

ADCIRC Simulation of Ocean Currents During Tropical Cyclone Senyar in the Malacca Strait

Rendy Syahril Amanu^{1*}, Purwanti Lelly Sabrina¹, Avrionesti¹ dan Sayful Amri²

¹Meteorology Study Program, Indonesian Agency for Meteorology, Climatology, and Geophysics College, Indonesia

²Climatology Study Program, Indonesian Agency for Meteorology, Climatology, and Geophysics College, Indonesia

*Korespondensi : rendy.syahril17@gmail.com

Abstract

Tropical cyclones are high-impact meteorological events in the near-equatorial Maritime Continent, and their influence on ocean currents in narrow, tidally energetic straits such as the Malacca Strait remains poorly quantified through hydrodynamic modeling. This study simulates the spatio-temporal evolution of ocean currents in the Malacca Strait during Tropical Cyclone (TC) Senyar (22 November-2 December 2025) using the Advanced Circulation (ADCIRC) finite-element hydrodynamic model. An unstructured mesh of 21,117 nodes and 39,205 elements, with a target resolution of approximately 2.5 km, was constructed for a domain spanning 0-8°N and 95-105°E, forced by eight tidal harmonic constituents and by ERA5-derived, OWI-formatted wind and pressure fields describing the TC Senyar wind field, using a two-day hyperbolic-tangent ramp to avoid spurious transients. Results show that current speeds intensified from a near-zero pre-cyclone state to a domain-wide maximum of 1.89 m/s, concentrated in the narrow channels of the southern Malacca Strait near the Riau Archipelago, during the intensification and peak phases of the cyclone. Time series extracted at five representative locations (Belawan, Kuala Tanjung, and the northern, central, and southern Malacca Strait) indicate that the southern strait experienced the strongest mean (0.316 m/s) and maximum (0.680 m/s) current speeds, while tidal periodicity persisted throughout the cyclone lifecycle, with the storm primarily modulating current magnitude rather than reversing the dominant semidiurnal flow pattern. These results provide a numerical representation of tropical-cyclone-modulated current dynamics in a monsoon- and tide-dominated strait.

Keywords: ADCIRC, ocean currents, tropical cyclone, Malacca Strait

INTRIDUCTION

The Malacca Strait is one of the busiest and most strategically important shipping corridors in the world, connecting the Indian Ocean to the South China Sea between the eastern coast of Sumatra and the Malay Peninsula. Its circulation has traditionally been described as tidally dominated, with surface currents flowing predominantly northwestward throughout the year at typical speeds of 0.1-0.7 m/s, as reproduced by three-dimensional baroclinic models such as the Hamburg Shelf Ocean Model (Rizal *et al.*, 2010). Subsequent modeling work extended this understanding to the coupled circulation of the Malacca Strait and the Andaman Sea, confirming that tidal forcing, wind stress, and heat flux jointly control the seasonal reversal of currents between the northeast and southwest monsoon periods (Rizal *et al.*, 2012).

Beyond the seasonal monsoon signal, the wind-driven component of circulation in the Malacca Strait has been shown to behave asymmetrically along the length of the strait: numerical experiments that isolate and superimpose tidal and wind forcing indicate that wind tends to enhance tidal currents in the wide northern section of the strait while weakening them in the narrow southern channel because of the interaction between tidal flow, wind-driven flow, and constricted bathymetry (Haditiar & Rizal, 2016). Because the strait is a shallow, semi-enclosed water body strongly governed by its bathymetry and geometry, three-dimensional non-hydrostatic tidal simulations have further shown that current ellipses and tidal asymmetry are amplified in these shallow, narrow reaches (Numerical study of tides in the Malacca Strait with a 3-D model, 2020).

This tide- and monsoon-dominated regime is occasionally disrupted by the passage of tropical

cyclones (TCs), which are rare at these near-equatorial latitudes but can generate severe, short-lived current anomalies. In late November 2025, the rare Tropical Cyclone Senyar formed directly over the Malacca Strait through an unusual interaction between a preconditioned Borneo Vortex, a strong northerly cold surge, and elevated regional sea surface temperature, subsequently making landfall on the east coast of northern Sumatra with substantial human and infrastructural impact (Yulihastin, 2026). Because such near-equatorial tropical cyclogenesis events are uncommon, their influence on ocean currents within an already dynamically complex strait has not been systematically resolved with a hydrodynamic model.

Tropical cyclones are known to generate strong sea-surface current responses through the combined effect of intense wind stress, low central pressure, and the translation speed of the storm, producing current anomalies that are typically biased toward the right of the storm track in the Northern Hemisphere and that can persist for several days after the storm has passed (Zhang *et al.*, 2020). In a narrow strait such as the Malacca Strait, where background tidal currents are already strong and topographically channeled, the superposition of cyclone-driven and tidal currents is expected to produce complex, spatially heterogeneous responses that are best captured through a numerical model with sufficient spatial resolution near the coastline and island chains.

The Advanced Circulation (ADCIRC) model is a widely used finite-element hydrodynamic model that solves the shallow-water equations, expressed through the Generalized Wave Continuity Equation, on unstructured computational meshes (Luettich *et al.*, 1992). Its unstructured-grid, continuous-Galerkin formulation allows mesh resolution to be increased locally near complex coastlines and narrow channels without a proportional increase in resolution elsewhere, and the model has been demonstrated to scale efficiently on parallel high-performance computing architectures for basin-to-channel-scale storm surge and current simulations (Tanaka *et al.*, 2011; Westerink *et al.*, 2008). These computational characteristics make ADCIRC particularly well suited to representing the Malacca Strait, whose geometry ranges from an open, several-hundred-kilometer-wide northern mouth to a channel only a few tens of kilometers wide punctuated by the Riau Archipelago in the south.

