The interannual variability of shallow meridional overturning circulation and its association with the south-west Indian Ocean heat content variability

Rahul U. Pai1,2 · Anant Parekh1 · Jasti S. Chowdary1 · C. Gnanaseelan1

Abstract
The present study examines the interannual variability of the Indian Ocean Shallow Meridional Overturning Circulation (SMOC) using century-long reanalysis data. The strength of the transport associated with SMOC is calculated using meridional overturning stream function. The highest SMOC variability is found between the latitudes 5° S and 15° S, which displayed enhancement in amplitude after 1940s. Strong and weak SMOC years are identified using standard deviation threshold. Strong SMOC years composite displayed excess southward transport (~ 2.5 Sv) and subduction over the South Indian Ocean. The associated southward heat transport (~ 0.25 PW) reduced the sea level and upper 200 m ocean heat content (OHC) over the Southwest Indian Ocean (SWIO). On the other hand, weaker SMOC years composite displayed weak heat transport, increased sea level and OHC over the SWIO. Tide gauge and satellite observations also displayed similar variation in sea level for respective phases of SMOC. Further analysis reveals that the SMOC variability is primarily driven by changes in the zonal wind stress south of the equator and displays close association with the Southern Oscillation Index. The Ocean model-based sensitivity experiments confirm that the OHC variability over SWIO is closely associated with the SMOC variability and is primarily driven by local wind forcing as a response to El Niño Southern Oscillation. However, the role of remote forcing from Pacific through oceanic pathway over SWIO is not evident. The present study provides a comprehensive understanding of the interannual variability of SMOC and its linkage to sea level and OHC variability over SWIO during the last century.

1 Introduction
The ocean’s ability to store and transport heat makes it an important component of the climate system. Large scale surface winds in the Tropical Indian Ocean produce a meridional circulation which plays a crucial role in the heat and salt budget of the Indian Ocean (e.g., Schott et al. 2002; Horii et al. 2013). On an annual scale, the main forcing responsible for Indian Ocean meridional circulation is the southwest monsoon wind stress north of equator (dominated by westerly winds) and easterly winds south of the equator result, the southward Ekman transport in both sides of the equator (Schott et al. 2002). Southward transports connect the upwelling zones in the Northern Hemisphere (primarily off Somalia) and the subduction zone in the southeastern Indian Ocean, forming a cross-equatorial cell (CEC, Garternicht and Schott 1997; Lee and Marotzke 1997; Miyama et al. 2003). A part of the subsurface equatorward transported water from the subduction zone is upwelled at Seychelles thermocline ridge forming a shallow tropical cell (STC) in South Indian Ocean. The CEC and STC collectively form the shallow meridional overturning circulation (SMOC) of the Indian Ocean and are mostly confined to the upper 500 m (Miyama et al. 2003). Schoenefeldt and Schott (2006) reported that the mean southward transport across the equator by CEC is 6 Sv (1 Sv = 10^6 m^3 s^-1) and heat transport is ~ 0.24 PW (1 PW = 10^15 W). SMOC variability considerably influences the redistribution of ocean heat, salt by transporting water mass and its properties between tropics and subtropics (McPhaden and Zhang 2002, 2004; Zhang and McPhaden 2006).

Studies reported that the SMOC displays variability from seasonal to decadal time scales (Wang and McPhaden 2017; Lee 2004; Schoenefeldt and Schott 2006). A significant
interannual variability of both CEC and STC is also reported by several studies (e.g., Schott et al. 2004; Meng et al. 2020). Ruijin et al. (2005) reported that the interannual variability of the meridional heat transport across the equator and sea surface temperature (SST) in the north Indian Ocean are closely related. Horii et al. (2013) studied seasonal to interannual variability of meridional currents using acoustic Doppler current profilers (ADCPs) at the central equatorial Indian Ocean (at 0°, 90° E) for the period 2002–2009. A significant correlation (~0.6) was found between the observed meridional transport and the Niño 3.4 index during the peak phase of El Niño Southern Oscillation (ENSO). They also suggested that the net meridional volume and heat transports are found to be more than normal southward transport when El Niño conditions occurred in the tropical equatorial Pacific. Contrary to this, lesser than normal southward transport was observed during La Niña years. This suggests the importance of remote forcing in modulating the SMOC mainly on the interannual time scale.

