



Internal wave–driven diurnal density stratification in the Eastern Arabian Sea

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Abstract. The pycnocline and the surface mixed layer are the most prominent indicators of diurnal variability in the ocean. We configured a coupled framework to characterize these processes by combining the Price–Weller–Pinkel model resolving mixed-layer dynamics, with an internal wave model based on the Garrett–Munk spectra accounting for vertical displacements. This coupled system is implemented at three OMNI buoy sites (AD08 (12°N, 68.65°E), AD09 (8.22°N, 73.28°E), and AD10 (10.34°N, 72.58°E)) in the Eastern Arabian Sea. Available *in-situ* observations validate the simulated hourly density variability, showing good agreement with the observed temporal variability. The coupled model further captures diurnal variability and associated isopycnal displacements over spatial scales of up to 10 km, demonstrating its capability to resolve fine-scale stratified structures. Further, the study presents how sound speed is modulated by the isopycnals displacement. To extend its applicability, the model is initialized using output from the 3D MITgcm during representative months (January, April, July, and October) of different seasons. For shallow-water regions, the modified shallow-water Garrett–Munk spectral configuration is implemented, leading to reduced RMSE in hourly density simulations compared to the deep-water configuration. This MITgcm-PW-GM integrated model demonstrates that the 3D MITgcm model can provide initial vertical density conditions at any location within its domain, enabling localized simulations of diurnal density variability. These results highlight the capability of the coupled–integrated framework to efficiently resolve mixed-layer variability and internal-wave–induced isopycnal displacements associated with diurnal forcing. The ability to resolve diurnal variability of internal wave also makes the framework valuable for regional environmental applications further advancing the



understanding of upper-ocean dynamics. In addition, it also supports applications such as simulation of acoustic field and its propagation losses which are crucial for naval operations.

1 Introduction

Internal waves (IW) are gravity-driven oscillations that propagate within the ocean interior along density stratification, generated when disturbances such as tidal flow over topography, wind forcing, or mesoscale variability displace isopycnal surfaces. This interaction induces vertical displacements of the density-stratified water column, which are subsequently restored by buoyancy forces acting under gravity (Garrett & Munk, 1979; Wunsch, 1975). These waves transport energy over long distances and induce substantial vertical displacements, contributing significantly to ocean mixing, nutrient redistribution, and variability in the underwater acoustic environment, with broader implications for large-scale ocean circulation. Internal tides (ITs) are IWs at quasi-tidal frequencies. The propagation and dissipation of IWs are strongly influenced by the vertical stratification and the structure of the mixed layer, which acts as an important boundary controlling the transmission and dissipation of IW energy. Under strong stratification, IWs are more effectively confined within the water column, reducing energy leakage to the surface mixed layer and to the bottom boundary layer. In contrast, weaker stratification allows more efficient transfer of IW energy to the surface mixed layer or the bottom boundary layer, where enhanced mixing and turbulent dissipation occur (Koue, 2025; Munk & Wunsch, 1998; Thorpe, 1977). A deeper mixed layer can store larger amounts of near-inertial energy generated by wind forcing and facilitate the downward propagation of this energy into the stratified thermocline as near-inertial IWs (Balmforth et al., 1998; D'Asaro, 1985; Pollard & Millard, 1970). Park et al. (2010) and Dohan and Davis (2011) demonstrated that deeper mixed layers enhance the vertical kinetic energy of near-inertial IWs and facilitate their propagation to deeper depths. Recently, Mu et al. (2026) showed that variations in mixed layer depth (MLD) account for approximately 41% of the variability in near-inertial IW energy. Czeschel and Eden (2019) used large-eddy simulations to show that turbulence at the base of the surface mixed layer can generate a broad spectrum of internal gravity waves, including near-inertial waves. Their results demonstrate that mixed-



layer turbulence acts as a moving obstacle to the stratified interior, enabling IW radiation that can partially penetrate the transition layer and propagate downward. Hence, accurate representation of mixed-layer dynamics is essential for understanding the generation and propagation of IWs. Among commonly used mixed-layer parameterizations, the Price–Weller–Pinkel (PWP) model has been shown to realistically capture seasonal variations in MLD, exhibiting relatively low biases when compared with year-long observational records (Damerell et al., 2020). The structure and evolution of the mixed layer also strongly influence the transfer of wind energy into near-inertial motions. Realistic simulations of mixed-layer processes reduce the overestimation of wind work and indicate that mixed-layer deepening can convert a portion of wind energy—approximately 11%—into potential energy, thereby modulating the energy available for near-inertial IWs (Alford, 2020). Once generated, the propagation and energy distribution of these waves within the thermocline are further influenced by stratification features such as thermohaline staircases, which can play an important role in vertical energy transport. The background IW field in stratified ocean layers is often described using the Garrett–Munk (GM) IW spectrum, which provides a statistical representation of IW variability across a wide range of frequencies and wavenumbers. Observational studies have shown that the horizontal wavenumber spectra of IW-induced vertical displacements closely follow the GM spectral form in stratified environments, indicating that the GM framework effectively captures the characteristics of the background IW field (Liu et al., 2024). Numerical simulations based on GM modal structures have also been used to reproduce IW-driven sound-speed variability, demonstrating that GM-based models can realistically represent observed IW amplitudes and modal properties (Krishna Kumar & Swain, 2005). In coastal and shelf regions, analyses of sound-speed variability further reveal the presence of broadband IWs with spectral characteristics like the deep-water GM spectrum, highlighting the significant role of IW-induced isopycnal displacements (IDs) in modulating sound-speed structure within the thermocline (Colosi et al., 2012). Thus, while the PWP model realistically represents mixed-layer dynamics, the GM IW spectrum describes IW-induced displacements in the stratified ocean subsurface, particularly near the pycnocline.



80 The northern Indian Ocean is distinguished by strong monsoon-driven circulation, sharp stratification
81 contrasts, and energetic mesoscale and IW activity. It comprises two major basins: Arabian Sea (AS) to
82 the west and the Bay of Bengal (BoB) to the east, separated by the Indian Peninsula. The AS, owing to
83 its complex bathymetry (Bijesh et al., 2021), intricate coastal geometry (Faruque & Ramachandran,
84 2014), strong density gradients (Nampoothiri et al., 2025), and the coexistence of dominant semidiurnal
85 and diurnal tidal currents (Subeesh et al., 2013), provides favorable conditions for the generation of
86 energetic IWs in stratified waters. Despite this, most studies over the past decade have focused on IW
87 dynamics in the eastern sector of the northern Indian Ocean, particularly the BoB and the Andaman Sea
88 (Lozovatsky et al., 2016; Mohanty et al., 2019; Yadidya et al., 2022). Although the AS and BoB lie within
89 the same latitudinal range and are both influenced by the seasonal reversal of monsoon winds, their
90 oceanographic characteristics differ substantially. During the summer monsoon (June–September), strong
91 southwesterly winds associated with the Findlater Jet prevail over the AS (Findlater, 1969), whereas
92 winds over the BoB are comparatively weaker. During March to May, the southeastern AS remains
93 warmer than its surrounding region. A distinctly warm sea surface temperature (SST) patch emerges in
94 the southeastern AS in March, intensifies through April, and expands northwestward by May. The SSTs
95 in the region reach their maximum during April–May (Kurian & Vinayachandran, 2007). The formation
96 of the mini-warm pool reflects the combined influence of strong solar heating, weak atmospheric forcing,
97 and limited oceanic mixing in the southeastern AS. The salinity distributions of AS and BoB also contrast
98 sharply. In the AS, surface salinity is relatively high in the northern region due to intense evaporation and
99 decreases toward the equator as low-salinity waters from the BoB intrude. In contrast, the BoB exhibits
100 lower surface salinity in the northern region (Prasad, 2004). Vertical salinity in the AS generally decreases
101 with depth below a subsurface maximum within the upper 100 m, whereas salinity in the BoB increases
102 with depth. These contrasting horizontal and vertical salinity structures result in stronger near-surface
103 stratification in the BoB and weaker stratification in the AS. Consequently, despite receiving comparable
104 solar radiation, the BoB maintains higher SST $> 28^{\circ}\text{C}$ and a persistently shallow MLD throughout the
105 year. In contrast, the AS exhibits greater spatial and seasonal variability in SST and MLD, with



pronounced cooling during the summer and winter monsoons, when the MLD can deepen to approximately 100 m (Rao et al., 1989; Prasad & Ikeda, 2002; Weller et al., 2002).