Despite the extensive body of work on the Malacca Strait's tidal and monsoon-driven circulation, no published study has yet used a coupled, unstructured-mesh circulation model such as ADCIRC to reconstruct the current field generated during an actual tropical cyclone event within the strait. This study therefore aims to (1) reconstruct the spatio-temporal evolution of ocean currents in the Malacca Strait during the full life cycle of TC Senyar using ADCIRC forced by tides and cyclone-derived wind and pressure fields, (2) identify the location and magnitude of current hotspots generated during the cyclone's intensification, peak, and weakening phases.

METHOD

Study Area and Period

The model domain covers the Malacca Strait and its adjacent waters between 0°-8°N and 95°-105°E, encompassing the eastern coastline of Sumatra, the western coastline of the Malay Peninsula, the Riau Archipelago, and the southern approach to the Andaman Sea (Figure 1). This domain was chosen because it captures the full length of the strait, from its wide northwestern mouth facing the Indian Ocean to its narrow southeastern outlet toward the South China Sea, together with the landfall region and the observed track of TC Senyar. Five representative locations distributed along the strait's north-south axis were selected for time-series extraction and statistical analysis: Belawan and Kuala Tanjung on the Sumatran coast, and the northern, central, and southern sections of the Malacca Strait proper.

The simulation period covers 22 November-2 December 2025 (10 days), spanning the full documented life cycle of TC Senyar, from its pre-cyclone genesis stage, through intensification and peak intensity, to weakening and the post-cyclone recovery of the background circulation. The cyclone originated and tracked within the Malacca Strait itself before making landfall on the northern Sumatran coast, with a best-track evolution of maximum sustained wind speed and minimum central pressure as summarized in Figure 2.

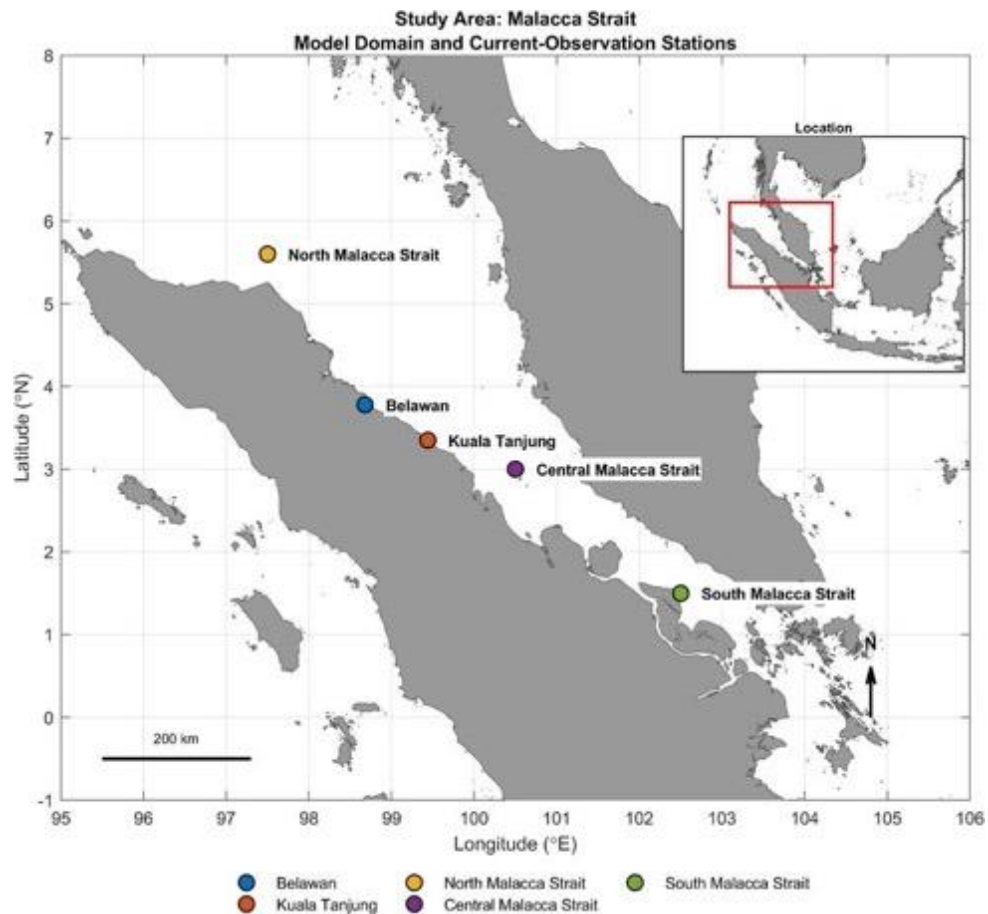


Figure 1. Study area of the Malacca Strait (red box, 0-8°N, 95-105°E) showing the observed track of Tropical Cyclone Senyar and the tide-gauge station used in this study
Evolution of Tropical Cyclone Senyar, 22 November - 2 December 2025