A recent study by Meng et al. (2020) found that CEC and STC exhibited significant variability on interannual to decadal timescales during 1958–2017 using reanalysis data and CEC and STC were negatively correlated during the study period. Chirokova and Webster (2006) studied interannual variability of Indian Ocean heat transport and found that the majority of the variability was associated with Ekman transport with maximum seen between the latitude 10° S to 20° S. The subtropical Southern Indian Ocean (SIO) is experiencing variation in heat accumulation, which effect to regional sea level variability (Volkov et al., 2020). The variability of heat content and sea level in the SIO is strongly influenced by large-scale climatic forcing in the Indo-Pacific region (Meng et al. 2020; Zhuang et al. 2013; Feng et al. 2010). The remote effect on the SIO heat content is possible by oceanic pathway changes in the upper-ocean heat content in the western equatorial Pacific or/and local changes in wind forcing in the SIO atmospheric pathway (Volkov et al., 2020). Lee et al. (2015) concluded that the Indian Ocean has become increasingly important in modulating global climate variability. Above discussion warrants for a detailed study of SMOC variability and its impact on heat transport and associated ocean heat content variability of the SIO. Considering the spatio-temporal constraints in observational data a detailed understanding of the SMOC variability was not possible. Century long ocean reanalysis data provided unprecedented opportunity to study the variability of SMOC during the last century and its impact on SIO heat content, sea level and temperature variability. This study attempts to understand the interannual variability of SMOC during last century using reanalysis dataset. The study also examines the relative contribution of local wind forcing and remote forcing from the Pacific through Indonesian Throughflow (ITF) over Indian Ocean with the help of model experiments.

The linkage between the SMOC variability and SIO Heat Content and sea level is also explored. Section 2 discusses the details of datasets, model experiments, and methodology used in the study. The validation of meridional currents of reanalysis data with observations is provided in Section 3. Results related to SMOC variability is discussed in Section 4. Sections 5 and 6 provide detailed descriptions of the impact of heat transport variability associated with SMOC on heat content, thermocline depth and sea level and the causes of variability, respectively. The summary and conclusion of the study are discussed in Section 7.

2 Datasets used, experiment details, and methodology

2.1 Datasets used

Various observational and reanalysis datasets are used for the present study. Ocean Surface Current Analyses Real-time (OSCAR) upper ocean current based on satellite data for the period of 1993–2009 are used as observed currents for validating model simulated upper ocean currents (https://www.esr.org/research/oscar/data-access/). Sikaholli et al. (2013) reported that over the Tropical Indian Ocean OSCAR product is able to capture the variability of the well-known surface current systems reasonably well. OSCAR has provided unprecedented information about global upper ocean currents (upper 30 m averaged). In addition, the in situ measurements from ADCP mooring deployed by Japan Agency for Marine-Earth Science and Technology (JAMSTEC) at 90° E on the equator, which offers sub surface observations of monthly horizontal currents, are used for validation. The data is available between the depths of 40 and 340 m with 8 m vertical resolution for the period November 2000 to March 2009 (Masumoto et al. 2005). The dataset is available at https://www.pmel.noaa.gov/tao/drupal/disdel/.

The ocean reanalysis product, Simple Ocean Data Assimilation (SODA) version 2.2.4 (Carton and Giese 2008) is used in this study (http://apdrc.soest.hawaii.edu/datadoc/soda_2.2.4.php). It is an extended ocean reanalysis product using the Parallel Ocean Program (POP) ocean model and the National Oceanic and Atmospheric Administration (NOAA)/National Centers for Environmental Prediction Twentieth Century Reconstruction version 2 winds (Giese and Ray 2011). It provides an estimate of the ocean on a 0.5° × 0.5° grid with 40 vertical levels for the period of 1871–2010. A summary of recent improvements in ocean reanalysis, along with an evaluation of their uncertainties, is provided by Balmaseda et al. (2015). In addition, data from Ocean Reanalysis System version 4 (ORAS4), a reanalysis product of European Center for Medium range Weather Forecast (ECMWF) is also used (https://www.cen.
uni-hamburg.de/en/icdc/data/ocean/easy-init-ocean/ecmwf-ocean-reanalysis-system-4-oras4.html). It is forced by the ERA-Interim reanalysis fluxes, uses Nucleus for European Modelling of the Ocean (NEMO) model (Madec 2008), the horizontal resolution is 1° in the extra tropics and a meridional resolution of 0.3° at the equator. It has 42 vertical levels with 18 of them in the first 200 m and the first level is at 5 m. NEMOVAR assimilates temperature and salinity profiles, and along-track altimeter-derived sea-level anomalies. In addition to the above, observed SST and global mean sea-level variations are used to modify the heat and freshwater budget respectively. Compared to a control ocean model simulation, ORAS4 improves the fit to observations, the interannual variability and seasonal forecast skill (Bal-maseda et al., 2013). Recent study by Karmakar et al. (2018) and Motoki and McPhaden (2017) highlighted the credibility of Ocean Reanalysis products with respect to observations. The time period of SODA and ORAS4 overlaps over the last decades of the twentieth century.

