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Investigation of Deep-Sea Zonal Currents in the Equatorial Indian Ocean Using Hybrid Coordinate Ocean (HYCOM, USA) Model Simulations

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Abstract

This study examines the variability and dominant oscillatory characteristics of deep zonal currents in the equatorial Indian Ocean using HYCOM model simulations during 2000–2007. The analysis focuses on the Western Equatorial Indian Ocean (WEIO), Central Equatorial Indian Ocean (CEIO), and Eastern Equatorial Indian Ocean (EEIO) at depths ranging from 500 m to 4000 m. Wavelet power spectrum analysis was applied to identify significant oscillation modes and temporal variability in zonal currents. The results indicate that intra-seasonal oscillations (ISOs) are the dominant and most persistent mode of variability in deep zonal currents across all regions and depths. Strong ISO signals were observed at 2000 m and 4000 m depths, particularly in the EEIO and CEIO during 2000–2007. Seasonal oscillations (SOs), semi-annual oscillations (SAOs), and bi-weekly variability were also significant, although their magnitudes were generally lower than ISOs. Seasonal oscillations dominated at WEIO during October 2003–October 2004, while SAOs were prominent during January–July 2004. Significant bi-weekly oscillations were identified at 4000 m depth during February–June 2004, indicating the influence of mesoscale and topographic processes. The study further demonstrates that large-scale climate phenomena such as El Niño, El Niño Modoki, Indian Ocean Basin Mode (IOBM), and Indian Ocean Dipole (IOD) strongly influenced zonal current variability. Combined El Niño, Modoki, and IOBM conditions enhanced ISOs during 2004, whereas weak El Niño and positive IOD conditions favoured SAOs during 2006. HYCOM simulations reproduced the observed zonal current variability effectively, showing persistent ISOs and seasonal reversals in flow direction. Positive variance and covariance between observations and model outputs confirmed strong agreement between modelled and observed zonal currents. Overall, the study highlights the significant role of intra-seasonal atmospheric forcing, climate variability, and eddy activity in controlling deep zonal current dynamics in the equatorial Indian Ocean.

Key words: Current meters, HYCOM Model, MJO, Deep-Sea currents, IS Oscillations.

1. Introduction

The Equatorial Indian Ocean (EIO) plays a fundamental role in maintaining the global energy balance by acting as a key region for strong ocean–atmosphere interactions. It serves as a host to several coupled climate phenomena, including the Indian Ocean Dipole (IOD), Madden–Julian Oscillation (MJO), Indian Ocean warm pool, Quasi-Biennial Oscillations (QBOs), and biweekly oscillations (BIOs). In addition, the EIO is dynamically linked with the atmospheric general circulation through the seasonal north–south migration of the Intertropical Convergence Zone (ITCZ). The wind system over the EIO exhibits unique seasonal characteristics that distinguish it from the Equatorial Atlantic and Pacific Oceans. While the annual mean winds are relatively weak during the monsoon seasons, strong westerly wind bursts occur during the transition periods of boreal spring (April–May) and autumn (October–November) (Schott and McCreary, 2001). Based on bathymetry and vertical structure, ocean currents are generally classified into surface, subsurface, and deep-sea currents. Each category plays a distinct role in the redistribution of momentum, heat, salt, and other oceanic properties.

One of the most prominent surface circulation features of the EIO is the occurrence of strong equatorial surface jets during the monsoon transition periods, known as Wyrtki Jets (Wyrtki, 1973). These jets appear twice a year—during spring and autumn—and are typically confined to the upper 100 m of the water column (Han et al., 1999; Iskander et al., 2011). The westerly wind bursts force strong eastward surface currents along the equator, leading to a deepening of the thermocline and a rise in sea level in the eastern basin, while the opposite conditions prevail in the west (Rao et al., 1989; Schott and McCreary, 2001; Nagura and McPhaden, 2010a). Wyrtki Jets play a crucial role in the zonal redistribution of mass, heat, salinity, and chemical and biological tracers within the equatorial and off-equatorial Indian Ocean (Reppin et al., 1999; Murtugudde and Busalacchi, 1999; McPhaden et al., 2015; Chatterjee et al., 2017). Observations from the long-term RAMA equatorial mooring array indicate that the spring jet transport in the central equatorial Indian Ocean reaches approximately 19.7 Sv, while the autumn jet transport is relatively weaker at about 14.9 Sv (McPhaden et al., 2015). Seasonal reversals in zonal current direction are also evident, with westward flow during spring and eastward flow during autumn (Nagura and McPhaden, 2016). The westward propagation during spring is associated with westward-moving surface winds linked to deep atmospheric convection migrating from the Maritime Continent toward the northern Bay of Bengal (Nagura and McPhaden, 2010b, 2016).

