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Marine Cold Spells Induced by Tropical Cyclone Seroja in the Savu Sea

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Abstract. Tropical Cyclone (TC) Seroja was the only TC recorded in the Savu Sea in 2021 and was among the first TCs to cause extensive damage to buildings and infrastructure on Indonesian land. Despite its significant impact, the TC effect on the oceanic thermal energy balance in this region remains poorly studied. This study examines the dynamical ocean response of the Savu Sea to TC Seroja using a combination of satellite-derived sea surface temperatures (SST) observations, TC best-track records, and atmosphere-ocean reanalysis output. The findings indicate that the Savu Sea is highly susceptible to cyclogenesis, as long-term mean SST consistently exceed 28 °C. Elevated Tropical Cyclone Heat Potential (TCHP) values above 80 kJ/cm² were observed prior to the development of TC Seroja, suggesting that substantial subsurface heat may have contributed to cyclone intensification in the Savu Sea. During the cyclone, TCHP values declined markedly below the climatological mean. The cyclone also induced a pronounced marine cold spells and Ekman pumping, which was associated with upwelling. Mixed-layer heat budget analysis demonstrates that upper Savu Sea cooling during TC Seroja was primarily driven by latent heat loss due to intense wind speeds. Furthermore, heat loss attributed to the residual term, representing turbulent mixing, was also considerable.

Keywords: Tropical Cyclone Seroja, Savu Sea, marine cold spells, upwelling, mixed-layer heat budget, latent heat loss.

Online summary text: This study examines the impact of Tropical Cyclone Seroja in 2021 on ocean temperatures in the Savu Sea, Indonesia. Unusually warm ocean conditions prior to the cyclone contributed to its intensification, while the storm itself caused rapid cooling through strong winds and ocean mixing. These results enhance our understanding of cyclone behavior in Indonesian waters and support improved disaster preparedness and climate risk management.

1. Introduction

Tropical cyclones (TCs) cause significant impacts, including destructive winds (Duan and Li, 2022; Yulihastin et al. 2023), extensive flooding from heavy rainfall (Potter et al. 2019; Latos et al. 2023), lethal storm surges (Kikuchi et al. 2009), and landslides (Latos et al. 2023; Shi et al. 2024). Collectively, these hazards result in substantial socio-economic disruption and severe ecological damage (Lenzen et al. 2019). Between 1970 and 2019, TC caused nearly 780,000 fatalities and economic losses exceeding 1.4 trillion USD (Douris and Kim 2021). Increasing coastal populations and intensifying global warming further heighten regional vulnerability to TCs (Rathore et al. 2022; Choi et al. 2024; Dutheil et al. 2024; Radfar et al. 2024; Nguyen and Hsu 2025; Zhou et al. 2025). Therefore, advancing the understanding of TC genesis and its complex environmental interactions is essential for mitigating future risks and reducing large-scale devastation.

The formation of TCs results from a complex interaction between upper-ocean thermal conditions and atmospheric forcing mechanisms. Cyclogenesis is influenced by the interaction of various equatorial waves that destabilize the atmosphere and promote convective development (Latos et al. 2023). Additionally, TC development requires low vertical wind shear to preserve the storm's structural integrity (Yulihastin et al. 2023) and sufficient latitudinal displacement from the equator to ensure an adequate Coriolis force for cyclonic rotation (Li and Toumi 2025). A sea surface temperature (SST) threshold of at least 26.5 °C is widely recognized as a primary indicator for TC initiation (Tory and Dare 2015), as it provides the latent heat energy required for intensification (Yu et al. 2025). However, SST alone does not fully represent the energy available for cyclones, since the influence of the subsurface ocean has often been overlooked. Recent studies indicate that subsurface variability, particularly the 26 °C isothermal depth, plays a significant role in modulating cyclogenesis (Jin et al. 2014; Huang et al. 2015; Gao et al. 2025). This depth governs the total ocean heat energy and determines the storm's resilience to self-induced cooling. Thus, understanding the vertical thermal structure of the subsurface ocean is crucial for a comprehensive assessment of the energy reservoir that sustains TCs during their most destructive phases.

