Intermediate circulation variability in the equatorial Indian Ocean

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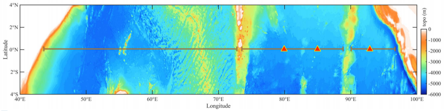
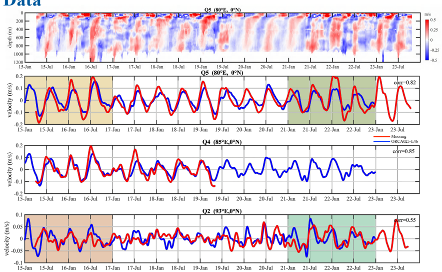
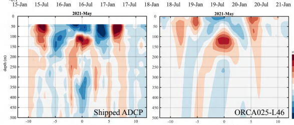
Motivation

The Equatorial Intermediate Current (EIC) is a zonal flow between 2°S and 2°N, extending from below the thermocline to ~1200 m depth. Together with the equatorial deep jets, it plays a key role in tropical ocean circulation and water mass distribution. These equatorial currents vary on intraseasonal to interannual timescales (Dengler et al., 2002; Marin et al., 2010; Ascani et al., 2015; Ménesguen et al., 2019). Here we study the vertical and zonal structure of intermediate currents, based on moored and shipboard velocity data and model output.



Data





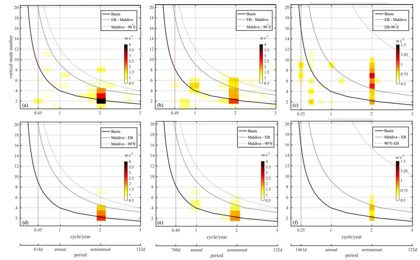
Moorings:
daily zonal velocity,
at 80°E, 85°E, and 93°E,
0-1200 m during 2015-2023.
Model ORCA025-L46:
daily zonal velocity,
in 2°S-2°N, 40°E-100°E,
with 1/4 degrees resolution,
0-4500 m, during 2000-2022.

Methodology

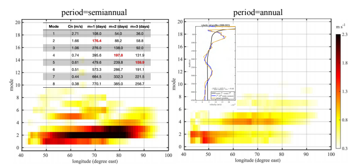
We analyze the vertical structure of equatorial currents using **vertical mode decomposition**, projecting velocity time series onto orthogonal vertical modes. These mode amplitudes are then transformed into the frequency domain using spectral analysis to create a **Frequency–mode spectrum**. To quantify uncertainty, we apply statistical fitting methods during the transformation from time–depth to frequency–mode space. Finally, we interpret equatorial wave propagation using **WKB ray theory** and **basin resonance** concepts from linear wave theory.

Basin modes in the equatorial Indian Ocean

To categorize the contribution of different vertical modes to the equatorial circulation, we classify the baroclinic modes into three groups: **low ($1 \le n \le 2$)**, **intermediate ($3 \le n \le 8$)**, and high($n > 8$) order, consistent with previous studies (Han et al., 2005; Tuchen et al., 2018).



- Low and intermediate baroclinic modes contribute significantly to zonal velocity variability
- At 80°E and 85°E: The 2nd baroclinic mode is the main contributor, enhanced by basin resonance. The 4th–6th baroclinic modes also show amplification likely due to subbasin resonance in the eastern basin, from the Maldives to the eastern boundary.
- At 93°E: The 3rd–8th baroclinic modes are more influential, and the 4th and 5th modes show strong energy, again due to subbasin resonance.

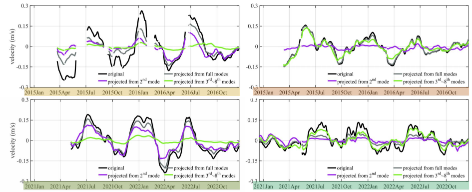


Mode	Cn (m/s)	m=1 (days)	m=2 (days)	m=3 (days)
1	2.71	108.0	54.0	36.0
2	1.66	176.4	88.2	58.8
3	1.06	276.0	138.0	92.0
4	0.74	395.6	197.8	131.9
5	0.61	479.6	239.8	159.9
6	0.51	573.3	286.7	191.1
7	0.44	664.5	332.3	221.5
8	0.38	770.1	385.0	256.7