Met Office Hadley Centre (EN4, Good et al. 2013) (http://www.metoffice.gov.uk/hadobs) ocean analysis and Ishii et al., (2003) (https://www.cen.uni-hamburg.de/en/icdc/data/ocean/ishii.html) historical ocean analysis, temperature, and salinity profile data are used to assess the upper ocean heat content variability. Delayed-time monthly mean sea level anomaly (SLA) maps are obtained from the Archiving, Validation, and Interpretation of Satellite Oceanographic Data (AVISO, Ducet et al. 2000) (ftp://ftp.aviso.altimetry.fr/global/delayed-time/grids/climatology/monthly_mean). They have a spatial resolution of (1/4° × 1/4°) and extend from 1993 to the present. This product is widely used to understand the regional as well as global sea level variability at various time scales (e.g., Unnikrishnan et al. 2015; Han et al. 2014). The tide gauge data from the Madagascar station NOSY-BE (13.4° S, 48.3° E) available for a shorter period (1958–1972) is also used (https://www.psmsl.org/data/). The 200 hPa horizontal winds and mean sea level pressure (MSLP) datasets from NOAA 20th Century version 2 (20CRv2) dataset are used. 20CR data contains objectively-analyzed 4-dimensional weather maps and their uncertainty from the late nineteenth to twenty-first century. The dataset is available at 2° × 2° resolution for the period spanning from 1871 to 2012. The Coordinated Ocean-ice Reference Experiments (CORE) framework defines protocols for performing global ocean–sea-ice coupled simulations forced with common atmospheric datasets, using the same bulk formulae. This dataset is just for the interannually varying forcing (IAF), as developed by Large and Yeager (2009) at National Center for Atmospheric Research (NCAR). The version 2 of the CORE-IAF (CIAF) is used in the present study (Griffies et al. 2011) (https://data1.gfdl.noaa.gov/nomads/forms/core/COREv2.html). It contains with 6 hourly shortwave and long wave radiation, 10 m surface wind fields, specific humidity, air temperature, monthly surface precipitation, and annual river runoff for period 1948–2009 (Large and Yeager 2009), which are used for model-based experiments.

### 2.2 Model and experiment details

The ocean general circulation model used in this study is Modular Ocean Model (MOM5), developed and supported by researchers at NOAA’s Geophysical Fluid Dynamics Laboratory (GFDL). It emerged from numerical ocean models developed in the 1960s–1980s by Kirk Bryan and Mike Cox at GFDL. The vertical mixing in the model is achieved through the K-profile parameterization (KPP) scheme (Large et al. 1994) using local and non-local mixing with Bryan-Lewis background diffusivity (Bryan and Lewis 1979). The model consists of a global grid with horizontal resolution 0.25° at the equator and increases to 8–11 km at higher latitudes. It consists of 50 vertical levels with vertical resolution of the upper 20 levels at 10 m resolution and gradually changes to a maximum thickness of ~370 m at 5000 m. The setup is also provided with a realistic topography of 0.5° resolution, which is derived from the 5-min global topography ETOPO5 (Earth Topography-5 min). More descriptive technical aspects of MOM are provided in Griffies (2012).

The global grid is initialized by Levitus et al. (1998) climatology of temperature and salinity profiles. The model is spun up for 50 years to attain a mean state using the climatological forcing (downwelling shortwave and longwave radiation, 10 m surface winds fields, specific humidity, air temperature, surface pressure, and surface precipitation) from NCAR climatology (Large and Yeager 2004). Following this, a control experiment (CTRL) is carried out using 6 hourly CIAF forcing fields from 1960 to 2009. Previous studies have assessed the contribution of local and remote forcing on the tropical SIO through oceanic pathways with the help of ocean model-based sensitivity experiments (Trenary and Han 2013; Ummenhofer et al. 2013; Mohapatra et al. 2020). This was achieved by restricting the interannual atmospheric forcing to the Indian Ocean basin, whereas climatological forcing was imposed elsewhere. In this study, sensitivity experiment is performed to investigate the contribution of the local wind forcing over the Indian Ocean to the SMOC variability. Here onwards, this experiment is referred to as IOSMOC. In IOSMOC, the CORE forcing fields are fixed to climatological mean, except the momentum fluxes over the Indian Ocean basin from 30° E–120° E, 30° N–35° S are allowed to evolve for the period 1960–2009. Hence, the solutions obtained from IOSMOC will exclude the possible variability impact of remote forcing from Pacific and Atlantic Oceans through ITF and Agulhas retroreflection, respectively.