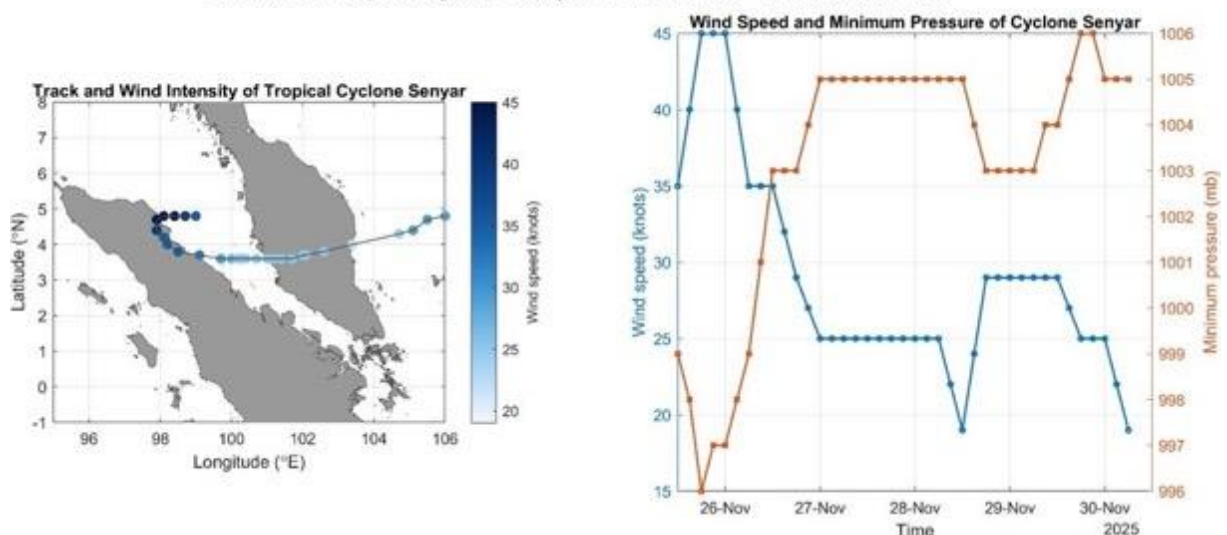


Figure 2. Track and wind-intensity evolution (left) and time series of maximum sustained wind speed and minimum central pressure (right) of Tropical Cyclone Senyar, 22 November-2 December 2025

Research Data

The ADCIRC model requires input datasets representing bathymetry, coastline geometry, tidal forcing, and atmospheric forcing. The datasets used in this study include GEBCO bathymetry, GSHHS coastline, TPXO10 tidal constituents, and ERA5 atmospheric variables. All datasets were processed into ADCIRC-compatible formats during the preprocessing stage.

Atmospheric forcing consisted of 10 m wind components (U10 and V10) and mean sea level pressure from ERA5 with a spatial resolution of $0.25^\circ \times 0.25^\circ$. The data covered the period of 22 November–2 December 2025 within the domain of 95° – 105° E and 0° – 8° N to represent the wind and pressure conditions during Tropical Cyclone Senyar.

Bathymetric data were obtained from GEBCO 2025 with a 15 arc-second resolution. The dataset covered 90° – 110° E and 13° S– 5° N to provide seabed depth information for mesh generation. Coastline information was derived from GSHHS high-resolution data to define land boundaries and wet-dry separation. Tidal forcing was obtained from TPXO10 harmonic constituents within the simulation domain and was applied as open boundary conditions for ADCIRC. The model requires several categories of input data to represent bathymetry, coastline, tidal forcing, and atmospheric forcing. Table 1 summarizes the datasets used as model input.

Table 1. Model input datasets and their functions

Data type	Source	Resolution	Time range	Acquisition
Surface wind (U10, V10)	ERA5	$0.25^\circ \times 0.25^\circ$	22 Nov –2 Dec 2025	95° – 105° E; 0° – 8° N
Mean Sea Level Pressure	ERA5	$0.25^\circ \times 0.25^\circ$	22 Nov –2 Dec 2025	95° – 105° E; 0° – 8° N
Bathymetry	GEBCO	15 arc-second	2025	90° – 110° E; 13° S– 5° N
Coastline	GSHHS	High resolution	2017	Global
Tidal harmonic constituents	TPXO10	Domain based	-	95° – 105° E; 0° – 8° N

1. Preprocessing

Preprocessing consisted of preparing all datasets listed in Table 1 into the formats required by ADCIRC. The GEBCO bathymetric grid was clipped to the study domain and interpolated onto the mesh node coordinates to define nodal depth values, with land nodes above mean sea level excluded from the wet domain. The mesh boundary and land-water mask were constrained using the GSHHS coastline database (Wessel & Smith, 1996), which defines the land boundary and the separation between permanently wet and intermittently wet-dry areas of the mesh. Tidal open-boundary conditions were derived from the TPXO10 global tidal model (Egbert & Erofeeva, 2002), providing elevation amplitude and phase for eight harmonic constituents (Q1, O1, P1, K1, N2, M2, S2, K2) at each open-boundary node. Ten-metre wind components (U10, V10) and mean sea-level pressure fields were obtained from the ERA5 reanalysis (Hersbach *et al.*, 2020) converted into the Oceanweather Inc. (OWI) input.

The unstructured triangular mesh was generated using a feature-size, distance-based mesh-generation workflow consistent with the OceanMesh2D framework (Roberts *et al.*, 2019), in which local element size is controlled by a combination of distance to the coastline, local bathymetric gradient, and a user-defined target resolution, followed by a force-balance smoothing algorithm to improve triangle quality. The resulting mesh, contains 21,117 nodes and 39,205 elements over the 0 – 8° N, 95 – 105° E domain, with a nominal target resolution of approximately 2.5 km. Resolution was refined automatically near the coastline, around the islands of the Riau Archipelago, and within the narrowest reach of the southern Malacca Strait, where current gradients are expected to be largest, while coarser resolution was retained in the open-ocean portions of the domain to control computational cost.