In addition to their role in genesis, TCs also induce significant oceanic responses, including the abrupt termination of pre-existing marine heatwaves (MHWs) and the subsequent onset of marine cold spells (MCSs) (Ushijima and Yoshikawa 2020; Kudryavtsev and Pivaev 2025). TCs can rapidly terminate MHWs through extreme SST cooling. For instance, TC Bavi resulted in cooling of up to 7 °C (Pun et al. 2025). However, research on these feedback mechanisms remains limited, as most studies mainly examine MHWs as precursors to TC intensification (Zhang et al. 2021; Rathore et al. 2022; Choi et al. 2024; Radfar et al. 2024; Nguyen and Hsu 2025; Zhou et al. 2025). A 20-year analysis demonstrates a significant (99%) inverse relationship between seasonal TC activity and MHW occurrence, suggesting that increased TC frequency is associated with reduced MHW intensity and duration (Pun et al. 2025). Through the induction of extreme surface cooling, TCs may also trigger MCS events (Looney and Foltz 2025; Pun et al. 2025; Guan et al. 2026). The abrupt shift from heat-driven cyclogenesis to pronounce sea-surface cooling produces thermal shock, which may disrupt aquatic ecosystems and coral reef fisheries (Habibullah et al. 2023; Liu et al. 2024; Handiani et al. 2025; Ningsih et al.

2025). Consequently, further investigation into the role of TCs in mediating rapid thermal reversals from extreme heat to cold spells is essential for effective marine hazard mitigation.

TC Seroja is recognized as one of the deadliest TCs in the Savu Sea, resulting in unprecedented destruction across East Nusa Tenggara. Previous studies have examined this event, focusing on its severe socio-economic impacts (Earl-Spurr 2022) and the underlying drivers (Latos et al. 2023; Yulihastin et al. 2023). However, most research on these drivers has primarily adopted an atmospheric perspective. For instance, Latos et al. (2023) reported that the unusual near-equatorial cyclogenesis of TC Seroja represents a perfect storm scenario. Intensified convection associated with the Madden-Julian Oscillation (MJO) interacted with coupled equatorial Rossby and Kelvin waves, accelerating vortex formation despite the weak Coriolis force in the region. Additionally, Yulihastin et al. (2023) found that MHWs and the formation of double vortices provided critical preconditions that facilitated cyclogenesis in the region. Despite these findings, research on the drivers of TC Seroja, particularly regarding subsurface processes, remains limited. This gap is significant, because subsurface ocean heat is essential for TC development and intensification under ongoing global warming (Jin et al. 2014; Huang et al. 2015; Gao et al. 2025). This study presents the first comprehensive assessment of TC Seroja from an oceanic perspective, focusing on subsurface drivers and the upper-ocean response. The analysis examines how elevated subsurface ocean heat facilitated intensification, as well as the mixing-induced processes that suppressed existing MHWs and subsequently triggered severe MCSs. By investigating the upper ocean thermodynamic evolution throughout the event, this research clarifies the role of TC Seroja in catalysing rapid transitions between oceanic thermal extremes.

2. Materials and Methods

2.1 Study Area

The study area spans 120°E to 125°E and 9°S to 12°S, encompassing the Savu Sea (Fig. 1a). Located between the Banda Sea and the Indian Ocean, the Savu Sea serves as a direct passage connecting the Indonesian seas with the Indian Ocean. The region experiences seasonally reversing monsoon winds, from the southeast during austral winter (April to November) and from the northwest during austral summer (December to March). These winds transport upper ocean waters from the Pacific Ocean to the Indian Ocean (Potemra et al. 2003; Wang et

al. 2020). Wind stress in the Savu Sea drives upwelling through Ekman pumping year-round, with maximum intensity in June and July (Potemra et al. 2003). During these months, the Savu Sea exhibits high chlorophyll-a concentrations and low SST, primarily due to coastal upwelling (Muskananfolo et al. 2021; Sie et al. 2025). The complex local topography further amplifies this process by strengthening surface winds, which enhances localized SST cooling and increases marine productivity (Sie et al. 2025). Conversely, air-sea heat flux is the primary driver of SST increases in October during the transition phase (Sie et al. 2025). On an interannual timescale, variations in local minimum SST and maximum chlorophyll-a concentrations are associated with the Indian Ocean Dipole phases, driven by sea level anomalies and remote forcing from the Indian Ocean (Sie et al. 2025).

