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The Critical Role of Subsurface Marine Heatwaves in the Intensification of Tropical Cyclone Senyar

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Abstract:

The development of Tropical Cyclone (TC) Senyar in November 2025 represented a rare cyclonic event in the near-equatorial Malacca Strait, a region typically considered free from storm activity. The thermal energy sources responsible for the formation of such cyclones, particularly the subsurface oceanic thermal energy, remain largely unexplored. This study investigates the contribution of subsurface heat during TC Senyar by integrating satellite-derived observations, TC best-track data, and high-resolution atmosphere-ocean reanalysis products. A persistent subsurface marine heatwave was observed, with temperatures exceeding 30 °C at depths of 50 to 60 meters, leading to a pronounced temperature inversion compared to cooler surface waters (less than 30 °C). Subsurface warming is likely controlled by equatorial currents that transport warm water masses into the strait. These warm waters remain confined beneath strong stratification resulting from low surface salinity. Assessment of tropical cyclone heat potential reveals exceptionally high values ($>100 \text{ kJ/cm}^2$) persisting from mid-2024 through 2025, a pattern potentially linked to the climatic transition from a strong positive to a negative Indian Ocean Dipole phase. Subsurface heat budget analysis indicates a negative temperature tendency throughout the occurrence of TC Senyar. Before the cyclone, cooling was primarily attributed to residual processes, consistent with vertical processes, but not explicitly resolved. During the cyclone, horizontal advection became the dominant mechanism for subsurface heat extraction. The strong upwelling associated with TC Senyar transported warm water from the subsurface reservoir to the surface. Consequently, the characteristic cold wake did not develop, enabling the cyclone to maintain its intensity by utilizing existing subsurface heat.

Keywords:

Tropical cyclone Senyar, Malacca Strait, subsurface marine heatwave, stratification, tropical cyclone heat potential, heat budget analysis, upwelling

1. Introduction

The Malacca Strait serves as a strategically important maritime corridor, linking the Andaman Sea in the west to the South China Sea (SCS) in the east (**Fig. 1a**). In November 2025, Tropical Cyclone (TC) Senyar as a rare meteorological event produced severe weather conditions, widespread tidal flooding, and landslides along the eastern coast of Sumatra. These events resulted in more than

1,200 fatalities and damage to over 300,000 houses (BNPB, 2025). The movement trajectory of this TC is well documented (**Fig. 1b**), revealing a shift pattern that directly affected a major shipping lane. This event caused significant disruptions to maritime logistics within one of the world's busiest shipping corridors. The occurrence of TC Senyar highlights an evolving risk profile for a region previously considered protected from intense cyclonic activity.

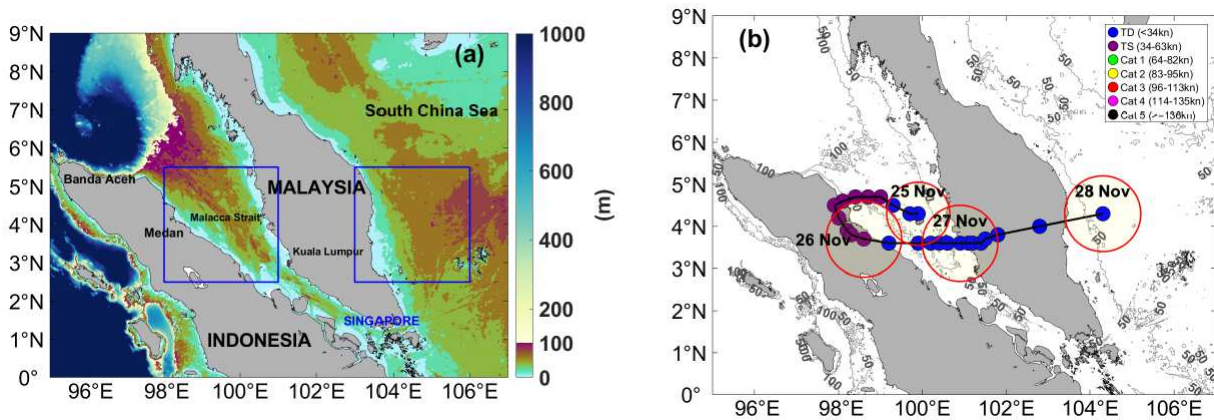


Fig. 1. Study area in the Malacca Strait and adjacent regions. **(a)** Bathymetry (m) is presented using dual-scale colorbars. Blue boxes indicate the areas of interest in the Malacca Strait (98–101°E, 2.5–5.5°N) and the South China Sea (103–106°E, 2.5–5.5°N). **(b)** The track of TC Senyar is shown, with red circles representing wind diameter (km) and grey contours marking the 50 m and 100 m isobaths.

Historically, the equatorial zone has been regarded as free from tropical storms, primarily because TCs have seldom been observed to form equatorward of 5 degrees latitude (Gray, 1968, 1998). The established paradigm was challenged by the occurrence of near-equatorial cyclones, particularly Typhoon Vamei, which developed near Singapore on December 27, 2001. The formation of Typhoon Vamei resulted from an uncommon synoptic interaction between a stationary Borneo Vortex and a strong cold surge (Chang et al., 2003). The emergence of TC Senyar in 2025, after a 24-year interval, further demonstrates that the Earth's background rotation is not an absolute requirement for tropical cyclogenesis if an initial vortex exists and can be intensified by other systems. Therefore, TC Senyar represents a rare and significant phenomenon that requires rigorous scientific analysis to elucidate the evolving mechanisms of low-latitude storm formation.

Previous research of TCs have predominantly relied on sea surface temperature (SST) as the primary parameter for predicting storm intensity (Knutson et al., 2010; Tory and Dare, 2015). However, SST alone does not fully represent the total energy available for cyclones, as the influence of the subsurface ocean is often overlooked. Recent studies indicate that subsurface variability, particularly the 26 °C isothermal depth, plays a significant role in influencing cyclogenesis (Jin et al., 2014; Huang et al., 2015; Mazza and Chen, 2021; Rathore et al., 2022; Ray et al., 2024; Gao et al., 2025). Recent investigations into subsurface warming suggest that subsurface current dynamics, rather than surface heat flux, frequently serve as the primary drivers (Saranya and Nam, 2024; Li et al., 2025). In addition, pronounced vertical stratification, strengthened by the presence of a barrier layer, is essential for maintaining heat within subsurface layers (Ismail et al., 2023, 2024; Shackelford et al., 2024; Manviel et al., 2026).

The passage of TCs typically results in pronounced upper-ocean cooling (Guan et al., 2021; Ling et al., 2021; Dac Da et al., 2023; Oey, 2023; John et al., 2024; Looney and Foltz, 2025; Pun et al., 2025). Cyclones frequently undergo self-induced cooling as a result of intense upwelling. The upward movement of cold subsurface water significantly lowers sea surface temperature and promotes storm dissipation. This mechanism can also trigger marine cold spells (MCSs) (Beliyana et al., 2026). However, with accelerating sea surface warming, the self-induced cooling effect of cyclones has weakened (Guan et al., 2026). When a subsurface warm layer is present, vertical mixing entrains warmer water rather than colder masses, which can effectively refuel the cyclone and allow it to maintain its intensity despite the storm's mechanical forcing. These complex ocean-atmosphere interactions underscore the importance of understanding the vertical thermal structure to accurately assess the energy reservoir that sustains TCs during their most destructive phases.

The development of TC Senyar in the Malacca Strait is closely associated with the influence of the Indian Ocean Dipole (IOD), due to the strait's direct connectivity with the Indian Ocean (Saji et al., 1999). This relationship is particularly pronounced during negative IOD phases, when warm SST anomalies are concentrated in the eastern Indian Ocean near the Indonesian archipelago (Saji and Yamagata, 2003). Additionally, SST variability within the Malacca Strait is strongly influenced by wind-driven circulation and sea-level gradients between the Indian Ocean and the SCS (Isa et al., 2020; Ibrahim and Yanagi, 2006). Furthermore, low salinity levels within this

narrow and shallow strait are hypothesized to significantly enhance stratification, thereby trapping heat within the subsurface layers. This process is similar to mechanisms observed in other regions. For example, in the Indian Ocean (Shackelford et al., 2024) and the Banda Sea (Ismail et al., 2024), strong stratification serves as a thermal barrier layer. The complex topography of the Malay Peninsula and Sumatra also creates a mechanical environment favorable for vorticity development. The interaction between topography and atmospheric processes is crucial for TC formation in the region, as land-ocean boundaries and mountain ranges can intensify low-level cyclonic circulation (Wang et al., 2020; Lui et al., 2026). Building on these regional dynamics, this study presents the first evidence of persistent subsurface warming in the Malacca Strait, identified as a critical role in the intensification of TC Senyar. Notably, the analysis reveals an absence of significant post-storm cooling, rather than the typical cold wake, storm-induced upwelling transferred warm water from subsurface to the surface. This feedback loop maintained a continuous energy reservoir, sustaining the cyclone's intensity near the equator despite the shallow bathymetry.