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2.3 Methodology

To quantify the strength of SMOC, meridional overturning stream function \( \Psi (y, z, t) \) is estimated.

\[
\Psi(y, z, t) = \int_{x_e}^{x_w} \int_{z}^{z_e} v(x, y, z, t) \, dx \, dz
\]  

(1)

where \( v(x, y, z, t) \) is the meridional velocity which is a function of zonal, meridional, vertical coordinates, and time, \( x_e \) and \( x_w \) are the eastern and western boundaries (Kanzow et al., 2009). To examine the impact of SMOC variability on the temperature, meridional heat transport \( Q(y, t) \) is calculated from \( v \) and potential temperature (\( \theta \)) from surface to 500m integrated along the zonal section spanning the ocean basin.

\[
Q(y, t) = \rho C_p \int_{z}^{z_e} \int_{x_e}^{x_w} \theta \, v \, dx \, dz
\]  

(2)

where \( \rho \) is the density of ocean water and \( C_p \) is the specific heat capacity of ocean water at constant pressure (Volkov et al., 2010). Also, the upper ocean heat content from surface to depth is estimated as in Eq. (3),

\[
OHC(x, y, t) = \rho C_p \int_{z}^{0} \theta \, dz
\]  

(3)

The annual anomaly of meridional overturning stream function is computed by subtracting the long-term mean meridional overturning stream function. The linear trend is removed from annual anomaly of meridional overturning stream function by detrending the data. The meridional overturning stream function anomaly spanning 50° E to 110° E and 8.5° S to 15° S (hereafter SMOC region) is considered to represent SMOC variability (e.g., Pai et al. 2022). That between the latitudes 5° N to the equator (hereafter the CEC region) is considered to represent CEC variability. The difference between SMOC and CEC variability is considered as STC variability. The Southern Oscillation Index (SOI) is estimated as the difference of MSLP anomaly between Tahiti (149° W, 17.5° S) to Darwin (130° E, 12.4° S).

3 Assessment of reanalysis data of meridional currents

Figure 1a and b display scatter plot of upper 30 m averaged meridional current (m s\(^{-1}\)) from ORAS4 and SODA with respect to OSCAR over the SMOC region during 1993–2009. This analysis suggests that the meridional surface currents of both ORAS4 as well as SODA display high correlation (0.89) with OSCAR. The error in

Fig. 1 Scatter plot of upper 30 m averaged meridional current (m s\(^{-1}\)) from (a) ORAS4 and (b) SODA with respect to OSCAR over SMOC region (8.5° S–15° S, 50° E–110° E) during the period 1993–2009. (c) Standard deviation profile of meridional current (m s\(^{-1}\)) from ORAS4 and SODA and ADCP at the location 0°, 90° E for November 2000 to December 2008.
meridional currents with respect to OSCAR for ORAS4 and SODA is 0.011 and 0.019 m s\(^{-1}\), respectively. In addition to the surface current observation, the subsurface meridional currents obtained from ADCP are also considered for validation. Figure 1c shows the standard deviation of meridional currents from ORAS4, SODA, and ADCP at the location 0°, 90° E during the period November 2000 to December 2008. It is important to note that SODA and ORAS4 display a similar vertical structure of meridional current variability with depth relative to ADCP observations. The maximum deviation in meridional currents is confined between the depth of 60 m and 100 m, which is underestimated by both SODA and ORAS4. The maximum deviation for ORAS4 is \(\sim 0.07\) ms\(^{-1}\) and for SODA is \(\sim 0.075\) ms\(^{-1}\) at 80 m depth. Below 120 m, the deviation of meridional current reduced gradually, ORAS4 underestimated whereas SODA estimations are closer to the observed. Above analysis supports meridional currents in ORAS4 and SODA are consistent with satellite and in situ observations and captured the variability of meridional currents. SODA dataset is available for longer period (during the last century 1871–2010) than ORAS4, motivation to use SODA dataset in further analysis to understand the variability in SMOC.

4 Shallow meridional overturning circulation variability

4.1 Shallow meridional overturning circulation

Figure 2a displays latitudinal distribution of mean meridional transport (Sv) for upper 60 m from SODA. It shows strong southward transport confined between equator and 20° S and peak of southward transport (\(\sim 17\) Sv) is observed between 5° S and 10° S. The strength of southward transport gradually decreases south of 10° S and changes its sign near 30° S. Figure 2b shows the mean meridional overturning stream function and meridional and vertical currents manifest SMOC from SODA data. Highest magnitude of meridional overturning stream function (\(>15\) Sv) is observed between the depth 50 to 250 m centered over the latitude 8° S. South of 15° S the vertical velocity is downward, denoting the region of mass convergence. Figure 2c shows the standard deviation of meridional overturning stream function for upper 60 m, highest deviation (\(\sim 2.2\) Sv) is found at 10° S. The standard deviation of meridional overturning stream function with depth (Fig. 2d) shows higher magnitude (\(>2.5\) Sv) below 150 m within the latitude band 10° S to 20° S and 0 and 5° N. Based on above analysis study regions from SMOC (50° E to 110° E and 8° S to 15° S) and CEC (50° E to 100° E and 0 to 5° N) are identified (Fig. 2e).
The mean of meridional volume and heat transport in the SMOC region is $-13.8$ Sv and $-1.5$ PW, respectively, and corresponding standard deviation is $1.9$ Sv and $0.22$ PW, respectively. However, over the CEC region, long-term mean of meridional volume and heat transport is $-2$ Sv and $-0.25$ PW and corresponding standard deviation is $1.3$ Sv and $0.15$ PW. Hence mean meridional volume/heat transport in CEC is smaller than SMOC region but variability is of almost same magnitude.