Previous studies over the North Indian Ocean using the GM model have predominantly focused on the eastern Indian region. Using the GM model, Sridevi et al. (2010) demonstrated that, off Bhimilipatnam along the east coast of India, low-frequency IWs in the thermocline significantly modulate sound-speed variability and acoustic propagation, while higher-frequency waves near the bottom arise from tidal flow over irregular topography. Sridevi et al. (2011) observed pronounced IW activity at a coastal station off Paradeep, along the east coast of India, using hourly temperature and salinity measurements. Using the GM model, they examined further space–time sound-speed perturbations associated with low-frequency IWs and their influence on acoustic propagation. Acoustic modelling revealed significant transmission-loss anomalies, with losses of up to ~38 dB for optimized source–receiver configurations in the presence of IWs. Yadidya et al. (2021) utilised a coupled modeling framework integrating the PWP model with a GM based IW model to simulate diurnal variability in the vertical density structure of the Andaman Sea. The coupled model realistically reproduced hourly density variations within the surface mixed layer and pycnocline when validated against *in-situ* observations, demonstrating its ability to resolve both surface-driven and IW induced processes. Further, recent studies in the AS have highlighted pronounced spatial and temporal variability in IT generation. Using the 3D- Massachusetts Institute of Technology General Circulation (MITgcm) model, Makar (2025, 2026) demonstrated that in the eastern AS, the ITs are predominantly generated near the Mumbai shelf–slope break and around the Lakshadweep and Maldives islands, exhibiting both seasonal and interannual variability driven by changes in stratification. Krishna and Balasubramanian (2005a) utilised a GM based IW model to simulate temperature, salinity, and sound-speed variability associated with IWs along the west coast of India. Using a modal representation consistent with the GM spectrum, the model is validated against field observations, showing good agreement between measured and simulated sound-speed variance. Hareesh Kumar et al. (2010) utilised a coupled modeling framework combining the GM spectrum and PWP model to simulate the temporal evolution of temperature profiles in the northeastern AS. The observed temperature variability clearly indicates the dominance of tidal processes, with pronounced semidiurnal (~12 h) and diurnal (~24 h)



periodicities in the region. Accurate simulation of short time-scale variability in temperature and salinity is crucial for naval operations, as it directly influences the surrounding acoustic environment. Previous studies in the eastern AS utilising the PWP model or the GM IW spectrum have largely focused only on temporal variability of IWs. In addition, most observational investigations rely on single-point mooring measurements, which restrict the ability to assess the spatial variability of IWs across the region. To address this limitation, the present study adopts a revised approach for solving the IW boundary-value problem, enabling the simulation of IW-induced IDs in both time and space. Specifically, diurnal variability in vertical density structure is investigated using modeling framework of MITgcm-PWP-GM. This study provides new insights into the dynamics of IWs and their influence on coastal and open-ocean variability, including impacts on upper-ocean stratification, acoustic conditions, and regional oceanic processes along the west coast of India.

2 Data and Methodology

The National Institute of Ocean Technology (NIOT), India, has deployed the Ocean Moored Network for the Northern Indian Ocean (OMNI) comprising moored buoys, at AD08 (12°N, 68.65°E), AD09 (8.22°N, 73.28°E), and AD10 (10.34°N, 72.58°E), with local water depths of approximately 4300, 2200, and 1800 m, respectively (Figure 1). The sensor configuration and measurement details are described by Venkatesan et al. (2013). Hourly observations of temperature and conductivity were recorded at multiple depths specifically at 1, 5, 10, 15, 20, 30, 50, 75, 100, 200 and 500 m. Additionally, the hourly Conductivity–Temperature–Depth (CTD) time-series data at Station A (Figure 1), located at 8.56° N, 76.45° E from 18:36 hour on 21 May 2009 to 07:29 hour on 25 May 2009 are also utilised for model validation and analysis. The observations are obtained from the Naval Physical and Oceanographic Laboratory (NPOL), India. The station is situated in a region with a local water depth of approximately 53 m, and the CTD measurements extend from the surface to 50 m depth at a vertical resolution of 1 m.

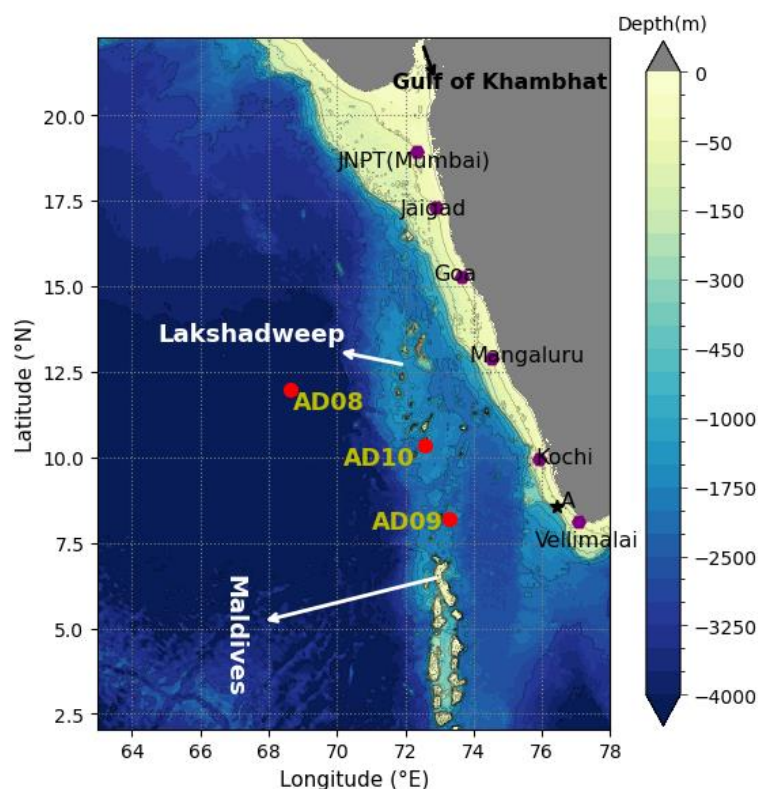


Figure 1: Model domain showing buoy locations (red dots), Station A (black star), and major maritime cities along the west coast of India (magenta dots) used for the seasonality analysis.

2.1 Configuration of MITgcm

In this study, the three-dimensional MITgcm (Marshall et al., 1997; <http://mitgcm.org/>) is utilised and configured specifically for the eastern AS. The model, formulated on a z-coordinate finite-volume framework, can operate in both hydrostatic and non-hydrostatic modes; the present simulations utilize the hydrostatic approximation. The governing incompressible Navier–Stokes equations are solved under the Boussinesq approximation on an Arakawa-C grid. The computational domain spans 2° – 22° N in latitude and 63° – 78° E in longitude (Figure 1), with a horizontal grid resolution of approximately 2.7 km. Bathymetric data are extracted from the GEBCO_2023 dataset at 15-arcsecond resolution (Figure 1). The model domain is discretized into 47 vertical levels, with a uniform 5 m resolution in the upper 150 m



gradually increasing toward the seabed to optimize computational efficiency. A no-slip boundary condition is applied at the bottom, while lateral boundaries are treated with free-slip conditions. Horizontal mixing is parameterized using the Smagorinsky formulation (Smagorinsky, 1963), and vertical mixing is represented by the K-profile parameterization scheme (Large et al., 1994). The beta-plane approximation accounts for the latitudinal variation of the Coriolis parameter. A time step of 120 s is employed in accordance with the Courant–Friedrichs–Lewy criterion, and an eight-grid point sponge layer is implemented near the boundaries to minimize artificial reflection of IWs. Atmospheric forcing includes hourly fields of specific humidity, air temperature at 2 m, wind speed at 10 m, surface net longwave and shortwave radiation, precipitation, and runoff, all derived from ERA5 reanalysis at 0.25° horizontal resolution. Initial temperature and salinity profiles are obtained from the Ocean Reanalysis System 5 (ORAS5), while open boundaries are forced with daily fields of temperature, salinity, and velocities to ensure realistic lateral exchange. Barotropic tidal forcing is incorporated through ten dominant constituents (M2, S2, K1, O1, K2, N2, P1, Q1, M4, and MS4) extracted from the TPXO regional Indian Ocean model (1/12° resolution). Simulations are performed monthly, with the last 2 weeks designated as analysis time period.

The 3D MITgcm configuration used in this study has been validated in Makar et al. (2025), where the same model setup was utilised. Barotropic tidal variability is validated by comparing the simulated sea surface elevation with available tide-gauge observations, yielding a correlation coefficient exceeding 0.93 and a root-mean-square error (RMSE) below 0.18 m for the examined case. Simulated sea surface circulation, temperature, and salinity fields also showed a good agreement with observations (AD08, AD09, AD10, and RAMA), with density RMSE values at buoy locations ranging from 0.1 to 0.48 kg m⁻³ for the examined case. Spectral analyses of density time series from buoy observations (AD08, AD09, AD10, and RAMA) and the corresponding model simulations show that the model accurately captures the energy peaks at the semidiurnal and diurnal bands, along with the dominant tidal constituents, including M2, K1, S2, and O1. Detailed results and further discussion of the model validation are provided in Makar et al. (2025).



2.2 Coupled model set up

The PWP model utilizes surface heat and momentum fluxes, in conjunction with the initial temperature and salinity profiles to resolve the vertical structure of the ocean's mixed layer (Price et al., 1986). The model explicitly represents free convective mixing within the mixed layer driven by surface heat loss, as well as entrainment at the base of the mixed layer and turbulent mixing associated with shear-flow instability. These processes are parameterized through physically based stability criteria that regulate vertical mixing in response to buoyancy and velocity shear. As a result, the model provides a robust framework for simulating the temporal evolution of mixed-layer depth and upper-ocean stratification under varying atmospheric forcing. The model simulates mixed-layer temperature and salinity by enforcing three stability criteria: static stability, mixed layer stability (bulk Richardson number ≤ 0.65), and shear flow stability (gradient Richardson number ≤ 0.25).

The GM model formulates the frequency spectral density as the product of the modal intensity and a normalized modal spectrum (Dashen et al., 1979)

$$\langle |a_j(\omega)|^2 \rangle = A_j^2 E_j(\omega) \quad (1)$$

The modal intensity is expressed as

$$A_j^2 = E_0 M (j^2 + j_*^2)^{-p/2} \quad (2)$$

where, E_0 is the mode amplitude, j is the number of mode, j_* is the mode amplitude damping, p is the mode amplitude spectrum slope and ω is the frequency.