2. Materials and Methods

2.1 Data

Potential temperature ($^{\circ}\text{C}$), sea water salinity (PSU), mixed layer depth (MLD, m), and current velocity components, specifically zonal and meridional velocities (m/s), were obtained from the Global Ocean Physics Reanalysis (GLORYS12V1). The GLORYS12V1 dataset, made available by the Copernicus Marine Environment Monitoring Service (CMEMS), is based on the NEMO model and integrates both satellite and in situ observations to accurately represent upper-ocean dynamics (Lellouche et al., 2021). The dataset provides a horizontal resolution of $1/12^{\circ}$ and is organized into 50 vertical depth levels. For the present analysis, daily outputs from 1 January 1993 to 23 December 2025 were used to investigate oceanographic processes and long-term variability within the study area. Important to note that the Malacca Strait is characterized by its narrowness, shallow depth, and complex topography. Consequently, reanalysis outputs may perform inadequately in this region, resulting in uncertainties and study limitations, such as resolution constraints (approximately 8 km), challenges in bathymetry representation, and biases in vertical mixing.

Atmospheric data were sourced from the ERA5 reanalysis dataset produced by the European Centre for Medium-Range Weather Forecasts (ECMWF). This dataset includes 10 m and 850 hPa wind speed (m/s). ERA5 offers hourly data at a spatial resolution of $0.25^\circ \times 0.25^\circ$ (approximately 28 km), providing high temporal consistency and comprehensive global coverage (Hersbach et al., 2020). All variables were collected for the period from 1 January 1993 to 23 December 2025. Large-scale convective activity over the study area was assessed using daily NOAA Interpolated Outgoing Longwave Radiation (OLR, W/m^2) data, obtained from the NOAA Physical Sciences Laboratory (PSL), Boulder, Colorado, USA (<https://psl.noaa.gov>).

2.2 Methods

Characteristics of TC Senyar were obtained from the International Best Track Archive for Climate Stewardship (IBTrACS) v4.01 database (Knapp et al., 2010; Gahtan et al., 2024), which supplies standardized storm data at 3- or 6-hour intervals. The TC track was used as the spatiotemporal reference for the analysis of MHWs and related oceanographic parameters. TC lifecycles, spanning from formation to dissipation, were synchronized with daily temperature datasets to assess thermal anomalies throughout the ocean water column.

Subsurface heat accumulation during TC development was evaluated by calculating the Tropical Cyclone Heat Potential (TCHP). Due to the shallow bathymetry of the Malacca Strait, where water temperatures throughout the entire water column frequently exceed 26°C , the integration depth was adjusted. A modification to the methodology described by Rathore et al. (2022) was proposed, instead of using the 26°C isotherm depth, TCHP was integrated from the surface to the seafloor to more accurately represent the available thermal energy. This modified approach is defined in Equation (1).

$$TCHP = \rho C_p \int_0^H (T(z) - 26) dz \quad (1)$$

Where T denotes temperature ($^\circ\text{C}$), ρ is potential density (1024 kg/m^3), C_p is the specific heat capacity of seawater (assumed constant at $3940 \text{ J/kg } ^\circ\text{C}$), and H is the seafloor depth in the ocean.

MHWs were identified using the methodology established by Hobday et al. (2016). Daily temperature climatology and 90th percentile thresholds were derived from the GLORYS12V1 dataset spanning 33 years (1 January 1993 to 23 December 2025). An MHW was defined as a

period when SST exceeded the 90th percentile for at least five consecutive. Successive events separated by gaps of two days or fewer were considered a single continuous event, whereas longer gaps delineated separate events days (Hobday et al., 2016). The high-resolution vertical profiles provided by the GLORYS12V1 dataset facilitated an analysis encompassing both surface and subsurface thermal structures. Temperature variations were examined at specific depth levels (surface, 15, 25, 40, 55, 65, and 77 m), selected according to the model's vertical resolution and data availability. All data processing followed the code implementation described by Zhao and Marin (2019).

The mechanisms responsible for MHW formation were investigated, with particular focus on the TC Senyar period. Due to the shallow bathymetry of the Malacca Strait (average depth less than 100 m) and the presence of a thin mixed layer (less than 20 m), the heat budget was calculated directly within the bottom layer. This methodology enables a direct evaluation of subsurface thermal dynamics, specifically the warming processes near the seafloor, which are frequently obscured in studies that focus solely on surface conditions. The present study examines the subsurface heat budget using the adapted framework of Ismail et al. (2023) and Warms and Karnauskas (2025), as presented in Equation (2).

$$\underbrace{\frac{\partial T_H}{\partial t}}_a = - \underbrace{\left(u_H \frac{\partial T_H}{\partial x} + v_H \frac{\partial T_H}{\partial y} \right)}_b + \underbrace{Res}_c \quad (2)$$

The terms in Equation (2), from left to right, correspond to: (a) the rate of temperature change over time (T_t), (b) horizontal advection ($Advh$), and (c) the unresolved residual (Res). In this context, T represents temperature ($^{\circ}\text{C}$), t denotes time, u and v are zonal and meridional current, respectively (in m/s), and H refers to the seafloor depth in the ocean (m). The residual term (Res) is determined by adding the temperature tendency (T_t) and horizontal advection ($Advh$). The residual term (Res) accounts for contributions from processes not explicitly resolved in this analysis, such as vertical transport, mixing process, numerical error, and potential uncertainties within the GLORYS12V1 dataset. Due to the complex bathymetry of the Malacca Strait, these unresolved processes may substantially affect the local thermal balance, especially during the energetic transition phases of TC Senyar. All heat budget parameters were calculated for the periods before, during, and after TC Senyar events in the study area. A negative (positive) value indicates that the ocean is losing (gaining) heat, resulting in cooling (warming).

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3. Results and Discussions

3.1 Longterm Thermal Anomalies and MHW Characteristics

A long-term statistical analysis was conducted to examine the vertical structure of thermal variability in the Malacca Strait by calculating the standard deviation of SST anomalies across multiple depth layers. This method enables the assessment of the magnitude of thermal fluctuations and identifies the depth layers where subsurface anomalies most significantly deviate from long-term climatology. **Fig. 2** presents the spatial distribution of long-term standard deviation for SST anomalies at selected depths (0, 15, 25, 40, 55, 65, and 77 m), revealing a distinct transition in variability from the surface to the subsurface. These depths were chosen based on data availability, as described in the Materials and Methods section. At the surface, the standard deviation remains relatively uniform (<1 °C), which indicates that large-scale atmospheric forcing primarily drives thermal fluctuations (**Fig. 2a**). In contrast, variability increases within the subsurface layers, especially in the Malacca Strait, where values surpass 2 °C from approximately 55 m to the seabed (**Figs. 2e–g**). This vertical divergence suggests that surface temperature is likely regulated by atmospheric processes, whereas subsurface thermal dynamics are primarily governed by internal oceanic mechanisms, as also observed by Li et al. (2025) in the East Japan Sea.

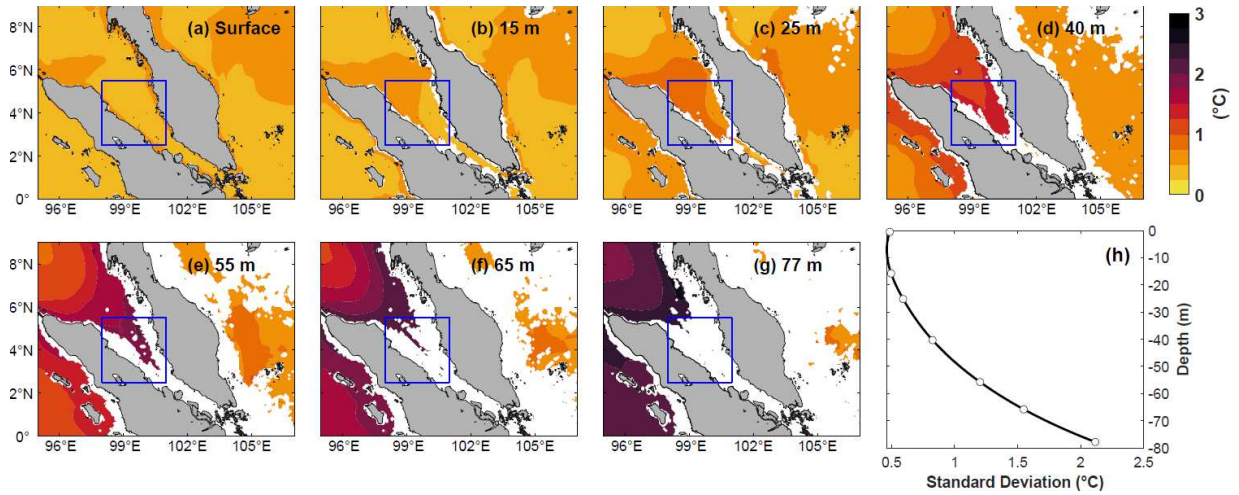


Fig. 2. Long-term standard deviation of sea temperature anomalies from 1 December 1993 to 23 December 2025. Panels (a–g) show the spatial distribution of temperature anomaly standard deviation values at each depth layer. Panel (h) presents the vertical profile of the mean sea temperature anomaly standard deviation averaged within the blue box.