2.2 Data

Remotely-sensed SST ($^{\circ}\text{C}$) data were obtained from the Operational Sea Surface Temperature and Sea Ice Analysis (OSTIA) reprocessed Level 4 dataset. The product is identified as “METOFFICE-GLO-SST-L4-NRT-OBS-SST-V2” and is available through the Copernicus Marine Environment Monitoring Service (Stark et al. 2007; Donlon et al. 2012; Good et al. 2020). This SST product is provided daily on a regular latitude-longitude grid with a spatial resolution of 0.05° by 0.05° . For the present analysis, the SST data are used for the period January 1982 to December 2024.

The zonal (u) and meridional (v) components (m/s) were obtained from the Global Ocean Physics Reanalysis (GLORYS12V1), which provides daily outputs at $1/12^{\circ}$ (approximately 8 km) horizontal resolution and 50 vertical levels for the period 1993–2020. GLORYS12V1, produced using the NEMO model and assimilating both satellite and in situ observations, offers a realistic representation of upper-ocean dynamics (Lellouche et al. 2021).

Atmospheric data were sourced from the ERA5 reanalysis dataset produced by the European Centre for Medium-Range Weather Forecasts (ECMWF). The dataset includes 10 m wind speed (m/s), 850 hPa wind speed (m/s), mean sea level pressure (MSLP, hPa), longwave radiation (J/m^2), shortwave radiation (J/m^2), latent heat flux (J/m^2), and sensible heat flux (J/m^2). ERA5 offers hourly data at a spatial resolution of $0.25^{\circ} \times 0.25^{\circ}$.

(approximately 28 km), which provides high temporal consistency and comprehensive global coverage (Hersbach et al. 2020). All variables were retrieved for the period from 1 January 1982 to 31 December 2024.

Large-scale convective activity over the Savu Sea region was assessed using daily NOAA Interpolated Outgoing Longwave Radiation (OLR, W/m²) data, obtained from the NOAA Physical Sciences Laboratory (PSL), Boulder, Colorado, USA (<https://psl.noaa.gov>).

2.3 Methods

The isothermal layer depth (ILD) was estimated following the methodologies outlined by de Boyer Montégut et al. (2004) and Holte and Talley (2009). ILD is defined as the interpolated depth where the temperature decreases by 0.2 °C from the 10 m reference depth, a criterion that minimizes diurnal variability (Breugem et al. 2008). The mixed layer depth (MLD) was obtained from the GLORYS12V1 dataset. The barrier layer thickness (BLT) was calculated as the positive difference between ILD and MLD, provided this difference exceeded 2 m (Ismail et al. 2024).

The role of subsurface heat accumulation during TC development was assessed by calculating the Tropical Cyclone Heat Potential (TCHP) using the methodology described by Rathore et al. (2022), as defined in Equation (1).

$$TCHP = \int_0^{D_{26}} \rho C_p (T - 26) dz \quad (1)$$

Where T denotes temperature (°C), ρ is potential density (1024 kg/m³), c_p is the specific heat capacity of seawater (assumed constant at 3940 J/kg °C), and D_{26} is the depth of the 26 °C isotherm in the ocean (Jangir et al. 2021).

MHWs and MCSs were detected using the methodology established by Hobday et al. (2016) and Schlegel et al. (2021). The daily SST climatology, as well as the 10th and 90th percentile thresholds, was calculated from the complete OSTIA Level 4 dataset over a 30-year climatological period (1 January 1982 to 31 December 2011). An MHW was identified when SST exceeded the 90th percentile for at least five consecutive days (Hobday et al. 2016), whereas an MCS was defined as SST falling below the 10th percentile for the same

duration (Schlegel et al. 2021). Successive events separated by gaps of two days or fewer were considered a single continuous event, whereas longer gaps delineated separate events. Given the comprehensive spatial and temporal coverage of the OSTIA dataset, only surface SST events were analysed. All data processing procedures adhered to the code implementation developed by Zhao and Marin (2019).

