Impact of tidal mixing on mixed layer depth variability in the Northern Bay of Bengal

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Abstract. This study aimed to investigate the influence of tidal mixing on the Mixed Layer Depth (MLD) in the Northern Bay of Bengal (NBoB), providing insights into regional variations in oceanic mixing processes. The data used in this study consisted of daily MLD observations over a two-year period (2022–2023) from the Copernicus Marine Environment Monitoring Service (CMEMS) data portal. The analysis focused on three regions within the NBoB, determined based on the Simpson-Hunter (SH) parameter calculations which indicate the intensity of tidal mixing. The first region, identified by low tidal mixing (evidenced by a high SH parameter), is located between 85°E-87°E and 18.5°N-20°N. The second region, characterized by high tidal mixing (or low SH parameter), spans 90°E-92°E and 21°N-23°N. The third region, with moderate tidal mixing, covers 92°E-94°E and 18.5°N-20.5°N. The study reveals that Region 1 has the highest average MLD (14.85 m), Region 2 has the lowest average MLD (9.02 m), and Region 3 has an intermediate MLD (12.58 m). These findings highlight an inverse relationship between tidal mixing intensity and MLD, with stronger tidal mixing linked to shallower MLD.

1 Introduction

The Bay of Bengal's upper ocean circulation and thermohaline structure exhibit sensitivity to varying wind strengths and river salinity conditions, with stronger winds affecting temperature at greater depths and influencing surface circulation, freshwater plume dispersion, and coastal upwelling, while these effects vary between the northern and southern Bay [1]. The NBoB experiences relatively regular monsoons. The Northeast (NE) monsoon

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occurs from November to February, while the Southwest (SW) monsoon occurs from June to September, with wind stress and wind speed being stronger in August compared to February [2]. The mixed layer depth (MLD) plays a crucial role in understanding climate change and biological systems [3]. MLD also controls the exchange of heat, momentum, and trace gases between the ocean and the atmosphere [4]. Understanding MLD variability is essential for predicting climate variations and the distribution of marine resources [5-6].

Tidal mixing is one of the key processes influencing MLD and also impacts Chlorophyll-a (Chl-a) concentrations on shorter timescales, which is important to reconstruct [7, 8]. The impact of tidal mixing on MLD varies spatially and temporally, depending on tidal current strength, water column stability, and topography [9]. Tidal mixing affects stratification and water mass mixing, where regions with lower tidal energy experience stratification due to reduced mixing [10]. Shallow areas or areas with strong tidal currents, such as the NBoB [7], remain vertically mixed throughout the year because tidal turbulence consistently overcomes the stratification effects of solar heating [9].

Previous studies have investigated the relationship between tidal mixing and MLD in various parts of the world's oceans. For example, Simpson and Hunter [10] proposed a method for calculating the tidal mixing parameter using the Simpson-Hunter (SH) equation. The SH parameter is used as a metric to measure the intensity of tidal mixing and its impact on stratification. Regions with low SH parameter values (indicating strong tidal mixing) tend to have reduced stratification and shallower MLDs. Conversely, regions with high SH parameter values (indicating weak tidal mixing) exhibit deeper MLDs due to stronger stratification.

In the NBoB, several studies have focused on the seasonal and interannual variability of MLD [5, 11-13]. However, the specific impact of tidal mixing on MLD in this region, particularly in the NBoB, remains underexplored. This study aims to fill this gap by investigating how tidal mixing influences MLD in the NBoB using the SH parameter as an analytical tool. The research aims to measure the impact of varying tidal mixing intensity on MLD in the NBoB using data from 2022-2023.

2 Materials and methods

The data used in this study includes mixed layer depth (MLD) data with a 1/12° resolution for the 2022-2023 period, sourced from The Copernicus Marine Environment Monitoring Service (CMEMS) [14-15]. Another dataset used is tidal currents data from the Tidal Model Driver (TMD) with a 1/4° × 1/4° resolution [16].

