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Comparative Analysis of Co-Tidal Patterns in the Sunda Strait Using Tide Gauges, Altimetry Data, and TPXO9v4a Global Tide Model

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ABSTRACT

The Sunda Strait, a narrow and topographically complex passage between Java and Sumatra, presents unique challenges for accurate tidal modeling. This study evaluates tidal dynamics across the strait using three data sources: in-situ tide gauge measurements, Jason-2/3 satellite altimetry (processed with ALES retracking), and the TPXO9v4a global barotropic tidal model. Harmonic analysis was conducted for eight principal constituents across four tide gauge stations, with amplitude and phase comparisons revealing substantial overestimation and lead bias in TPXO—particularly for M2, where amplitude discrepancies exceeded 500%. Altimetry data showed closer agreement, especially in semidiurnal constituents, but remained limited by land contamination and coarse temporal resolution. Co-amplitude and co-phase maps constructed from the datasets revealed complex propagation features, including strong spatial phase gradients and potential amphidromic behavior, not captured by TPXO. Statistical tests confirmed significant differences between model and observational datasets. Additionally, tidal regime analysis using form factor classification confirmed a consistent mixed, mainly semidiurnal regime, though altimetry occasionally overestimated diurnal influence. These findings demonstrate the inadequacy of global tidal models alone in resolving nearshore dynamics and support the use of integrated observational-modeling frameworks for improved regional tidal characterization in Indonesia's coastal waters.

Keywords: Coastal Altimetry, TPXO9v4a, Harmonic Analysis, Sunda Strait, Co-tidal Chart

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1. Introduction

Tides are a fundamental aspect of the coastal hydrodynamic environment, providing essential information for geodetic referencing, hydrographic charting, and coastal infrastructure planning (Nadzir & Adil, 2024). Accurate tidal characterization is crucial for coastal engineering, hydrography, and navigation. Their spatial expression is commonly represented through co-tidal charts, which describe the distribution of tidal amplitude and phase and help reveal tidal wave propagation, resonance, and local amplification processes (Haigh et al., 2020; Pugh & Woodworth, 2014). Co-tidal charts are instrumental in determining the timing and spatial variability of tidal waves, which support the definition of vertical datums, aid in coastal zone management, and enhance the safety of maritime navigation, especially in maritime nations like Indonesia. In Indonesia, with over 16,000 islands and the world's second-longest coastline, the need for accurate co-tidal information is particularly urgent because the country has an extensive coastline, a complex archipelagic geometry, and a limited distribution of long-term tide gauge stations. This challenge is especially critical in the Sunda Strait, one of the main maritime corridors in Indonesia and part of ALKI I, where strong tidal variability intersects with intensive shipping activity, narrow bathymetry, and complex coastal morphology (Sobaruddin et al., 2017; Susanto et al., 2016).

Conventional co-tidal charts have traditionally relied on tide gauge and direct field measurement data. However, the sparse distribution of tide gauges in Indonesia undermines spatial interpolation quality (Fenoglio-Marc et al., 2012; Fitriana et al., 2022). Satellite altimetry, particularly from missions like Jason-2 and Jason-3, provides valuable sea surface height (SSH) observations with near-global coverage. Still, accuracy degrades near the coast due to signal contamination from land, sea state bias, and reduced retracker performance (Birol et al., 2021; Nadzir & Hasan, 2025; Passaro, Rose, et al., 2018; Vignudelli et al., 2019). Corrections are typically applied for wet tropospheric delay, ionospheric delay, sea state bias, instrumental effects, dynamic atmospheric correction, and inverse barometer

effects to mitigate these challenges, though residual errors often remain significant in coastal zones due to land contamination and complex bathymetry (Passaro, Nadzir, et al., 2018). At the same time, global tide models such as TPXO provide complete spatial fields of tidal amplitude and phase, but their performance in narrow tropical straits with strong bathymetric gradients and nonlinear coastal effects remains insufficiently validated (Carrere et al., 2021; Egbert & Erofeeva, 2021). Therefore, in a setting such as the Sunda Strait, it is still unclear whether model-based and altimetry-based tidal parameters are sufficiently consistent with local tide-gauge observations to support reliable co-tidal mapping.

Modern co-tidal chart generation leverages a combination of satellite altimetry, tide gauge networks, and numerical tidal modeling. Traditional harmonic analysis, while still foundational, has been greatly enhanced through data-assimilative global models like TPXO, FES2014, and GOT4.10c, which provide constituent-specific amplitude and phase fields with high spatial resolution (Hart-Davis et al., 2021; Lyard et al., 2021; Querin et al., 2021; Ray, 2013). Coastal altimetry improvements—such as the ALES retracker and SAR altimetry from Sentinel-3—have pushed the effective observation window closer to the coastline, reducing biases and improving reliability for co-tidal analysis in complex nearshore regions (Chen et al., 2023). In recent years, unstructured-grid hydrodynamic models like ADCIRC and SCHISM have gained traction. These models allow fine-scale simulation in areas with steep gradients and convoluted coastlines, enabling better representation of resonance zones, amphidromic systems, and wave reflection patterns (Yu et al., 2017). The integration of these tools marks a significant advancement in the generation and validation of co-tidal charts, especially in topographically complex and data-scarce regions. However, the benefits of these developments are not automatically transferable to narrow tropical straits, where observational sparsity, coastal contamination, and unresolved bathymetric controls may still produce substantially different co-amplitude and co-phase patterns.

