STUDY OF INTERNAL TIDE CHARACTERISTICS IN THE EASTERN ARABIAN SEA USING OBSERVATIONS AND NUMERICAL MODELS

by

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ABSTRACT

Internal tides (ITs), generated by the interaction of barotropic tides with oceanic stratification and bottom topography, are an important component of the oceanic internal wave field. They contribute significantly to vertical mixing, energy redistribution, and thermohaline circulation, thereby influencing regional and global ocean dynamics. Despite their importance, the characteristics and variability of ITs in the eastern Arabian Sea (AS) remain relatively unexplored compared to other regions of the North Indian Ocean. Therefore, the present study utilizes *in-situ* observations, reanalysis products, and numerical model simulations to investigate the generation, propagation, and variability of ITs in the eastern AS and to improve our understanding of the processes governing their spatial and temporal evolution in the region. *In-situ* observations obtained from the moored buoys AD08 (12°N, 68.65°E), AD09 (8.22°N, 73.28°E), and AD10 (10.34°N, 72.58°E) during 2018 are analyzed to investigate the tidal variability in the region. The analysis reveals that both semidiurnal and diurnal tidal components contribute significantly to the IT field. Among the tidal constituents, M_2 and K_1 are found to be the most dominant, followed by S_2 and O_1. The spectral analysis of density and baroclinic currents indicates stronger IT activity at locations characterized by relatively shallow bathymetry and proximity to island chains, emphasizing the important role of local topographic features in modulating IT dynamics over the region. Furthermore, the three-dimensional Massachusetts Institute of Technology General Circulation Model (MITgcm) was utilized to simulate ITs by forcing the model with ten major tidal constituents (M_2, S_2, K_1, O_1, K_2, N_2, P_1, Q_1, M_4, and MS_4). The simulations identified three primary IT generation hotspots or sub-domains (SDs) in the eastern AS: (i) along the continental shelf-slope of 130 m depth off Mumbai coast (SD1) (ii) the Lakshadweep Islands (SD2), and (iii) the Maldives Islands (SD3). The simulated ITs exhibit distinct propagation characteristics across the identified generation hotspots. In the northern continental shelf–slope region (SD1), the generated ITs propagate primarily in two branches toward the southwest and west. At the Maldives (SD3), a substantial fraction of the energy propagates westward. In contrast, the Lakshadweep region (SD2) experiences the superposition of waves originating from multiple generation sites resulting in a complex propagation pattern without a distinct preferred direction. The MITgcm simulations are performed for January, April, July, and October, representing the winter, pre-monsoon, monsoon, and post-monsoon seasons, respectively, and provide the first comprehensive high-resolution assessment of the seasonal variability of ITs in the eastern AS. The energy budget

analysis reveals pronounced seasonal variability in both semidiurnal and diurnal ITs. Semidiurnal barotropic to baroclinic energy conversion and energy fluxes attain their maxima during April in the northeastern AS and during July around the Lakshadweep and Maldives regions. In contrast, enhanced diurnal energy conversion is observed particularly during January and July along the Mumbai shelf–slope and around the Lakshadweep–Maldives region. Throughout all seasons, the Maldives region emerges as the most energetic IT generation hotspot, exhibiting substantially stronger semidiurnal energy conversion than the diurnal component, while the diurnal and semidiurnal contributions are nearly comparable over the Mumbai shelf–slope and Lakshadweep regions.

Significant interannual variability in IT energetics is evident over the eastern AS, potentially modulated by large-scale climate modes such as the El Niño–Southern Oscillation (ENSO) and the Indian Ocean Dipole (IOD). Three decades (1993–2023) of ERA5 and ORAS5 ocean reanalysis data, together with 15 years (2009–2023) of high-resolution numerical simulations, are utilized to characterize the interannual variability of IT generation and energetics over the eastern AS and to assess their relationship with ENSO and IOD variability. Barotropic-to-baroclinic energy conversion exhibits a systematic enhancement during positive IOD conditions, particularly when coincident with El Niño events. The strongest enhancement is observed in the southeastern AS during January and April of the year following the event, as well as during October of the event year. At the peak of positive IOD phases, energy conversion is up to 58% higher than that observed during La Niña–negative IOD conditions, irrespective of tidal frequency or generation locations. El Niño-positive IOD years are also characterized by increased IT propagation and dissipation. Analysis of reanalysis datasets indicates that this amplification is primarily associated with strengthened density stratification, resulting from weaker wind forcing, enhanced net surface heat flux, and reduced vertical mixing during positive IOD and El Niño events.

The diurnal variability of ITs over the eastern AS is further investigated using a coupled and integrated modelling framework. It combines the Price–Weller–Pinkel (PWP) mixed-layer model, a Garrett–Munk (GM) spectrum-based internal wave model, and high-resolution MITgcm simulations to represent the IT dynamics. To improve applicability in data-sparse regions, the MITgcm-derived temperature and salinity fields are incorporated into the PWP–GM framework, resulting in an integrated modelling system capable of simulating diurnal density variability and associated IT-induced displacements. The performance of both the coupled and integrated frameworks is evaluated and validated against available observational datasets. The results reveal a distinct vertical structure in diurnal density variability, characterized by relatively weak fluctuations near the surface, increasing variability with depth, attaining its maximum variability within the pycnocline (typically between 75 and 100 m), and subsequently decreases below. The application of iterative optimal interpolation using NEMO-derived temperature and salinity fields further demonstrates the advantages of data assimilation in improving the representation of hourly density variability. Assimilation reduces the RMSE of the daily standard deviation of hourly density relative to simulations without data assimilation. Simulations also reveal energetic internal-wave-induced isopycnal displacements over a 10 km horizontal range. These displacements exhibit a strong correspondence with sound-speed variability, with positive displacements generally associated with reduced sound speed and upward shifts of sound-speed contours, while negative displacements correspond to increased sound speed and downward contour displacements. For shallow-water environments (~50 m depth), a modified GM spectrum is implemented and evaluated against CTD observations. The modified formulation provides a more realistic representation of internal-wave-induced variability, yielding lower RMSE values in simulated density and buoyancy frequency than the conventional deep-water GM spectrum. Following validation, the integrated modelling framework is applied along the west coast of India at six locations along the 50 m isobath during January, April, July, and October 2018. Simulations reveal pronounced seasonal and spatial variability in internal-wave-induced isopycnal displacements, with maximum amplitudes reaching approximately 18 m and exhibiting distinct north–south shifts in their distribution across seasons. The variability is closely linked to seasonal changes in upper-ocean stratification, highlighting its key role in regulating IT propagation and energy redistribution in shallow coastal waters.

Overall, this thesis advances the understanding of IT dynamics in the eastern AS across hourly, seasonal, and interannual timescales through a unified observational–modelling framework. By integrating *in-situ* observations, high-resolution numerical simulations, reanalysis products, and a coupled-integrated modelling system, the study identifies stratification as the primary mechanism governing IT generation and propagation in the eastern AS. The developed framework further enables the investigation of internal-wave-induced displacements and associated sound-speed variability in data-sparse regions, providing valuable insights for underwater acoustics, sonar performance, and operational naval applications. These findings establish a robust foundation for future studies of ocean mixing and regional circulation variability.