This research focuses on three different regions within the NBoB, as shown in Fig. 1, each characterized by different levels of tidal mixing, as indicated by the SH parameter. Region 1, identified with low tidal mixing (high SH parameter), is located between 85°E and 87°E, and 18.5°N to 20°N. Region 2, characterized by high tidal mixing (low SH parameter), spans from 90°E to 92°E and 21°N to 23°N. Region 3, with moderate tidal mixing, covers 92°E to 94°E and 18.5°N to 20.5°N [7]. The data for each region were obtained by averaging the values from all grids within the designated box.

The Simpson-Hunter (SH) parameter is calculated by formula [7, 10]:

$$SH = log_{10}\left(\frac{h}{U_{tides}^3}\right), \tag{1}$$

where h is the average of depth of each region box, $U_{tides} = \sqrt{u^2 + v^2}$ is currents caused by the tides from 11 components (K1, K2, M2, M4, Mn4, Ms4, N2, O1, P1, Q1, S2). For the calculation of the SH parameter, the hourly tide data (u and v) is averaged to daily data, following the temporal resolution of the MLD data. To analyze the MLD and SH parameters, time series, violin plots, and statistical calculations are presented.

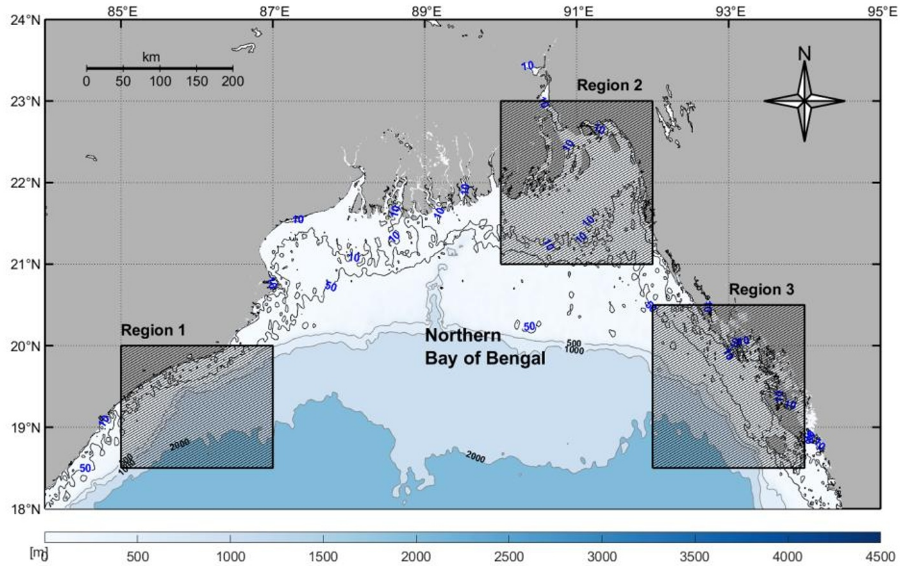


Fig. 1. Bathymetry of the Northern Bay of Bengal (NBoB). The color bar indicates depth in meters. This research will focus only in 3 regions, namely, Region 1 (85°E-87°E, 18.5°N-20°N), Region 2 (90°E-92°E, 21°N-23°N), and Region 3 (92°E-94°E, 18.5°N-20.5°N). The bathymetry data are derived from SRTM30+ [17].

3 Results and discussion

Fig. 2 presents time series data for MLD, tidal currents, and the SH parameter across the three study regions from January 2022 to December 2023.

In general, Fig. 2a shows that the highest MLD values occur in Region 1, followed by Region 3 and Region 2. Fig. 2b displays the highest tidal currents in Region 2, followed by Region 3 and then Region 1. Meanwhile, Fig. 2c shows the highest SH parameter values in Region 1, followed by Region 3 and Region 2. This indicates that the strongest tidal mixing occurs in Region 2, followed by Region 3 and Region 1.

Fig. 3 shows violin plots depicting the distribution of MLD and SH parameters across Regions 1, 2, and 3 from January 2022 to December 2023. Each violin plot combines the features of a box plot and kernel density estimation, providing a more detailed view of the data distribution in each region. The density estimation indicates where data points are concentrated or sparse, with wider sections of the plot representing higher data frequency. The horizontal lines within the violins indicate the mean, while the white dots represent the median [18]. In each region, the violin plot clearly visualizes the variability of the MLD and SH parameters, allowing for comparisons of distribution shapes, central values, and spread between the two variables.