In the Indonesian context, tidal studies have mainly focused on model evaluation, regional harmonic analysis, or local sea level variability rather than on explicit co-tidal chart comparison across multiple datasets. Studies such as Nugroho et al. (2018) have assessed the tidal model's performance across the Indonesian seas and highlighted persistent underestimation of amplitude in narrow straits and the difficulty in resolving mixed semidiurnal-diurnal regimes. Additionally, regional-specific studies have mainly focused on specific coastal sectors such as the western coast of Lampung (Julianto et al., 2021), the Java Sea (Putra & Pratomo, 2017), and eastern Indonesian waters (Nurhayati & Wijaya, 2024). Umaroh et al. (2017), using altimetry-derived sea level data in the Arafura Strait, found considerable variability that could be linked to local bathymetric influences and forcing. Ichikawa, (2023) found that based on the sea surface height variation, a current flowed from Celebes Sea to Java Sea. However, for the Sunda Strait specifically, a systematic evaluation of whether tide gauges, coastal altimetry, and a global tide model produce consistent M2 co-amplitude and co-phase patterns is still lacking, only covered partly on a sea-level rise study on the Banten side (Nadzir et al., 2025). This gap is important because the Sunda Strait is not only a scientifically complex tidal environment, but also a high-priority maritime corridor requiring accurate tidal information.

Accordingly, this study evaluates the consistency of M2 tidal amplitude, phase, and co-tidal patterns in the Sunda Strait using three data sources: four tide gauge stations, Jason-2/3 coastal altimetry dataset processed with ALES retracker, and TPXO9v4a global tide model. The focus on M2 is motivated by its dominant role in the semidiurnal tidal signal and its central importance for co-tidal interpretation in the region. Rather than assuming that all datasets contribute equally, this study explicitly tests whether coastal altimetry adds meaningful spatial information beyond tide gauges and a global tide model in a narrow tropical strait. The results are expected to support improved regional tidal mapping, coastal modeling, and geodetic applications requiring accurate phase and amplitude information.

2. Data and Methods

2.1. Study Area

The Sunda Strait (Selat Sunda) is a major marine passage separating the islands of Sumatra and Java, with an average width of ~30 km and water depths ranging from shallow coastal zones (~10 m) to deeper central basins exceeding 100 m, as depicted on **Figure 1**. It serves as a critical segment of Indonesia's Archipelagic Sea Lanes (ALKI I), enabling the movement of both domestic and international maritime traffic between the Java Sea and the Indian Ocean (Hastuti & Cahyono, 2019). Beyond its geopolitical significance, the Sunda strait plays a crucial role in oceanographic and tidal dynamics within the maritime continent. Hydrodynamically, Sunda Strait is influenced by multiple interacting forces: Indian Ocean swell propagation, seasonal monsoon winds, and strong tidal forcing from both the Indian Ocean (predominantly semi-diurnal) and the Java Sea (where mixed tides dominate). This results in complex tidal characteristics, often leading to the formation of amphidromic points, resonance zones, and non-linear tidal interactions (Daryabor et al., 2016; Mujiasih et al., 2025). The strait's unique geometry—featuring a bottlenecked passage, multiple small offshore islands (e.g., Sangiang, Sebuku), and rugged bathymetry—further complicates tidal wave propagation, energy dissipation, and phase lag distribution (Li et al., 2018; Tondang et al., 2020). Previous studies have observed spatial inconsistencies in tidal amplitude and phase along the strait's length, suggesting strong lateral tidal gradients that may not be adequately captured by coarse-resolution

global models or sparse observational networks (Oktavia et al., 2011; Pratama et al., 2020). Additionally, the Sunda Strait is subject to tectonic and volcanic influences, including proximity to the Krakatau volcanic complex, which may introduce transient sea level disturbances and morphological changes affecting local tidal dynamics (Susanto et al., 2016). These natural complexities make the Sunda Strait an ideal natural laboratory for testing co-tidal chart generation methods and evaluating the synergy between tide gauge, altimetry, and model-based tidal datasets.

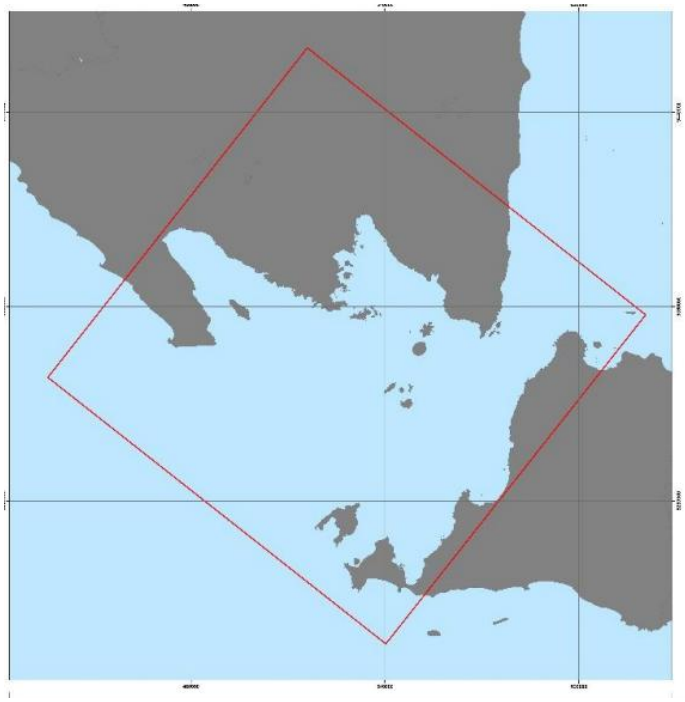


Figure 1. Study Area

2.2. Data and Methodology

This study integrates three datasets—tide gauge observations, Jason-2/3 coastal altimetry, and the TPXO global tide model—to construct and compare co-amplitude, co-phase, and co-tidal charts of the M2 constituent in the Sunda Strait. In this framework, tide gauges are treated as the primary local observational reference, TPXO9v4a is used as the principal spatial tide model, and coastal altimetry is used as an additional dataset to test whether it contributes useful spatial information in a narrow tropical strait. Additionally, the official administrative provinces boundary on the study area (available on https://tanahair.indonesia.go.id/) are also acquired. The workflow consists of data acquisition, quality control, harmonic analysis, and spatial harmonization.