2. Model Configuration and Simulation Run

The ADCIRC model was configured using the fort.15 parameter file to simulate the hydrodynamic response of the Malacca Strait during Tropical Cyclone Senyar. The model applied the nonlinear, finite-amplitude, two-dimensional depth-integrated (2DDI) shallow-water

formulation, which solves the conservation of mass and momentum equations on an unstructured finite-element mesh (Luettich et al., 1992). This formulation was selected because the study focused on the spatial and temporal variation of depth-averaged ocean currents under the influence of tidal and atmospheric forcing. The hydrodynamic calculation in ADCIRC is based on the Generalized Wave Continuity Equation (GWCE) combined with the depth-integrated momentum equation. The continuity equation is expressed as:

$$\frac{\partial \zeta}{\partial t} + \nabla \cdot (Hu) = 0$$

where ζ represents the free surface elevation, H is the total water depth, and u is the depth-averaged horizontal velocity vector. The momentum equation is calculated as:

$$\frac{\partial u}{\partial t} + (u \cdot \nabla)u + fk \times u = -g\nabla\zeta + \frac{\tau_s - \tau_b}{\rho H} + D$$

where f is the Coriolis parameter, g is gravitational acceleration, τ_s is the surface wind stress, τ_b is the bottom friction stress, ρ is the seawater density, and D represents horizontal momentum diffusion. The surface wind stress was calculated from the atmospheric forcing input derived from ERA5 wind components. The wind stress applied to the ocean surface is expressed as:

$$\tau_s = \rho_a C_D |U| U$$

where ρ_a represents air density, C_D is the drag coefficient, and U is the wind velocity magnitude. The atmospheric pressure forcing from ERA5 was applied to represent the pressure gradient generated during the passage of Tropical Cyclone Senyar.

The ADCIRC simulation was initialized using a cold-start condition at 22 November 2025 00:00 UTC. The initial water surface elevation and current velocity were set to zero throughout the computational domain. The model was integrated continuously for 10 days until 2 December 2025 00:00 UTC with a computational time step of 1 second. The total number of simulation outputs was stored at hourly intervals to provide temporal current variations during the cyclone event. Because the model was initiated from a static condition, the tidal and atmospheric forcing terms were not applied instantaneously at full magnitude. ADCIRC implemented a gradual forcing adjustment using a hyperbolic-tangent ramp function to minimize numerical oscillations and artificial gravity waves during the initial simulation period. The ramping process was applied for 2 days from 22 to 24 November 2025. The forcing adjustment was expressed as:

$$F(t) = F_{max}R(t)$$

where $F(t)$ represents the forcing magnitude applied at time t , F_{max} represents the final forcing amplitude, and $R(t)$ is the ramping coefficient varying from 0 to 1 during the adjustment period. After the ramping duration was completed, the tidal, wind, and pressure forcing reached their full magnitudes.

During the ramp period, the simulated velocity field primarily represented the numerical adjustment process rather than the physical ocean response. Therefore, model outputs from 22 to 24 November 2025 were excluded from physical interpretation. The dynamically valid simulation results were analyzed starting from 24 November 2025 00:00 UTC until the end of the simulation period. The 22 November output was only retained to demonstrate the initial adjustment behavior of the numerical model.

The current magnitude was calculated from the simulated horizontal velocity components obtained from ADCIRC output files. The current speed calculation was performed using:

$$V = \sqrt{u^2 + v^2}$$

where V represents the current speed, while u and v represent the eastward and northward velocity components, respectively. The current direction was calculated using:

$$\theta = \tan^{-1} \left(\frac{u}{v} \right)$$

where θ represents the current direction relative to geographic north. These calculated velocity parameters were subsequently used for spatial mapping, hotspot identification, and temporal statistical analysis. The ADCIRC configuration applied in this study included tidal forcing from eight harmonic constituents (Q1, O1, P1, K1, N2, M2, S2, and K2), meteorological forcing from ERA5 wind and pressure fields, bottom friction parameterization, wetting and drying processes, and horizontal turbulence diffusion.

3. Post-processing

Model output was written as global, time-stamped depth-averaged current velocity fields (east-west and north-south components) at the mesh nodes at hourly intervals (WTIMINC = 3,600 s). Post-processing consisted of (1) computing current speed and direction at every node and time step from the raw velocity components, (2) extracting instantaneous current-vector maps at five representative times corresponding to the pre-cyclone, intensification, peak, weakening, and post-cyclone phases of TC Senyar (Section 3.2), (3) compositing the maximum current speed attained at each node over the full simulation period to identify the spatial envelope and hotspot of cyclone-modulated currents (Section 3.3), and (4) extracting hourly current-speed and current-direction time series at the five representative locations (Belawan, Kuala Tanjung, and the northern, central, and southern Malacca Strait) and computing summary statistics (mean, maximum, minimum, standard deviation, time of maximum, and mean direction) for the full simulation period (Section 3.4). All spatial fields were rendered on the 0-8°N, 95-105°E domain grid with a common color scale (0-0.9 m/s) to allow direct visual comparison between phases.

RESULT AND DISCUSSION

1. Evolution of Tropical Cyclone Senyar

The best-track reconstruction (Figure 2) shows TC Senyar tracking slowly westward through the Malacca Strait at approximately 3.5-4.8°N before curving toward the northern Sumatran coast near 98°E. Maximum sustained wind speed increased from about 35 knots on 25 November to a peak of 45 knots late on 25-26 November, coinciding with a minimum central pressure of approximately 996 mb, before the storm weakened steadily through 27-30 November as its central pressure recovered toward 1005 mb. This evolution defines the five forcing phases adopted for output extraction in this study: pre-cyclone (22 November), intensification (24 November), peak (26 November), weakening (29 November), and post-cyclone (2 December).

2. Spatial Evolution of Simulated Ocean Currents

Figures 3-7 show the simulated depth-averaged current vector and speed fields output by the model at the five forcing phases described above. During the pre-cyclone/ramp-up phase (Figure 3, 22 November 01:00), current speeds remain below 0.05 m/s across virtually the entire domain, consistent with the two-day forcing ramp described in Section 2.3.3, and this phase is therefore excluded from further physical interpretation.