Table 1, derived from Fig. 2 and Fig. 3, provides summary statistics including the minimum (Min), maximum (Max), mean, and standard deviation (STD) for MLD and SH parameters in Regions 1, 2, and 3.

According to Table 1, MLD in Region 1 has a Min of 10.53 m, Max of 30.02 m, Mean of 14.85 m, and STD of 4.13 m, indicating the highest MLD variation compared to Regions 2 and 3. Conversely, Region 2 has a Min MLD of 8.65 m, Max of 12.18 m, Mean of 9.03 m, and STD of 0.37 m, showing the lowest MLD variation among the regions.

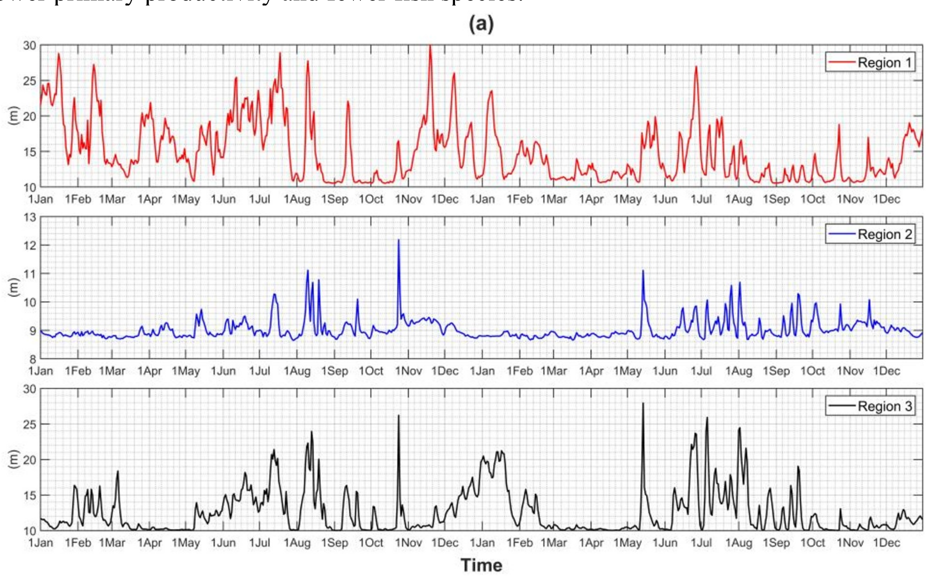
The SH parameter in Region 1 has a Min of 7.8, Max of 9.84, Mean of 8.47, and STD of 0.45, showing the highest SH parameter variation compared to Regions 2 and 3. Conversely,

Region 2 has a Min SH parameter of 2.34, Max of 3.37, Mean of 2.79, and STD of 0.25, indicating the lowest SH parameter variation among the regions.

The results from Fig. 2 and Table 1 reveal significant trends linking MLD variations and tidal mixing across Regions 1, 2, and 3. The shallowest MLD in Region 2 appears to correlate with high tidal currents and low SH parameter values, indicating strong tidal mixing. This inverse relationship between MLD and tidal mixing is further supported by the deeper MLD and high SH parameter values in Region 1, which suggest weak tidal mixing. The MLD and SH parameter distribution patterns shown in Fig. 3 align consistently with the findings in Fig. 2 and Table 1 across all regions.

[19] classified SH parameter values into three categories: strong tidal mixing for values below 2, moderate tidal mixing for values between 2 and 2.8, and weak tidal mixing for values above 3. Meanwhile, the results from Fig. 2 and Table 1 indicate strong tidal mixing in Region 2, with values ranging from 2.34 to 3.37; moderate tidal mixing in Region 3, with values between 4.96 and 6.72; and weak tidal mixing in Region 1, with values ranging from 7.8 to 9.84. These differences highlight the unique characteristics of the NBoB. These findings are consistent with those of [7], which also reported strong tidal mixing in Region 2, moderate mixing in Region 3, and weak mixing in Region 1.

