sea level (TSL), and halosteric sea level (HSL) variability in the upper 2,000 m of the tropical Southwest Indian Ocean (SWIO). (b) The ocean heat content (OHC) in the upper 2,000 m, upper 300 m, and the 300–2,000 m layers of the tropical SWIO. The calculations in (a) and (b) are based on the MOAA data set. (c) and (d) are derived from the EN4 data set. (e) and (f) are derived from the Ishii data set.

tropical SWIO during the past two decades (W. Lu et al., 2019; Su et al., 2021), compared to the OHC increase in the upper 300 m which contributes only moderately.

3.4. Factors Driving the Thermal Expansions in the Upper 2,000 m

To further investigate mechanisms responsible for thermal variations in the tropical SWIO, we decompose temperature changes into heave and spice components based on the three data sets. Results show that the upper-layer (0–300 m) temperature trend during 2002–2021 can be largely explained by changes in the heave component (Figure 3), which is supported by the deepening isopycnals between 5°S and 15°S. This has been investigated extensively (e.g., Han et al., 2010). On the other hand, strong warming spice signals exist below the thermocline in the tropical SWIO and are primarily within the 500–1,800 m or density range of 27.1–27.8 kg/m^3 where the tropical/subtropical Intermediate Waters are located (Figures 3c, 3f, and 3i; Herraiz-Borreguero & Rintoul, 2011; Portela et al., 2020; Schmidtko & Johnson, 2012). Previous studies have reported the heat loss within the Antarctic Intermediate Water (AAIW) in the SIO during the Argo period which is attributed to the volume decrease of AAIW, indicating the weakened formation of AAIW in the SIO (Kolodziejczyk et al., 2019; Zhang et al., 2021). Therefore, this anomalous spice change could be associated with a weakened isopycnal transformation of cooler AAIW from higher latitudes to the tropics (e.g., Fine, 1993; Portela et al., 2020; Wefer et al., 1996).

We also examine the trends of multiple atmospheric forcing, including wind stress, Ekman pumping, as well as sea surface heat flux anomalies during 2002–2021 (e.g., Huang et al., 2022, 2023; Li & Han, 2015). As shown in Figure 4a, atmosphere circulation is featured as an anticyclonic wind stress trend during 2002–2021, which