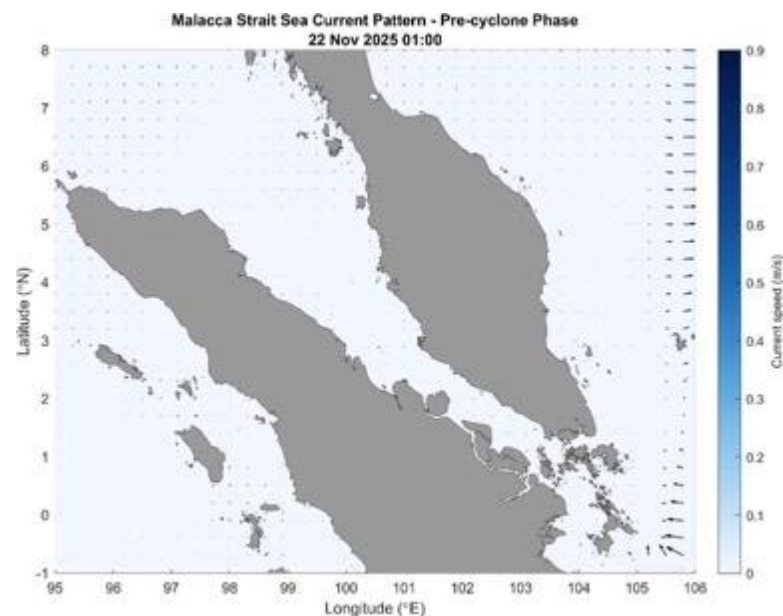


Figure 3. Simulated current field during the pre-cyclone/ramp-up phase, 22 November 2025 01:00 UTC

By the intensification phase (Figure 4, 24 November 12:00), the model output shows a well-developed current jet along the axis of the southern Malacca Strait, with speeds reaching 0.6–0.9 m/s in the narrow reach near the Riau Archipelago (approximately 100.5–101.5°E, 2–3°N), together with a strong, broadly northeastward-flowing current along the outer, eastern boundary of the domain toward the South China Sea.

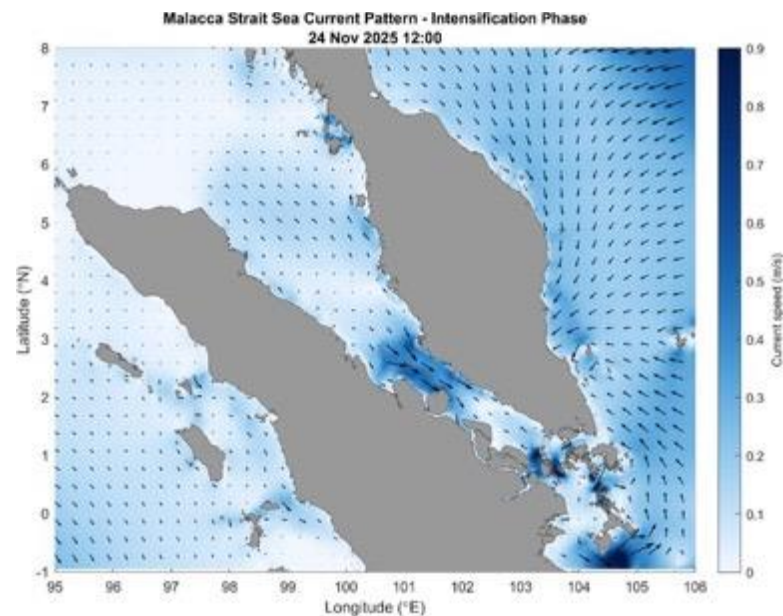


Figure 4. Simulated current field during the intensification phase, 24 November 2025 12:00 UTC

At the peak of the cyclone (Figure 5, 26 November 00:00), the modeled current field shows two distinct zones of intensification: a broad area of strong (>0.7 m/s) current in the northeastern portion of the domain, and a persistent, channel-following jet through the southern strait and the Riau Archipelago exceeding 0.8 m/s locally. The central and northern portions of the strait show comparatively moderate current speeds (0.1–0.3 m/s), reflecting the strong spatial heterogeneity of the current response resolved by the model along the length of the strait.

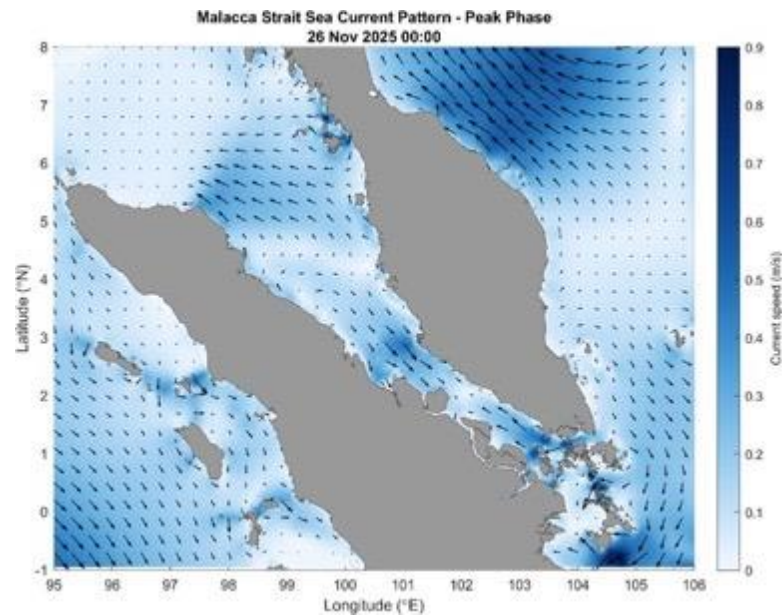


Figure 5. Simulated current field at the peak intensity of TC Senyar, 26 November 2025 00:00 UTC

During the weakening phase (Figure 6, 29 November 00:00), current speeds along the eastern, South China Sea-facing boundary and around the Riau Archipelago remain elevated in the model output, while the jet within the central strait axis has relaxed compared to the peak phase, indicating a lagged response in the outer domain relative to the strait interior.