2.2.1. Tide Gauge and its Harmonic Analysis

Hourly sea level data from four tide gauge stations—Ciwandan, Marina Jambu, Panjang and Kota Agung—managed by Indonesia's Geospatial Information Agency (BIG, https://srgi.big.go.id/tides) were used, covering the period 2015–2020. Each station was selected based on proximity to the coastline and data continuity. Basic quality control was applied, including outlier removal using interquartile filtering, gap-filling through linear interpolation (for gaps < 6 hours) and consistent referencing to Mean Sea Level (MSL) to allow cross-comparison. Harmonic analysis of these tide gauge time series was conducted using the classical least squares method (Pawlowicz et al., 2002). Although several major constituents were computed for tidal regime classification, the present analysis focuses on the M2 constituent because it is the dominant semidiurnal constituent and the basis for the co-tidal chart in this study.

2.2.2. Coastal Altimetry Data

Coastal altimetry-derived Sea Surface Height (SSH) data were sourced from the Jason-2 and Jason-3 missions. These data were processed using the Adaptive Leading Edge Subwaveform (ALES) retracker to improve accuracy near the coast (Passaro et al., 2014, 2015) and were acquired from openADB portal (https://openadb.dgfi.tum.de/en/). All tracks within ±0.5° of the Sunda Strait were considered, namely on pass 153, 166, 229 and 242. Corrections applied to SSH included wet and dry tropospheric delay ($trop_{wet}, trop_{dry}$), ionospheric delay ($iono$), sea state bias (ssb), and dynamic atmospheric correction (iB) as shown in **Equation (1)**, in addition to alt as the satellite altitude above the reference ellipsoid and h as the altimeter range. Altimetry time series were harmonically analyzed at each point using the same technique as for the tide gauges, after binning along-track data into 3-km spatial radius and removing anomalous cycles (Nadzir, 2017).

$$SSH = alt - h - trop_{wet} - trop_{dry} - iono - ssb - iB \quad (1)$$

Because Jason repeat-orbits revisit approximately every 10 days, direct harmonic estimation is affected by tidal aliasing. Therefore, the harmonic analysis of binned altimetry data was performed using constituent frequencies adjusted for the repeat-cycle aliasing, following the procedure described by Julianto et al. (2021) and Lase & Nadzir, (2025). The resulting harmonic constants were then used for pointwise comparison against tide gauges and for spatial mapping.

2.2.3. TPXO9v4a Tide Model

The TPXO9v4a global tide model from Oregon State University (https://www.tpxo.net/home) provides amplitudes and phases of major tidal constituents at 1/30° spatial (Egbert & Erofeeva, 2021). The model is based on barotropic assimilation of multiple altimetry missions, including Topex/Poseidon, Jason, and Envisat. For the Sunda Strait, 49 model grid points were extracted within the area of interest to represent the spatial pattern of M2

amplitude and phase. For station-based comparison, the nearest TPXO grid node to each tide gauge station was selected. For mapping, all extracted TPXO points were retained to preserve the model's spatial structure across the strait.

2.2.4. Processing Methodology

After all data are acquired, the next step is to compute and retrieve harmonic tidal constituents out of each data, as shown in **Figure 2**. The intercomparison was carried out in two steps. First, a 1-day visual comparison between tide gauge observations and TPXO-predicted tides was performed to assess short-term coherence of tidal oscillations. A 24-hour window was used in the visual comparison because it captures one complete daily tidal oscillation and allows a straightforward assessment of waveform agreement, phase offset, and amplitude difference between observations and model output. Second, quantitative validation focuses primarily on the M2 amplitude and phase, which form the basis of the co-amplitude, co-phase, and co-tidal analysis. Additional constituents were retained only for tidal regime classification. For the TPXO tide model, it is directly computed from the model itself, as it is available on each principal tidal constituent, one of them is M2. To allow coherent spatial and temporal comparison as an accuracy metric with Root Mean Square Error (RMSE) as the parameter, all datasets were harmonized, using tide gauge location as the reference location for altimetry and global tide models. Meanwhile, the co-tidal chart is built with a unified spatial grid of 0.16° x 0.16° (10 arc-minutes) resolution. M2 amplitude and phase values from each dataset were interpolated using inverse distance weighted (IDW) algorithm as utilized on Simarmata et al. (2023). Co-amplitude and co-phase maps were constructed using GMT (Wessel et al., 2019) and GIS software. Differences in amplitude and phase were statistically validated with forty sample points using Root Mean Square Difference (RMSD), Pearson correlation coefficient (r) and paired z-test for significant differences in mean amplitude and phase. These sample points were selected from the common interpolated domain to represent the spatial variability of M2 amplitude and phase across the study area, covering the northern, central, and southern parts of the strait. Additionally, the tidal regime (Formzahl number) from the study area are computed using **Equation (2)** (Huang & Yu, 2024). This enabled categorization into semi-diurnal, mixed, or diurnal regimes (Hogarth et al., 2021). In the final co-tidal chart, the interpolated M2 co-amplitude field was displayed as a raster surface, while the M2 co-phase field was represented by contour lines, so that both the spatial distribution of tidal range and the propagation pattern could be interpreted simultaneously.