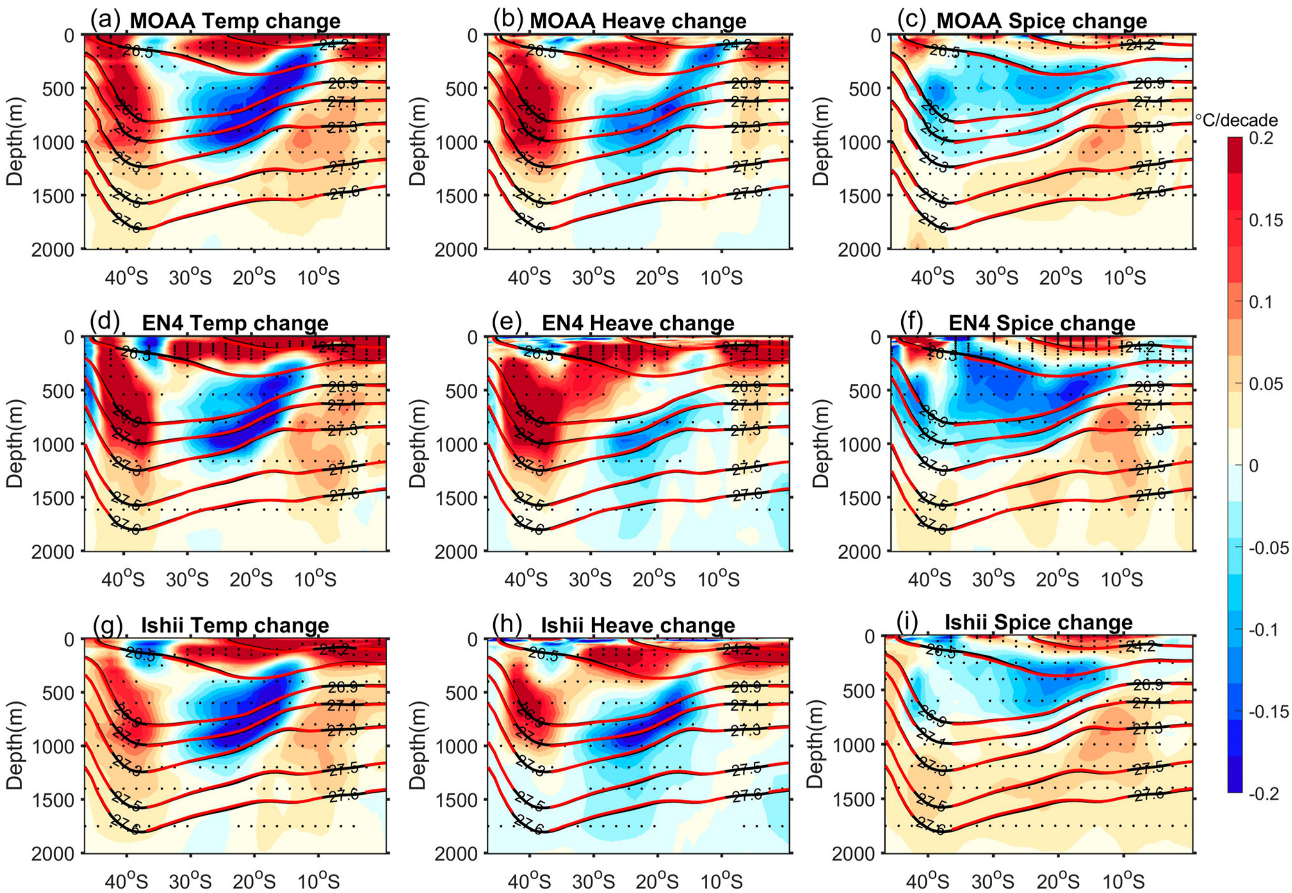

Figure 3. Zonal averages of the linear trends in the (a) potential temperature, (b) heave, and (c) spice components (°C/decade) in the western South Indian Ocean (0°–50°S, 50°–80°E) during 2002–2021 derived from the MOAA data set. (d–f) and (g–i) are the same as (a–c) but for EN4 and Ishii data sets. The black (red) contours represent the mean isotherms for 2002–2011 (2012–2021). Based on the Mann-Kendall significance test, the solid dots represent trends greater than 95% statistical significance.

induces downward Ekman pumping and can lead to increasing OHC (Figure 2). The JRA55 data set indicates the net surface heat loss from ocean to the atmosphere (Figure 4b), which does not favor upper 300 m OHC increases. Similar surface heat flux anomalies can also be seen in other reanalysis products (e.g., ERA5 data, figure not shown). These results suggest that the OHC increase in the upper 300 m is mainly attributed to the wind-driven Ekman pumping.

The intense impact of heave on temperature change in the tropical SWIO is mainly concentrated within the upper 300 m and gradually diminishes with increasing depth (Figures 3b, 3e, and 3h). Notably, the spice component displays a more substantial influence on temperature variations than the heave component within the 300–2,000 m layer, with spice changes accounting for 71% of the overall OHC increase (Figures 3c, 3f, and 3i). Unlike previous

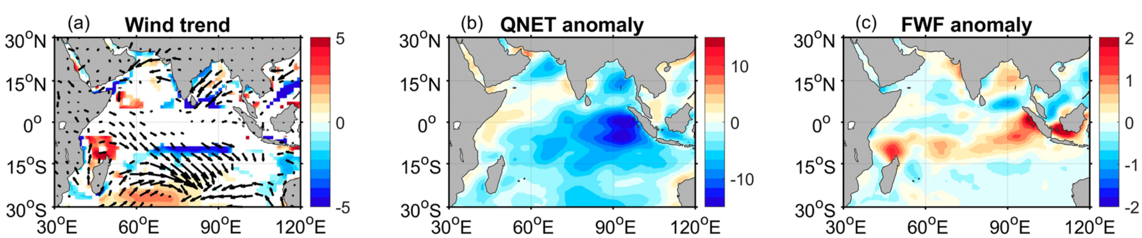

Figure 4. (a) Trends of 18-month low-pass-filtered surface wind stress (N/m^2/decade) and Ekman pumping velocity (10^{-7} m/s/decade), (b) net surface heat flux anomaly (W/m^2), (c) freshwater flux anomaly (mm/day) in the Indian Ocean during 2002–2021. The wind stress and Ekman pumping velocity trends below the 95% confidence level are not plotted.

studies, this study highlights that the spice change dominates deeper ocean heat uptake and thus SSL_{2000} rise during the recent two decades (Figures 3 and 4).