M is the normalization factor given as

$$M^{-1} = \sum_{j=1}^{\infty} (j^2 + j_*^2)^{-p/2} \quad (3)$$

Here, j_* and p are empirical parameters derived from observations. For deep-water conditions, $j_* = 3$ and $p = 2$ (Colosi & Flatté, 1996), whereas in shallow-water $j_* = 1$ and $p = 3$ or 4 (Yang & Yoo, 1999).

The modal frequency spectrum for deep water is expressed as

$$E_j(\omega) = \frac{4}{\pi} \frac{f \sqrt{\omega^2 + f^2}}{\omega^3} \quad (4)$$

And for shallow water it is expressed as (Yang & Yoo, 1999)



$$E_j(\omega) = \frac{f\sqrt{\omega^2 - f^2}}{\omega^2 \sqrt{N^2 + \omega^2 - f^2}} \quad (5)$$

Where f is the inertial frequency and N is the average buoyancy frequency.

The statistical properties derived from the GM power spectrum, together with the IW eigenvalues and mode shapes obtained using finite-difference Sturm sequence (Wilkinson, 1965), bisection (Carnahan & Luther, 1969), and inverse-iteration techniques, are utilised to generate IW displacements. In this formulation, the distribution of IW energy across vertical modes is assumed to be independent of its frequency distribution. Detailed descriptions of these numerical methods are provided by Wilkinson (1965) and Evans (2000).

The diurnal variability of density is simulated using an offline coupling between the PWP model and IW model based on the GM spectrum. The PWP model is first used to simulate diurnal variations in mixed-layer temperature and salinity. Subsequently, the IW model simulates internal wave-induced vertical displacements, which are then imposed on the mixed-layer temperature and salinity profiles generated by the PWP model. The PWP model is one-dimensional, while the IW model is two-dimensional. Over a limited horizontal range of approximately 10 km, the mixed-layer properties are assumed to remain horizontally uniform. This horizontal scale is significant because internal gravity waves in the ocean thermocline typically exhibit horizontal wavelengths from the order of 10 m up to ~ 10 km (Parnum et al., 2017), with the larger scales dominating sound-speed perturbations relevant to acoustic propagation in the upper ocean. The IWs introduce spatially non-uniform fluctuations in the sound-speed field, that lead to range-dependent refraction, scattering, and coherence loss of acoustic energy within the acoustic waveguide. Numerical studies of underwater sound propagation through IW fields - including analyses of transmission loss and spatial coherence at frequencies in the hundreds of Hz over ranges of order 10 km - have demonstrated that IW induced sound-speed variability produces measurable deviations from range-independent propagation predictions (Oba & Finette, 2002). Moreover, the GM IW spectrum provides a robust statistical model for background IW energy across horizontal scales up to tens of kilometers, making it a practical and widely accepted choice for connecting IW displacement statistics with the perturbations experienced by acoustic fields at these distances (Samelson et al., 2019). Under



this assumption, at each time step, the vertical gradients of temperature and salinity obtained from the PWP model at the buoy location are combined with the IW-induced displacements computed by the IW model over the specified range. This procedure yields the IW-induced fluctuations in temperature and salinity.

The coupled temperature (T_p) and salinity (S_p) profiles simulated by the PWP model are modified by the IW-induced displacements (ζ) generated by the IW model to produce the final temperature (T) and salinity (S) fields from the coupled framework.

$$T(r, z, t) = T_p(z) + \zeta(r, z, t) \frac{\partial T_p}{\partial z} \quad (6)$$

$$S(r, z, t) = S_p(z) + \zeta(r, z, t) \frac{\partial S_p}{\partial z} \quad (7)$$

The density field is calculated using the UNESCO 1983 (EOS-80) polynomial formulation, where the secant bulk modulus K is used in the computation.

$$\rho(S, T, p) = \rho(S, T, 0) / [1 - \rho / K(S, T, p)] \quad (8)$$

The resulting density is then used to estimate IDs, which represent the amplitudes of IWs and are examined over the 10 km range. The ID is defined in terms of the density anomaly relative to the range-mean density $\bar{\rho}$, where the density anomaly is given by $\rho'(r, z) = \rho(r, z) - \bar{\rho}(z)$ and the ID is expressed as

$$\eta(r, z) = \frac{\rho'(r, z)}{d\rho/dz} \quad (9)$$

The sound speed (c) is computed following the Thermodynamic Equation of Seawater 2010 (TEOS-10) formulation (IOC, SCOR et al. 2010).

2.3 Experimental design

A coupled modelling framework combining the PWP mixed-layer model and IW model based on GM spectrum is employed in this study. The simulations are conducted at a vertical resolution of 1 m, achieved through linear interpolation of moored buoy temperature and salinity observations from AD08, AD09,



and AD10. The model time step and horizontal range increment are fixed at 1 hour and 0.5 km, respectively. Surface forcing to the PWP model consists of net shortwave and longwave radiation, latent and sensible heat fluxes, zonal and meridional wind stresses, and precipitation rate. Owing to the unavailability of *in-situ* surface flux measurements, the ERA5 reanalysis products are used. The reliability of the ERA5 surface fluxes is further evaluated against flux observations from the RAMA buoy located at 15.14°N, 65.10°E (ID: 2300011) for the period from 08 November 2019 (15:00 hr) to 20 November 2019 (13:00 hrs), as concurrent fluxes, temperature, and salinity observations are available during this period. Since ERA5 is a reanalysis product that assimilates a broad range of observational datasets, including RAMA buoy observations, both datasets exhibit similar day-to-day variability in density (figure not shown). Therefore, ERA5 fluxes are subsequently used for the simulations. For each day, the PWP model is initialized at 00:00 IST and integrated for a 24-hour period to obtain mixed-layer-modified temperature and salinity profiles. Since buoy observations are available only upto 500 m depth, the PWP model is run exclusively over this upper 500 m layer. Subsequently, to extend the profiles to the full local water-column depth, the PWP-simulated temperature and salinity fields (0–500 m) are appended with daily ORAS5 reanalysis data below 500 m, yielding complete T–S profiles spanning the local bottom depth. These merged profiles are then used for the GM model, which is configured with 20 vertical modes for deep-water sites (>1500 m) and 5 modes for shallow-water sites (~50 m), from which the IW–induced temperature, salinity, and density fields are subsequently derived. Longwave and shortwave radiation extinction coefficients are prescribed as 0.6 m and 20 m, respectively. This modelling procedure is repeated daily from 1 January to 31 October 2018 for all the three buoys; data beyond October are excluded due to increased noise and reduced data quality. Hereafter, this configuration is referred to as the “Coupled model”.

An integrated modelling framework is constructed by coupling a three-dimensional MITgcm simulation with the previously described coupled model. The MITgcm is configured separately for four representative months—January, April, July, and October—chosen to characterize winter, pre-monsoon, monsoon, and post-monsoon seasonal conditions, respectively. For each selected month, the MITgcm is integrated continuously over the full duration of the month in 2018. To minimize the influence of initial



transients, the first ten days of each simulation are treated as spin-up and excluded from further analysis. Consequently, model output from the remaining 20–21 days is retained for analysis across all four seasonal simulations. Daily fields extracted from the MITgcm output beginning on the 11th day of each month are used to initialize the coupled model at 00:00 IST. This initialization is performed once per day for each of the four months, and the resulting simulations form the basis of the subsequent analysis. The complete modelling strategy combining MITgcm and the coupled model is hereafter referred to as the “Integrated model”.

The applicability of the two modelling configurations depends on the availability of observational data. When *in-situ* temperature and salinity profiles are accessible in near real-time, the coupled model can be directly initialized with these observations to capture location-specific diurnal variability in density. In contrast, under conditions where real-time observations are unavailable, an alternative approach is adopted in which background day-to-day variability is first generated using the three-dimensional MITgcm, while higher-frequency (hourly) variations are subsequently resolved using the coupled model. As demonstrated in the subsequent section, the MITgcm integrated within the coupled framework produces a more realistic representation of diurnal density variability compared to simulations performed without coupling.

3 Results and Discussion

3.1 Model validation

Daily density variability is quantified using the standard deviation calculated from moored buoy observations, the PWP model, the coupled model, and the integrated model. Figure 2 compares the monthly averaged profiles of daily standard deviation derived from the AD09 buoy, which is the southernmost of the three buoy locations. Since the PWP model represents variability only within the mixed layer, the standard deviation is zero below the MLD for all months. During winter, the mixed layer at AD09 does not deepen substantially in either the observations or the coupled model simulations. In contrast, the integrated model exhibits a comparatively deeper MLD, which can be attributed to the



ORAS5 data, as illustrated in Fig.2(a). Since the MITgcm is initialized and forced at the boundaries using ORAS5 fields, such differences between the model output and observations are expected and largely arise from uncertainties in the initial and boundary conditions. Naqvi et al. (2006) reported that mixed-layer deepening in the eastern AS is spatially non-uniform. Although regions of enhanced latent heat flux and net heat loss are present over the southeastern AS, the deepest mixed layers are observed farther north. In the southern region, surface convective cooling associated with high latent heat flux is suppressed by the advection of low-salinity waters (< 35.5 psu) from the BoB via the West India Coastal Current. Consequently, deep mixed layers are largely confined to the northern AS (Vijith et al., 2016). This spatial pattern is well reproduced by our model simulations (Figure 2a–b). The coupled model shows good agreement with the observations throughout the winter period. During the transition period, it is characterized by weaker winds (Figure 2c–e), the mixed layer remains relatively shallow. This period also coincides with the development of the AS mini-warm pool, in which shallower MLDs are consistently observed (Nyadjro et al., 2012). The coupled and integrated model successfully reproduces this shallow mixed-layer structure. AD09, located in the southeastern AS, typically experiences strong southwesterly winds during the summer monsoon, which drive intense wind-induced mixing. Consequently, the deepest MLD are observed between June to August (Figure 2 f–h). The associated variability during the summer monsoon months is well captured by the PWP, coupled, and integrated model simulations. During the post-monsoon transition period in September-October (Figure 2i–j), both coupled and integrated model shows good agreement with the observations.