Below the surface layer, the Equatorial Undercurrent (EUC) develops in the EIO due to basin-wide pressure gradient forces. Unlike the Pacific EUC, the Indian Ocean EUC is comparatively weaker and exhibits strong seasonal variability, primarily driven by reversing monsoon winds (Reppin et al., 1999; Schott and McCreary, 2001). The EUC is typically observed during boreal winter and spring, aligned with the thermocline core (Chen et al., 2015, 2019), although it occasionally appears during summer and autumn at depths between 90 and 170 m, as recorded by RAMA moorings (Iskandar and McPhaden, 2011). The forcing mechanisms of the EUC vary seasonally. During summer, eastward pressure gradients generated by downwelling Rossby waves reflected from the eastern boundary dominate, whereas in winter, the EUC is influenced by upwelling Kelvin and Rossby waves in combination with seasonal easterly winds. On intraseasonal timescales of 30–70 days, EUC variability is largely controlled by lower-mode baroclinic Kelvin and Rossby waves (Iskandar and McPhaden, 2011). Interannual variations in the undercurrents are also closely linked to the IOD, affecting heat and mass redistribution and contributing to sea surface temperature variability (Zhang et al., 2014; Nyadjro and McPhaden, 2014).The semi-annual cycle of zonal winds over the equator arises mainly from the meridional advection of easterly momentum by cross-equatorial monsoon winds (Ogata and Xie, 2011). Intra-seasonal variability of Wyrtki Jets is influenced by internal instabilities as well as local wind forcing (Sengupta et al., 2001, 2007; Masumoto et al., 2005). On interannual timescales, equatorial current variability is associated with large-scale climate models such as ENSO and the IOD, with the positive phase of the IOD weakening zonal winds and the negative phase strengthening them (Gnanaseelan et al., 2012). Biweekly oscillations with periods ranging from 10 to 30 days have been widely observed in meridional velocities and are attributed to mixed Rossby–gravity (Yanai) waves (Yanai and Maruyama, 1966; Smyth et al., 2015). These waves play a critical role in meridional heat transport and energy redistribution within the equatorial region.

While surface and subsurface currents are primarily wind-driven, deep-sea currents are governed by thermohaline processes arising from temperature and salinity gradients, basin-scale density variations, bottom friction, and turbulence. Despite their importance in heat and carbon sequestration, deep-sea currents in the EIO remain poorly studied due to observational limitations. Most existing studies focus on surface and subsurface layers, leaving a significant knowledge gap in understanding deep-ocean circulation. Recognizing this gap, the present study aims to investigate the characteristics and dominant oscillations of equatorial deep-sea currents in the EIO using both observations and HYCOM model simulations. Wavelet analysis is employed to identify significant variability at depths ranging from 2000 to 4000 m. This work represents one of the few attempts to comprehensively describe equatorial deep-sea current behaviour in the Indian Ocean using combined observational and modelling approaches

2.Data and Methodology

2.1. Wave Let Analysis:

Wavelet analysis mathematical representation: Wave let analysis become a common tool for analysing localized variations of power with time series. By decomposing time series in to frequency space are is able to determine both dominant modes of variability and how these modes vary with time. The wave let analysis transform has been used to for numerical studies in geophysics including tropical convection (Wang and Han 1994), El Nino southern oscillations (ENSO; Gu and Philander 1995), (wang and wang 1996), and Dispersion Oceanic waves (Meyers et al.1993), wave growth and breaking (Lia 1994), coherent structure of turbulent flow (Farge 1992). Fourier transformation gives limited amount of information on characteristics of time varying signal. A FT reveals frequencies present in the whole time series information about an individual event would be lost (Kantha

&Clayson, 2000). Wave let transform expands time series in to frequency –space in to time-frequency space and can find localized intermittent periodicities.
(Grims et al..2004).
https://paos.colorado.edu/research/wavelets/
The total energy conserved in wavelet transform (Parseval's theorem) , Wavelet analysis is

$$\sigma^2 = \frac{\delta j \delta t}{c\delta . N} \sum_{N=0}^{N-1} \sum_{j=0}^{j} \left| w_n s_j \right|^2 / s_j$$

σ^2 is variance, σ summed of reconstructions, the distribution for Fourier spectrum is

$$\frac{N\left|\widehat{X_K}\right|^2}{2\sigma^2} \rightarrow \frac{1}{2} p_x x_2^2$$

k-each frequency Index, $\rightarrow distributed\ as$, the corresponding distribution for local wavelet power spectrum is

$$\frac{\left|w_{n(s)}\right|^2}{\sigma^2} \rightarrow \frac{1}{2} p_x x_2^2$$

At each time new scale $|\widehat{x_k}|^2$ is Chi-Square distributed with two DF's denoted by x_2^2 , p_k mean spectrum at Fourier frequency k that to be corresponding scale s.

Th etime averaged wavelet spectrum (Global wavelet spectrum) over a certain period

$$\overline{w}_n^2\,(s) = \frac{1}{n_a} \sum_{n=n_1}^{n_2} |w_n\,(s)|^2$$

N is index arbitrary assigned to mid-points n_1 and n2 ; n_a= n_1-n_1 no.of points averaged over .

