COMMENTARY

Equatorial waves substantially modulate currents in the tropical Indian Ocean

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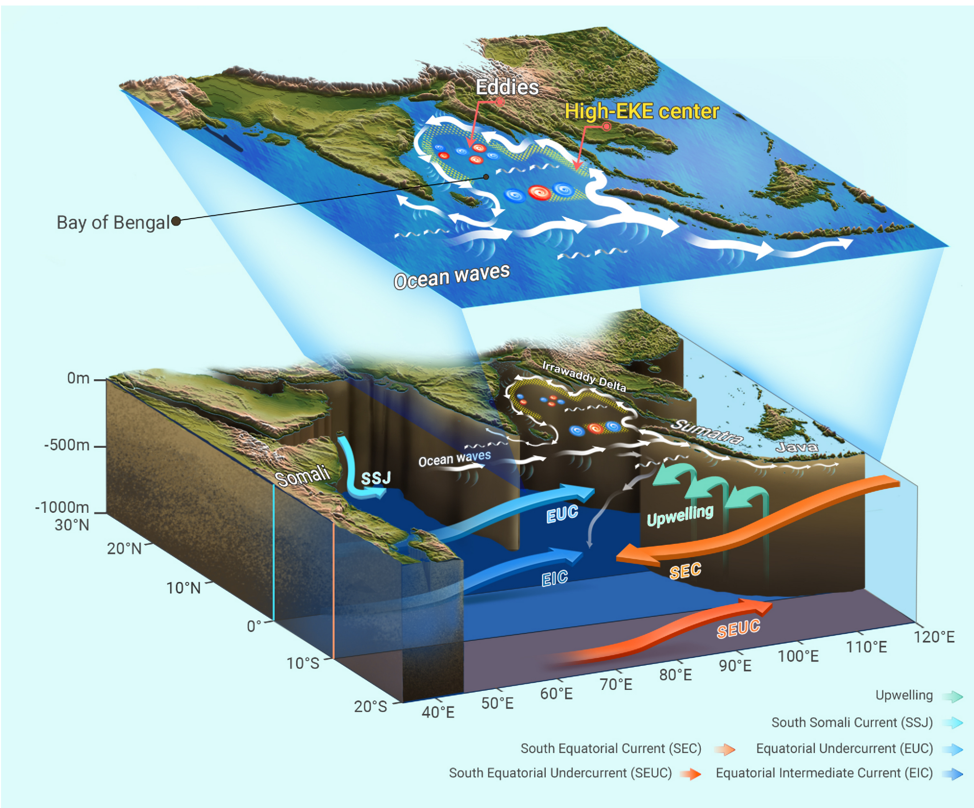

Figure 1. Sketch of equatorial waves modulating currents.

The Indian Ocean is a key component of the global thermohaline conveyor, linking global mass and heat exchanges, and has contributed to a quarter of the global oceanic heat uptake over the last two decades, fundamentally affecting weather and climate globally and regionally, especially its rim countries hosting one-third of the world's population. To date, our knowledge of the complex Indian Ocean circulation that reverses with the monsoon is the poorest among the three ocean basins (Pacific, Atlantic, and Indian).

Equatorial ocean waves, excited by wind forcing, propagate in the zonal and vertical directions along the equator (white bulk arrows in Figure 1). They also transmit energy to off-equatorial regions in the form of coastal Kelvin waves and reflected Rossby waves from the eastern boundary. Theoretical and modeling studies[1] suggest that ocean waves take only several months to cross the equatorial Indian Ocean and thus effectively regulate ocean currents at various timescales. The advent of satellite observations and the establishment of underwater observation networks, such as the Research Moored Array for African–Asian–Australian Monsoon Analysis and Prediction (RAMA), the Argo program, and the Eastern Tropical Indian Ocean Observation Network by the Chinese Academy of Sciences, during recent decades have significantly advanced our detection and understanding of the Indian Ocean circulation. In this note, we summarize the results on the roles of equatorial ocean waves in affecting the surface and subsurface circulations of the tropical Indian Ocean at various timescales, particularly the seasonal-to-interannual timescales.