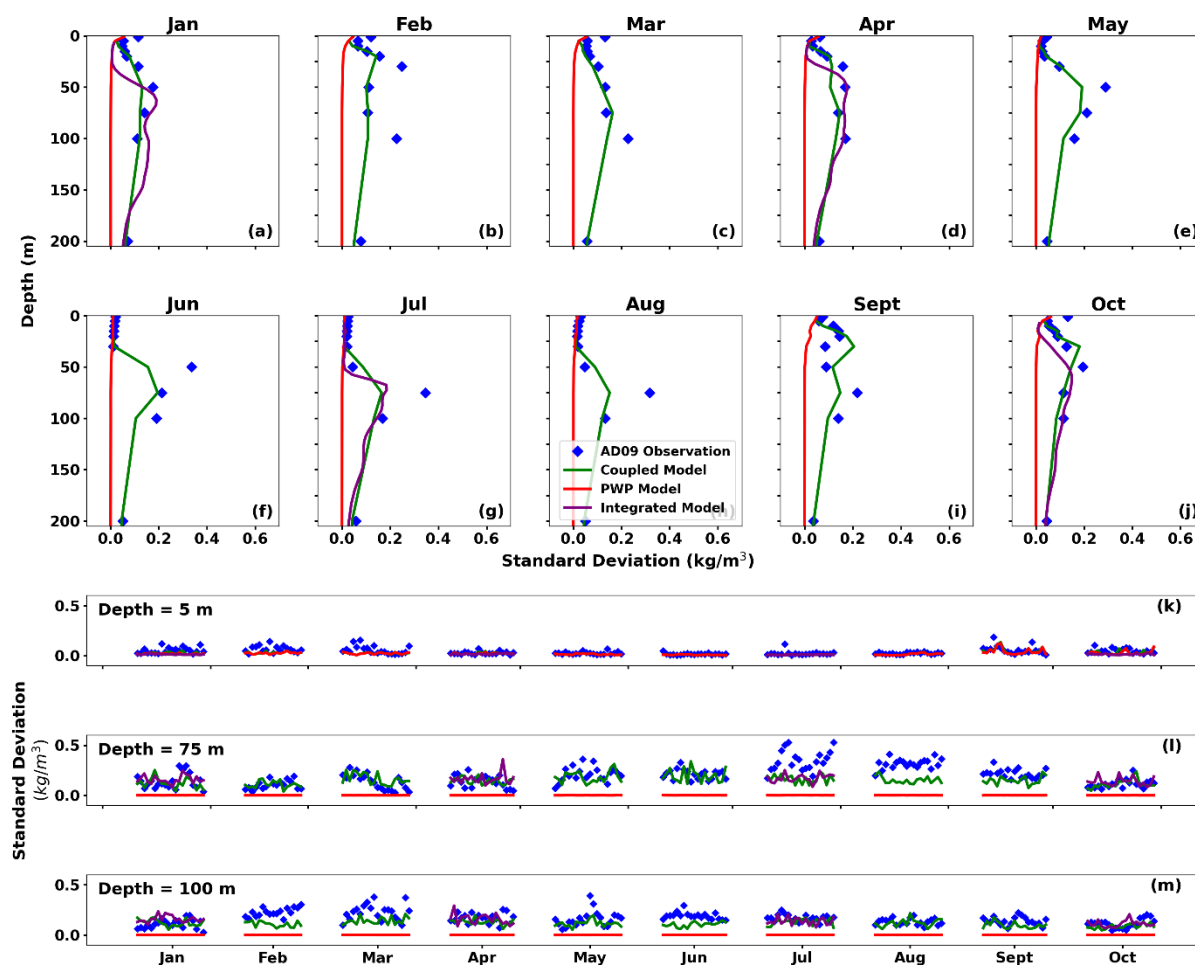


Figure 2: (a–j) Monthly mean profiles of the daily standard deviation of density from AD09 observations (blue dots), the PWP model (red), the coupled model (green), and the integrated model (violet). (k–m) Time series of daily standard deviation at depths of 5, 75, and 100 m

Figures 2(k–m) present the time series of daily standard deviation at depths of 5, 75, and 100 m. The PWP model exhibits variability only at 5 m, with no standard deviation at 75 and 100 m. Overall, the time-series comparison indicates that both the couple and integrated model simulations are in good agreement



with the observations. Some discrepancies remain in the integrated model, particularly at 75 and 100 m during October, where the variability is underestimated. For the coupled model, elevated standard deviation values, particularly at 5 m during February, March, and September (pre- and post-monsoon periods), are primarily attributed to the influence of hourly surface flux forcing. Nevertheless, the magnitude of these differences remains small. Apart from these minor deviations, the PWP, coupled, and integrated model simulations show overall good agreement with the available AD09 observations.

A similar comparison is performed for the eastern AS using *in situ* observations from the AD10 buoy (Figure 3). Located near AD09, AD10 exhibits a MLD variability comparable to that observed at AD09. The coupled and integrated models show good agreement with the observations across most depths. However, in October, the near-surface observational data at 5 and 10 m are highly noisy and therefore are excluded from the coupled model analysis. The diurnal variability is found to increase with depth from the surface, reaching a maximum between 75 and 100 m, before decreasing below this level for most months. During January, the integrated model exhibits a deeper MLD compared to both the observations and the coupled model, likely attributed to ORAS5 reanalysis. An underestimation by the model is evident at 100 m depth during June–August. This bias is likely associated with the strong southwesterly monsoon winds and enhanced upper-ocean mixing during this period, processes that may not be fully represented by the PWP and GM parameterizations. In addition, the absence of observational constraints between 100 and 200 m in the coupled model setup may further contribute to reduced accuracy at these depths. When strong density gradients occur between adjacent depth levels, the use of interpolated profiles can also dampen simulated diurnal variability, consistent with earlier findings for the Andaman Sea (Yadidya et al., 2021).