Global wavelet spectrum

$$\overline{w}^2(s) = \frac{1}{n} \sum_{N=0}^{N-1} |w_n\ s|^2$$

2.2. The Hybrid Coordinate Ocean Model (HYCOM):

HYCOM is a council of a multi-institutional effort supported by the National Ocean Partnership Program (NOPP) in part of the Global Ocean Data Assimilation Experiment (GODAE). The HYCOM model is the data-assimilative hybrid isopycnal-sigma-pressure (generalized) coordinate ocean model. The HYCOM model provides real time three-dimensional Ocean state. The HYCOM model considered boundary conditions of coastal and regional models and boundary conditions for the atmospheric coupled prediction models. In the Hybrid model, the coordinates are isopycnic in the open and stratified ocean and terrain following coordinates in the shallowcoastal region. The z-level coordinates to study the mixed layer and unstratified ocean. The HYCOM will provide the fixed depth intervals near shore data. For handling the heating and cooling cycle in both deep and shallow regions, the above said coordinates were chosen with the collaboration of the University of Miyami Modeling group and the Naval Research Laboratory.In order to provide the physical processes in the mixed layer and its non-local effect, slab-typeKraus-Turner mixed layer such as K-profile parameterization (KPP) (Large et al., 1994) schemewas used for the model mixed layer study. To study the deep-sea currents validation with deepsea currents of RCM with the HYCOM Model, the wavelet and filtered band-pass analysis wereperformed for zonal and meridional currents. The contribution of background internal wavebreaking, shear instability wave mixing, and double diffusion in the Ocean interior isparameterized. In the surface boundary Layer, the influence of wind-driven mixing, surface buoyancy fluxes, and convective instability is parameterized. The KPP algorithm alsoparametrizes the influence of non-local mixing of T and S, which permits the development ofcounter gradient fluxes. The required zonal and meridional currents daily data at 77^0E, 83^0E, and 93^0E along the Equator during 2002 was downloaded from the website. http://tds.hycom.org/thredds/catalogs/GOMl0.04/GOMl0.04_022_agg.html Hybrid coordinate Ocean Model (HYCOM) is a primitive–equation model which is containing 5 prognostic governing equations. Two equations meant for horizontal velocity components, amass continuity of layer thickness tendency equation, and two conservation equations for pair offthermodynamics variables, such as salt and temperature or salt density.

The model equations written in (x, y,z) coordinates, where s is an unspecified vertical coordinate are

$$\frac{\partial v}{\partial t_s} + \nabla_s \frac{v^2}{2} + (\zeta + f)k \times v + \left(s\frac{\partial p}{\partial s}\right)\frac{\partial v}{\partial s} + \nabla_s.\mathrm{M}\text{-}\mathrm{P}\nabla_S\, \alpha = -g\,\frac{\partial \tau}{\partial p} + \left(\frac{\partial p}{\partial s}\right)^{-1}\nabla_s \left(v\frac{\partial p}{\partial s}\, \nabla_s \left(v\frac{\partial p}{\partial s}\, \nabla_s\, v\right)\right.$$

$$\frac{\partial}{\partial t_s}\left(\frac{\partial p}{\partial s}\right) + \nabla_s\left(v\,\frac{\partial p}{\partial s}\right) + \frac{\partial}{\partial}\left(s\frac{\partial p}{\partial s}\right) = 0$$

$$\frac{\partial}{\partial t_s}\left(\frac{\partial p}{\partial s}\theta\right) + \nabla_s.\left(v\,\frac{\partial p}{\partial s}\theta\right) + \frac{\partial}{\partial s}\left(s\frac{\partial p}{\partial s}\theta\right) = \nabla_s\left(v\,\frac{\partial p}{\partial s}\, \nabla_s\, \theta\right) + \chi_\theta$$

$$\text{Where } \zeta = \frac{\partial v}{\partial x} - \frac{\partial u}{\partial y} \text{ relative vorticity}$$

3. Results and discussions

3.1. Study of Deep-Sea Zonal Currents from HYCOM Model Currents

To investigate the variability and validate the deep-sea zonal currents observed by Recording Current Meters (RCM), HYCOM model zonal current data were analysed using wavelet and band-pass filtered techniques. Daily zonal current data along the equator at 77°E, 83°E, and 93°E during 2002 were extracted from the HYCOM model. The analysis focused on identifying dominant oscillation modes such as intra-seasonal oscillations (ISOs), seasonal oscillations (SOs), semi-annual oscillations (SAOs), and bi-weekly variability at different depths ranging from 500 m to 4000 m.

At the Western Equatorial Indian Ocean (WEIO, 77°E), the wavelet power spectra at 500 m depth revealed strong and persistent intra-seasonal oscillations with high spectral power from May to December 2002, accompanied by bi-weekly oscillations from August to October (Figure-3.14a). The dominance of ISOs at this depth indicates strong short-term atmospheric and oceanic forcing affecting upper intermediate zonal currents. Bi-weekly oscillations suggest the influence of mesoscale variability and transient atmospheric disturbances. At 1000 m depth, ISOs remained highly significant from May to October 2002 with enhanced spectral power (Figure-3.14b), indicating the downward propagation of intra-seasonal variability into deeper ocean layers.

At 2000 m depth, ISOs were observed from April to July 2002, while seasonal oscillations also appeared in the power spectra (Figure-1 c). The coexistence of seasonal and intra-seasonal oscillations demonstrates the combined influence of large-scale seasonal forcing and shorter-period atmospheric variability on deep zonal currents. At 4000 m depth, seasonal oscillations became the dominant mode from July to December 2002, while ISOs were observed during March to June and August to September 2002 (Figure-1d). This indicates that seasonal forcing exerts a stronger influence in abyssal waters, whereas ISOs remain as secondary but persistent oscillatory signals. Overall, the study at 77°E showed that ISOs were the most prominent oscillations at 500 m, 1000 m, and 2000 m depths, while seasonal oscillations dominated at 4000 m depth.

In the Central Equatorial Indian Ocean (CEIO, 83°E), the HYCOM zonal current analysis also revealed significant intra-seasonal variability. At 500 m depth, ISOs were dominant from June to August 2002 (Figure-2 a), indicating enhanced short-period variability during the summer season. At 1000 m depth, seasonal oscillations were significant throughout the entire year 2002, while ISOs appeared from March to May 2002 (Figure-2 b). The persistence of seasonal oscillations suggests the strong impact of monsoonal forcing and equatorial circulation variability on zonal currents at intermediate depths.