TC tracks and characteristics were sourced from the International Best Track Archive for Climate Stewardship (IBTrACS) Version 4.01. IBTrACS compiles and standardizes best-track data from multiple operational agencies worldwide, including the Joint Typhoon Warning Center (JTWC) and the Japan Meteorological Agency (JMA) (Knapp et al. 2010; Gahtan et al. 2024). The database offers detailed storm information, including center position, maximum sustained wind speed, and minimum central pressure at 3- or 6-hour intervals. The temporal evolution of each TC served as the reference period for examining the development, persistence, and decay of MHWs and MCSs. TC lifetimes were defined from formation to dissipation, and these intervals were aligned with daily SST, MHW, and MCS datasets to assess the progression of upper-ocean thermal anomalies before, during, and after TC passages.

The mechanisms driving MHW and MCS formation in the study area were investigated, with particular attention to the drivers contributing to the prominent MCS period during TC Seroja, as detailed in the “Results and Discussion” section. The contributions of net air-sea heat flux, horizontal advection, and entrainment were evaluated using a mixed-layer heat budget analysis, following the method outlined by Ismail et al. (2023) and Warms and Karnauskas (2025).

$$\frac{\partial T_a}{\partial t} = \underbrace{\frac{Q_o - Q_{pen}}{\rho c_p h}}_b - \underbrace{\left(u_a \frac{\partial T_a}{\partial x} + v_a \frac{\partial T_a}{\partial y} \right)}_c - \underbrace{\left(\frac{T_a - T_{-h}}{h} \left(\frac{\partial h}{\partial t} + u_{-h} \frac{\partial h}{\partial x} + v_{-h} \frac{\partial h}{\partial y} \right) \right)}_d + \underbrace{Res}_e \quad (2)$$

The terms in Equation (2), from left to right, represent to: (a) the rate of temperature change over time, also referred to as mixed layer temperature (MLT) tendency (T_t), (b) the contribution of net air-sea heat flux (Q_{net}), (c) horizontal advection ($Advh$), (d) the entrainment process (Ent), and (e) the unresolved residual (Res). In this context, T represents temperature ($^{\circ}\text{C}$), t denotes time, ρ is the seawater 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 refers to the MLD (m). The subscript

158 α indicates a vertically averaged quantity over the MLD, while the subscript $-h$ denotes the value at the base of
159 the MLD.

160 In the net air-sea heat flux term (b), Q_o (W/m^2) is defined as the sum of shortwave radiation (Q_{SW}), longwave
161 radiation (Q_{LW}), sensible heat flux (Q_{SN}), and latent heat flux (Q_{LT}). Additionally, Q_{pen} represents the fraction
162 of shortwave radiation that escapes through the base of the MLD. Q_{pen} is calculated using the Paulson and
163 Simpson (1977) formula, which is $Q_{pen} = 0.47 \times Q_{SW} \left(R_1 e^{-\frac{h}{\zeta_1}} + R_2 e^{-\frac{h}{\zeta_2}} \right)$. The constants R_1 , R_2 , ζ_1 , and ζ_2
164 are set to 0.61, 0.38, 1.52, and 18, respectively, as specified by Shee et al. (2019).

165 The residual term (Res) is determined by subtracting the contributions of net air-sea heat flux (Q_{net}),
166 horizontal advection ($Advh$), and entrainment (Ent) from the rate of temperature change in the MLD (T_t). All
167 heat budget parameters were calculated for the periods preceding, during, and after MCS events in the area
168 study. A negative (positive) value indicates that the ocean is losing (gaining) heat, resulting in cooling
169 (warming).