To further investigate the vertical extent of extreme thermal events, we examined the spatial distribution of long-term MHW characteristics across various depth layers. **Fig. 3** illustrates the spatial distribution of long-term MHW characteristics at depths of 0, 15, 25, 40, 55, 65, and 70 meters. In this study, we used cumulative intensity metric, as it comprehensively represents both MHW duration and mean intensity. At the surface, cumulative intensity remains relatively uniform at less than 20 °C/days (**Fig. 3a**), whereas the subsurface layers exhibit a markedly different pattern. In the Malacca Strait, the highest cumulative intensity values are observed in the subsurface, reaching up to 160 °C/days from 55 meters to the seabed (**Figs. 3e–g**). A similar trend is evident for maximum intensity, which remains consistent at 2–3 °C at the surface (**Fig. 3i**) but increases substantially in deeper layers, exceeding 5 °C between 55 meters and the bottom (**Figs. 3m–o**).

Long-term analyses of SST anomaly standard deviation and MHW characteristics indicate that subsurface temperature variability substantially exceeds that observed at the surface (**Figs. 2 and 3**). The findings demonstrate persistent subsurface warming below the surface layers of the Malacca Strait, with the most pronounced anomalies occurring between 55 meters and the seabed. Research on such deep-seated thermal anomalies in this region remains limited. Although prior research on MHWs in this region has primarily focused on surface observations (Beliyana et al., 2023), we present the first evidence of subsurface warming and subsurface MHWs in the Malacca Strait. The existence of this hidden heat reservoir indicates that the region is influenced by complex internal oceanic dynamics rather than being solely regulated by surface heat fluxes, underscoring a critical yet frequently overlooked component of the regional thermal budget.

Elevated subsurface temperatures often indicate the intrusion of water masses originating from other regions that move beneath the surface layers (Saranya and Nam, 2024; Li et al., 2025). In addition, increased precipitation and river runoff can generate pronounced stratification, forming a barrier layer that inhibits vertical mixing (Ismail et al., 2024; Shackelford et al., 2024). As a result, subsurface heat becomes trapped, persisting for extended periods and exhibiting greater resistance to dissipation than surface heat, which is more readily cooled by wind and rainfall.

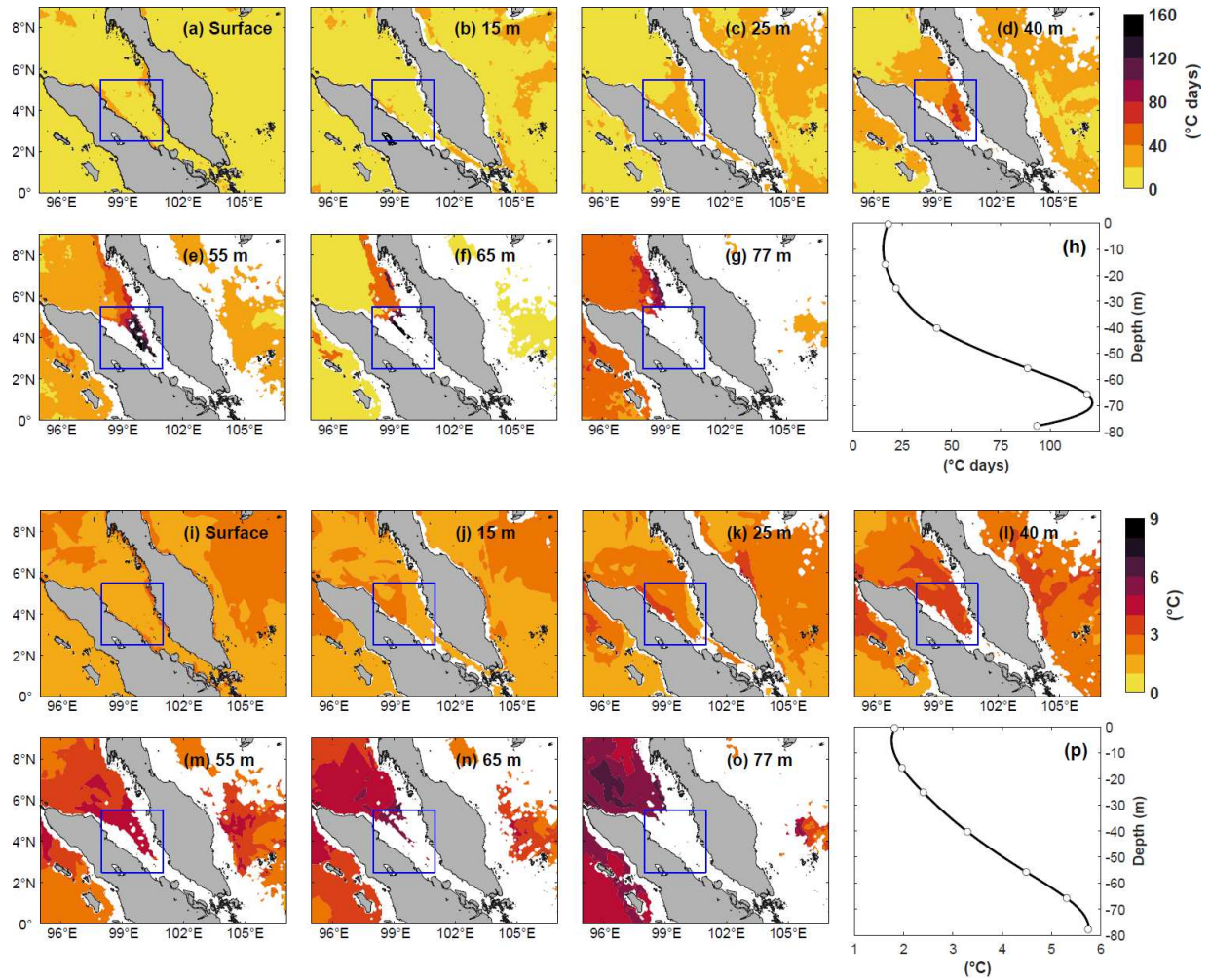


Fig. 3. Long-term cumulative intensity and maximum intensity of MHWs from 1 December 1993 to 23 December 2025. Panels (a–g) and (i–o) present the spatial distribution of MHW cumulative intensity and maximum intensity, respectively, for each depth layer. Panels (h) and (p) show the vertical profiles of mean cumulative intensity and mean maximum intensity, respectively, averaged within the blue box.

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234 3.2 The Role of Subsurface Warming in Promoting TC Senyar Intensification

235 To evaluate the thermal energy available for TC intensification, the TCHP was analyzed, as shown
 236 in **Fig. 4**. TCHP accounts for the heat content within the subsurface layer, rather than merely at
 237 the surface. This metric offers a more comprehensive assessment of the ocean's capacity to sustain
 238 and intensify atmospheric disturbances such as TC Senyar. During the period from 2023 to 2025,
 239 TCHP values demonstrated a consistent upward trend, peaking in 2025 (**Fig. 4c**). The highest
 240 TCHP values were observed west of Sumatra, exceeding 200 kJ/cm², while the Malacca Strait

recorded values above 150 kJ/cm². These values substantially surpass the established minimum threshold of 60 kJ/cm² required for TC intensification (Mainelli et al., 2008), suggesting a heightened potential for TC development in the region. The temporal analysis of mean TCHP in the Malacca Strait corroborates this upward trend from 2023 to 2025 (**Fig. 4d**). Average TCHP values in 2023 and 2024 remained below the climatological mean. However, a marked increase began in mid-2024 and persisted throughout 2025, with TCHP consistently exceeding the climatological average. These findings indicate that, prior to the formation of TC Senyar in November 2025, subsurface heat had accumulated for nearly one year, thereby enhancing the ocean's energy reservoir for the cyclone. This study provides strong evidence of association, but not definitive causation. During the passage of TC Senyar in November 2025, a reduction in TCHP was recorded (**Fig. 4d**), although this change was not statistically significant.

It is hypothesized that the record-high TCHP observed in 2025 is closely associated with the phase of the IOD. The IOD represents a dominant mode of interannual variability in the Indian Ocean (Saji et al., 1999) and significantly influences the oceanographic conditions of the Malacca Strait due to its direct connectivity with the Indian Ocean basin. During the study period, the region experienced a strong positive IOD in 2023, transitioned to neutral conditions in 2024, and developed a negative IOD in 2025. A positive IOD is characterized by cooler-than-normal SST in the southeastern Indian Ocean near Indonesia, whereas a negative IOD is characterized by anomalously warm SSTs in the eastern Indian Ocean (Saji and Yamagata, 2003). The transition from a strong positive IOD to a negative IOD phase in 2025 functioned as a significant energy release mechanism, resulting in a substantial influx of warm water toward the Indonesian maritime continent. This shift facilitated the accumulation of subsurface heat and the elevated TCHP levels observed during that year.

To validate this mechanism, vertical temperature profiles in the Malacca Strait were analysed for several years exhibiting a transition from positive to negative IOD phases (1999, 2021, and 2025) and compared with a prominent negative IOD year (2010), focusing on the month of November. Analysis indicates that subsurface warming in the Malacca Strait was not only identified in 2025, but significant thermal anomalies were also observed in 1999, 2010, and 2021 (**Supplementary Material Fig. S1**). The 2025 event was the most extreme, with subsurface temperatures exceeding

30 °C at depths of approximately 60 m. In previous years, the core of the heat reservoir was generally restricted to shallower depths of around 40 m. The downward displacement of the warm layer indicates a progressive intensification and deepening of subsurface heat accumulation over time. This trend suggests that the thermal structure of the strait is becoming increasingly compressed. Further investigation is required to elucidate the long-term evolution of these deepening subsurface extremes and their potential to contribute to future intensification events.