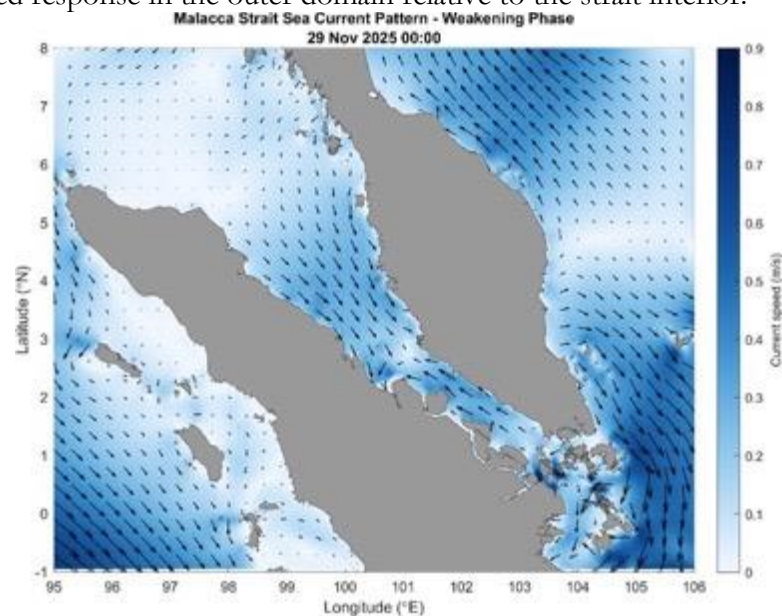


Figure 6. Simulated current field during the weakening phase, 29 November 2025 00:00 UTC

By the post-cyclone phase (Figure 7, 2 December 00:00), the simulated current field has largely reorganized into a pattern resembling the background, non-cyclonic circulation of the strait, with the strongest currents concentrated along the strait axis and near the southwestern, Indian Ocean-facing boundary, and comparatively weaker currents in the northern half of the domain.

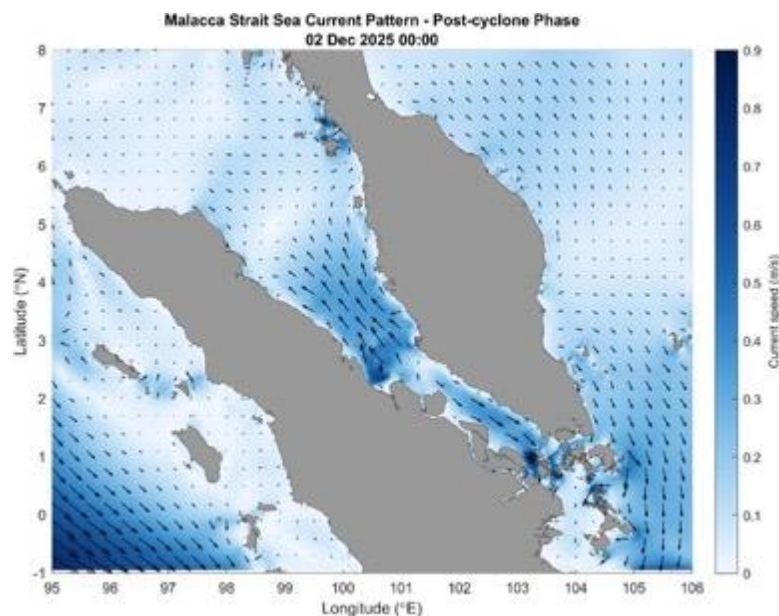


Figure 7. Simulated current field during the post-cyclone recovery phase, 2 December 2025 00:00 UTC

3. Maximum Current Envelope and Hotspot Identification

Figure 8 presents the composite maximum current speed attained at every node throughout the full 22 November-2 December simulation period, computed from the hourly model output as described in Section 2.3.3. The overall domain maximum simulation current of 1.89 m/s occurs in the narrow channel of the southern Malacca Strait among the islands of the Riau Archipelago (approximately 104.2°E, 0.7°N), the same region identified in Section 3.2 as the location of the strongest and most persistent current jet across the intensification, peak, and weakening phases. A secondary band of high maximum current speed (0.6-0.8 m/s) extends along the entire eastern flank of the domain and connects to the southeastern outlet toward the South China Sea, while the central and northern strait reach comparatively lower maximum speeds (0.3-0.5 m/s).