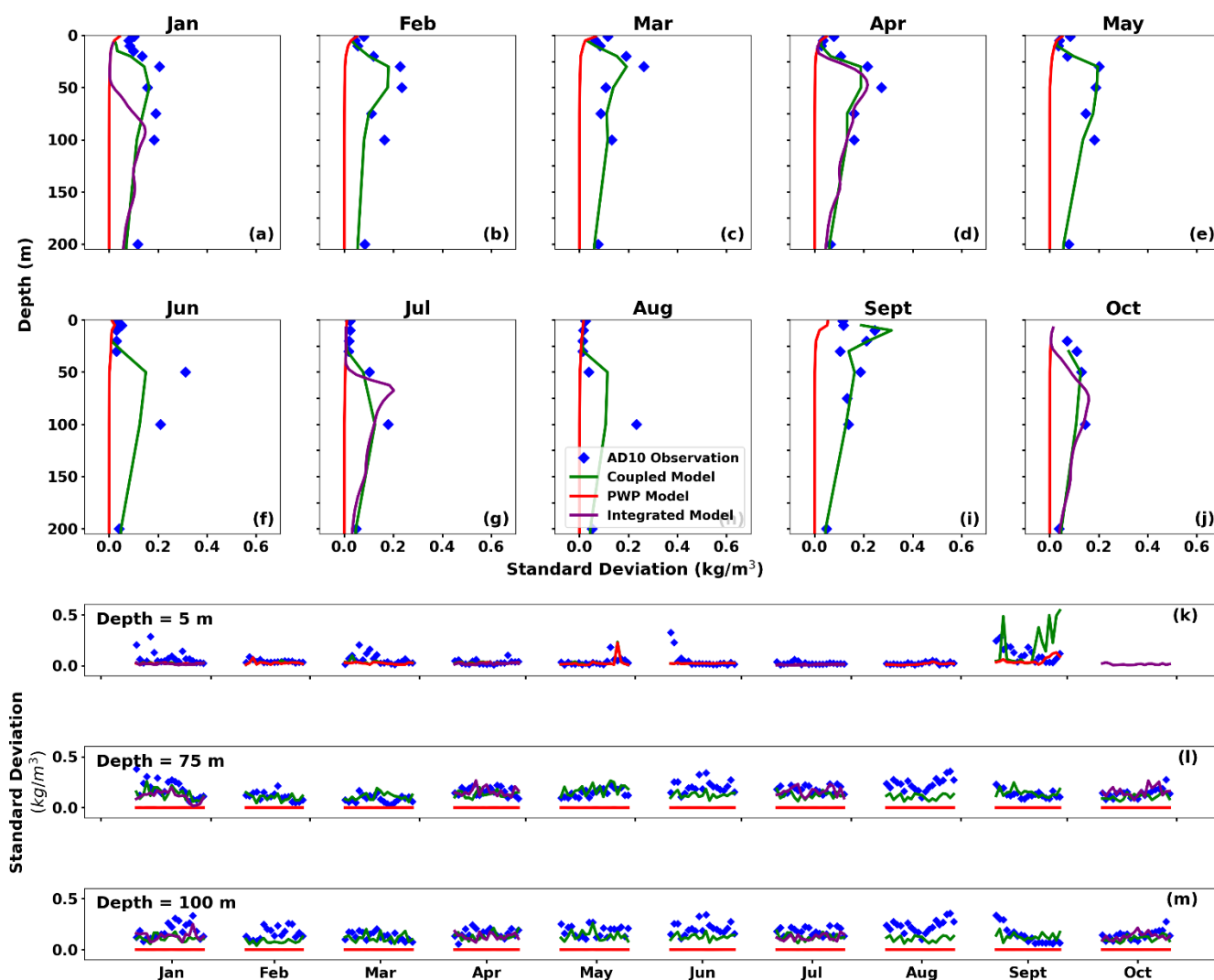


Figure 3: (a–j) Monthly mean profiles of the daily standard deviation of density from AD10 observations (blue dots), the PWP model (red), the coupled model (green), and the integrated model (violet). (k–m) Time series of daily standard deviation at depths of 5, 75, and 100 m

Time-series comparisons (Figure 3k–m) indicate overall agreement between the model simulations and observations, except for a few spikes at 5 m depth during September in the coupled model. Additionally,



as observational data at 5 m are not considered for October, the daily standard deviation shown in Fig. 3k for that month represents only the integrated model. Analysis of the daily standard deviation of density at 5, 75, and 100 m further demonstrates that the coupled model reproduces the observed diurnal variability well through October. Overall, Figure 3 highlights that the PWP, coupled, and integrated models successfully capture the diurnal density time-series variability, showing close agreement with the AD10 observations.

Among the three available moored buoys, AD08 is located at the northernmost position and is deployed over the deepest local water depth compared to the other sites. As shown in Fig. 4a–j, the observed standard deviation at AD08 remains within 0.2 kg m^{-3} throughout the study period and at all the observation depths including at subsurface for the observation data. This indicates that, relative to AD09 and AD10, the diurnal variability at AD08 is comparatively weaker. As AD08 is located north of AD09 and AD10, it exhibits a comparatively deeper mixed layer depth (MLD) during winter in both the observations and the coupled model. However, even at this location, the integrated model shows a deeper MLD, likely attributed to limitations in the ORAS5 data. However, this deepening is modest, as the deepest winter MLDs in the eastern AS are largely confined to the regions of farther north, typically beyond 22° – 23° N. Consistent with the seasonal cycle observed at the other sites, the deepest MLD at AD08 occur during the southwest monsoon period (June–September), while shallower MLD prevail during the transition seasons (pre and post-monsoon). It is further noted that the MLD during the summer monsoon in AD08 is deeper than that observed in AD09 and AD10. The integrated model shows overall good agreement with the observations, except in January, when it exhibits a deeper MLD, and in April, when a slight underestimation is evident up to 50 m depth. The coupled model, however, shows good agreement with the AD08 observations across all depths and months up to October.

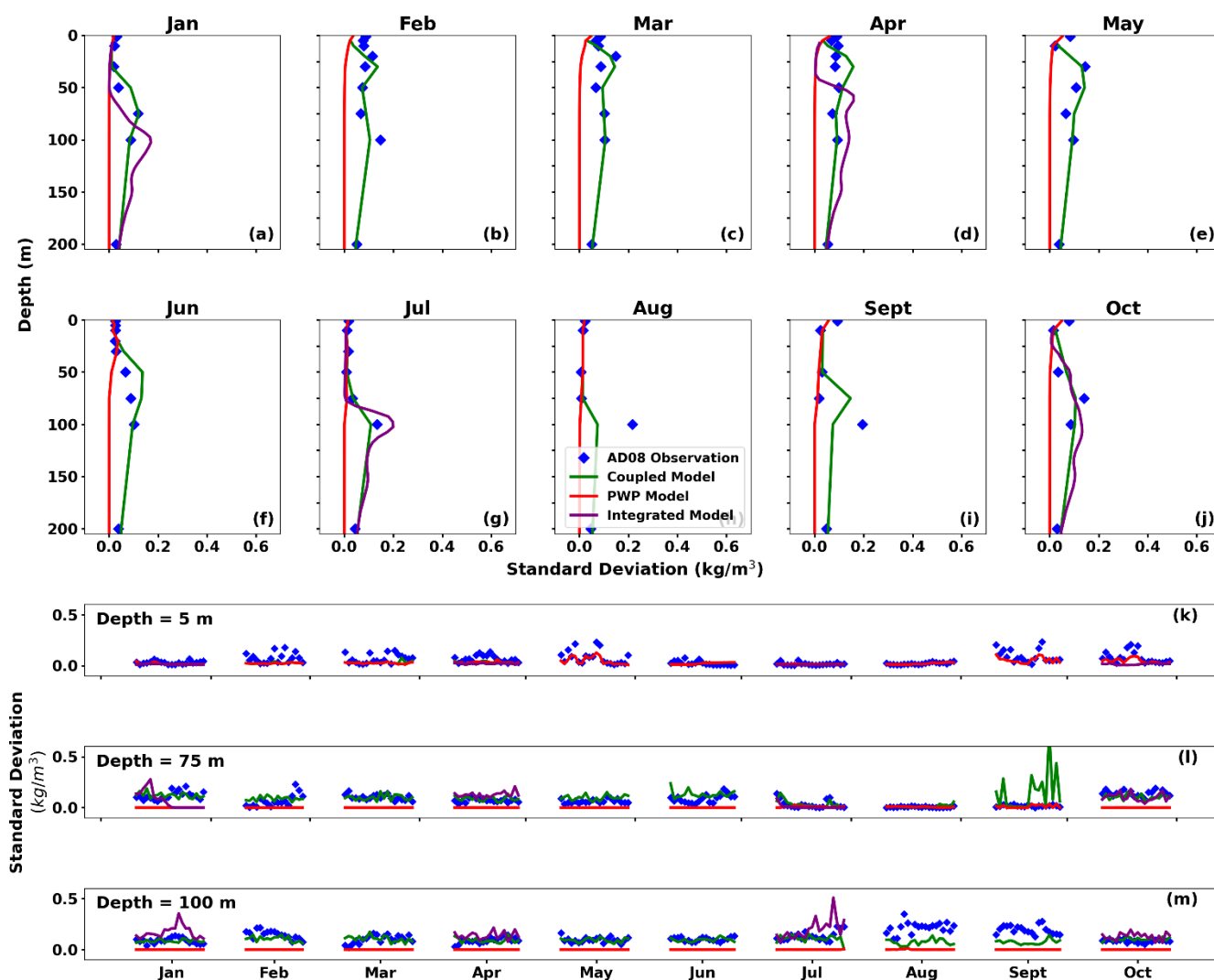


Figure 4: (a–j) Monthly mean profiles of the daily standard deviation of density from AD08 observations (blue dots), the PWP model (red), the coupled model (green), and the integrated model (violet). (k–m) Time series of daily standard deviation at depths of 5, 75, and 100 m



3.2 Coupled Model

Figure 5 illustrates the vertical structure of ID simulated by the coupled model at the moored buoy locations for the representative months of January, April, July, and October, corresponding to the winter, pre-monsoon, monsoon, and post-monsoon seasons, respectively. The distribution of ID shown in Fig. 5 represents an instantaneous spatial snapshot within a 10 km range at 23:00 IST on the 20th day of each month in 2018. This time frame is particularly selected because, in our MITgcm analysis, the period begins from the 11th day, and the chosen snapshot represents the midpoint of the analysis window. Although the coupled model is initialised by observations rather than MITgcm output, the same snapshot is retained to ensure consistency throughout.