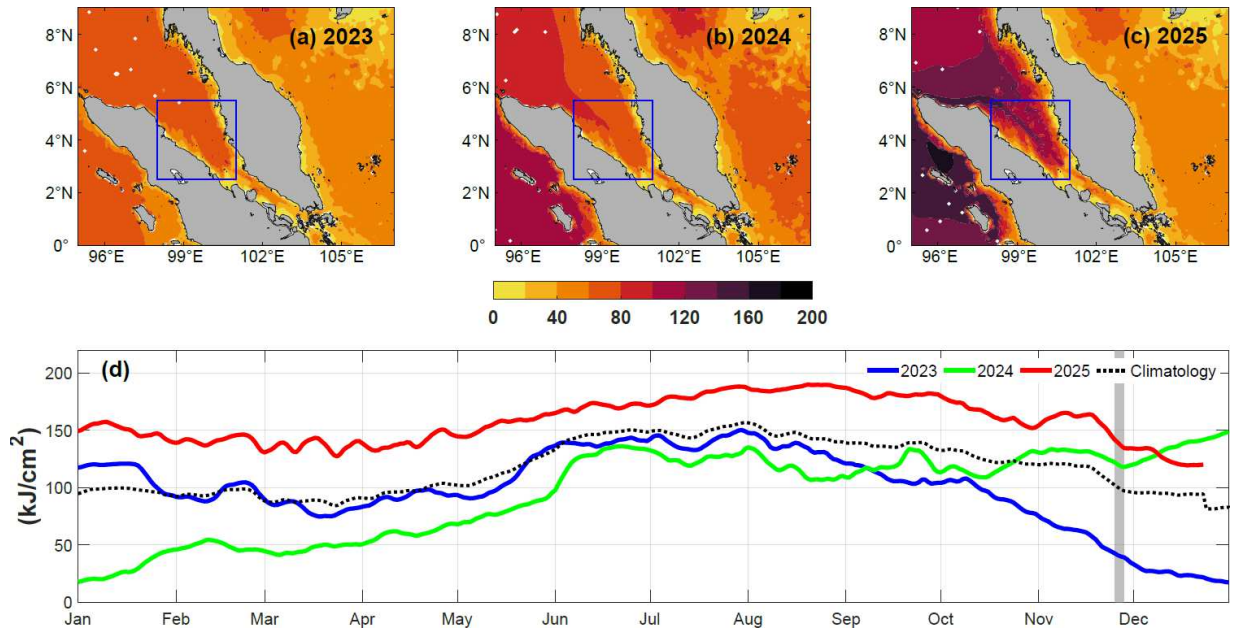


Fig. 4. (a–c) Spatial distributions of TCHP (in kJ/cm^2) for the annual averages of 2023, 2024, and 2025, respectively. **(d)** Temporal variation of TCHP from 2023 to 2025, averaged within the blue box, overlaid with the 1993–2025 climatological mean.

To further support the critical role of the subsurface in the development of MHWs and the intensification of TCs, a vertical temperature profile analysis was performed for the Malacca Strait and the SCS during the 2023–2025 period, as well as across before (22–24 Nov), during (25–26 Nov), and after (27–29 Nov) TC Senyar (**Fig. 5**). In the Malacca Strait, the 2025 temperature profile reveals anomalies that significantly exceed the climatological mean, indicating pronounced warming throughout that year (**Fig. 5a**). In contrast, although the SCS also remained above the climatological average over the past three years, the magnitude of warming was considerably less than that observed in the Malacca Strait (**Fig. 5b**).

The discrepancy in thermal patterns is further highlighted when analyzing the specific phases of TC Senyar: before, during, and after. In the Malacca Strait, all three phases consistently demonstrate that the highest temperatures are present in the subsurface rather than at the surface (**Fig. 5c**). A distinct heat bulge is observed at depths of 50–70 m, where temperatures exceed 30 °C, while surface temperatures remain below 30 °C. This subsurface heat core reached its maximum intensity before the cyclone, diminished during the event, and was lowest after the passage of the storm. This progression indicates substantial heat uptake by the cyclone from the subsurface reservoir. In contrast, the SCS profiles display values consistently above the climatological mean across all phases, with nearly uniform temperatures of approximately 29 °C from the surface to 50 m, followed by a sharp decline below 60 m (**Fig. 5d**).

The temperature inversion observed in the Malacca Strait, characterized by subsurface temperatures exceeding those at the surface, represents a distinctive oceanographic feature. The maintenance of cooler surface temperatures is likely due to substantial river runoff and intense regional precipitation, which generates a low-salinity surface layer and establish a robust barrier layer. This barrier effectively traps heat within the subsurface, a mechanism also documented by Shackelford et al. (2024) in the Indian Ocean. The resulting stratification creates a persistent thermal reservoir that intensifies subsurface MHWs and supplies the necessary energy for TC Senyar. This process inhibits the typical sea-surface cooling that generally follows cyclone passage (Guan et al., 2021; Oey, 2023).

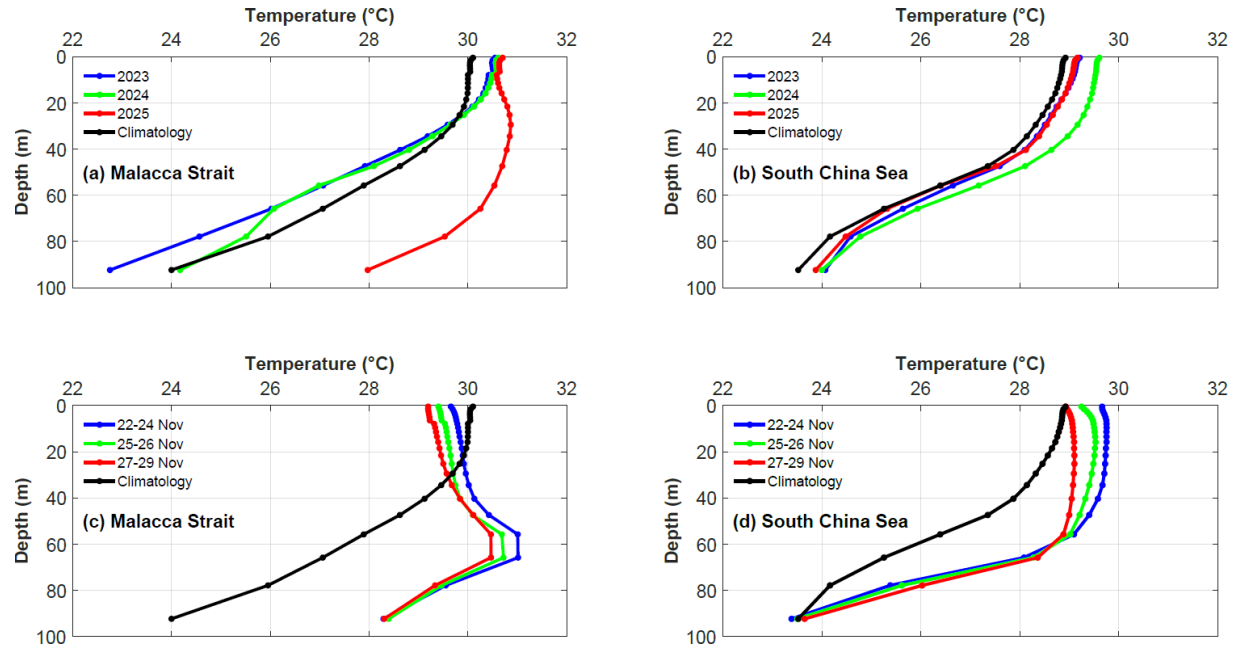


Fig. 5. Vertical ocean temperature profiles for the Malacca Strait (left column) and South China Sea (right column). Panels (a–b) present annual means for 2023, 2024, and 2025 relative to the climatology (1993–2025). Panels (c–d) show profiles before (22–24 Nov), during (25–26 Nov), and after (27–29 Nov) TC Senyar, overlaid with the long-term climatology.

This distinctive vertical thermal structure exerts a direct influence on the temporal evolution of MHWs in the study area. To further assess this effect, the daily progression of MHW characteristics was analyzed at multiple depths (surface, 15, 25, 40, 55, and 65 m) in both the Malacca Strait and the SCS during November–December 2025, with particular attention to the period surrounding the passage of TC Senyar (**Fig. 6**). In the Malacca Strait (**left panels**), the most intense MHWs were observed at depths of 55 and 65 m (**Figs. 6e–f**), where temperatures exceeded 31 °C. In contrast, no MHW events were detected from the surface to 40 m during November–December 2025. During the passage of TC Senyar, a cooling trend occurred from the surface to a depth of 25 m (**Figs. 6a–c**), however, this cooling was insufficient to produce significant temperature decreases or to initiate MCSs. Although the MHWs at 55 and 65 m depths showed some weakening during the cyclone, the magnitude of this reduction remained minimal. In contrast, the SCS (**right panels**) exhibited MHW occurrences across all depth layers, although the temperature magnitudes in these layers were substantially lower than those observed in the Malacca Strait.