At 2000 m depth, intra-seasonal oscillations with periods ranging from 64 to 90 days were observed from March to September 2002, while seasonal oscillations were significant during June and July 2002 (Figure-2 c). These long-period ISOs indicate the influence of large-scale atmospheric oscillations such as the Madden–Julian Oscillation (MJO) and equatorial wave dynamics. At 4000 m depth, ISOs became the foremost oscillatory mode from May to September 2002, whereas seasonal oscillations persisted throughout the year (Figure-2 d). The presence of strong ISOs even at abyssal depths demonstrates the ability of atmospheric and oceanic variability to penetrate into the deep ocean through vertical energy propagation and large-scale circulation adjustments.

At the Eastern Equatorial Indian Ocean (EEIO, 93°E), the variability of zonal currents exhibited highly persistent and energetic intra-seasonal oscillations across all depths. At 500 m depth, two distinct ISO modes were identified. The first mode occurred at periods of 16–32 days from February to June 2002, while the second mode appeared at 64–90 days from May to October 2002 (Figure-3 a). The shorter-period oscillations were categorized as sub intra-seasonal oscillations, indicating enhanced high-frequency variability in the eastern basin. The persistence of these oscillations suggests strong ocean-atmosphere coupling and active equatorial wave processes.

This oscillatory trend continued up to 1000 m depth, indicating vertical coherence in zonal current variability. At 2000 m depth, 30–60-day oscillations were observed during May–July and September–December 2002 (Figure-3 b). Seasonal oscillations were present from June to October 2002, while intra-seasonal oscillations occurred from March to November at periods of 32–64 days. The persistence of ISOs across all depths at 93°E demonstrates that the eastern equatorial Indian Ocean is strongly influenced by intra-seasonal atmospheric forcing and equatorial dynamical processes. The study concluded that ISOs were the most prominent and persistent oscillations at 93°E throughout the water column.

To understand the direction and variability of zonal flows associated with ISO and SO variability, a 20–90-day band-pass filtered analysis was performed on HYCOM zonal currents at 500 m depth during 2002 (Figure-4 a). The analysis revealed two dominant seasonal flow regimes (Figure-3.20a). Eastward zonal currents were observed at 77°E and 83°E from March to July, while westward flow dominated at 77°E, 83°E, and 93°E from July to November. Transitional periods between these seasonal regimes showed eastward flow at 77°E and westward flow at 83°E and 93°E, indicating strong spatial variability in zonal circulation along the equator.

At 1000 m depth, eastward flow was observed from February to June at 77°E, while westward flow prevailed at 83°E and 93°E (Figure-4 b). High current magnitudes were recorded at 77°E during March–April and at 93°E during November–December under eastward flow conditions. The zonal currents at 77°E and 83°E generally maintained eastward flow patterns, whereas the zonal component at 93°E remained more variable and predominantly westward except during winter seasons.

At 2000 m depth, winter season currents were more variable at 93°E compared to 77°E and 83°E along the equator (Figure-4 c & d). Eastward flows were observed at 77°E and 83°E from August to December, while westward flow prevailed at 83°E and 93°E. During May to July, westward flow dominated simultaneously at 77°E, 83°E, and 93°E. Only one significant eastward flow event was observed from January to March at 83°E. These results indicate strong seasonal reversals and spatial differences in deep zonal circulation across the equatorial Indian Ocean.

Overall, the HYCOM model analysis demonstrated that intra-seasonal oscillations are the dominant and persistent mode of variability in deep zonal currents across the equatorial Indian Ocean. Seasonal oscillations, bi-weekly variability, and flow reversals also contributed significantly to deep ocean circulation patterns. The observed variability reflects the combined influence of atmospheric forcing, equatorial wave dynamics, monsoonal circulation, and oceanic adjustment processes in controlling deep-sea zonal currents.