4.2 Interannual variability in SMOC during last century

Figure 3 shows the detrended meridional overturning stream function anomaly over the SMOC region during the period 1871–2010 for upper 60 m (depth up to which annual mean meridional currents are southward) over SMOC, CEC, and STC regions. Note that the variability in STC is estimated as the difference in stream function anomaly over SMOC and CEC. Figure 3a shows the time series of meridional overturning stream function anomaly, whenever the years with negative anomaly lesser than one standard deviation are considered strong SMOC years and positive anomalies higher by one standard deviation are considered weak SMOC years, since meridional transport is southward. It is to be noted that the SMOC displays strong interannual variability after 1940s. Based on the above analysis during the study period, 15 strong and 12 weak events are identified (Table 1). Meridional stream function over the SMOC region and vertical velocity anomaly over the subduction zone displays significant positive correlation (0.56), indicating phase relation between them. The variability in STC is found to be in phase (correlation is 0.48) with SMOC variability and CEC is found to be out of phase (correlation is approx. $-0.5$), which is consistent with Meng et al. (2020), who reported using ORAS5 dataset during the period 1958–2016. The CEC (Fig. 3b) and STC (Fig. 3c) variability is also examined with vertical velocity anomaly

![Fig. 3](image)

Table 1  The strong and weak SMOC years identified based on the standard deviation of meridional overturning stream function over the SMOC region from SODA during the period 1871–2010

| Strong SMOC years | Weak SMOC years |
|-------------------|-----------------|
| 1871, 1880, 1881, 1882, 1883, 1884, 1885, 1887, 1888, 1937, 1964, 2005, 2006, 2008, 2009 | 1903, 1912, 1913, 1914, 1923, 1941, 1943, 1949, 1950, 1959, 1962, 1991 |
over Somali-Oman coast and (Fig. 3b; 43° E–48° E, 2° N–10° N) Seychelles Thermocline Ridge (Fig. 3c; 50° E–65° E, 3° S–12° S) region. Vertical velocity anomaly over the Somali-Oman coast and Seychelles Thermocline Ridge displays negative correlation with the meridional stream function over the CEC and STC, respectively.

In order to study the spatial structure of SMOC during strong and weak SMOC years composite analysis is carried out. Figure 4a and b show the depth-latitude plot of meridional overturning stream function anomaly and meridional and vertical currents anomaly for strong and weak years composite respectively. Figure 4c indicates the difference between stream function, meridional and vertical currents for strong composites to weak composite years. During the strong SMOC years (Fig. 4a), anomalous southward transport is reported in the upper ocean over 0° to 20° S. The stronger transport of about \(-2.4\) Sv is confined between the latitude band 2° S to 17° S below 50 m, where standard deviation is maximum (Fig. 2b). For the weak years (Fig. 4b), the transport is anomalously northward with higher magnitude confined between 2° S and 18° S. Vertical velocity over the subduction region during strong and weak SMOC years shows anomalous subduction and upwelling, respectively. The difference from strong composite to that of weak suggests that the maximum changes occur between the latitudes 5° S and 15° S, with peak near 10° S. Also, large variation in vertical velocity is observed between 10° S and 20° S. Figure 4d and e shows spatial distribution of the vertical velocity anomaly composite for strong and weak SMOC years, respectively. Negative and positive anomaly of the vertical velocity manifest anomalous subduction and upwelling, respectively. The anomalous upwelling/subduction is observed dominating over the region south of 10° S. Strong SMOC years (Fig. 4d) are associated with anomalous subduction whereas weak SMOC years (Fig. 4e), indicating anomalous upwelling south of 10° S. The difference in the vertical velocity composite for strong and weak year (Fig. 4f) suggests that large variability occurs between the latitudes 10° S and 20° S over South West Indian Ocean (SWIO).