3.5. Manometric Sea Level Change

Manometric sea level change is a significant contributor to global mean sea level rise over the last two decades (e.g., Meyssignac et al., 2019). The contribution of manometric component to the sea level variability varies on regional scales (Johnson & Chambers, 2013). First, freshwater input from glacier retreats and ice sheet melting will redistribute rapidly throughout the global ocean basins via the barotropic waves (Lorbacher et al., 2012) and contribute to part of the manometric sea level increase in the tropical SWIO during 2002–2021, while the SSL change due to meltwater input is slower and smaller (Stammer, 2008). Second, local manometric sea level is also modulated by ocean circulation changes driven by anomalous wind stress curl (Chambers & Willis, 2008). As shown in Figure 4a, anticyclonic atmosphere circulation can cause surface convergence and manometric sea level rise. Additionally, strong freshwater input occurs in the tropical SIO (Figure 4c), favoring manometric sea level increase over the last two decades.

4. Discussion and Summary

Over the tropical SWIO, sea level exhibits a distinct falling trend from the 1960s to the early 2000s. However, since the early 2000s, we found that this multidecadal sea-level fall in the tropical SWIO shifts to a strong rising trend of 4. 05 ± 0.56 cm/decade. Budget analysis finds that SSL rise of 1. 20 ± 0.20 cm/decade in the upper 2,000 m accounts for 30% of the total sea level rise in the tropical SWIO. The manometric component, estimated from three GRACE products, exhibits an increasing trend of 1. 65 ± 0.20 cm/decade that contributes to 41% of sea level rise. The residual term explains about 29% of the sea level rise in the tropical SWIO during 2002–2021.

The warming in the upper 300 m could be explained by the downward Ekman pumping (Figure 4a). The comparison of atmospheric circulation suggests that the multidecadal variability of thermal expansion in the upper ocean is closely associated with local atmospheric circulation change (Han et al., 2010),with the shift in wind trends over the SIO from a cyclonic pattern during 1960–1999 to an anticyclonic pattern during 2002–2021 (Figure S1 in Supporting Information S1). Moreover, the warming in the 300–2,000 m layer induces greater importance than the upper layer which was overlooked by prior studies (e.g., Jin et al., 2018; Schwarzkopf & Böning, 2011).

This subsurface warming is primarily contributed by spice change which may be attributed to water mass intrusion from higher latitudes over the last two decades. Particularly, the warming signal of spice component in the 300–2,000 m layer has become stronger than that during 1960–1999 (Figure S2 in Supporting Information S1; Figure 3). Overall, the SSL_{2000} trend reversal in the early 2000s is due to the combined effect of sea surface wind change and water mass variability below the thermocline. There have been many studies investigating the essential impact of local wind and remote forcing from the Pacific on the upper-ocean thermal expansion and sea level change in the tropical SWIO (e.g., Jin et al., 2018; Li & Han, 2015). This study is the first to report the critical role of deeper ocean change and the meridional pathway of water mass in modulating sea level variability in tropical SWIO.

Manometric sea level, on the other hand, makes a critical contribution to rapid sea level rise in the tropical SWIO, which received limited attention in previous studies (e.g., Jin et al., 2018; Li & Han, 2015). In addition to the freshwater input due to glacier retreat and ice sheet melting in polar regions, the manometric sea level rise in the tropical SWIO is favored by local wind forcing and freshwater input from the atmosphere.

The limitation of this study lies in the indirect estimation of abyssal ocean SSL change. During 2002–2021, the residual term in the sea level budget shows a rate of 1.19 ± 0.20 cm/decade, which accounts for approximately 29% of the total sea level rise (Table S1 in Supporting Information S1). However, the most significant rise occurs during the first 3 years (Figure S3 in Supporting Information S1) and the residual term during 2005–2021 only shows an insignificant linear trend of 0.35 ± 0.30 cm/decade. Therefore, the indirect estimation may include large uncertainties due to noticeable differences among products (Liang et al., 2021; Liu et al., 2020). Overall, our study emphasizes the importance of observations (Purkey & Johnson, 2013) or reconstruction (Bagnell & DeVries, 2021; Su et al., 2020) in the deep ocean, as well as diminishing uncertainties in sea level budgets.

Data Availability Statement

The satellite altimetry data is downloaded from https://data.marine.copernicus.eu/. The GRACE data sets are obtained from https://grace.jpl.nasa.gov/data/get-data/monthly-mass-grids-ocean/. The EN4 data set is from Good et al. (2013). The MOAA-GPV Argo data is from Hosoda et al. (2008). The Ishii data is obtained from Ishii et al. (2017). The ORAS4 data set is available from Balmaseda et al. (2013). The JRA55 data set is obtained from Kobayashi et al. (2015).

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