$$F = \frac{K_1 + O_1}{M_2 + S_2} \quad (2)$$

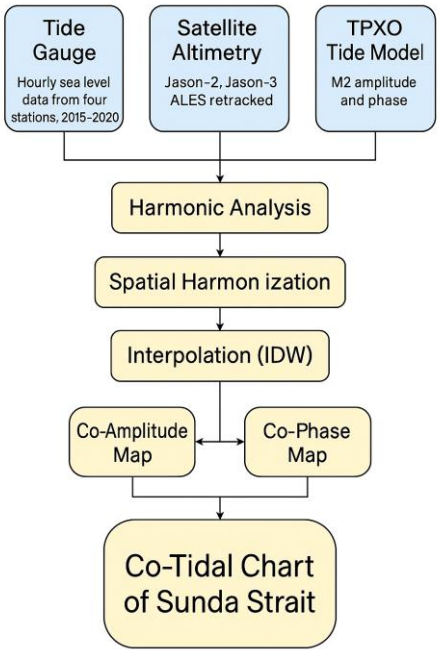


Figure 2. Flowchart of the Processing

3. Results and Discussion

3.1. Correlation Similarity Analysis

To assess short-term coherence between observational and model-based tidal data, a comparative analysis of 1-day sea level records (24-hour duration) from tide gauge stations and the TPXO9v4a global tidal model was conducted for the M2 tidal constituent. This analysis provides insight into the temporal fidelity of the model in replicating the local tidal signal at each station. **Figure 3** illustrates overlayed time series plots of observed (tide gauge) and modeled (BIG and TPXO) sea level data for Panjang station as an example. In general, TPXO and BIG tide models reproduce the primary tidal cycles, capturing both high and low water events, with visible alignment of waveform patterns. However, slight amplitude underestimation and minor phase shifts are evident in some stations—particularly at Kota Agung and Panjang. These discrepancies are likely due to the TPXO model's spatial resolution (~1/30°) and its simplified bathymetric representation in complex coastal environments.

To quantify these observations, Pearson correlation coefficients were calculated, revealing high linear correlation across all stations: 1) Ciwandan: r = 0.96; 2) Marina Jambu: r = 0.93, 3) Panjang: r = 0.91, and 4) Kota Agung: r = 0.89. The corresponding Root Mean Square Error (RMSE) values ranged from 6.8 cm (Ciwandan) to 11.7 cm (Kota Agung), confirming the relatively higher error in regions where model misrepresentation of local bathymetry and coastal complexity is more likely. These findings are consistent with previous regional evaluations of TPXO in Indonesian waters. For example, (Nurhayati &

Wijaya, 2024) found systematic underestimation of tidal amplitude and phase delays in narrow straits of the Indonesian archipelago when using TPXO models. Similarly, (Munir et al., 2020) showed that TPXO-derived sea levels in Makassar Strait exhibited strong correlation with in-situ records ($r > 0.9$) yet consistently underestimated high water marks due to spatial smoothing in the assimilation.

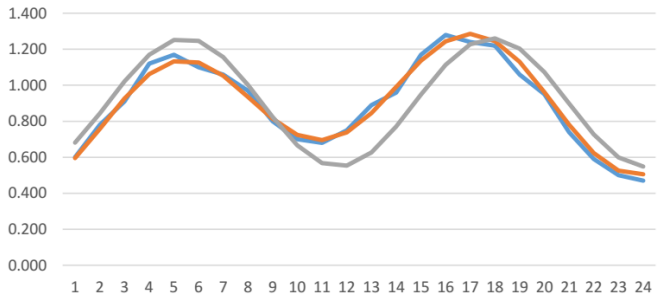


Figure 3. Visual comparison on Panjang TG

Additional discrepancies may also arise from tidal asymmetry and shallow-water constituents (e.g., M4), which are not represented in TPXO (Green, 2010). In high-gradient areas such as the Sunda Strait, tidal wave transformations due to bathymetric bottlenecks, bottom friction, and reflection further complicate the comparison. Despite these limitations, the high correlation levels suggest TPXO remains a robust reference for large-scale tidal analysis in the Sunda Strait. Nevertheless, for high-precision applications such as geodetic datum realization, coastal hydrodynamic modeling, or inundation forecasting, local enhancement through in situ data assimilation or high-resolution regional modeling is recommended.

3.2. Harmonic Principal Tidal Constituents Comparison

This section compares the harmonic parameters—specifically amplitude and phase—of eight principal tidal constituents derived from three data sources: tide gauge observations, TPXO9v4a global tidal model output, and satellite altimetry (Jason-2/3 with ALES retracking). The goal is to evaluate consistency in constituent estimation across observational and model-based platforms and identify spatial or source-dependent deviations within the Sunda Strait.

The harmonic analysis of the four tide gauge stations—Panjang, Kota Agung, Ciwandan, and Marina Jambu—reveals distinct spatial variability in the amplitude of the principal tidal constituents, as listed on **Table 1.** The most dominant constituent across all stations is M2, with amplitudes ranged from 4 cm for S2 (Ciwandan) to 8 cm for M2 (Panjang and Marina Jambu) where semi-diurnal constituents are consistently ranked higher than the diurnal constituents . It is consistent with the expected strong mixed-semidiurnal regime in the Sunda Strait (Holgate et al., 2013). In detail, Panjang and Marina Jambu display the strongest M2 amplitudes, each at 7.9 cm, indicating high energy semidiurnal forcing in the mid-northern and eastern sections of the Strait. S2 amplitudes are also significant at Panjang (5.8 cm) and Kota Agung (5.8 cm), contributing to the total semidiurnal energy. Ciwandan, in contrast, shows significantly lower amplitudes for M2 (2.1 cm) and S2 (2.1 cm), which may reflect either a local node or bathymetric shielding near the mouth of Banten Bay. The presence of K2 at 2.8–3.7 cm in some stations suggests a notable second-order semidiurnal component, possibly driven by local resonance or interactions with topographic features (Talke & Jay, 2020; Zaron, 2017). Meanwhile, K1 dominates the diurnal spectrum at Kota Agung (7.4 cm) and Ciwandan (2.6 cm), likely influenced by the mixed tidal character entering from the Java Sea and Coriolis effects in these coastal configurations. O1 and P1 values are moderate (e.g., O1: 2.7 cm at Kota Agung, P1: 1.4 cm), highlighting the contribution of lunar diurnal tides.