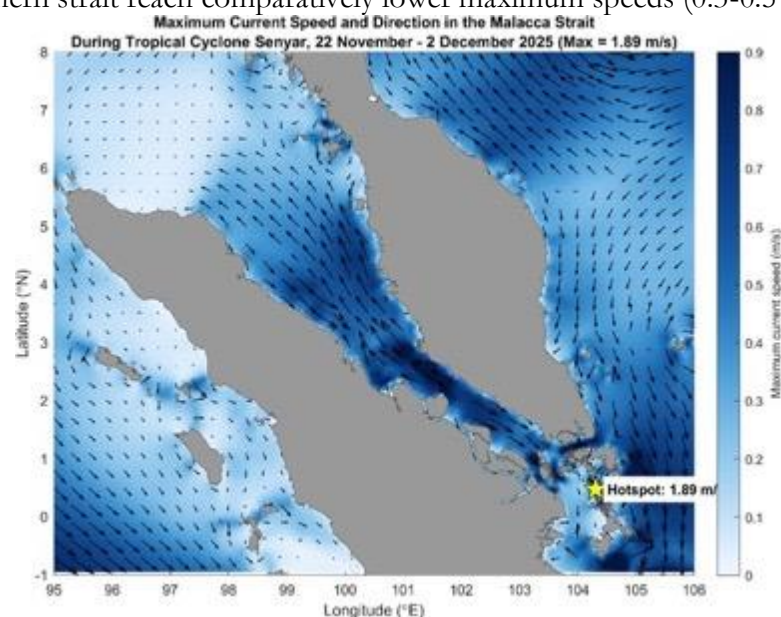


Figure 8. Composite maximum current speed and direction across the Malacca Strait during TC Senyar, 22 November-2 December 2025, with the domain-wide hotspot (1.89 m/s) indicated

4. Temporal Variation and Statistics at five representative locations

Table 2 summarizes the current-speed statistics extracted at the five representative locations over the full simulation period, and Figure 9 presents the corresponding hourly time series of current speed (upper panel) and current direction (lower panel).

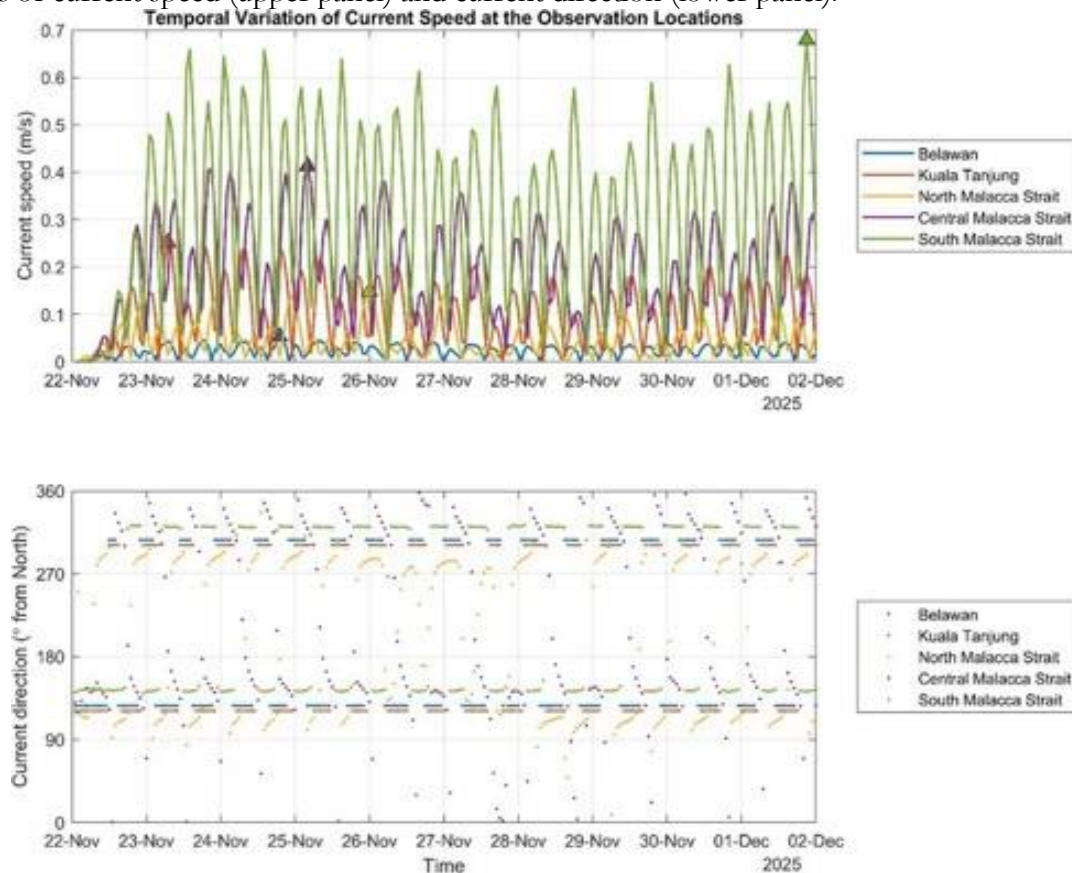


Figure 9. Time series of simulated current speed (upper panel) and current direction (lower panel) at five representative locations, 22 November-2 December 2025. Triangular markers indicate the time of maximum current speed at each location

Table 2. Current-speed statistics at five five representative locations

Location	Mean (m/s)	Max (m/s)	Min (m/s)	Std. Dev. (m/s)	Time of max (UTC)	Direction (°N)
Belawan	0.024	0.053	<0.001	0.012	24 Nov 2025 19:00	126.8
Kuala Tanjung	0.106	0.252	<0.001	0.064	23 Nov 2025 07:00	121.2
North Malacca Strait	0.048	0.148	<0.001	0.034	26 Nov 2025 00:00	211.1
Central Malacca Strait	0.192	0.413	<0.001	0.103	25 Nov 2025 04:00	121.8
South Malacca Strait	0.316	0.680	<0.001	0.182	1 Dec 2025 21:00	212.1

The southern Malacca Strait recorded both the highest mean (0.316 m/s) and the highest maximum (0.680 m/s) current speed among the five representative locations, more than double the values recorded at the central strait (mean 0.192 m/s, maximum 0.413 m/s) and substantially higher than those at Belawan (mean 0.024 m/s, maximum 0.053 m/s). Kuala Tanjung exhibited a

higher mean and maximum current speed than the open-water northern strait location, indicating that local bathymetric characteristics and flow-path configuration may exert a stronger influence on the current intensity resolved by the model at this location than proximity to the coastline. These spatial differences suggest that the simulated current response varied considerably along the Malacca Strait, with stronger current speeds occurring in the southern and central sections of the modeled domain.