![Fig. 4 Depth-latitude section for meridional overturning stream function anomaly (shaded, Sv) and anomaly of meridional and vertical currents (ms\(^{-1}\), vectors) for (a) strong and (b) weak SMOC years and (c) their difference. Please note that the vertical velocity is multiplied by a factor of 10\(^{3}\). Anomalous vertical velocity (ms\(^{-1}\)) at 75 m during (d) strong and (e) weak SMOC years and their difference (f). Springer]
5 Heat transport variability associated with SMOC

Figure 5a and b shows the composite of meridional heat transport anomaly for strong and weak SMOC years. During strong SMOC years meridional heat transport anomaly is southward, denoting excess transport of heat to the south of the equator (Fig. 5a). The maximum transport is seen between the latitude 2° S and 17° S below 50 m with a magnitude of about –0.25 PW. During weak SMOC years (Fig. 5b), structure of heat transport is opposite (northward) to that of strong SMOC years. Figure 5c and d shows composite of vertical profile of temperature anomaly over SWIO for strong and weak SMOC years from SODA and EN4 analysis during the period 1900–2010. Temperature anomaly profile associated with strong SMOC years display negative anomaly at upper 250 m (Fig. 5c), with maximum value of −0.7 °C (−0.35 °C) around the depth of 50 m in SODA (EN4). For the weak years, the maximum positive anomaly of ~0.4 °C (~0.3 °C) is found at around the 50 m (100 m) in SODA (EN4) (Fig. 5d). These analysis reveals that the strong SMOC years caused cooling and weak SMOC years produced warming in upper 200 m over the SWIO, which is also supported by the EN4 analysis data. Figure 5e and f show the corresponding changes in the vertical profile of density, during the strong SMOC years increase in the upper ocean density and during the weak SMOC years reduction in the density in the upper ocean is found. This variation in the density is consistent with the upper ocean heat changes; thus, circulation not only modifies the heat distribution but also the vertical stability of the upper ocean, strong SMOC enhances the stability of the upper ocean and weak SMOC suppresses the upper ocean stability in SWIO.

6 SMOC variability and their association with south west Indian Ocean thermal structure

Figure 6 shows the composite of 200 m Ocean Heat Content Anomaly (OHCA200) during strong and weak SMOC years from SODA (Fig. 6a, b) during the period 1871–2010. To examine the consistency in the results obtained, the composites of OHCA200 during strong and weak years from two ocean analysis datasets, EN4 (Fig. 6c, d) and Ishii (Fig. 6e, f) are estimated during the period 1959–2010 and 1945–2010, respectively. It also shows correlation and regression analysis between OHCA200 and SMOC variability during respective periods. OHCA200 during strong SMOC years (Fig. 6a) displays negative anomalies over the SWIO, off Somali coast, whereas positive anomalies in south of 20° S, south eastern Indian Ocean, and strong positive anomaly in Bay of Bengal (BoB), which is other way in the EN4 and Ishii analysis (Fig. 6c and e). Weak SMOC years composite shows positive anomalies in SWIO and off Somali coast while rest of the region displayed negative OHCA200 (Fig. 6b). It is important to note that relative magnitude of OHCA200 are lesser in Ishii than SODA and EN4 (Fig. 6d and f). The contour in the Fig. 6a, c, and e represents the correlation between OHCA200 and SMOC variability index during the respective periods. The dot denotes the correlation above 90% confidence level. In addition, inter-correlation for
OHCA200 variability among data product SODA, EN4, and Ishii for south-west Indian Ocean is found greater than 0.7. This analysis reveals that the SMOC variability influences the SWIO heat content, supported by the EN4 and Ishii data and displayed significant positive correlation with 90% confidence level in all the three datasets; however, OHCA200 signal for other regions failed to have consensus with all the three data products.

Figure 7a shows the time series of meridional overturning stream function anomaly and OHCA200 for the SWIO. The correlation between them for the study period is 0.32, which supports in phase variation. Figure 7b shows the time series of upper ocean current divergence and thermocline depth anomaly, and Fig. 7c shows time series of upper ocean current divergence and OHCA200 for the SWIO; correlation between them is negative. This indicates that variation in thermocline depth and OHCA200 are out of phase with the divergence of the upper ocean circulation. Figure 7d shows the evolution of OHCA200 with the SLA over the SWIO. Analysis reveals that OHCA200 and SLA displayed coherent variability in the SWIO with correlation 0.83 for SODA. The tide gauge data for the shorter period
(1958–1972) from the Madagascar station NOSY-BE (13.4° S, 48.3° E) also displayed a coherent sea level variation and OHCA200 with 0.72 correlation coefficient supporting the results obtained from SODA. In addition, correlation analysis for sea level data during the recent period from satellite with the OHCA200 for SWIO also confirmed in phase relation with correlation coefficient 0.6. Above analysis confirms that during the weak SMOC years, heat transport gets converged in the SWIO, which leads deepening of thermocline and increase of OHCA200 and sea level rise and vice versa during the strong SMOC years.