In contrast, the TPXO9v4a model yields significantly higher amplitudes for these same constituents. For example, TPXO estimates for M2 across corresponding spatial grid points range from ~33.3 to 34.6 cm, compared to an average tide gauge value of 5.1 cm, representing a mean overestimation of approximately 28.2 cm (~553%) for M2 alone. This overestimation trend is also found in the other constituents, particularly S2 and K2, with smaller—but still noticeable—biases for diurnal tides like K1 and O1. This bias is likely due to TPXO's limited resolution (~1/30°) and absence of localized coastal effects such as friction, reflection, and shallow-water transformation. As (Arbic, 2022; Ray et al., 2011) have shown, barotropic tidal models assimilating altimetry are robust offshore but struggle near complex coastlines due to unresolved bathymetry and missing physics. For coastal altimetry (Jason-2/3 with ALES retracking), M2 amplitudes retrieved near Panjang and Marina Jambu average around 18.3 cm, which is still higher than the observed 7.9 cm but notably closer than TPXO. This suggests a mean overestimation of ~11.2 cm (~220%) for M2 when using altimetry with additional discrepancy detected on further semi-diurnal and diurnal constituents (S2 with 152% overestimation, K1 with 100% overestimation and O1 with 129% overestimation).

The coastal altimetry results occupy an intermediate position between tide gauges and TPXO. It shows better agreement to the tide gauges than TPXO, particularly for semi-diurnal constituents. However, accuracy degrades for diurnal constituents—especially in narrow coastal channels—due to signal aliasing, land contamination, and reduced waveform quality. These results are in line with previous research (Birol et al., 2025; Nadzir et al., 2015). They observed that retracking (e.g., ALES) improves coastal performance, under-filtering and geophysical corrections still induce systematic amplitude biases. The altimetry data recorded amplitude ranged between 2.4 mm to 84.3 cm throughout the study region. One note needs to be taken that the coastal altimetry data, due to its observation system, is distributed in a crisscross pattern that resembles their ground track, which differs a bit from the tide gauges

that are a point-wise observation or tide model that is in the form of regular rectangular grid.

Table 1. Amplitude of Principal Tidal Constituents on 4 TG

Panjang		Kota Agung		Ciwandan		Marina Jambu	
Cons	Value [cm]	Cons	Value [cm]	Cons	Value [cm]	Cons	Value [cm]
M2	7.9	K1	7.4	K1	2.6	M2	7.9
S2	5.8	S2	5.8	M2	2.1	S2	4
K2	3.7	M2	3	S2	2.1	K1	1.9
N2	2.2	K2	2.8	K2	1.8	O1	1.4
K1	1.7	O1	2.7	P1	1.3	K2	1.2
O1	1	N2	1.4	N2	1	P1	0.8
P1	0.6	P1	1.4	O1	0.6	N2	0.5
Q1	0.2	Q1	0.2	Q1	0.1	Q1	0.2

Phase values represent the timing of the maximum of each tidal constituent relative to reference time and are essential for understanding the spatial propagation of tidal waves. The observed variations across the four stations in the Sunda Strait reveal complex spatial and temporal dynamics, listed on **Table 2**.

M2 phase varies considerably across stations, with values ranging from 74.7° at Kota Agung to 286.6° at Ciwandan, indicating a delay in tidal wave arrival as the wave propagates along the strait. The large difference (~210°) between Kota Agung and Ciwandan suggests wave reflection or amphidromic behavior, consistent with known complexities in the Sunda Strait (Yuningsih & Saputra, 2021). Panjang (264.5°) and Marina Jambu (112.8°) also show significant offsets, suggesting tidal wave entry from both ends (Java Sea and Indian Ocean), with wave interaction in between. Similar spatial shifts are evident in S2 and K2 phases, further indicating nonlinear propagation and refraction effects induced by local bathymetry and the narrow passage geometry. The N2 constituent follows the M2 pattern but appears more erratic—possibly reflecting its smaller amplitude and greater susceptibility to local influences and noise. Meanwhile, diurnal phases are highly variable, especially for K1 and O1, K1 ranges from 23.6° (Panjang) to 332.4° (Marina Jambu) while O1 also exhibits wide variability, from 155.6° (Panjang) to 359.4° (Marina Jambu). This dispersion may reflect the mixed tidal regime and Coriolis-induced tidal rotation, as well as tidal resonance within embayment and (Masson & Fine, 2012). The consistent increase in diurnal phases from west (Panjang, Kota Agung) to east (Ciwandan, Marina Jambu) may hint at an eastward tidal wave propagation for diurnal constituents, in contrast with semidiurnal propagation. The wide inter-station phase differences, especially in M2 and K1, imply the possibility of amphidromic systems or standing wave characteristics in the strait, where phase shifts significantly over short distances. Similar observations were made by (Kusuma et al., 2021) in their study of tides in the Jakarta Bay, where bathymetric constrictions led to phase jumps.