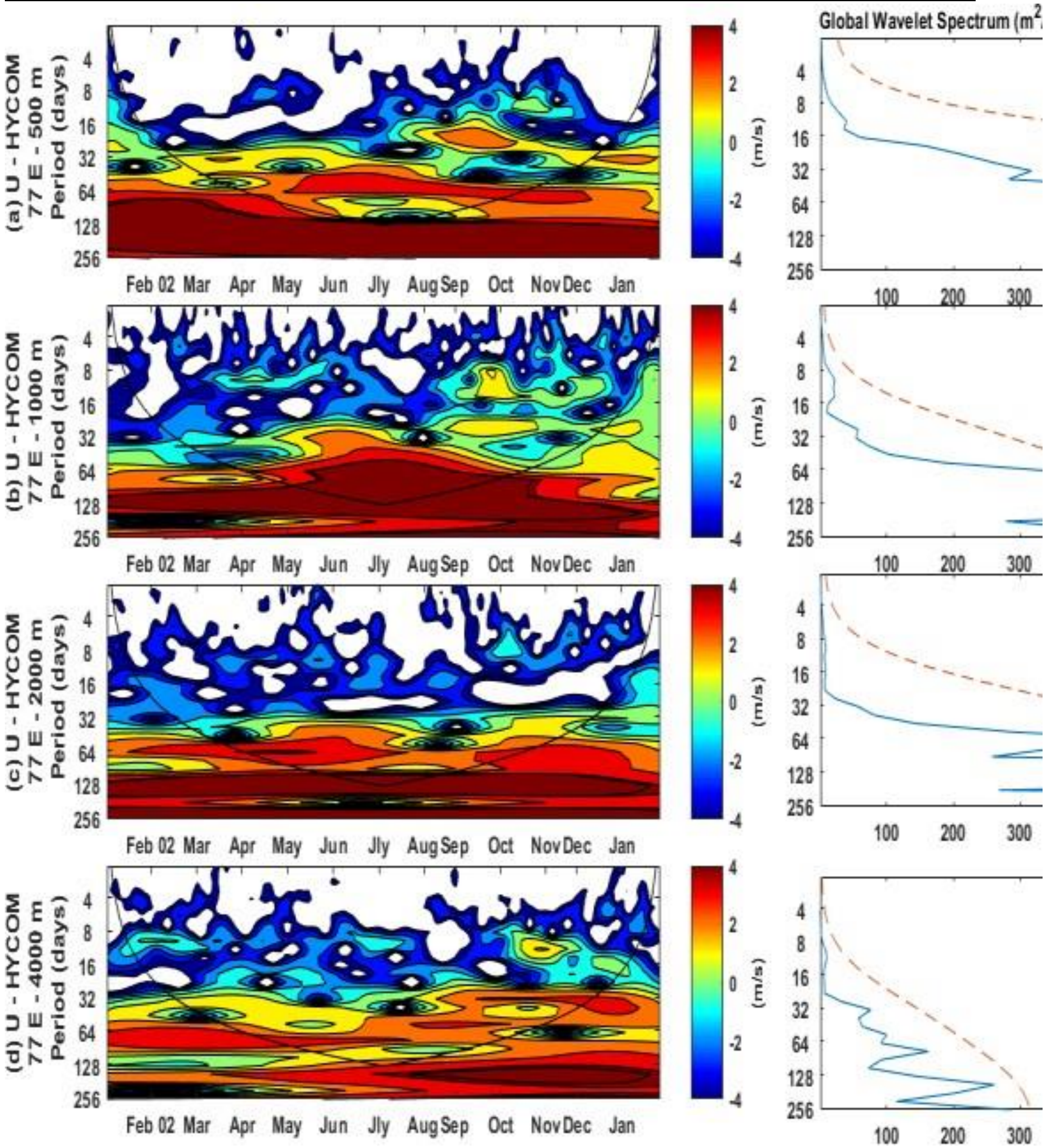

Figure-1: Wavelet power spectra and globalspectra of HYCOM model zonal currents (m/s); a) WEIO (77^0E) in 500 m depth from January 2002 to December 2002, b) 1000 m depth, c) 2000 m depth, and d) 4000 m depth from January 2002 to December