170 **3. Results and Discussions**

171 **3.1 Long-term Climate Background and Trends**

172 During the 43-year period from 1982 to 2024, the mean SST across Indonesian waters, including the Savu
173 Sea, consistently exceeded 28°C (Fig. 1b). Analysis of this four-decade dataset indicates a persistent warming
174 trend, with the Savu Sea experiencing a warming rate greater than 0.01°C per year. Notable thermal hotspots
175 were observed in the Maluku Sea, Makassar Strait, Karimata Strait, Arafura Sea, and Western Australia, where
176 the warming trend surpassed 0.025°C per year (Fig. 1c). Furthermore, the annual MLD in the Savu Sea remains
177 relatively shallow, averaging approximately 20 m, in contrast to the Southern Indian Ocean, where the MLD
178 can exceed 30 m (Fig. 1b). The combination of accelerating warming trends and a shallow mixed layer
179 necessitates close monitoring due to potential impacts on regional ocean-atmosphere interactions.

180 Atmospheric analysis shows that the Savu Sea is characterized by relatively low mean surface winds,
181 averaging approximately 2 m/s (Fig. 1d). In contrast, the Southern Indian Ocean experiences stronger winds

182 exceeding 10 m/s, with southeasterly winds as the dominant atmospheric flow. These results suggest that the
183 low surface wind speeds in the Savu Sea facilitate intense surface warming by limiting vertical mixing, thereby
184 increasing heat accumulation at the surface, as supported by previous studies (Liu et al. 2024; Ningsih et al.
185 2025).

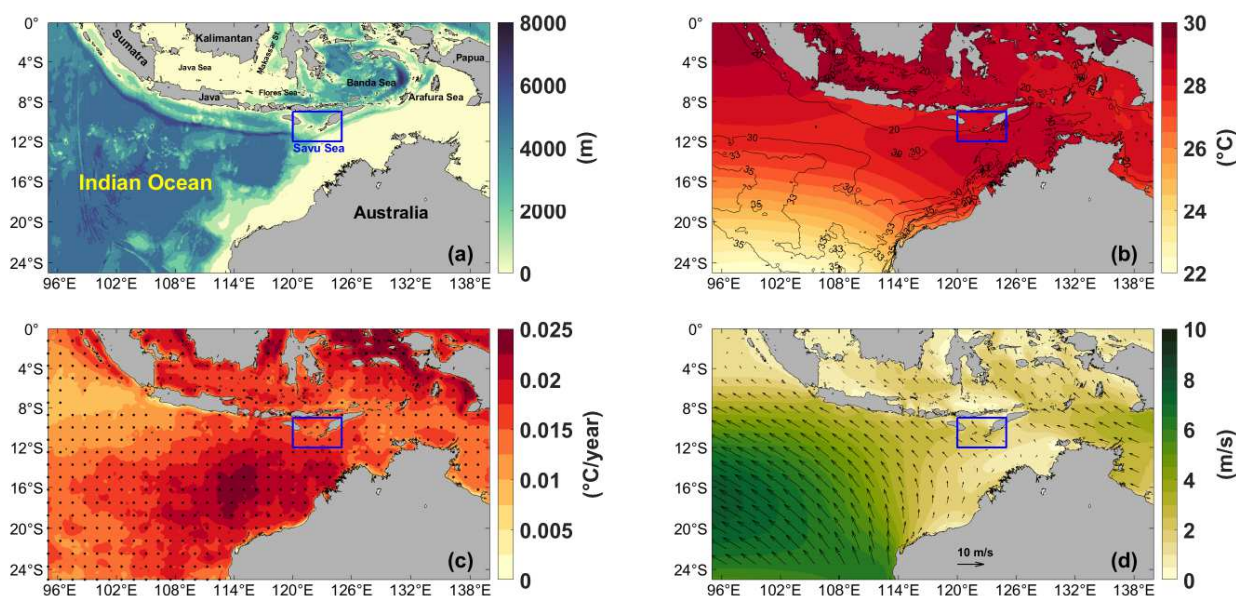


Fig. 1. (a) Bathymetry of the southern Indian Ocean (95–140°E and 0–25°S), with the Savu sea area of interest (120–125°E and 9–12°S) indicated by a blue box. **(b)** Annual mean SST (in °C, shaded), overlaid with contours of annual mean MLD (in m). **(c)** Long-term linear SST trend from 1 Jan 1982 – 31 Dec 2024. Black dots indicate statistically significant confidence level (p -value < 0.05). **(d)** Annual mean wind speed (m/s, shaded), overlaid with vectors of annual mean surface winds. The blue box denotes the region used for the time series in **Figs. 2 and 3**.