7 Mechanism responsible for interannual variability of SMOC

Figure 8 shows the time series of upper 60 m meridional heat transport (MHT) anomaly and zonal wind stress anomaly over the SMOC region (Fig. 8a), time series of SOI and zonal wind stress anomaly over the SMOC region (Fig. 8b), and time series of MHT and SOI (Fig. 8c) during study period (1871–2010). Time series of zonal wind stress anomaly and MHT show coherent variation between them with correlation coefficient 0.82. This suggests that during the study period, stronger SMOC are associated with the anomalous easterlies and weaker SMOC are associated with anomalous westerlies over the SMOC region. However, MHT and zonal wind stress displayed negative correlation coefficient (−0.33 and −0.31) with the SOI (Fig. 8b and c), indicating that the negative SOI (i.e., El Niño condition) favoring below normal easterly wind stress in the SIO and corresponding southward heat transport is less than its normal and vice versa when SOI is positive. This analysis manifests that the MHT variability is driven by the zonal wind anomaly which is to some extent forced by the ENSO variability. Hence, the strong years are associated with La Niña and weak SMOC years are associated with El Niño. Hence, the heat transport and OHCA200 in the SWIO is driven by atmospheric pathway connected with the eastern Pacific temperature anomaly. Figure 9a and b shows the composite of zonal wind stress variability during strong and weak SMOC years; it further confirms that strong SMOC years are associated with stronger
easterly wind anomaly with magnitude of 1 to 1.5 m/s over the SIO (5° S to 25° S) and weak SMOC years are associated with westerly wind anomaly with same magnitude. It is clear from the Fig. 8c that the changes in local surface wind circulation driving the variability in MHT (Fig. 9a and b) have association with ENSO. It would be also important to explore how ENSO conditions over central and eastern equatorial Pacific alter the local surface wind circulation. Figure 10a and b indicate the composite of velocity potential (shaded, 10^6 m^2 s^{-1}) and divergent wind anomalies (vector, m s^{-1}) at 200 hPa during the strong and weak SMOC years. During strong SMOC years, strong anomalous upper level convergence over central equatorial Pacific and divergence over central Indian Ocean is observed. The anomalous velocity potential indicates that the center of maximum divergence is situated at central Indian Ocean. Also, the center of maximum convergent component is extended from central to eastern equatorial Pacific denoting La Niña-type conditions. Similar pattern in upper level divergence and velocity potential has been reported in previous studies during La Niña (e.g., Raj Deepak et al. 2019). It is noted that the pattern of velocity potential and upper level wind divergence is in opposite phase during weak SMOC years with respect to strong years (Fig. 10b), indicating El Niño type conditions in eastern Pacific. During the weak SMOC years, the center of anomalous convergence is situated at eastern equatorial Indian Ocean. Hence, the analysis suggests that the La Niña-type conditions persists over the equatorial Pacific enhances
the upper level wind divergence over the Indian Ocean. Similarly, the El Niño conditions over equatorial Pacific weakens the upper level wind divergence over the Indian Ocean. This drives the variation in surface winds as observed in Fig. 9.

In order to confirm the role of wind variability to the SWIO heat content, sea level, and thermocline variability, ocean model based experiments are carried out for the period 1962–2009. In the CTRL experiment, ocean model is forced by interannually varying forcing over the global ocean. Whereas in IOSMOC experiments only interannually wind forcing allowed over Indian Ocean and rest of the forcing fields are long term mean over the global ocean. It is important to note that the strong and weak years for the model study period are identified based on standard deviation of annual mean meridional overturning stream function in the CTRL (Table 2). The composite of meridional overturning stream function anomaly and anomalous SMOC for strong and weak years from CTRL is shown in Fig. 11a, b.

Table 2  Strong and weak SMOC years identified based on standard deviation (0.87 Sv) stream function over SMOC region from CTRL run during the period 1960–2009

| Strong years | 1969, 1972, 1975, 1976, 1982, 1984, 1988, 1999, 2000 |
| Weak years  | 1963, 1968, 1973, 1987, 2003, 2007  |

Negative and positive anomalies of transport, with magnitude more than 2 Sv below 150 m depth, is reproduced by the model during strong as well as weak years, respectively in CTRL. In comparison with the spatial pattern of anomalous SMOC obtained from SODA (Fig. 4a and b), CTRL simulation underestimates meridional transport anomalies; however, it captured pattern of transport anomalies corresponding to strong and weak SMOC year composite. It is also important to note that CTRL could simulate anomalous downwelling during strong and upwelling during weak SMOC years, around 10° S. Above analysis supports that though CTRL underestimates the magnitude of the meridional anomaly strength but reproduces a pattern of meridional overturning stream function anomaly consistent with SODA. Figure 11c and d show composite of meridional overturning stream function anomaly and anomalous SMOC for strong and weak years from IOSMOC. The strong and weak SMOC pattern and vertical motions are well captured, though magnitudes are underestimated. This analysis reveals that the change in SMOC largely depends on the interannual variation of the local wind over SIO. Figure 12 shows the composite of OHCA200 and SLA for strong (Fig. 12a, c) and weak (Fig. 12b, d) years from CTRL and IOSMOC experiments, respectively. CTRL displays negative anomaly of OHCA200 in the SWIO for strong year composite
Fig. 11 Composite of meridional overturning stream function anomaly (Sv, shaded) and SMOC anomaly (m s⁻¹, vectors) during strong (a, c) and weak years (b, d) from CTRL and IOSMOC experiments during the period 1960–2009. It is important to note that the vertical current is multiplied by a factor of $10^4$.