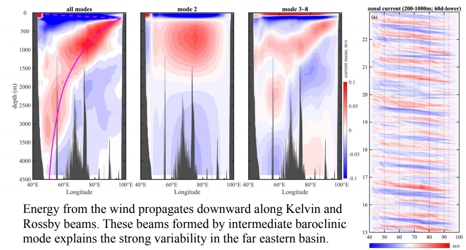
- Semiannual signal has full-basin resonance at the 2nd baroclinic mode. The 5th baroclinic mode is resonant west of the Maldives and the 4th baroclinic mode east of the Maldives.
- Annual signal has full-basin resonance at the 4th baroclinic mode. The western boundary variability is dominated by the 1st and 2nd baroclinic mode annual cycle (ratio>0.42).

Interannual events

The equatorial beams under the superposition of lower-order modes propagate energy more efficiently to deeper layers, playing a crucial role in shaping the vertical structure of the zonal current from 200 to 1200 m. Strong EIC events were observed in 2015–2016 and 2021–2022.



- At 80°E in the central basin, the EIC reconstructed using 2nd baroclinic modes closely matches that from all-mode alone, confirming its dominance.
- At 93°E in the eastern basin, the best match comes from the 3rd–8th modes, indicating that intermediate modes are more important for the EIC there.



Energy from the wind propagates downward along Kelvin and Rossby beams. These beams formed by intermediate baroclinic mode explains the strong variability in the far eastern basin.

Conclusion

- Moored observations in the Equatorial Indian Ocean reveal both semiannual and annual variability in the Equatorial Intermediate Current (EIC).
- Basin resonance enhances the 2nd baroclinic mode semiannual cycle and 4th baroclinic mode annual cycle, while sub-basin resonance amplifies 4th-6th baroclinic modes semiannual cycle between the Maldives and the eastern boundary.
- The Wind-driven Kelvin and Rossby beams, formed by the superposition of intermediate baroclinic modes, explain interannual events in the far eastern basin.

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The Equatorial Intermediate Current (EIC) impacts the distribution and the transport of biogeochemical tracers such as oxygen. The EIC in Indian Ocean, covering the range from 200 to 1000 m between 2°S and 2°N , has higher velocity and a lower-frequency variability in the central basin than in the east. The EIC variability is forced by the wind stress forming equatorial beams and is also strengthened by basin resonance. We use zonal current velocity timeseries of 2015-2023 obtained from different equatorial moorings and a continuous timeseries of 2000-2022 years derived from a global NEMO ocean model configuration at 0.25° horizontal resolution with 46 z-levels (ORCA025.L46) and apply the method of vertical mode decomposition aiming to characterize equatorial zonal velocity variability of the Indian Ocean by equatorial beams, baroclinic modes, and equatorial basin resonance.

From west to east, the Indian Ocean is divided by the topography into three subbasins. The west basin is from the western boundary to the Maldives Islands at 73°E; the central basin is from 73°E to the 90°E ridge; the east basin is from 90°E to the eastern boundary. The frequency – baroclinic mode decomposition of the velocity field shows that semiannual and annual signals are the most significant components. For semiannual signals, the second to fourth baroclinic modes contribute at the mooring locations at 80°E and 85°E, while the fifth to eighth modes dominate at 93°E, indicating the essential role of higher baroclinic modes in the eastern basin. For annual signals, lower baroclinic modes are more significant in the east than in the central subbasin. The model output agrees with the observed distribution of contributing baroclinic modes. Observations further reveal several strong EIC events occurring in 2015-2016 and 2020-2021. Atmospheric data showed corresponding strong anomalies in zonal wind stress and outgoing long-wave radiation. Sea surface temperature anomalies happened along with them. With the distribution of the contributing baroclinic mode, the equatorial beams could explain the strong current events at intermediate depths. The energy input from atmospheric forcing propagates along beams, which are predominantly formed by the second baroclinic mode in the central basin and by the superposition of several higher baroclinic modes in the eastern basin. Future research would focus on the role of equatorial beams in the deeper current variability with the knowledge of contributed baroclinic modes in the Indian Ocean.