The TPXO9v4a model shows relatively consistent M2 phases across the region, centered near 354°–355°, with small standard deviations across the 49 spatial points. When compared to the tide gauge observations at Panjang, the phase difference is ~90.5° earlier (TPXO: ~355° vs. TG: 264.5°) whereas at Kota Agung, the TPXO leads by ~280° (TG: 74.7° vs. TPXO: ~355°). This phase lead is symptomatic of TPXO's inability to resolve shallow water delay and channelized wave trapping, resulting in a homogenized propagation signal. These phase differences exceed the 15–30° thresholds often cited for acceptability in coastal applications (Pan et al., 2025), indicating the need for regional tide modeling or assimilation of local observations. Altimetry-derived phases (from ALES retracking) show greater spatial variability and closer agreement with tide gauges with M2 altimetry phase averages ~266°, closely matching Panjang TG (264.5°). For diurnal constituents, phase errors increase, likely due to longer period signal interference and sampling bias (K1 altimetry ~162° vs. Ciwandan TG: 144.9°). This pattern confirms that ALES enhances coastal phase retrieval, especially for the dominant semi-diurnal constituents. Nevertheless, altimetry still suffers from random cycle noise, signal contamination near land, and the limited temporal resolution of ~10-day repeat cycles—issues known to affect phase fidelity (Abessolo et al., 2023). The observed phase biases—especially from TPXO—may lead to significant temporal misalignments in tidal prediction, which is problematic for tsunami early warning calibration, real-time coastal flooding models, and hydrodynamic model boundary conditions. Despite improvements from coastal altimetry, harmonic analysis of tide gauges remains the most accurate source for phase timing, especially in complex topography like Sunda Strait.

Table 2. Phase of Principal Tidal Constituents on 4 TG

Panjang		Kota Agung		Ciwandan		Marina Jambu	
Con	Value [°]	Con	Value [°]	Con	Value [°]	Con	Value [°]
M2	264.5	M2	74.72	M2	286.6	M2	112.8
S2	115.4	S2	102.4	S2	45.1	S2	316.1
N2	208.7	N2	82.2	N2	26.2	N2	255.7
K2	307.4	K2	88.93	K2	16.96	K2	68.27
K1	23.64	K1	176.8	K1	144.9	K1	332.4
O1	155.6	O1	290.5	O1	334.5	O1	359.4
P1	285.69	P1	191.67	P1	274.56	P1	266.84
Q1	142.82	Q1	37.53	Q1	159.56	Q1	237.14

3.3. Co-Amplitude and Co-Phase Analysis

To further investigate the spatial characteristics of tidal propagation in the Sunda Strait, co-amplitude and co-phase maps for the principal semidiurnal (M2) constituent were constructed using three datasets: tide gauge harmonic analysis at four coastal sites, TPXO9v4a tidal model outputs at 49 spatial points, and Jason-2/3 altimetry with ALES retracking as shown in **Figure 4**. These visualizations offer an integrative view of tidal wave energy distribution and propagation patterns, enabling evaluation of model consistency and spatial coherence in the region. The co-amplitude maps reveal pronounced differences in tidal energy distribution between the TPXO model and the observational datasets. For the M2 constituent, TPXO9v4a displays a smooth spatial gradient of amplitude, ranging from ~33 to 35 cm, peaking towards the southwest opening to the Indian Ocean. However, tide gauge data indicate lower values (max 7.9 cm) and sharper local gradients, especially near embayment such as Kota Agung and Ciwandan. Similarly, Jason-2/3 altimetry shows intermediate amplitudes (~18 cm) with more spatial variability than TPXO but still lacks the fine resolution necessary to resolve complex coastal geometry. These discrepancies suggest TPXO's smoothing effect and absence of localized dissipation processes such as bottom friction and channel resonance (Erkoç & Doğan, 2023).

Co-phase maps for M2 constituents exhibit even stronger spatial gradients and complexity. TPXO9v4a shows near-uniform M2 phases around 354–356°, implying a planar wave front propagation from southwest to northeast. However, tide gauge phases vary drastically (e.g., M2: 74.7° to 286.6°), indicating either amphidromic features or phase lags induced by bathymetric bottlenecks and coastline curvature. The altimetry-derived phases from ALES retracked data align more closely with tide gauges in semidiurnal constituents (e.g., M2 ~266°), but are noisier and less coherent for diurnal constituents due to waveform degradation and limited repeat cycles, in line with known limitations discussed by (Zaron & Egbert, 2006). Notably, potential amphidromic behavior is inferred from the sharp M2 phase shift between Kota Agung and Ciwandan (>200° over ~100 km), indicating either a standing wave pattern or a reflection node in the Strait. This is consistent with regional tidal modeling studies in the Indonesian Seas that detect partial amphidromes near the Sunda Strait (Nuraghnia et al., 2021). The M2 co-phase patterns from both TPXO and altimetry are highly scattered, with altimetry showing better agreement with tide gauge phase but suffering from inconsistencies due to land proximity. The spatial mismatch between model-based (TPXO) and observed (tide gauge and altimetry) co-tidal parameters reflect TPXO's offshore optimization and its limited representation of coastal bathymetric features. Similar findings have been reported in other narrow tropical straits such as the Makassar Strait and Malacca Strait, where model-based predictions underestimate tidal complexity due to coarse resolution and missing shallow-water dynamics. While Jason-2/3 altimetry improves phase representation relative to TPXO, its coarse temporal sampling (10-day cycles) and cross-track spacing (~5–8 km) still limit its ability to resolve tidal spatial gradients within a narrow strait. Nevertheless, when combined with tide gauge calibration, altimetry offers a promising pathway toward improving coastal tidal atlases (Piccioni et al., 2018). In conclusion, the co-amplitude and co-phase maps reveal that TPXO performs reliably offshore but shows large deviations in coastal phase and amplitude near constricted channels. Jason-2/3 improves amplitude and phase for semidiurnal constituents but remains suboptimal for diurnal constituents. Taken together, the co-amplitude and co-phase maps confirm that the Sunda Strait has a more spatially variable M2 structure than implied by TPXO alone.