Fig. 12 Composite of upper 200 m ocean heat content anomaly (shaded, $10^9$ J m⁻²) and sea level anomaly (contour, cm) during strong (a, c) and weak (b, d) years from CTRL and IOSMOC experiments, respectively.
and positive anomaly of OHCA200 for weak SMOC years (Fig. 12a, b). North BoB and south east Indian Ocean show weak OHCA200 and opposite to SWIO, however Arabian Sea does not show any change during these years. Corresponding changes in the SLA are also reported in the SWIO, for negative OHCA200, SLA of the order of ~3 cm and for positive OHCA200, SLA of the order of 4 cm is found. Similar analysis is carried for IOSMOC, which reproduced the OHCA200 and SLA spatial pattern like in CTRL for the strong and weak SMOC years composites. Analysis supports that the OHCA200 and SLA reported for the strong and weak SMOC years are driven by the wind forcing and role of Pacific variability through oceanic pathway is negligible.

8 Summary and conclusion

The variability of Indian Ocean SMOC during the last century (1871–2010) is studied using SODA reanalysis data. The validation of upper ocean meridional currents from SODA with respect to that of OSCAR as well as ORAS4 confirmed that SODA data is consistent with observation and captures the observed variability over the study region. The magnitude of the annual mean meridional overturning stream function over the study region (8.5° S–15° S, 50° E–110° E) is considered as SMOC strength. Strong SMOC years are identified based on the meridional overturning stream function positive anomaly estimated over SMOC region greater than its standard deviation. Similarly, a weak SMOC year is considered based on the stream function negative anomaly less than its standard deviation. The composite analysis of stream function anomaly for strong years reveals a maximum southward transport (~2.5 Sv) between the latitude band 5° S and 15° S within the first 500 m and minimum transport during weak SMOC years. Also, for strong and weak SMOC years, the heat transport (~0.25 PW) associated with SMOC is also displaying the peak between the same latitude. The impact of meridional heat transport variability associated with SMOC to temperature, upper ocean stability, upper 200 m ocean heat content, thermocline depth and sea level is also examined. This analysis reveals that strong SMOC leads to negative upper ocean temperature, heat content, sea level and thermocline depth anomaly whereas weak SMOC leads to opposite anomaly in the SWIO. Correlation analysis of meridional overturning stream function anomaly with the oceanic heat content anomaly during the study confirms negative correlation over the SWIO with the confidence level of 90%. This pattern of correlation and heat content anomaly for the SWIO is also supported by the EN4 and Ishii independent ocean analysis data. In addition, analysis with the tide gauge sea level data from Madagascar station NOSY-BE (13.4° S, 48.3° E) with OHCA200 as well as SLA data from satellite observation shows significant correlation, which confirms that SMOC variability modulates SWIO upper ocean heat content and sea level. SMOC, zonal wind south of equator in Indian Ocean, and SOI in Pacific show coherent evolution, indicating the influence of eastern Pacific temperature (ENSO) variability on SMOC variability. The upper level divergence and velocity potential over Indian Ocean are consistent with the surface circulation, indicating Pacific variability influence through atmospheric bridge on SMOC variability. To confirm the role of atmospheric pathway contributing to the SMOC variability, ocean model-based CTRL and sensitivity experiment (IOSMOC) is carried out, in which only Indian Ocean is forced with interannually varying wind fields and the climatological winds are retained over rest of the domain for forcing. The results from the IOSMOC experiment reveals that the strong and weak events identified in SMOC are not associated with remote forcing from Pacific through oceanic pathways, but are mainly due to local wind response to ENSO. This suggests that the atmospheric teleconnection associated with ENSO, leads to SMOC interannual variability resulted south west Indian Ocean heat content, sea level and thermocline depth interannual modulation.

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Author contribution AP and RUP designed and conceptualized the study. The generation of plots and code development is done by RUP. Model experiments and analysis are carried out by RUP under supervision of AP. RUP, AP, JSC, and CG have contributed to the discussions as well as in manuscript writing.

Data availability The details of publicly available datasets are mentioned in Sect. 2. The model outputs used in this study are not publicly available and can be accessed from the corresponding author upon reasonable request.

Code availability All of the figures in the study are prepared using free visualization tool PyFerret.

Declarations

Ethics approval The manuscript has not been submitted/published elsewhere previously.

Consent to participate Not applicable.

Consent for publication Not applicable.

Conflict of interest The authors declare no competing interests.
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