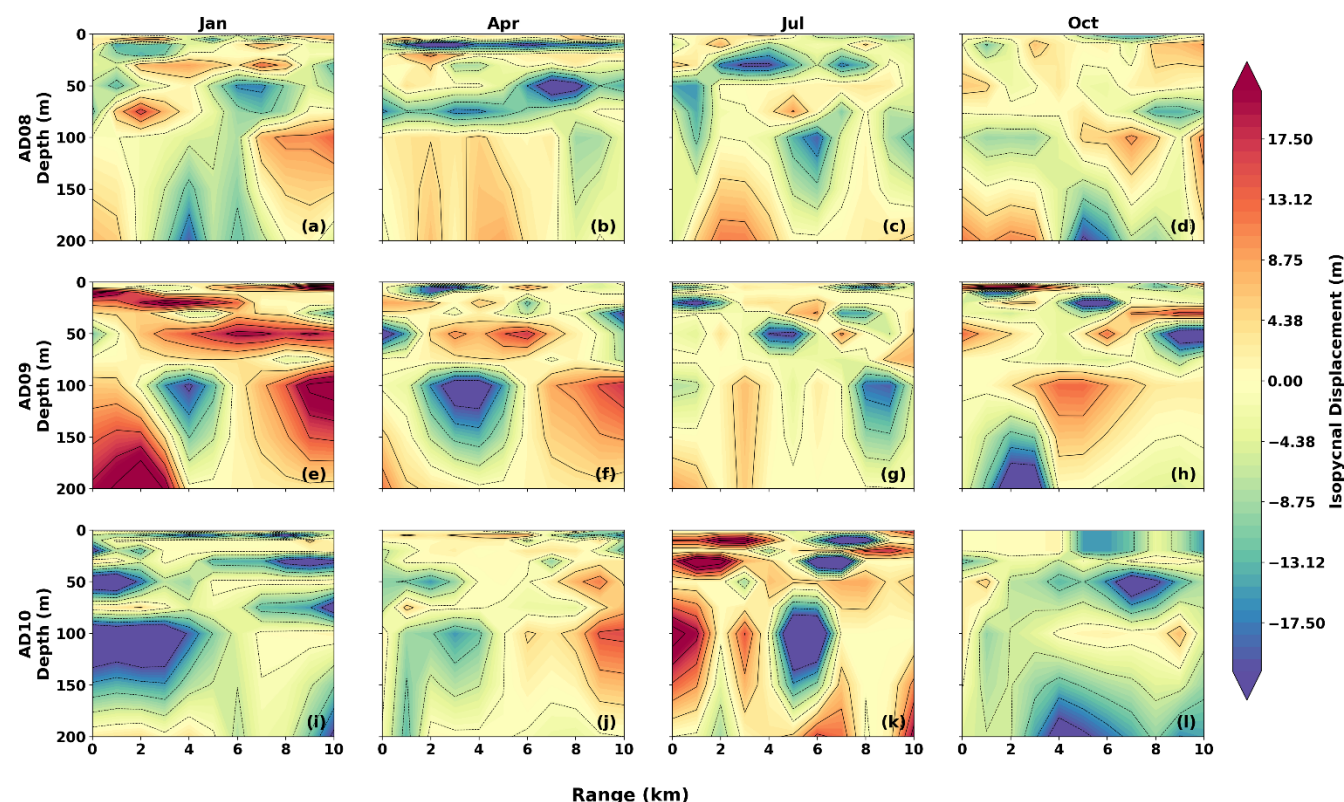


Figure 5: Vertical distribution of ID within a 10 km range of the AD08, AD09, and AD10 buoy locations, simulated using the coupled model at 23:00 IST on the 20th day of January, April, July, and October 2018.



431

432 Figure 5(a–d) depicts the ID at the AD08 buoy location, with representative snapshots at 23:00 h on the
433 20th day of 2018 for January, April, July, and October, representing the winter, pre-monsoon, monsoon,
434 and post-monsoon seasons, respectively. In January, the maximum positive ID reaches approximately 16
435 m at a depth of 75 m (Figure 5a), while the strongest negative displacement is about 20 m at 200 m depth.
436 In April, the positive ID attains a peak value of 9.8 m at 20 m depth (Figure 5b), whereas the negative
437 displacement intensifies to nearly 28 m at 50 m depth. During July, a maximum positive ID of around
438 11.5 m is observed at 200 m depth (Figure 5c), accompanied by a negative displacement of about 22 m
439 at 30 m depth. In October, the positive ID reaches approximately 11.7 m at 100 m depth (Figure 5d),
440 while the corresponding maximum negative displacement is ~22 m at 200 m depth. These results indicate
441 that the depth of maximum displacement varies seasonally at the AD08 location. Similarly, at the AD09
442 buoy location, the ID exhibits marked variability across the selected months (Figure 5e–h). In January,
443 the maximum positive ID reaches approximately 34 m at a depth of 200 m, while the corresponding
444 negative displacement is about 22 m at 100 m depth. In April, the positive ID attains a peak value of 17.5
445 m at 100 m depth, whereas the negative displacement strengthens to nearly 28 m at 15 m depth. During
446 July, a maximum positive ID of around 10 m is observed at 50 m depth, accompanied by a pronounced
447 negative displacement of about 27 m at 20 m depth. In October, the positive ID reaches approximately
448 21.8 m at 15 m depth, while the maximum negative displacement intensifies to nearly 29 m at 200 m
449 depth. At the AD10 buoy location, the maximum IDs (Figure 5i–l) also exhibit clear seasonal variability.
450 In January, the maximum positive ID is approximately 4.2 m at a depth of 75 m, while the corresponding
451 maximum negative displacement reaches about 27 m at 15 m depth. In April, the positive ID increases to
452 nearly 15.3 m at 100 m depth, accompanied by a negative displacement of about 15.7 m at 50 m depth.
453 During July, both positive and negative displacements attain comparable magnitudes, with a maximum
454 positive ID of ~28 m and a negative ID of ~28.2 m, both occurring at around 30 m depth. In October, the
455 positive ID decreases to approximately 6.9 m at 100 m depth, whereas the maximum negative
456 displacement intensifies to about 26 m at 50 m depth.



The persistent occurrence of strong IDs within a 10 km horizontal scale and near the pycnocline (Figure 5) indicates energetic IW activity at all three buoy locations. These waves drive pronounced vertical excursions of stratified layers and contribute to variability in the subsurface density structure.

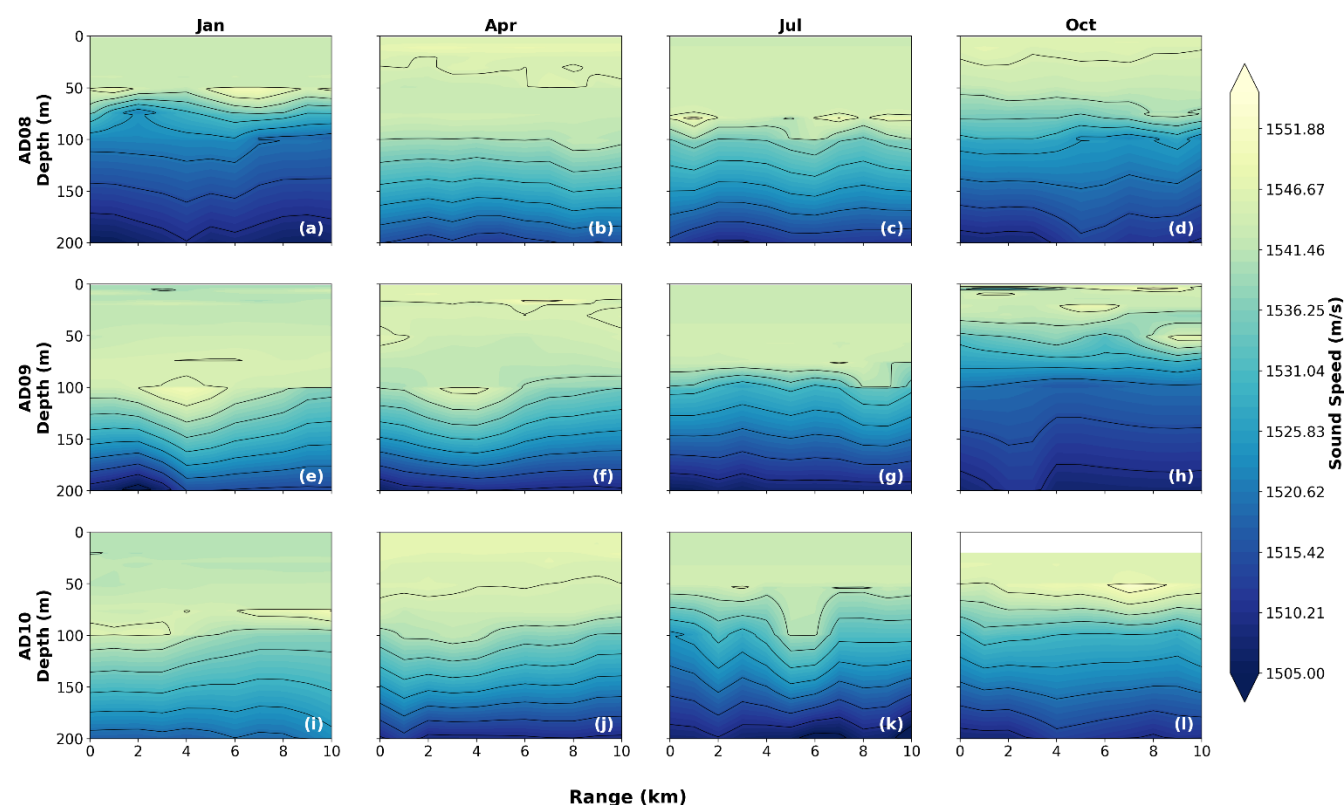


Figure 6: Vertical distribution of sound speed within a 10 km range of the AD08, AD09, and AD10 buoy locations, simulated using the coupled model at 23:00 IST on the 20th day of January, April, July, and October 2018.