TCs typically induce intense vertical mixing in the upper ocean, which produces a trail of cooler SSTs, known as a cold wake, along their trajectory, as documented by Pun et al. (2025) for TC Bavi in the East China Sea and in global studies by Dac Da et al. (2023). However, this pronounced cooling effect was absent during TC Senyar in the Malacca Strait, where MCSs did not develop despite the cyclone's passage. We suggest that vertical heat exchange through entrainment and upwelling transport warmer subsurface water to the surface. This process is consistent with the mechanism described by Gao et al. (2025), who demonstrated that strong pre-cyclogenesis winds can perturb the ocean interior to depths exceeding 100 m due to entrainment and upwelling. This persistent heat supply to the surface inhibited the typical sea-surface cooling process. As a result, the TCHP during TC Senyar decreased only slightly (**Fig. 4d**). The ongoing energy transfer from the subsurface reservoir allowed the cyclone to sustain its intensity by preventing self-induced ocean cooling.

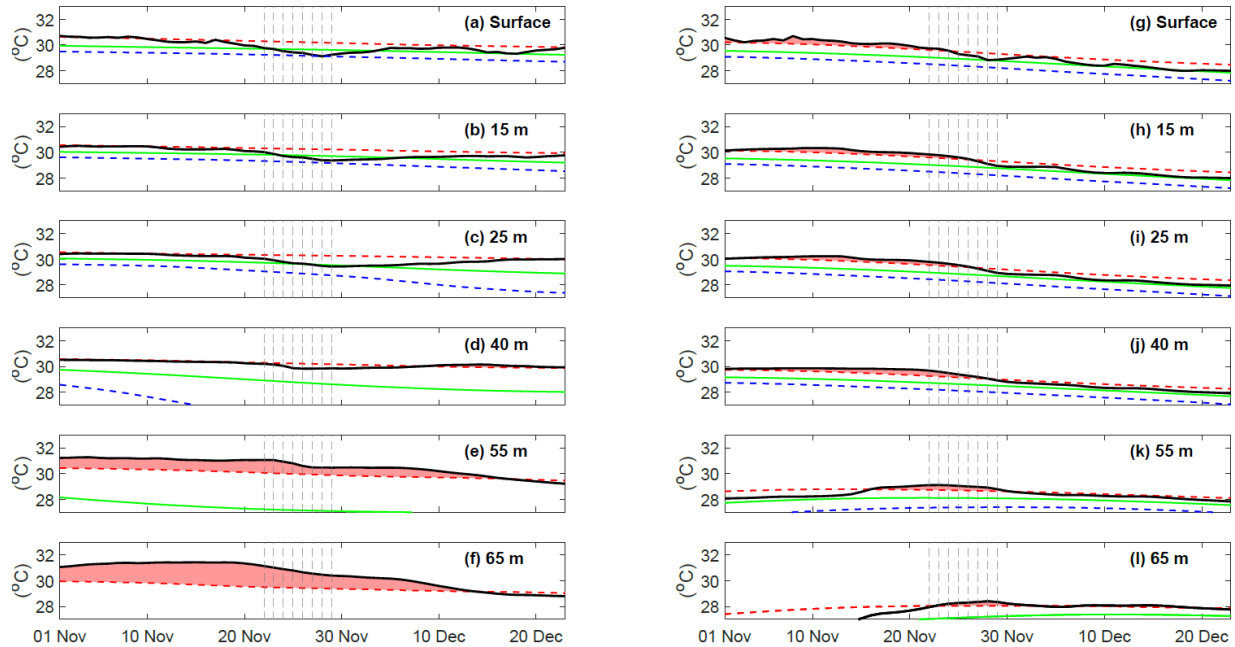


Fig. 6. Temporal evolution of MHWs in the Malacca Strait (left column) and South China Sea (right column). Panels (a–l) show MHW development at specific depth layers (surface, 15 m, 25 m, 40 m, 55 m, and 65 m) from 1 November to 23 December 2025. Black lines indicate daily temperature, solid green lines represent climatology, and red and blue dashed lines correspond to the 90th and 10th percentile thresholds, respectively (all in °C). Red shading highlights MHW events (temperature above the 90th percentile). Vertical grey dashed lines delineate periods before, during, and after TC Senyar (22–29 November 2025).

3.3 Advection Dynamics and Barrier Layer Effects

To elucidate the physical mechanisms responsible for the observed subsurface heat accumulation, this study examines ocean circulation patterns and their role in transporting warm water masses. Analysis of the interactions between currents and thermal structures at various depths enables identification of the specific pathways that contribute to subsurface warming within the Malacca Strait (**Fig. 7**). The analysis encompasses three periods: before, during, and after the passage of TC Senyar. For conciseness, only the before period results are presented here. The during and after phases are included in **Supplementary Material Figs. S2 and S3**. Subsurface warming localized at depths of 50–60 m (**Figs. 4–6**) appears to be driven by a subsurface equatorial current at similar depths. This current moves northward, transporting warm water masses ($>30\text{ }^{\circ}\text{C}$) into the Malacca Strait (**Figs. 7e–g**). The strong subsurface inflow of warm water peaked during the pre-TC period and weakened during and after the event. In contrast, from the surface to 25 m depth, the flow was dominated by an influx from the SCS into the Malacca Strait. This surface-layer current also transported warmer waters, reaching maximum intensity during and after phases of the cyclone.

Under neutral conditions, SST ranges from $27\text{ }^{\circ}\text{C}$ to $30\text{ }^{\circ}\text{C}$ and is primarily regulated by wind-driven circulation and sea-level gradients between the Indian Ocean and the SCS (Isa et al., 2020). This dynamic environment facilitates significant seasonal exchanges of water masses. During the Southwest Monsoon, the Malacca Strait experiences intrusions of cool, deep, saline water from the Andaman Sea. Conversely, the Northeast Monsoon introduces low-salinity water from the SCS, attributed to increased river discharge and substantial regional precipitation (Ibrahim and Yanagi, 2006). Although surface dynamics are well documented, research addressing the concurrent interactions of currents and temperatures within the subsurface layers of the Malacca Strait remains limited.

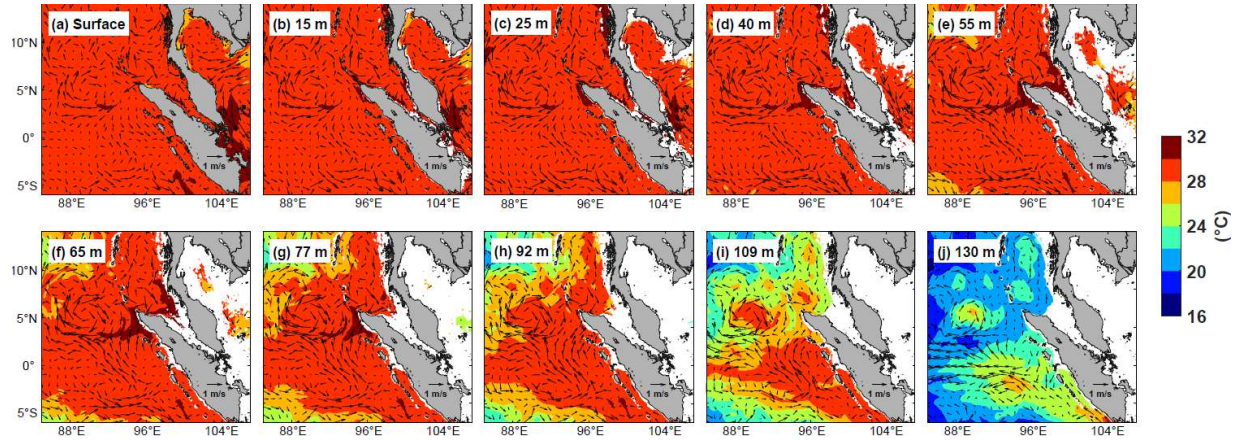


Fig. 7. Mean spatial distribution of sea temperature and ocean currents prior to TC Senyar (22–24 Nov 2025) in the Malacca Strait and adjacent regions. Panels (a–j) show distributions at the following depths: surface, 15, 25, 40, 55, 65, 77, 92, 109, and 130 m. Color shading denotes sea temperature ($^{\circ}\text{C}$), while vectors represent ocean current velocity (m/s).

A quantitative evaluation of the subsurface layer's thermal response to TC Senyar was performed using a heat budget analysis within the Malacca Strait across three distinct periods: before, during, and after TC Senyar (**Fig. 8a**). The heat budget analysis across all three periods demonstrates a consistent negative temperature tendency. The most pronounced cooling occurs during the pre-TC period, followed by the during-TC period, with the minimum negative value observed in the post-TC phase. This pattern indicates a decline in subsurface temperatures as a direct response to TC Senyar. These results suggest that, both prior to and during the event, subsurface heat was actively utilized to support the intensification of the cyclone.

In the pre-TC period, the residual term was the primary driver of the observed cooling (**Fig. 8a**). The pronounced negative residual value is consistent with vertical processes but not explicitly resolved. During the TC period, the temperature tendency remained negative but was less pronounced compared to the pre-TC phase (**Fig. 8a**). Horizontal advection increased significantly and became a more influential factor than the residual term. This change underscores the important role of intensified ocean currents in redistributing thermal energy during the storm's passage. In the post-TC period, the temperature tendency weakened substantially, indicating that the subsurface environment began to stabilize toward its climatological norm. During this recovery phase, horizontal advection became positive and contributed to gradual re-warming, while the residual term remained slightly negative, indicating a persistent but diminishing cooling effect.