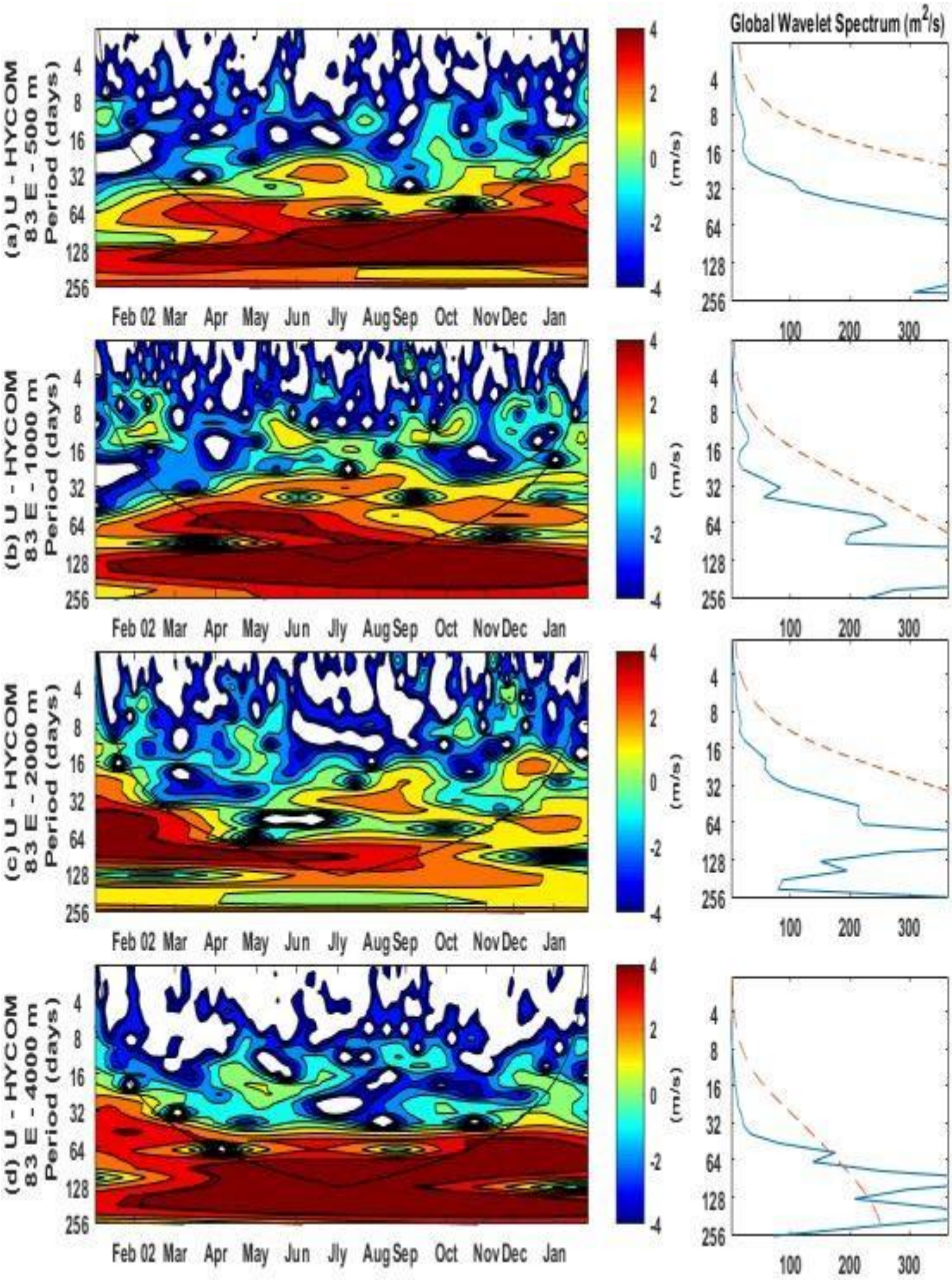

Figure-2: Wavelet power spectra and global spectra of HYCOM zonal currents (m/s); a) CEIO (83^{0}E) in 500 m depth from January 20002 to December 2002, b) 1000 m depth, c) 2000 m depth, and d) 4000 m depth from January 2002 to December 2002.

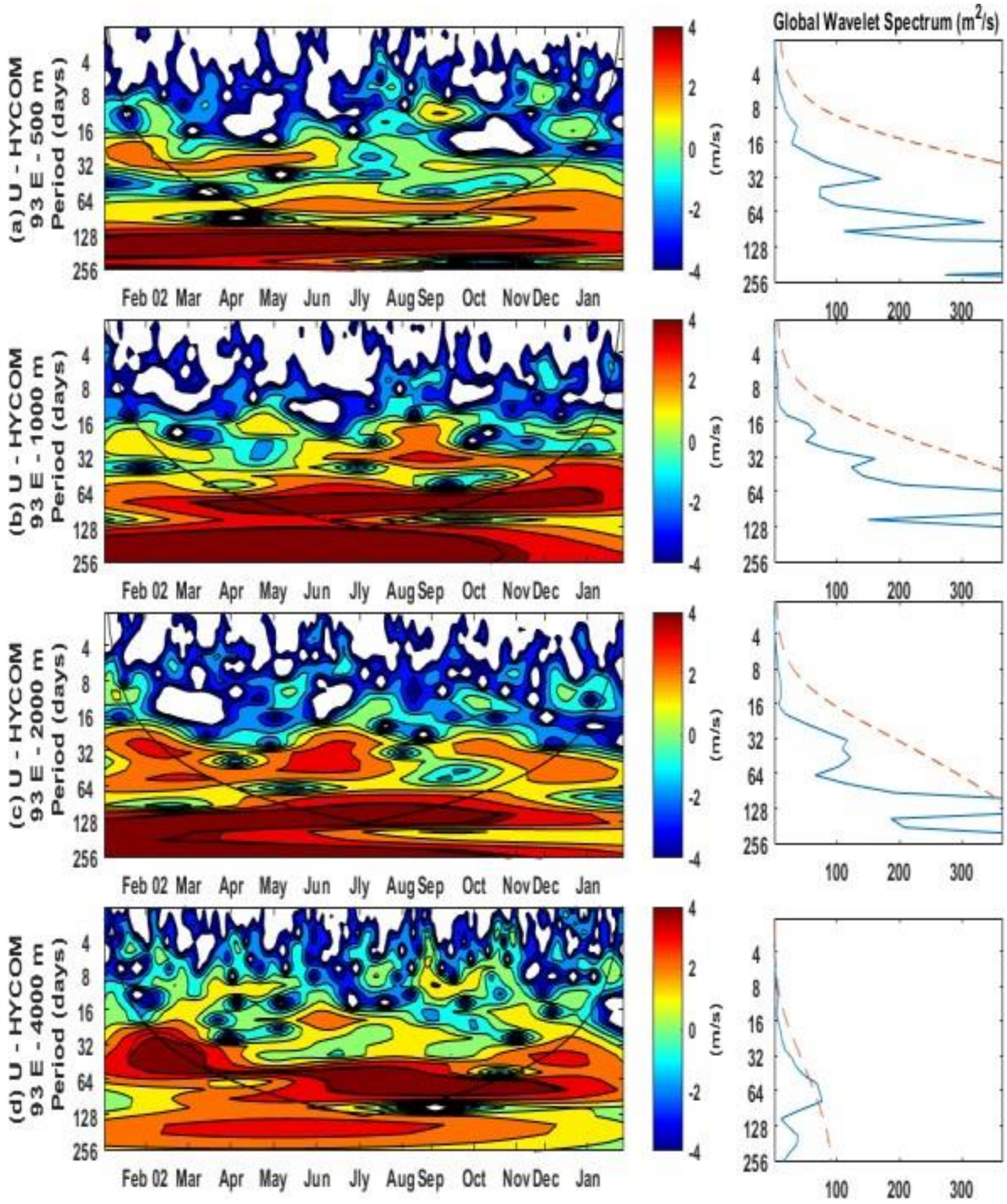

Figure-3: Wavelet power spectra and global spectra of HYCOM Model zonalcurrents (m/s); a) EEIO (93^{0}E) in 500 m depth from January 2002 to December2002, b) 1000 m depth, c) 2000 m depth, and d) 4000 m depth from January 2002 to December 2002.