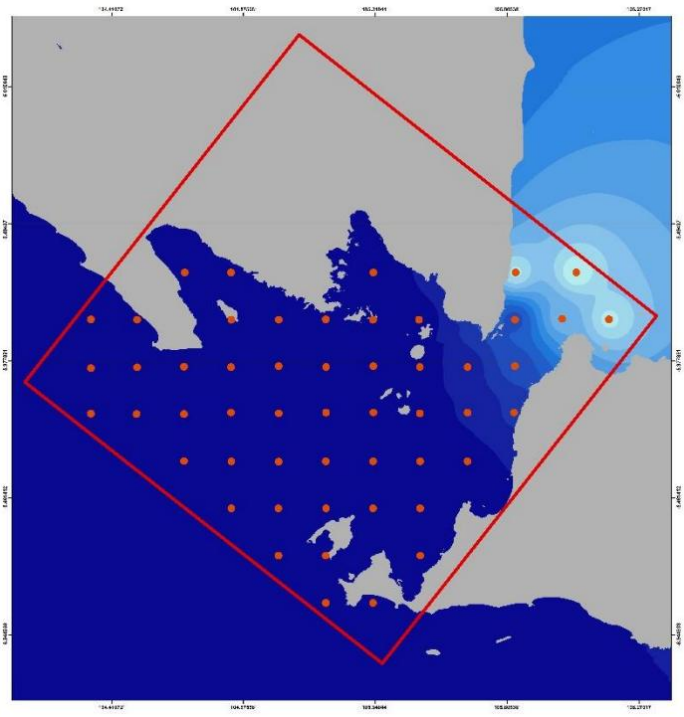


Figure 4. Co-amplitude map of M2 for TPXO model

3.4. Statistical Validation and Co-Tidal Analysis

Evaluation of consistency between datasets, statistical comparisons were performed between TPXO9v4a, Jason-2/3 ALES altimetry, and tide gauge-derived tidal constituents. The validation focused on M2 amplitude and phase at reference locations corresponding to tide gauge sites, using three statistical metrics: Root Mean Square Difference (RMSD), Pearson correlation coefficient (r), and paired-sample z-test for significance in mean differences. The TPXO vs TG comparison shows a large amplitude of overestimation and phase leads, consistent with previous regional analyses. A z-test confirms that both amplitude and phase differences are statistically significant at the 95% confidence level. In contrast, Jason-2/3 ALES vs TG comparison shows significantly lower RMSD values and

stronger correlation (r = 0.84), particularly in amplitude, confirming altimetry's improved representation of coastal tide characteristics. However, small but significant differences in phase remain, especially for diurnal constituents (K1, O1), which are more susceptible to temporal aliasing and noise in altimetry time series. These findings support earlier work by (Cazenave et al., 2018), who emphasized the relative performance improvement of coastal altimetry when retracked properly but cautioned about remaining phase biases. Similarly,(Morrow et al., 2019) found that even advanced altimetry still underperforms compared to in-situ tide gauges when used in regions with complex coastal geometry. These statistical tests confirm that while TPXO provides broad regional consistency, its coastal fidelity is limited, and altimetry, although more accurate, still benefits from ground-truth calibration.

A better visualization of tidal wave propagation in both space and time (co-tidal chart) was constructed for the M2 constituent. This chart overlays both co-amplitude (lines of equal amplitude) and co-phase (cotidal lines indicating simultaneous high tide occurrence) using unified gridded data (0.16° × 0.16° resolution) interpolated from all three datasets. The GMT software (Wessel et al., 2019) was used in combination with GIS tools to integrate harmonic constituent values from tide gauges, TPXO9v4a outputs, and Jason-2/3 altimetry. The resulting co-tidal map in **Figure 5** highlights several key tidal propagation features: 1) Co-phase lines trend from southwest to northeast, consistent with the dominant M2 wave entering from the Indian Ocean and propagating toward the Java Sea, 2) Large co-phase shifts (up to ~200°) are detected between the southern and northern ends of the strait, particularly between Kota Agung and Ciwandan. These may indicate partial amphidromic systems or reflection zones, consistent with the findings of (Nuraghnia et al., 2021), 3) Regions near Ciwandan and eastern Panjang exhibit amplitude minima, possibly reflecting bathymetric damping or nodal interference, 4) The bending and crowding of co-phase lines near the strait constriction suggest rapid tidal transitions, potentially linked to hydraulic controls and shallow-water amplification. Unlike TPXO9v4a, which produces near-linear co-phase fronts, the co-tidal chart developed here reveals spatially variable, nonlinear wave behavior—indicative of resonance and partial standing waves that global barotropic models typically miss. Thus, the co-tidal chart serves as a valuable diagnostic tool for identifying propagation anomalies and planning further hydrodynamic simulations or infrastructure development (e.g., tide prediction, harbor design, or early warning systems).

Thus, the statistical test and the co-tidal chart support the same conclusion: for the Sunda Strait, tide gauges remain the most reliable local reference, TPXO provides the most stable regional background, and coastal altimetry should be treated as supplementary rather than dominant evidence.