Analysis of the horizontal advection term demonstrates a clear distinction between its zonal and meridional components throughout all periods (**Fig. 8b**). Zonal advection remained consistently negative, functioning as a cooling mechanism by transporting cooler water masses from adjacent regions into the study area. In contrast, meridional advection was consistently positive, contributing to the warming of the subsurface heat budget. These findings indicate that zonal currents tended to reduce subsurface heat, whereas meridional transport, likely driven by the northward-flowing currents shown in **Fig. 7**, continuously introduced warmer water masses into the Malacca Strait, thereby partially compensating for the cyclone-induced cooling.

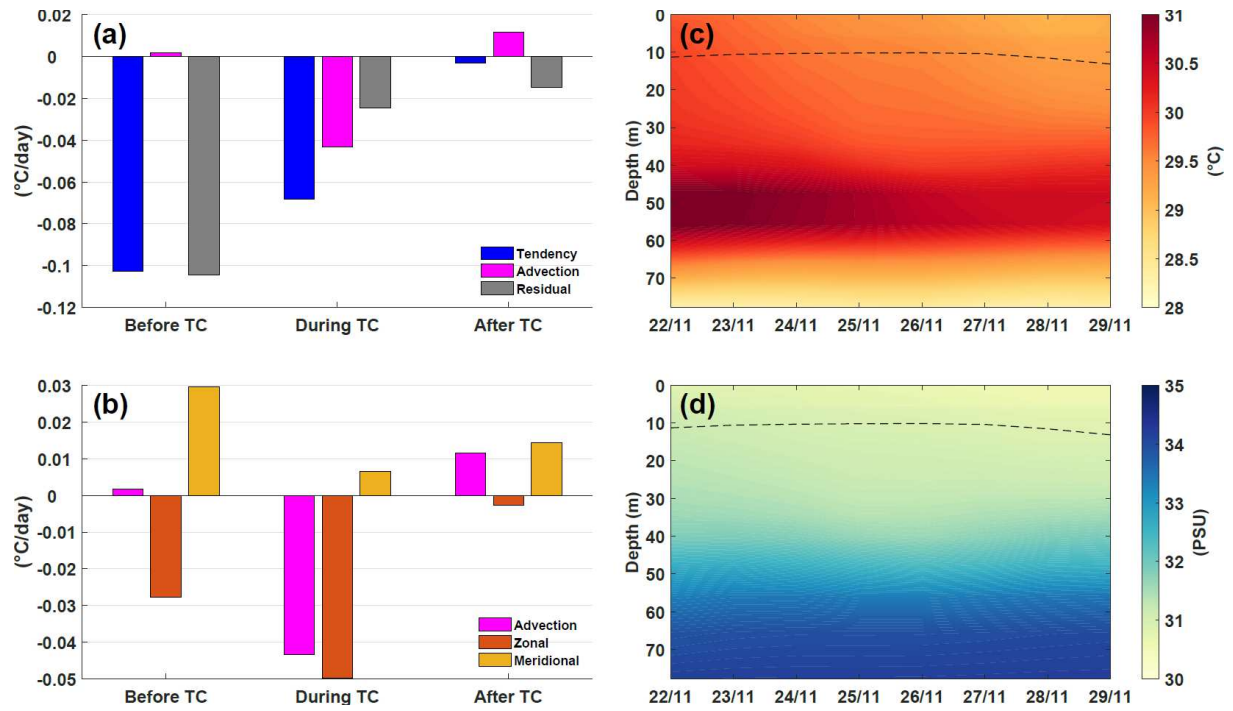


Fig. 8. Heat budget analysis in the subsurface and vertical water column structure during the life cycle of TC Senyar. **(a)** Temporal evolution of temperature tendency (blue), horizontal advection (magenta), and residual (grey) in $^{\circ}\text{C}/\text{day}$ across pre-TC, during-TC, and post-TC phases. **(b)** Decomposition of horizontal advection into zonal (orange) and meridional (yellow) components. **(c–d)** Time-depth cross-sections of seawater temperature ($^{\circ}\text{C}$) and salinity (PSU) from 22 to 29 November 2025, averaged within the blue box shown in **Fig. 1**. The dashed line represents the evolution of the MLD.

Vertical profiles of temperature and salinity in the Malacca Strait during the TC Senyar period (Figs. 8c and d) indicate the presence of a subsurface heat reservoir. A localized core of warm water exceeding 30 °C is observed at depths of 50 to 60 meters, coinciding with a high-salinity layer above 34 PSU. The overlying low-salinity surface layer, approximately 30 PSU, creates strong stratification that traps thermal energy within the subsurface and restricts heat exchange with the atmosphere prior to the cyclone's arrival. Subsurface cooling observed after November 25 (Fig. 8c) corroborates the heat budget analysis (Fig. 8a) and indicates that this deep-seated heat reservoir served as the energy source for the intensification of TC Senyar. These findings indicate that the Malacca Strait served as a major thermal powerhouse. Subsurface heat accumulation, maintained by strong salinity stratification, provided the energy required for the intensification of TC Senyar.

3.4 Multiphase Ocean-Atmosphere Response to TC Senyar

To clarify the atmospheric drivers and vertical transport mechanisms responsible for these oceanic responses, spatial-temporal patterns of wind speed at 850 hPa, OLR, and Ekman Pumping Velocity (EPV) were examined during the various phases of TC Senyar (Figs. 9–11). The 850 hPa wind patterns demonstrate the cyclogenesis process (Fig. 9). A distinct cyclonic circulation developed over the Malacca Strait on 22 November and reached maximum intensity by 25 November. During this period, wind speeds exceeded 15 m/s, while speeds within the storm's eye remained below 5 m/s. This spatial arrangement, characterized by a high-velocity wind ring surrounding a calm center, is characteristic of TC structure. The development of intense vorticity was likely amplified by the unique geography of the Malacca Strait, which is bordered by the high mountain ranges of Malay Peninsula and Sumatra (Lui et al., 2026). These topographical constraints, together with favorable atmospheric conditions, served as a physical funnel for circulation. Wind speed began to dissipate on 28 November as it moved southeastward.

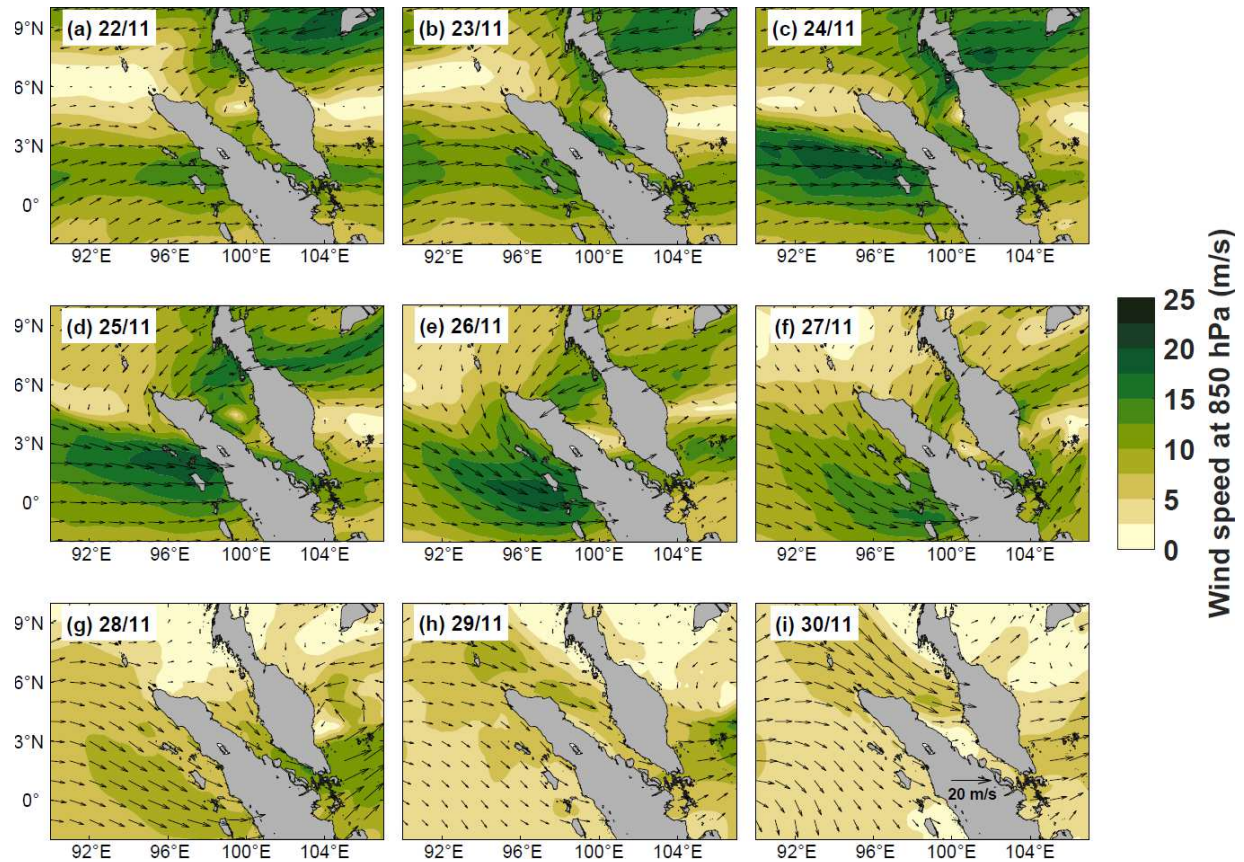


Fig. 9. Spatial evolution of wind speed at 850 hPa before, during, and after TC Senyar (22–30 November 2025). Panels (a–i) present daily averaged wind speed (shaded, m/s) and wind vectors (arrows) at the 850 hPa level.