The HYCOM-simulated zonal currents in the equatorial Indian Ocean exhibit clear multi-scale oscillatory behavior, primarily governed by intra-seasonal oscillations (ISO), seasonal oscillations (SO), and semi-annual oscillations (SAO). These oscillations are not isolated dynamical features but are strongly linked to large-scale climate teleconnections, including ENSO (El Niño–Southern Oscillation), Indian Ocean Dipole (IOD), and El Niño Modoki, which modulate their intensity, persistence, and vertical structure.

The dominance of ISO in HYCOM zonal currents across 77°E, 83°E, and 93°E at multiple depths (500–2000 m) is closely associated with variability in tropical atmospheric convection driven by ENSO-related circulation anomalies. During El Niño and La Niña phases, changes in Walker circulation and wind stress over the Indian Ocean enhance or suppress equatorial wave activity, thereby modulating ISO strength. In particular, strong ISO signals in the model during 2002 are consistent with periods of active ENSO–IOD coupling, which intensifies equatorial wind forcing and promotes enhanced intra-seasonal variability.

The presence of strong seasonal oscillations in HYCOM zonal currents, especially at 77°E and 83°E, reflects the direct influence of the monsoon system and IOD-related basin-wide SST gradients. Positive and negative IOD phases modify zonal wind stress across the equatorial Indian Ocean, leading to strengthened or weakened seasonal current reversals. For example, enhanced SO activity in the model corresponds to periods when IOD-induced SST anomalies reinforce monsoonal wind patterns, intensifying seasonal flow transitions.The semi-annual oscillations (SAO) observed particularly at CEIO are linked to the twice-yearly reversal of monsoon winds and associated equatorial wave adjustments. These SAO signals become more pronounced under combined ENSO–IOD interactions, where basin-scale SST anomalies reinforce semi-annual forcing mechanisms.

At 93°E (EEIO), the persistent and vertically coherent ISO signal throughout the water column indicates strong sensitivity to Madden–Julian Oscillation (MJO)-driven atmospheric convection, which itself is modulated by ENSO and Modoki events. Enhanced ISO activity during specific periods reflects active MJO phases combined with favorable ENSO background conditions.

Bi-weekly oscillations observed in upper layers are also indirectly linked to short-period atmospheric variability associated with MJO propagation and wind bursts, which are often intensified during ENSO–IOD transition phases. Overall, HYCOM zonal current variability demonstrates that intra-seasonal, seasonal, and semi-annual oscillations are not purely oceanic features but are dynamically forced by large-scale climate teleconnections. ENSO, IOD, and Modoki events regulate wind stress, SST gradients, and equatorial wave propagation, thereby controlling the amplitude, duration, and vertical penetration of zonal current oscillations across the equatorial Indian Ocean.