It appears that strong tidal mixing may have a potential relationship with lower MLD. Further recommendations suggest observing other areas with high tidal strength for additional insights. The findings of this study have important implications for the distribution and abundance of fish in the NBoB. Tidal mixing significantly influences the physical and biological properties of the ocean. [20] and [21] researched tidal mixing and found that during periods of high tidal energy with pronounced tidal mixing, essential nutrients are brought to the surface layer, fostering photosynthetic growth. In Region 2, characterized by strong tidal mixing, nutrient-rich waters are uplifted, enhancing primary productivity and supporting a robust food web that attracts pelagic fish and higher trophic-level predators. The presence of fish in this region is supported by the findings of [22] and [7]. Region 2 exhibits high concentrations of Chl-a and nutrients, with phosphate being limited during the post-monsoon period and light availability constrained during the remainder of the year [7,22]. In contrast, in Region 1, where tidal mixing is weak, nutrient upwelling is limited, potentially leading to lower primary productivity and fewer fish species.



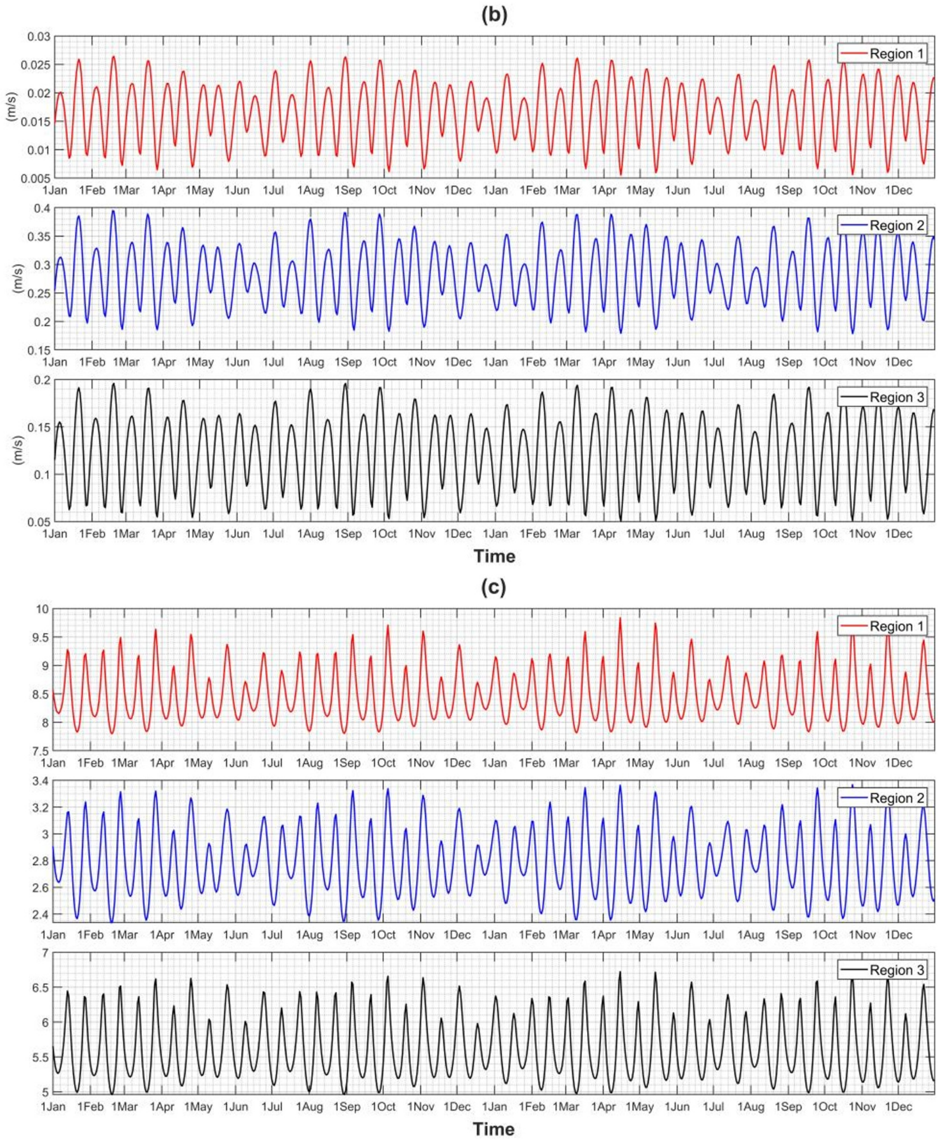


Fig. 2. Time series of (a) MLD, (b) tidal currents, and (c) SH parameter in Region 1, 2, and 3 from January 2022 to December 2023.