The timing of the maximum current speed also differed among the representative locations. At Kuala Tanjung and the central strait, the maximum occurred relatively early in the simulation, on 23 and 25 November, respectively, during the period when Tropical Cyclone Senyar was approaching and the simulated current field exhibited strong temporal variability. At the northern strait, the maximum occurred close to the peak phase of the cyclone on 26 November 00:00 UTC, indicating a close temporal correspondence between the cyclone phase and the simulated current response at this location. In contrast, the southern strait reached its overall maximum current speed of 0.680 m/s on 1 December 2025 at 21:00 UTC, several days after the cyclone had weakened and moved inland. This temporal offset indicates that the maximum simulated current at the southern strait did not occur simultaneously with the peak phase of Tropical Cyclone Senyar. However, the present analysis does not quantitatively distinguish the relative contributions of tidal variability, wind forcing, and the persistence of the circulation response to the occurrence of this delayed maximum. Therefore, the late occurrence of the maximum current is interpreted here as a temporal characteristic of the numerical simulation rather than as definitive evidence of a delayed along-strait momentum adjustment. A quantitative assessment of the mechanisms responsible for this temporal offset would require additional analysis, such as lag or cross-correlation analysis between current velocity, tidal variability, wind stress, and cyclone intensity, which is beyond the scope of the present study.

The current-direction time series (Figure 9, lower panel) shows that all five representative locations exhibit a pronounced and regular oscillation consistent with the semidiurnal tidal cycle throughout the simulation period, including during the peak phase of the cyclone. The mean current direction clusters around 120–127° (south-southeast) at Belawan, Kuala Tanjung, and the central strait, and around 211–212° (southwest) at the northern and southern strait locations. These directional patterns reflect the reversing, along-strait orientation of the dominant flow axis simulated at the respective locations. The persistence of the regular oscillation throughout the cyclone passage suggests that the simulated current direction remained strongly influenced by the prevailing tidal regime, while the cyclone-related atmospheric forcing was reflected mainly in variations in current magnitude. Thus, the results indicate that Tropical Cyclone Senyar modified the temporal magnitude of the simulated current field without producing an evident fundamental change in its dominant directional oscillation during the simulation period.

5. Model Validation and Limitations

A major limitation of this study is the absence of independent in-situ current observations during the Tropical Cyclone Senyar event. Although tide-gauge observations may provide information on water-level variability, they cannot directly validate the depth-averaged current velocity simulated by the two-dimensional ADCIRC configuration. Direct validation of current magnitude and direction would require measurements from ADCPs, current meters, or other oceanographic instruments at locations representative of the modeled circulation.

Consequently, the current-speed values obtained at Belawan, Kuala Tanjung, and the three representative sections of the Malacca Strait are model-derived results rather than observationally validated current measurements. The maximum simulated current speed of 1.89 m/s should therefore not be interpreted as an observationally confirmed value. Instead, it represents the maximum current magnitude produced by the numerical experiment under the applied tidal, wind, and atmospheric-pressure forcing.

The absence of current observations also limits the quantitative assessment of model uncertainty, particularly for the magnitude and timing of the strongest current response. Nevertheless, the simulation provides a physically based reconstruction of the spatial and temporal current response under the specified model configuration and forcing conditions. Future studies

should incorporate available ADCP or current-meter observations, particularly within the southern Malacca Strait and around the Riau Archipelago where the model produces the strongest current response, to quantitatively evaluate model performance using statistical metrics such as RMSE, correlation coefficient, bias, and skill score.

In addition, although the simulation shows that the maximum current speed in the southern Strait of Malacca occurred several days after the peak phase of Tropical Cyclone Senyar, the present study does not quantitatively evaluate the lagged relationships among tidal variability, wind stress, cyclone intensity, and current response. Therefore, the occurrence of the delayed maximum current is reported as a characteristic of the numerical simulation and is not interpreted as definitive evidence of delayed momentum adjustment. Future studies incorporating lag or cross-correlation analysis and independent current observations would be useful for quantitatively determining the mechanisms controlling the timing and magnitude of the current response.

CONCLUSIONS AND RECOMMENDATIONS

The ADCIRC simulation, run on a unstructured mesh with a nominal 2.5 km resolution and forced by eight tidal harmonic constituents together with ERA5-derived cyclone wind and pressure fields, reproduced the spatio-temporal evolution of ocean currents in the Malacca Strait across the full life cycle of Tropical Cyclone Senyar (22 November-2 December 2025). The model output shows a clear progression from a ramp-affected, near-zero pre-cyclone current field to strongly intensified currents during the intensification and peak phases, with a domain-wide maximum current speed of 1.89 m/s concentrated in the narrow channels of the southern Malacca Strait near the Riau Archipelago. Current statistics extracted at five representative locations show that the southern strait produced the strongest mean (0.316 m/s) and maximum (0.680 m/s) current speeds of all stations, followed by the central strait (mean 0.192 m/s, maximum 0.413 m/s), while Belawan and the northern strait produced the weakest current response. Across all stations, the simulated current direction retained a regular semidiurnal oscillation throughout the cyclone's passage, indicating that TC Senyar acted primarily to modulate the magnitude of the current field rather than to reverse its underlying tidal periodicity. These results provide a numerical reconstruction of the spatial and temporal current response of the Malacca Strait to Tropical Cyclone Senyar under the specified tidal and atmospheric forcing conditions. However, because independent current observations were unavailable, the simulated current magnitudes and temporal variations could not be quantitatively validated against in-situ measurements. Therefore, the results should be interpreted as model-derived estimates rather than observationally confirmed current conditions.

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