Equatorial waves play crucial roles in causing current variations in the equatorial Indian Ocean, such as the surface Wyrtki Jet, the Equatorial Undercurrent (EUC; approximately 50-150 m) in the thermocline and the Equatorial Intermediate Current (EIC; approximately 200-1200 m) in the subthermocline layers. Equatorial waves can be categorized as directly forced Kelvin and Rossby waves and reflected Rossby waves from the eastern boundary. Reflected Rossby waves at the eastern boundary have larger amplitudes in the eastern basin because they are direct reflections of incoming equatorial Kelvin waves. In addition, as Rossby wave energy beams penetrate down to the deeper ocean at a deeper angle than Kelvin wave beams, most of the energy in the intermediate layer results from Rossby waves. Thus, the seasonal EUC in the eastern basin and the seasonal EIC in the whole basin are mainly attributed to the reflected Rossby waves from the eastern boundary. For instance, according to the estimation from a continuously stratified linear ocean model from 2001 to 2011, the simulated EIC, averaged over 1°S-1°N and 60-95°E at depths of 200-1200 m, reaches ~4.2 cm/s in July in relation to the reflected Rossby waves, as compared to the ~1.6 cm/s contributed by the directly forced waves. On the other hand, the seasonal EUC in the western basin and the Wyrtki Jet over the basin are mainly attributed to the directly forced waves associated with equatorial easterly and westerly winds, respectively. For instance, using the same linear ocean model, we estimated that the EUC core speed, averaged at 1°S-1°N, 60-70°E and 40-140m, is 15.8 cm/s in March due to the directly forced waves and 7.4 cm/s caused by the reflected Rossby waves. It is worth noting that both the Wyrtki Jet and the EUC exhibit significant interannual variabilities, which are primarily influenced by directly forced waves. In contrast, the interannual variability of the EIC is relatively weak.

Equatorial-origin waves effectively regulate off-equatorial currents in the central and eastern parts of the Indian Ocean. In the southeastern tropical Indian Ocean, local monsoon winds cause a seasonal upwelling from June to October. The upwelling zone coincides with the eastern pole of the Indian Ocean Dipole in the Indian warm pool, particularly along the Sumatra-Java coasts, and thus can play an important role in regulating regional and global climate. The thermocline depth is a good indicator of upwelling, and its intraseasonal and interannual variabilities are mainly due to remote forcing from the equatorial Indian Ocean in addition to the local forcing. Taking the interannual variation as an example, ocean model experiments indicate that the standard deviation of the simulated thermocline depth anomaly, represented by the 23°C isothermal anomaly, is 15.3 m for the Control Run, 5.5 m for the local forcing experiment, and 11.0 m for the remote forcing experiment.[2]

The remote Kelvin waves driven by the equatorial wind propagate along the equator and subsequently along the Sumatra-Java coasts, effectively modulating the thermocline depth of the upwelling zone. During boreal summer-fall (August–October), when the thermocline is relatively shallow (~84 m), the sea surface temperature anomaly in the upwelling zone is primarily driven by the upwelling process. Subsequently, the reflected Rossby waves spread upwelling signals from the coasts into the interior. In contrast, during boreal winter-spring (November–April), when the thermocline is relatively deep (~100 m), the SST anomaly is decoupled from thermocline variability and dominated by local surface heat flux.[2]

The Bay of Bengal is a semiclosed marginal sea located in the northeastern Indian Ocean. The complicated mass and energy exchange between the marginal sea and the equatorial ocean is an important topic in the field of physical oceanography. Observations suggest that eddy-like structures occur near 5°N off the northwest corner of Sumatra (circles along 5°N in Figure 1), inducing pronounced intraseasonal meridional current anomalies with an amplitude of ~0.4 m/s and a typical period of 30-50 days in the upper 150 m across the entire southern Bay of Bengal.[3] These eddy-like structures are largely manifestations of symmetric Rossby waves, which result primarily from intraseasonal wind stress forcing in the equatorial waveguide and reflection of the equatorial Kelvin waves at the eastern boundary. Ocean model experiments reveal that the standard deviation of sea surface height anomalies there induced by remote equatorial forcing has a comparable magnitude (1.61 cm) with that induced by total forcing (1.80 cm)[3]. Similarly, in the mid-depth along 5°N in the southern Bay of Bengal, there are semiannual zonal currents associated with the reflected Rossby waves forced by semiannual winds along the equator, where local wind forcing shows a predominant annual cycle.