Daily climatological analysis demonstrates that TC Seroja developed during a period marked by elevated SST and a shallow MLD, conditions characteristic of the March-April-May (MAM) season in the Savu Sea (Fig. 2a). At the peak of the event (2–6 April 2021), the MLD remained anomalously thin. This shallow mixed layer facilitated rapid SST intensification, as the reduced water volume exposed to solar radiation led to a concentrated accumulation of thermal energy at the surface.

During this period, both the ILD and BLT reached their seasonal minimums (Fig. 2b). A shallow ILD confines the warm water reservoir to the near surface, while a thin BLT indicates limited density stratification due to salinity variations. In the case of TC Seroja, the thin BLT allowed more direct interaction between the surface layer and the cooler thermocline during cyclone-induced mixing. Despite this, the pre-existing high SST and shallow MLD provided sufficient initial enthalpy flux to support cyclone development (Zhang et al. 2021; Yulihastin et al. 2023).

Daily climatological data show that surface wind speeds in the Savu Sea are consistently low during the MAM season (Fig. 2c), primarily due to the monsoonal transition period. The weakening of the horizontal pressure gradient during this transition reduces vertical mixing and evaporative cooling, thereby facilitating elevated SST. However, interannual variability is evident, as some years exhibit notable increases in wind speed during this period. For instance, in 2021, the passage of TC Seroja resulted in wind speeds exceeding 11 m/s, which represents a significant deviation from the seasonal mean.