Similarly, sound speed is computed within a 10 km horizontal range, and an illustrative snapshot corresponding to the same time (20th day at 23:00 h), consistent with the ID shown in Fig. 5, is presented in Fig. 6. A comparison of Figs. 5 and 6 reveals a clear and coherent correspondence between isopycnal



motion and sound-speed variability. Regions of positive (upward) ID are consistently associated with an upward shift of sound-speed contours, whereas negative (downward) displacements correspond to a downward modulation of the sound-speed structure. The magnitude of the sound-speed response scales with the strength of the ID, with larger ID amplitudes producing more pronounced vertical excursions of sound-speed contours on the order of several meters. Such IW-induced density perturbations can substantially alter sound-speed structure and acoustic propagation characteristics, including transmission loss, with direct implications for underwater acoustics, sonar performance, and naval operations. In addition, energetic IWs contribute to enhanced vertical mixing and stratified variability, influencing nutrient redistribution, biogeochemical cycling, and regional ecosystem dynamics

3.3 Integrated model

The integrated model framework consists of a sequential integration between the MITgcm, the PWP mixed-layer model, and a GM IW model. The MITgcm provides the daily background state, while higher-frequency (hourly) variability is resolved through the coupled modeling system. The coupled framework is adopted to improve the representation of diurnal temperature and salinity. Table 1 summarizes the overall root-mean-square error (RMSE), averaged over depth (up to 200 m) and time, of diurnal density variability at the AD09 buoy location for the standalone MITgcm simulation and the integrated model. For all the four months, the integrated model exhibits lower RMSE than the standalone MITgcm simulations. Overall, these results demonstrate that embedding MITgcm within the coupled framework improves the representation of diurnal density variability, producing a more realistic simulation compared to the uncoupled MITgcm run.



Table 1. Overall root-mean-square error (RMSE), averaged over depth (up to 200 m) and time, of diurnal density variability at the AD09 buoy location for the standalone MITgcm simulation and the integrated model for January, April, July, and October 2018.

	RMSE (kg/m ³) (Observation vs MITgcm model)	RMSE (kg/m ³) (Observation vs Integrated Model)
Jan	0.3149	0.2938
Apr	0.3057	0.2634
Jul	0.6198	0.4406
Oct	0.3297	0.3242

Further, shallow- and deep-water environments exhibit distinct physical characteristics, necessitating different modeling approach. Accordingly, as described in Section 2.2, the shallow- and deep-water outputs of the integrated model are compared with CTD observations collected at Station A (Figure 1), where the local water depth is approximately 53 m. Comparison of the mean density profiles derived from the approximately five days of available observations with the integrated model output indicates improved agreement under the shallow-water configuration. Across most depths, the RMSE between the observations at Station A and the integrated model is larger for the deep-water configuration than for the shallow-water configuration. The depth-averaged mean density RMSE for the shallow-water configuration is approximately 0.014 kg m⁻³ lower than that of the deep-water configuration. Similarly, the buoyancy frequency analysis shows that, across most depths, the RMSE associated with the deep-water configuration of GM model is substantially higher than that of the shallow-water integrated model configuration. The depth-averaged RMSE for the shallow-water configuration is approximately 1.544 cph lower than that of the deep-water configuration, as shown in Fig 7. The observations correspond to May,



a period characterized by the development of the mini-warm pool in the southeastern AS. Station A is located within this region, where elevated surface temperatures lead to enhanced near-surface stratification and, consequently, higher buoyancy frequency in the upper water column. The observed increase in near-surface buoyancy frequency associated with the mini-warm pool is consistently captured by both shallow- and deep-water configurations (not shown here) of the integrated model, indicating that the model adequately represents the seasonal stratification signal in this region.

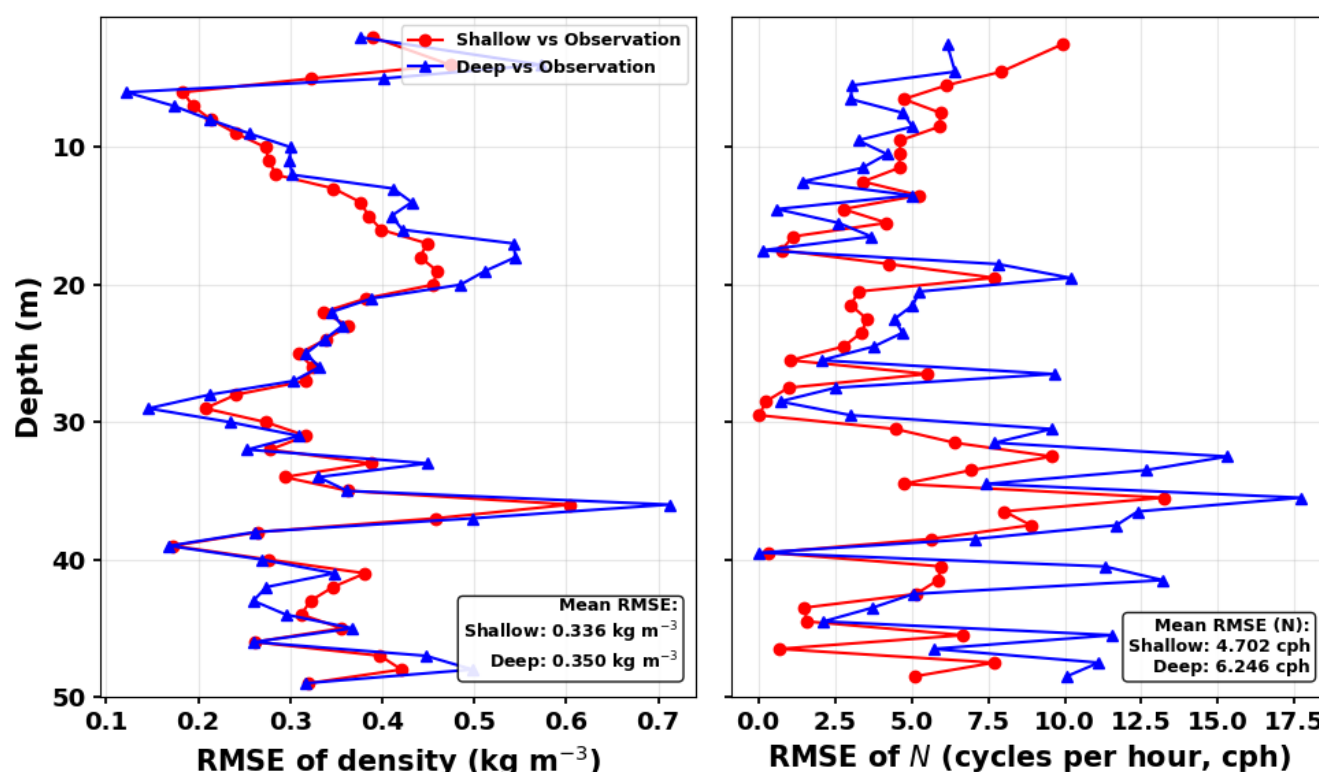


Figure 7: Time-averaged RMSE profiles of density (left panel) and buoyancy frequency (right panel) at Station A, comparing observations with the shallow-water (red) and deep-water (blue) model configurations. Depth-averaged RMSE values are indicated in the lower-right corner of each panel.

Based on this validation, the integrated model for shallow-water configuration is subsequently utilised to estimate IW-induced ID along the west coast of India. The analysis is conducted for four representative



months (January, April, July, and October) at six locations spanning south to north along major maritime regions of the western Indian coast (Figure 1), generating the ID across the 10 km horizontal range, as shown in Fig. 8. Six study locations, located geographically from south to north—Vellimallai, Kochi, Mangaluru, Goa, Jaigad and Mumbai, are shown in Fig. 1. The selected sites lie along the 50 m bathymetry contour and exhibit relatively uniform local bathymetry, representative of shallow-water conditions (Bianconi, 2002). Figure 8 illustrates snapshot corresponding to 23:00 IST on the 20th day of each selected month and illustrate the seasonal evolution of upper-ocean stratification along the west coast of India. At the selected snapshot (23:00 IST on day 20), the spatial distribution of ID along the west coast shows considerable variability among locations and seasons. In January, the maximum positive ID is observed at Mangaluru - Kochi, reaching ~12 m at a depth of around 17.5 m. In April, the maximum positive ID is observed at both Mangaluru and Mumbai, reaching ~9–12 m, with the peak displacement typically occurring at a depth of 32.5 m. During July, the largest positive ID is found at the northernmost location, Mumbai while Vellimallai at this snapshot experiences a strong negative ID too. In October, the largest displacement is observed at Mangalore - Kochi, reaching ~8 m at 32.5–47 m depth. Overall, the presence of significant ID along the west coast at this snapshot, highlights the strong influence of IWs in the shallow coastal regions.