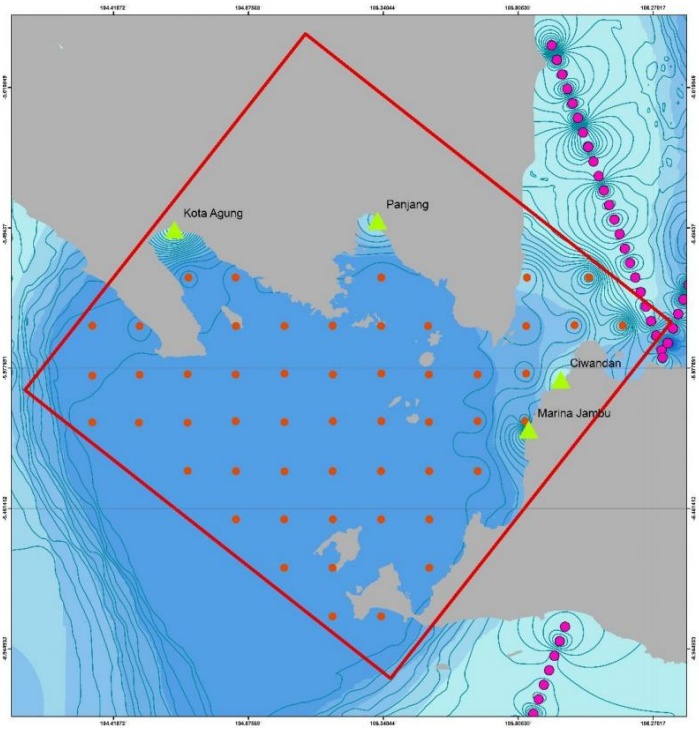


Figure 5. Co-tidal map of M2 for the study area

3.5. Tidal Regime Analysis

Tidal regime classification is essential to understand the dominant temporal characteristics of sea level variability at a given location, typically categorized as diurnal, semidiurnal, or mixed (predominantly diurnal or semidiurnal). In this study, the classification is based on the amplitude ratios of principal harmonic constituents derived from tide gauges—particularly M2 and K1—as recommended by the International Hydrographic Organization (IHO) and supported by prior coastal studies. Using amplitude data from all three datasets, calculated F values are listed on **Table 3**. All stations exhibit a mixed, mainly semidiurnal regime under TG and TPXO estimates, consistent with prior classifications for the Sunda Strait and its surroundings (Julianto et al., 2021). Notably, altimetry-derived form factors tend to be higher (e.g., Panjang: 1.226) and approach the threshold for a "mixed, mainly diurnal" regime. This overestimation stems from: 1) Coastal altimetry's tendency to overestimate diurnal constituents (e.g., K1, O1) due to land contamination and sampling aliasing, 2) Underestimation or misrepresentation of semidiurnal constituents in nearshore environments with complex waveforms, 3) The relatively identical form factor values from TG and TPXO in this case result from harmonic constants in TPXO being extracted from the model grid point nearest each tide gauge, but not incorporating localized bathymetric damping or reflection. While TPXO reproduces bulk harmonic ratios reasonably, it lacks the spatial resolution to model true tidal transformation. As (Arbic, 2022) noted, global barotropic models like TPXO perform best offshore and cannot resolve form factor

transitions induced by narrow embayment or coastal shoaling. The altimetry-based classification, however, diverges slightly toward more diurnal character, especially at Panjang and Kota Agung. This could introduce misclassification risks if used without tide gauge correction, particularly in coastal hydrodynamic modeling, sediment flux estimation, and tidal energy feasibility studies. Thus, while all three datasets indicate a mixed tidal regime, only TG data offer high confidence in resolving subtle transitions in tidal character—critical for coastal planning and hazard assessments. These findings support the use of hybrid approaches combining tide gauge calibration with satellite altimetry for accurate tidal regime mapping.

Table 3. F-values for 4 TG based on three datasets

Station	TG	TPXO	ALT	Classification
Kota Agung	0.518	0.518	1.017	Mixed, mainly semidiurnal
Panjang	0.525	0.525	1.2266	Mixed, mainly semidiurnal
Ciwandan	0.431	0.431	0.778	Mixed, mainly semidiurnal
Marina Jambu	0.504	0.504	0.786	Mixed, mainly semidiurnal

4. Conclusions

This study presents a comprehensive comparison of tidal dynamics in the Sunda Strait using tide gauge observations, satellite altimetry (Jason-2/3 ALES retracking), and the TPXO9v4a global tide model. Results from harmonic analysis show that while TPXO replicates the general tidal regime, it significantly overestimates amplitudes and leads in phase compared to in-situ data, particularly in semidiurnal constituents (e.g., M2 overestimation up to 553%). Coastal altimetry, although showing improved accuracy in amplitude and phase representation—especially for M2—still exhibits noise and aliasing issues in diurnal constituents. Co-tidal and co-phase maps reveal that TPXO tends to oversmoothed spatial gradients and fails to resolve local bathymetric effects, whereas tide gauges capture sharp phase transitions indicative of partial amphidromic systems. The constructed co-tidal charts show clear evidence of complex tidal wave propagation, with potential reflection nodes between stations. Statistical validation confirms significant discrepancies between TPXO and observational datasets, while altimetry performance—though better—still requires calibration against local tide gauges. Tidal regime analysis confirms a consistent mixed, mainly semidiurnal pattern across all stations. Overall, this study emphasizes the limitations of standalone global models in narrow, topographically complex regions, and highlights the value of hybrid approaches that integrate tide gauge calibration with coastal altimetry to enhance regional tidal mapping accuracy.

5. Conflict of Interest

The authors declare no competing interest in the article.

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