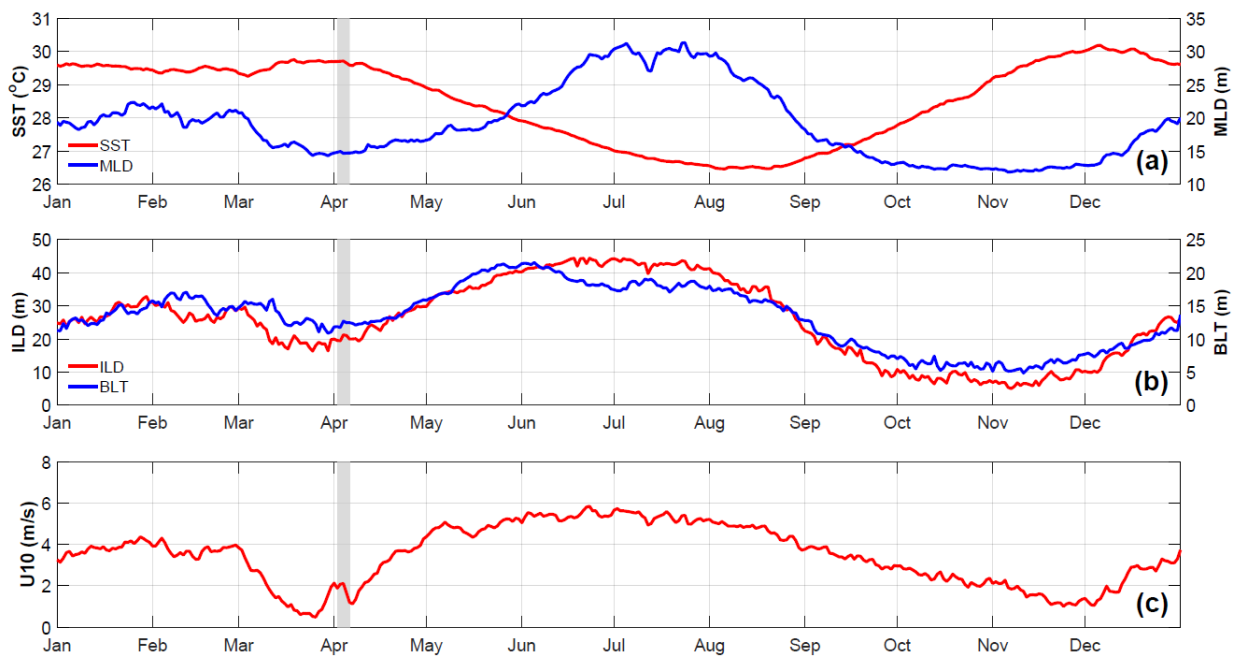


Fig. 2. Daily climatology of area-averaged properties in the Savu Sea. **(a)** SST (°C) and MLD (m), **(b)** ILD (m) and BLT (m), and **(c)** U10 (m/s). SST and U10 data cover 1 Jan 1982 to 31 Dec 2024, while

MLD, ILD, and BLT (panels a and b) cover 1 Jan 1993 to 31 Dec 2024. Grey shading denotes the period of TC Seroja (2–6 April 2021) in the Savu Sea.

3.2 Ocean-Atmospheric Preconditioning Leading Up to TC Seroja

In 2021, atypical ocean-atmosphere patterns were documented, with TC Seroja exerting a primary influence. At the beginning of the year, SST anomalies fluctuated, displaying positive values in January followed by a cooling phase in February. A modest positive SST anomaly reappeared in March; however, surface temperatures declined sharply by approximately $-1.5\text{ }^{\circ}\text{C}$ during the passage of TC Seroja from 2 to 6 April 2021 in the Savu Sea. This pronounced decrease, referred to as a 'cold wake,' resulted from intense cyclone-induced vertical mixing and upwelling (Fig. 3a). MLD anomalies exhibited an inverse relationship with SST. During the cyclone event, the MLD deepened slightly (Fig. 3a), suggesting a downward expansion of the mixed layer due to mechanical stirring by strong surface winds (Ushijima and Yoshikawa, 2020; Wang et al. 2024; Ningsih et al. 2025).

Oceanic responses were closely linked to atmospheric anomalies. Wind speed anomalies remained low in January, became positive in February, and increased further through March. At the peak of TC Seroja, wind speed anomalies increased sharply, reaching nearly 10 m/s above the climatological mean (Fig. 3b). This intensification coincided with a significant decrease in MSLP, which dropped 7 hPa below climatology (Fig. 3b). The resulting steep pressure gradient likely contributed to the extreme surface winds, which subsequently initiated ocean surface cooling and mixed layer deepening (Ushijima and Yoshikawa, 2020; Kudryavtsev and Pivaev, 2025). This sequence of events demonstrates a strong storm-scale ocean-atmosphere coupling, where atmospheric forcing directly modifies the upper-ocean structure. In February, atmospheric patterns similar to those observed in April during TC Seroja were present (Fig. 3b). Elevated wind speeds and reduced MSLP, although less pronounced than during the peak of TC Seroja, suggest the presence of a tropical disturbance. A detailed analysis of this event is beyond the scope of the present study.

Beyond SST analysis, TCHP was examined to assess the influence of subsurface thermal reservoirs to the storm's development. From January to late March 2021, THCP values consistently surpassed the climatological

mean, then decline sharply as TC Seroja intensified (Fig. 3c). In comparison, TCHP during the same periods in 2020 and 2022 remained considerably lower. These results indicate that anomalous subsurface heat accumulation likely played a substantial role in TC Seroja's intensification (Fig. 3c), consistent with previous findings on the importance of subsurface conditions in tropical cyclogenesis as reported by Gao et al. (2025).