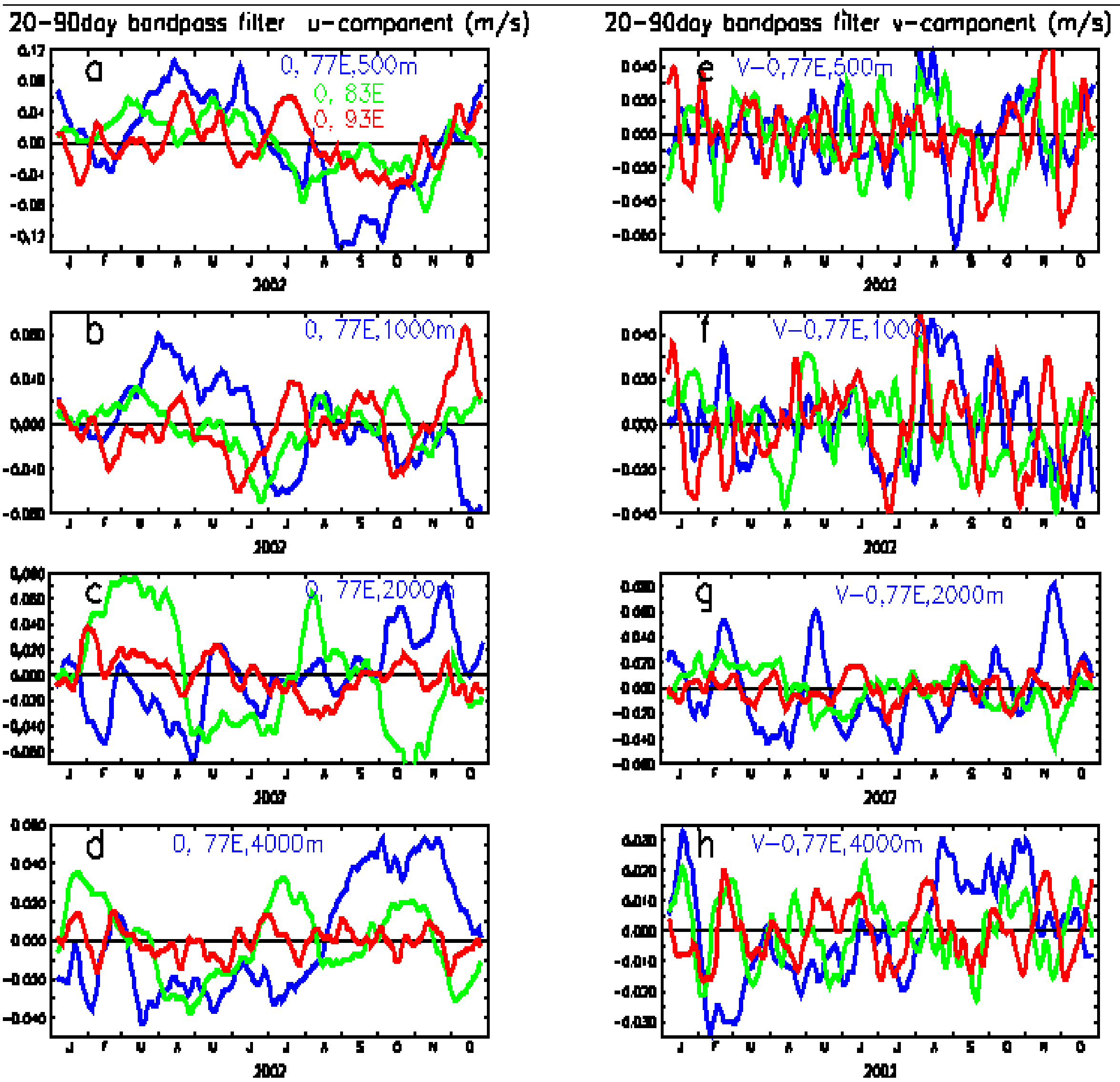

Figure-4: 20–90-day band pass filtered HYCOM model zonal and meridional (m/s) currents among 77E, 83E&93E along the Equator. a) U-500m b) U-1000m, c) U-2000mand d) U-4000m and e) V-500m, f)1000m, g) 2000m and h) 4000m depths during 2002 ye

4. Conclusions:

The study demonstrated that HYCOM zonal currents in the equatorial Indian Ocean were predominantly influenced by intra-seasonal oscillations (ISOs), semi-annual oscillations (SAOs), seasonal oscillations (SOs), and bi-weekly variability at different depths and regions. Strong combined signals of ISOs and SAOs with high spectral power were observed at the Central Equatorial Indian Ocean (CEIO) from June to December 2001 and at the Eastern Equatorial Indian Ocean (EEIO) during February 2001 to March 2002, July to November 2001, and March 2000 to March 2002 at 2000 m depth. These oscillatory signals indicate that deep zonal currents are strongly modulated by both short-term atmospheric forcing and longer seasonal variability. At 2000 m depth, semi-annual oscillations were the dominant mode from January to July 2004, while seasonal oscillations represented the second significant mode. ISOs were particularly significant from October 2002 to February 2003 and January to March 2004. In the EEIO, ISOs were identified as the foremost significant oscillations from February 2003 to October 2004, whereas SAOs were dominant from January to September 2004 in zonal currents. These findings suggest that intra-seasonal variability plays a major role in controlling deep zonal current fluctuations across the equatorial Indian Ocean. At 4000 m depth, bi-weekly oscillations occurring from February to June 2004 and ISOs from January to March 2004 were identified as important modes of variability in zonal currents. ISOs also remained significant from January to April 2007, while seasonal oscillations were dominant from December 2006 to February 2007. Persistent ISO periods from October 2006 to May 2007, October 2006 to December 2007, and February to May 2007 were observed at WEIO at 2000 m depth, demonstrating the long-duration nature of intra-seasonal variability in deep zonal currents.

Large-scale climatic phenomena strongly influenced zonal current variability. The combined effects of El Niño, El Niño Modoki, and the Indian Ocean Basin Mode (IOBM) enhanced ISOs during 2004, while neutral ENSO conditions and anomalously warm oceanic conditions supported strong ISOs during 2003 at 4000 m depth. Weak El Niño conditions combined with positive Indian Ocean Dipole (IOD) events favored semi-annual oscillations during 2006, whereas El Niño associated with negative IOD conditions strengthened ISOs during 2007 at 1000 m depth. These results highlight the strong relationship between deep zonal current variability and coupled ocean–atmosphere climate processes.

HYCOM model simulations further revealed that ISOs were persistent at 93°E across all depths in modeled zonal currents. At 500 m depth, significant ISOs were observed during May–November, February–April, and October–December, while bi-weekly oscillations with periods of 8–16 days occurred during February–March and July–September 2002. At 2000 m depth, ISOs were present during September–October and April–May 2002. Winter zonal currents were more variable at 93°E compared to 77°E and 83°E at 2000 m depth. The filtered HYCOM zonal currents showed eastward flow at 77°E and 83°E from August to December, whereas westward flow dominated at 83°E and 93°E. During May to July, westward flow prevailed at 77°E, 83°E, and 93°E. The RMSD values were close to the magnitude range of observed zonal currents, while positive variance and covariance between RCM observations and HYCOM simulations indicated that modeled and observed zonal currents moved in similar directions and were significantly correlated.

5.Recommendations:

On basis of the important of Deep-Sea currents role, the deep-sea currents are playing significant role on bio-geo-and physical aspects of oceans. The deep-sea currents can measure and estimate the CO_2 variations over depth wise in interior of the ocean, that can be possible by attaching the chemical and biological sensors with mooring systems. In additions to that the study of deep-sea currents is very useful to underwater security purpose for the country in Military. The study of deep-sea currents can possible to understand the link with various intrusion water from south and northern part of the Indian Ocean.

6.Acknowledgements:

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