The evolution of OLR is presented on **Fig. 10**. Negative OLR anomalies indicate strong convective activity, which is typically associated with thick cloud cover and heavy precipitation, both of which are key indicators of tropical storm development. In contrast, positive anomalies correspond to suppressed convective activity and clear-sky conditions. Beginning on 22 November, intense convective activity was detected over the Malacca Strait and adjacent areas. This activity intensified, reaching a peak on 25 November with values of -150 W/m^2 . After this peak, the convective center gradually shifted eastward. By 29 November, clear-sky conditions prevailed over the Malacca Strait, indicating the dissipation of the storm system from the region. This large-scale atmospheric forcing likely contributed to the intensification of the storm as the convective center traversed the region.

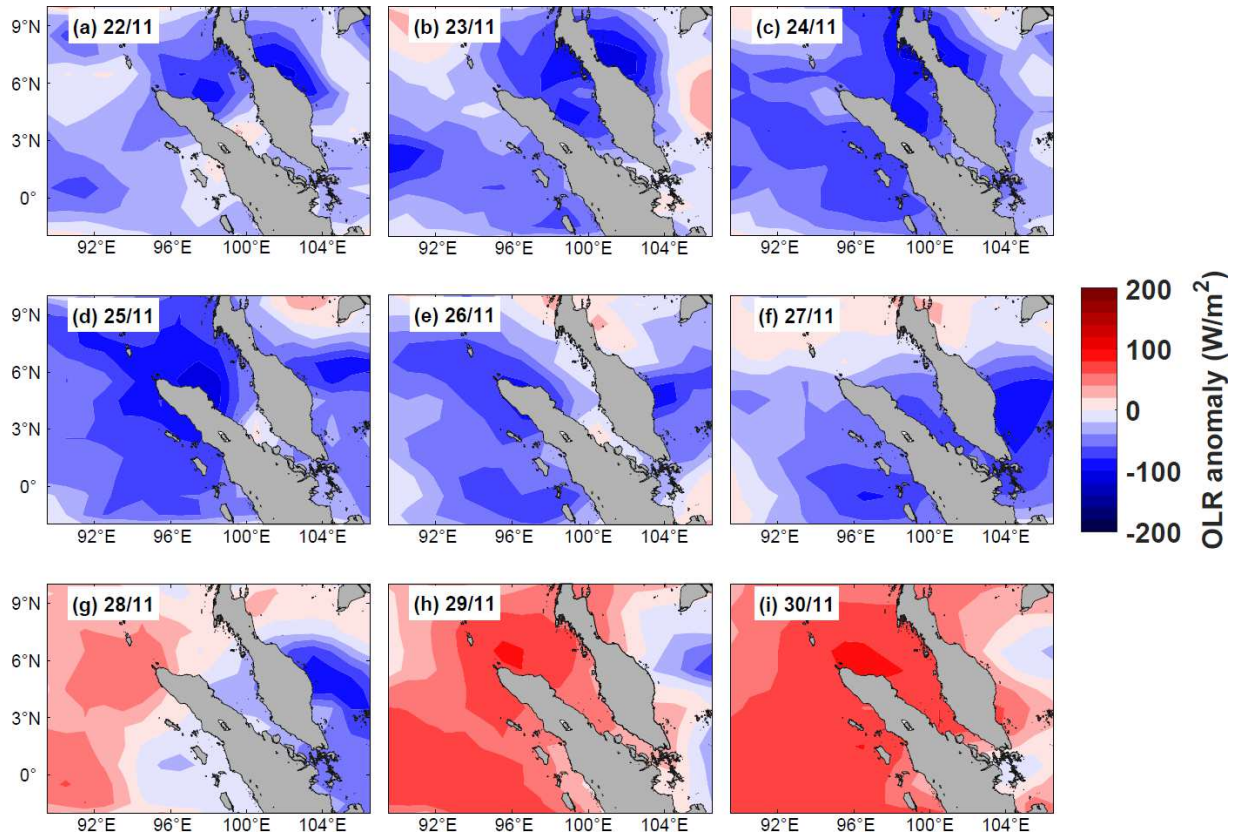


Fig. 10. Spatial evolution of OLR (W/m^2) before, during, and after TC Senyar (22–30 November 2025). Panels (a–i) present anomaly OLR (shaded, W/m^2).

Vertical transport mechanisms, as indicated by EPV, were analyzed to assess the oceanic response to TC Senyar (**Fig. 11**). Positive EPV values correspond to upwelling, whereas negative values denote downwelling. From 22 November, significant upwelling was observed in the Malacca Strait, persisting until 25 November and peaking at $20 \times 10^{-5} \text{ m/s}$. As prevailing winds shifted toward the eastern coast of Sumatra, Ekman transport was deflected to the right, away from the coast, as a result of the Coriolis effect. This deflection led to surface mass divergence, which in turn initiated the upwelling of deeper water masses.

Notably, the upwelling observed in this event differs from the typical process in most regions, which generally transports cold water from depth to the surface. In this case, upwelling entrained warmer water from the subsurface reservoir to the surface, thereby maintaining SST despite the intense mechanical forcing of the storm. Overall, intensified winds, strong convective activity, and vigorous upwelling were observed several days before the arrival of TC Senyar. These processes

reached their maximum on November 25, after which their intensity decreased, and the Malacca Strait gradually returned to its climatological norm.

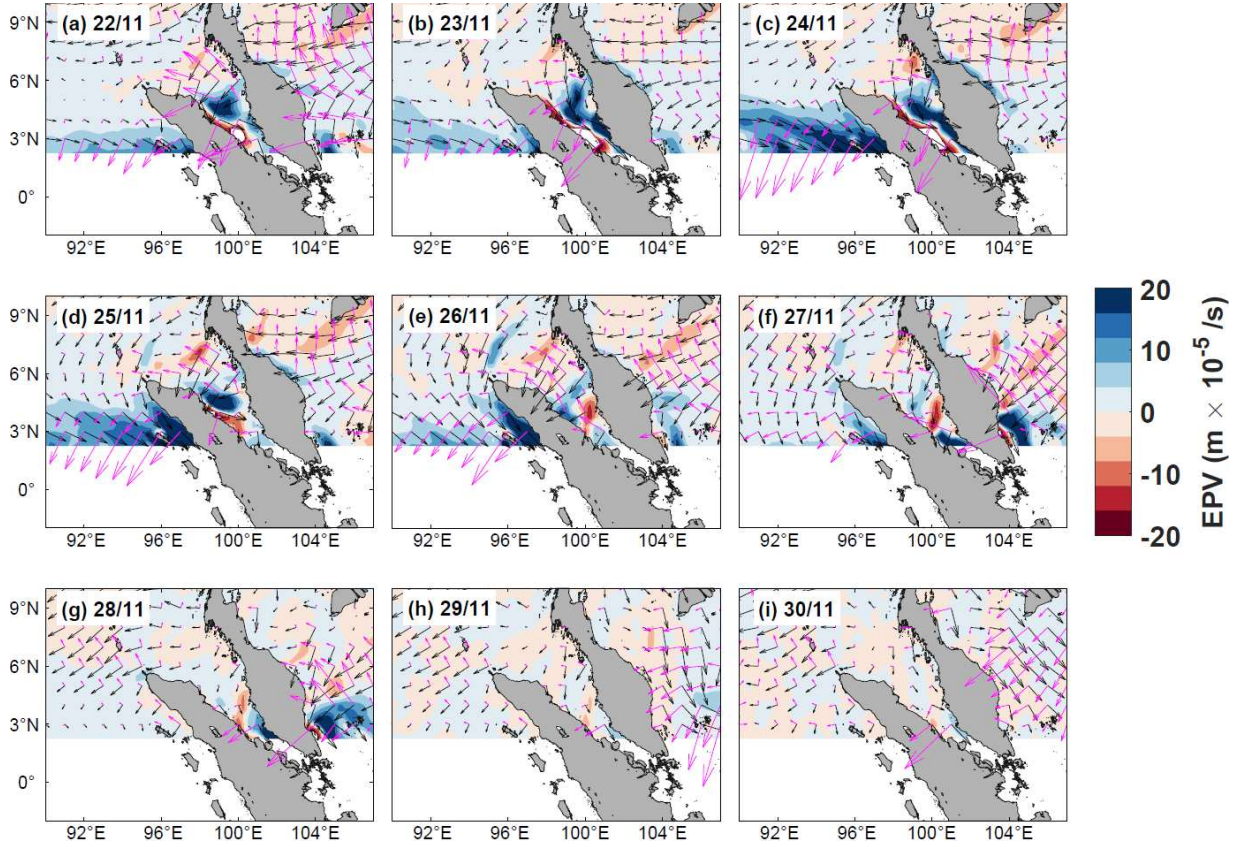


Fig. 11. Spatial evolution of EPV (m/s) before, during, and after TC Senyar (22–30 November 2025). Panels (a–i) present daily averaged EPV (shaded, m/s), wind stress vectors (black arrows), and Ekman transport (magenta arrows). Positive velocity represents upwelling, while negative velocity represents downwelling.