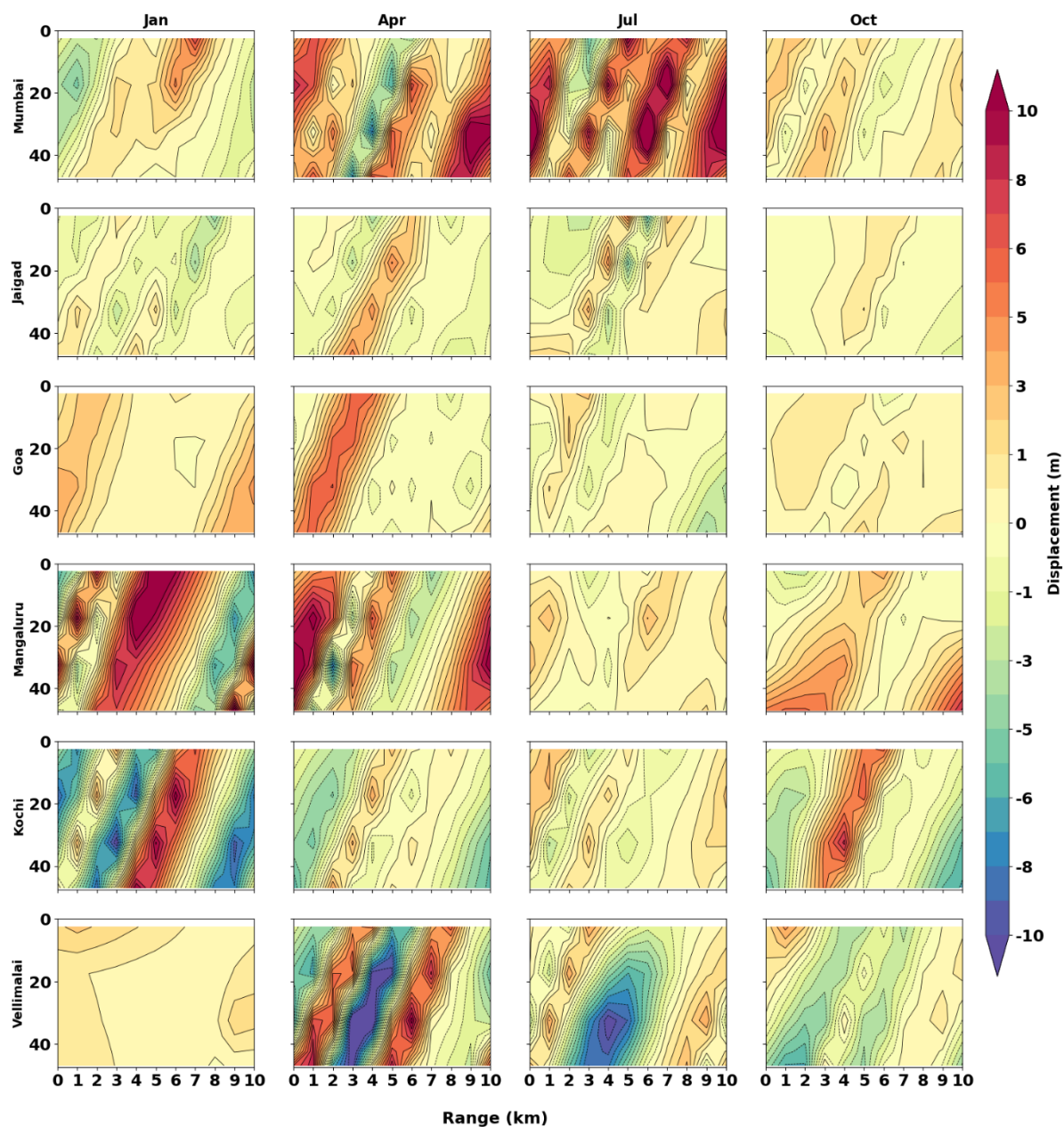


Figure 8: Vertical distribution of ID within a 10 km range offshore to Vellimalai, Kochi, Mangaluru, Goa, Jaigad, and Mumbai, simulated using the integrated model for shallow water at 23:00 IST on the 20th day of January, April, July, and October 2018.



548

549 During January (winter), enhanced surface heat loss over the northern AS cools the surface waters,
550 increasing density and promoting vigorous vertical mixing, which results in a deep mixed layer toward
551 the northern sector near Mumbai. The Mumbai location exhibits a maximum ID of 14 m on 27 January,
552 occurring at a depth of 32.5 m. In contrast, over the southern region near Vellimallai-Kochi, the intrusion
553 of low-salinity waters from the BoB leads to reduced surface density and the development of stratification
554 near the surface despite wintertime cooling. Vellimallai-Kochi records a maximum ID of ~18 m at a depth
555 of 17.5 m. By April (pre-monsoon), the west coast transitions into a warming regime characterized by
556 weak winds and increasing net surface heat flux, favoring the rapid establishment of thermal stratification.
557 The maximum ID is generally observed in the Mumbai–Jaigad region, reaching up to ~18 m, whereas at
558 the southern location of Kochi, the maximum ID is lower by approximately 4 m. Overall, the magnitude
559 of maximum ID shows an increasing tendency toward the northern locations, although these peak values
560 occurred at different dates and times. In the northern sector (Jaigad–Mumbai), weak mechanical mixing
561 combined with sustained surface heat gain results in strong near-surface stratification and elevated
562 buoyancy frequency, effectively preconditioning the upper ocean for the onset of the southwest monsoon.
563 During July, intense wind-driven coastal upwelling in the southern and central sectors (Kochi–
564 Mangaluru) brings cooler, denser subsurface waters to the surface, enhancing vertical mixing. These
565 locations experienced their maximum ID near the surface, at depths of approximately 12.5–17.5 m, with
566 magnitudes ranging between 13 and 18 m. Farther north (Jaigad–Mumbai), where upwelling weakens,
567 the maximum ID occurs at deeper depths of 32.5 m, with magnitudes of ~16 m. In October, the post-
568 monsoon transition is marked by weakening winds allowing stratification to re-establish at deeper depths
569 along the coast. The relaxation of monsoonal forcing suppresses coastal upwelling, particularly in the
570 southern sector, while surface warming and freshwater inputs enhance near-surface stratification.
571 Mumbai, influenced by freshwater influx from the Gulf of Khambat (Rao et al., 2009) exhibits a
572 maximum ID of ~17 m at a depth of 17.5 m. In contrast, at the southern location like Kochi the maximum
573 ID generally occurs with magnitudes of ~12m. Overall, the seasonal evolution highlights the dominant



574 role of air-sea heat fluxes, wind-driven mixing, and coastal upwelling in controlling stratification along
575 the west coast of India.

576 4 Conclusions

577 This study demonstrates the effectiveness of a coupled and integrated modelling framework in capturing
578 the diurnal and spatial variability of density structures in the eastern AS. The PWP model, coupled with
579 the IW model based on the GM spectrum, successfully simulates both temporal and spatial variations
580 (upto 10 km) in density profiles. The IW eigenvalue problem is solved using a finite-difference–Sturm
581 sequence–bisection–inverse iteration method, enabling the computation of spatial distributions of IDs
582 along with their temporal evolution. The coupled model results are validated against daily standard
583 deviation profiles for different months at AD08, AD09, and AD10, showing pronounced monthly and
584 seasonal variability in the diurnal density field over the eastern AS, which the model reproduces
585 reasonably well. Furthermore, the computed ID and sound speed fields are compared, revealing that
586 positive ID corresponds to an upward shift of the sound-speed contours, whereas negative ID results in a
587 downward shift of the sound-speed structure.

588 In addition, an integrated modelling approach is implemented by initializing the coupled framework with
589 outputs from 3D MITgcm simulation for four representative months corresponding to different seasons.
590 The integrated model demonstrates improved skill in simulating diurnal variability compared to the
591 standalone 3D MITgcm. However, the integrated model tends to underestimate variability within the
592 mixed layer during January. This limitation is primarily attributed to the ORAS5 reanalysis data used to
593 initialize the MITgcm simulations. For shallow-water regions, the modified shallow-water configuration
594 of the GM spectrum is incorporated, resulting in lower RMSE in hourly density simulations relative to
595 the deep-water configuration. Further, along the west coast of India—from the southern location at
596 Vellimallai to the northern site near Mumbai—within the shallow-water region, we evaluated the diurnal
597 variability in ID over a 10-km range induced by IWs for January, April, July, and October 2018. Our
598 analysis reveals that the largest positive IDs along the west coast of India are seasonally dependent.



During winter, peak displacements are observed in the southern sector, whereas in the remaining seasons, the northern region tends to dominate, with positive IDs reaching up to ~18 m at a local water depth of ~50 m, indicative of substantially energetic IW activity in the shallow coastal environment. In summary, both the coupled and integrated model configurations are systematically validated for multiple months in the eastern AS, and their performance is quantitatively assessed. The framework enables the estimation of IDs and sound speed variability within a spatial range of 10 km, thereby providing valuable inputs for acoustic studies. This study offers significant potential for investigating temporal and spatial variations in acoustic propagation and transmission losses. The integrated modelling approach can serve as a practical tool for investigating upper-ocean processes, particularly the role of IWs in modulating subsurface stratification and diurnal variability. Besides, it offers potential applications for naval operations where real-time temperature and salinity observations are often limited to simulate diurnal acoustic fields and its propagation losses in the presence of IWs.

Code and data availability. The source code for the Price–Weller–Pinkel (PWP) model used in this study is available from the public GitHub repository: https://github.com/earlew/pwp_python_00.git. Xmitgcm (Abernathey et al., 2021) and xgcm (Abernathey et al., 2022) are used for post-processing of the MITgcm model simulations. ORAS5 data are obtained from the Copernicus Marine Service: <https://doi.org/10.48670/moi-00024>. The ERA5 data sets are openly available from the Copernicus Climate Data Store. Hourly single-level variables are obtained from the ERA5 reanalysis single-level product (Hersbach et al., 2023b; <https://doi.org/10.24381/cds.adbb2d47>). The moored buoy data can be requested from the Indian National Centre for Ocean Information Services (INCOIS) website (<https://www.incois.gov.in/site/datarequisitionform.jsp>).

Author contributions. PM: conceptualization, formal analysis, investigation, methodology, software, validation, visualization, writing (original draft, review and editing). ADR: conceptualization,



methodology, supervision, visualization, writing (review and editing). BY: conceptualization, methodology, visualization, software, writing (review and editing). VP: writing (review and editing).

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