As the equatorial-origin waves further transmit energy to the eastern and western Bay of Bengal, they contribute to eddy formation near the tip of the Irrawaddy Delta off Myanmar[4] (circles approximately 16°N in Figure 1), enhance the eddy kinetic energy in the Bay of Bengal,[3] accounting for approximately half of the eddy kinetic energy near the coastal area (yellow-shading in Figure 1), and contribute to the formation of the dipole eddy in the northwestern Bay of Bengal in spring (two circles in the western bay in Figure 1). Budget analysis suggested that the nonlinear effects, especially the advection effect, are indispensable for the generation of these eddies in both the eastern and western basins.

Equatorial-origin waves effectively contribute to the circulation and its transport in the western part of the Indian Ocean. There are many examples of remotely dominated or strongly influenced circulations in the western basin, including Somali currents, Somali undercurrents, the Lakshadweep high and low in the southeastern Arabian Sea, and the seasonal cycle of sea level along the west coast of India. They are significantly contributed by westward propagating Rossby waves, primarily driven by remote wind forcing from the Bay of Bengal and equatorial Indian Ocean through coastal Kelvin wave propagation. Analytic solutions to the linear, continuously stratified equations relevant to observed phenomena in the Indian Ocean have been obtained[1].

According to the time-dependent Sverdrup relation, the meridional transport in a time-dependent circulation is the sum of local wind stress curl contribution and a time-delayed contribution related to the layer thickness at the eastern boundary. Driven by the strong Asian monsoon winds, the Indian Ocean circulation north of 10°S exhibits significant seasonal discrepancy or even seasonal reversal rather than steady ocean circulation. Through equatorial and coastal Kelvin waves and Rossby waves in basin interior, the effect of wind stress forcing associated with atmospheric intraseasonal oscillations, monsoon, and large-scale climate modes eventually manifests in the layer thickness of the eastern boundary, and thus affects the currents in the western basin via the delayed Rossby waves. Taking the southward Somali Current circulation in the western Indian Ocean as an example, we estimated that half of the monthly meridional transport at 7°N during boreal winter originated from the time-delayed contribution from the eastern boundary.

It should be mentioned that the currents in the southern Indian Ocean south of 10°S are less affected by the equatorial waves, because the equatorial-origin energy transmitted to this area is low and because the strong currents associated with the Indonesian Throughflow play a dominant role in these regions. Even so, as revealed by observations and reanalysis data, the key South Equatorial Current, a band of westward current between 10-20°S across the basin, works in concert with the upwelling off the Sumatra-Java coast, the EUC and the South Equatorial Undercurrent to facilitate the three-dimensional freshwater exchange of the Indian Ocean. This collective effort resulted in salting anomalies in the surface layer but freshening anomalies in the subsurface layer during the extreme positive Indian Ocean Dipole events in 1994, 1997, 2006 and 2019 over the last three decades. The vertically opposite salinity anomalies tend to thicken the mixed layer and thin the barrier layer, which benefits for maintaining the colder sea surface temperature in the Southeast Indian Ocean and thus the extreme positive Indian Ocean Dipole events.

In the tropical Indian Ocean, a large fraction of intrasersonal waves are associated with the Madden–Julian oscillation. As the Madden–Julian oscillation becomes increasingly predictable in a warming climate,[5] monitoring equatorial surface wind and equatorial waves may help predict coastal sea level and thermocline variations and thus inundation and biological activities in the Bay of Bengal, and help predict upwelling/downwelling and sea surface temperature anomalies in the eastern tropical Indian Ocean and thus the Indian Ocean Dipole events. To further enhance our understanding of the Indian Ocean circulation, it is essential to emphasize the study and observation of the underexamined mid- to deep-layer circulation in the tropical southern Indian Ocean, which plays an important role in global oceanic material and energy transport, as well as climate effects. Additionally, we need to enhance hydrological and meteorological observations in the poorly sampled western Indian Ocean, which will aid in our understanding of the cross-equator exchange, the meridional overturning circulation structure, and water source linkages between different currents. Given the significance of the Indonesian Throughflow in the Indian Ocean Circulation, as well as the Agulhas Leakage and topography, multidisciplinary joint observations are essential in the southeastern basin, southwestern basin, and the Indian Ocean Ridges, as these observations will not only enhance our comprehension of circulation but also inform our understanding of ocean heat content redistribution, water mass variations, and biogeochemical cycles.

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DECLARATION OF INTERESTS

The authors declare no competing interests.