The interaction between atmospheric forcing and oceanic dynamics in the Malacca Strait established conditions favorable for the intensification of TC Senyar. The underlying physical mechanisms are summarized in the conceptual schematic (**Fig. 12**). This schematic illustrates the preservation, extraction, and dissipation of subsurface heat across the three distinct phases (pre-, during, and post-event) of the cyclone's life cycle.

During the pre-TC period, the atmosphere exhibited wind intensification and early convective activity (**Figs. 9 and 10**). Subsurface observations revealed a heat reservoir exceeding 31 °C, confined at depths of 50 to 60 m (**Figs. 5–8**) and insulated by strong stratification resulting from

the low-salinity surface layer (**Fig. 8d**). This subsurface warming was likely influenced by equatorial currents transporting warm water masses at similar depths (50–60 m) (**Fig. 7**). Additionally, strong warm upwelling during cyclones facilitated the upward transport of thermal energy (**Fig. 11**), thereby preparing the ocean for cyclone intensification.

During the TC period, the arrival of TC Senyar over the Malacca Strait initiated intense air-sea interactions, marked by strong winds and vigorous convective activity (**Figs. 9 and 10**). Although warm advection from the equator weakened relative to the pre-TC phase (**Fig. S2**), the strong cyclonic forcing promoted significant warm upwelling (**Fig. 11**). No cold wake was observed during this phase. This process continuously transported heat upward, resulting in a negative temperature tendency within the subsurface layers (**Fig. 8**). As a result, subsurface MHW intensity decreased (**Fig. 6**), indicating that the cyclone relied on extracting localized, trapped heat to support its intensification.

Following the passage of TC Senyar, atmospheric conditions stabilized, characterized by weak winds (**Fig. 9**) and clear skies returning (**Fig. 10**). Oceanic energy extraction decreased, leading to weaker warm upwelling (**Fig. 11**). Warm advection from the equator also remained reduced (**Fig. S3**). Consequently, subsurface MHWs were less intense than those initially observed (**Fig. 6**), indicating a substantial depletion of the warm reservoir. During this period, the Malacca Strait progressively dissipated residual oceanic perturbations and approached its climatological norm.

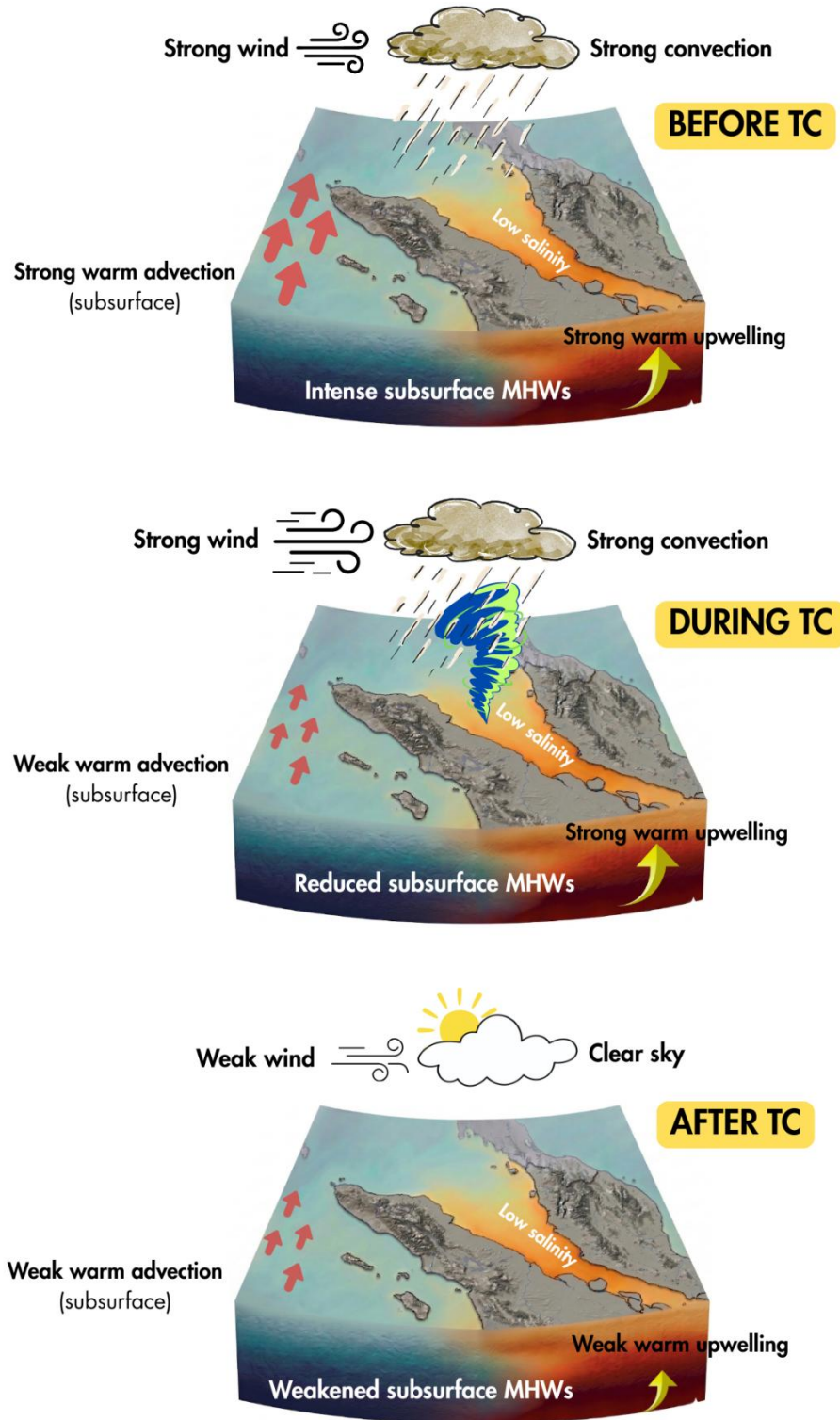


Fig. 12. Conceptual schematic diagram. This diagram illustrates the physical mechanisms that influence subsurface MHWs throughout the life cycle of TC Senyar at various phases: **(top)** before the cyclone (22–24 November 2025), **(middle)** during the cyclone (25–26 November 2025), and **(bottom)** after the cyclone (27–29 November 2025).

Conclusion

Over the period from 1993 to 2025, subsurface MHWs in the Malacca Strait exhibited greater intensity compared to surface events. Analysis of vertical temperature profiles indicates a persistent temperature inversion, with subsurface temperatures at depths of 50–60 meters exceeding 30 °C, while surface temperatures remained below this value. This research provides the first evidence of persistent subsurface warming in the Malacca Strait. These findings significantly advance the understanding of subsurface thermal dynamics in the Indonesian seas, particularly in the Malacca Strait, and their association with the formation of TC Senyar.

The thermal energy that fueled TC Senyar accumulated well before the storm's formation. TCHP values began increasing in mid-2024 and remained elevated throughout 2025, resulting in a sustained buildup of oceanic heat. This increase in TCHP is likely associated with the climatic transition from a strong positive IOD phase to a negative IOD phase. However, the precise relationship warrants further investigation. Equatorial currents at depths of 50 to 60 meters played a critical role in transporting warm water masses into the strait. The accumulated heat was retained below the surface due to strong stratification, which was maintained by low surface salinity.

Analysis of the subsurface heat budget indicates a persistent negative temperature tendency throughout the evolution of TC Senyar. Before the cyclone's arrival, cooling was mainly controlled by residual processes, consistent with vertical processes, but not explicitly resolved. In contrast, during the cyclone's passage, horizontal advection became the dominant mechanism responsible for subsurface heat extraction. Unlike typical cyclones that induce surface cooling, intense upwelling in the Malacca Strait transported trapped warm water to the surface. Consequently, the characteristic cold wake did not develop. This mechanism enabled the cyclone to sustain its intensity by utilizing the pre-existing subsurface heat reservoir, which would otherwise have remained isolated beneath the stratified surface layer. Subsurface warming in the Malacca Strait serves as a significant energy source for TCs. However, the development of these cyclones also depends on specific atmospheric triggers. Therefore, systematic monitoring of both oceanic and atmospheric conditions is necessary to enhance preparedness and mitigation strategies for future storm events.

Data availability:

The GLORYS12V1 dataset is accessible through the Copernicus Marine Service (<https://doi.org/10.48670/moi-00021>). ERA5 data are available from the Copernicus Climate Change Service (C3S) Climate Data Store (<https://doi.org/10.24381/cds.adbb2d47>). IBTrACS data are provided by the U.S. National Centers for Environmental Information (NCEI) (<https://doi.org/10.25921/82ty-9e16>).

Conflicts of interest:

The authors declare that they have no conflicts of interest.

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Author contributions:

Erlin Beliyana: Conceptualization, Formal analysis, Methodology, Software, Visualization, Writing – original draft, Writing – review and editing. **Mochamad Furqon Azis Ismail:** Conceptualization, Formal analysis, Methodology, Funding acquisition, Supervision, Writing – review and editing. **Abdul Basit:** Conceptualization, Formal analysis, Supervision. **Arief Suryo:** Formal analysis, Supervision. **Afiq Mahasin:** Data curation, Visualization.

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Supplementary material:

Supplementary Figures can be accessed in the online version of this article.

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