Table 1. Minimum (Min), maximum (Max), mean, and standard deviations (STD) of MLD (unit in m) and SH parameter (dimensionless) for Regions 1, 2, and 3.

Variables	Regions	Min	Max	Mean	STD
MLD	1	10.53	30.02	14.85	4.13
	2	8.65	12.18	9.03	0.37
	3	10.01	27.93	12.58	3.13
SH parameter	1	7.80	9.84	8.47	0.45
	2	2.34	3.37	2.79	0.25
	3	4.96	6.72	5.63	0.44

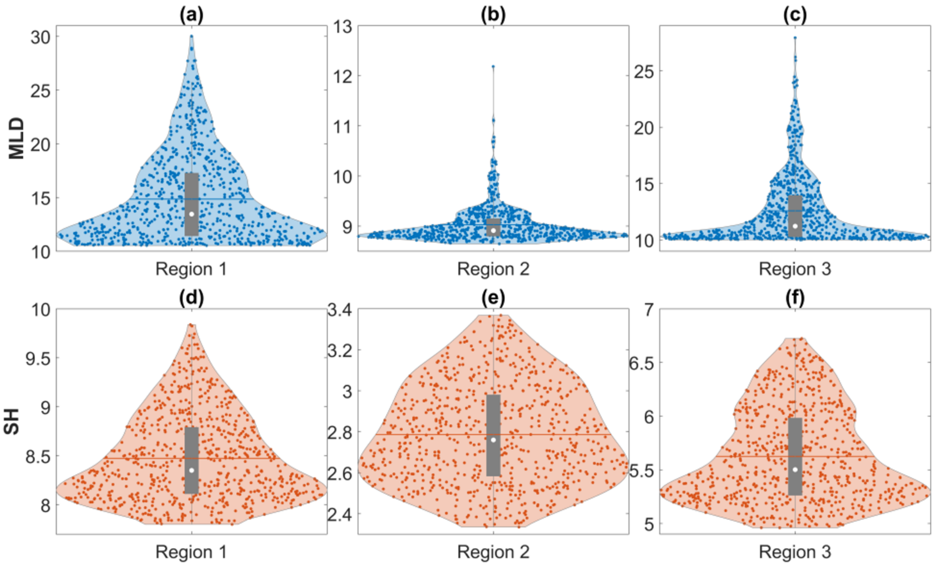


Fig. 3. Violin plot of MLD (blue color) and SH parameters (orange color) in Region 1, 2, and 3 from January 2022 to December 2023. The plot shows the data distribution, density estimation, boxplot, mean (horizontal lines), and median (white dots) for each region.

4 Conclusions

In conclusion, the analysis of MLD, tidal currents, and SH parameters in Regions 1, 2, and 3 reveals distinct patterns in their distribution and variability. Region 1 consistently shows the highest MLD and SH values, while Region 2 experiences the strongest tidal currents and the lowest variability in both MLD and SH parameters. Strong tidal mixing is identified in Region 2, with SH parameter values ranging from 2.34 to 3.37; moderate tidal mixing is observed in Region 3, with values between 4.96 and 6.72; and weak tidal mixing is present in Region 1, with values ranging from 7.8 to 9.84. The distributions of MLD and SH parameters highlight the differences in variability and central tendencies among the regions, with Region 1 exhibiting the greatest variation and Region 2 demonstrating the least variability. These findings suggest a potential relationship between strong tidal mixing and lower MLD, particularly in Region 2, where nutrient-rich waters are uplifted, supporting primary productivity. Future studies should focus on areas with strong tidal current forces to better understand the relationship between tidal mixing and MLD, as well as their implications for biological productivity and ecosystem dynamics.

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