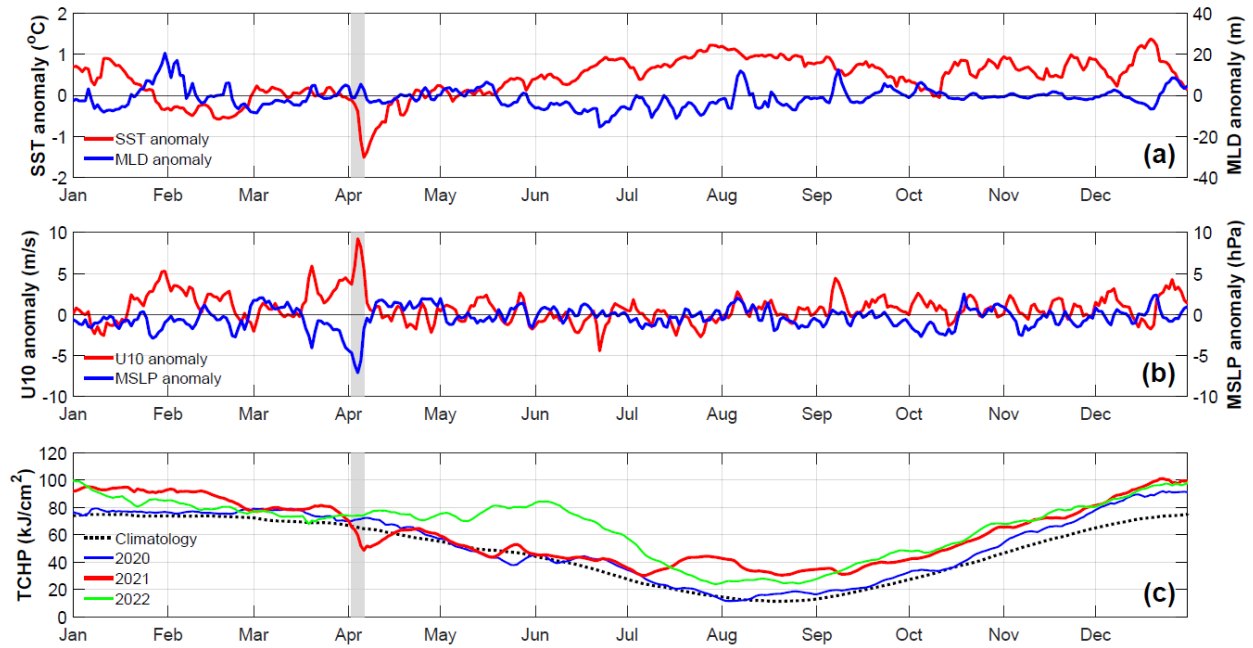


Fig. 3. Daily anomalies of area-averaged properties in the Savu Sea during 2021. **(a)** SST anomaly ($^{\circ}\text{C}$) and MLD anomaly (m), **(b)** U10 anomaly (m/s) and MSLP anomaly (hPa), **(c)** daily TCHP for 2020–2022, overlaid with the long-term daily climatology (kJ/cm^2). Grey shading denotes the period of TC Seroja (2–6 April 2021) in the Savu Sea.

In addition to the pronounced TCHP identified in this study, Latos et al. (2023) argued that TC Seroja resulted from an unusual superposition of the active MJO, Kelvin waves, and Equatorial Rossby waves. In this context, Kelvin waves contributed to increased moisture and extreme convection, while Rossby waves provided the initial vorticity necessary for cyclonic vortex development. The interaction among these waves generated a highly unstable atmospheric environment, which was further intensified by anomalous SST warming in the region. Furthermore, Yulihastin et al. (2023) highlighted that, in conjunction with elevated SSTs in 2021, a double vortex mechanism located within the Savu Sea and across Flores acted as a mechanical engine. This

mechanism facilitated energy consolidation and likely triggered the intense cyclonic rotation that preceded the formation of TC Seroja.

3.3 Evolution of TC Seroja and Ocean Response

Fig. 4a illustrates the trajectory of TC Seroja across the Savu Sea and adjacent waters. The cyclone remained over the Savu Sea from 2 to 6 April, before moving southward into the Indian Ocean on 7 April. SST along the cyclone's path consistently exceeded 29 °C (Fig. 4b), surpassing the established thermodynamic threshold of 26.5 °C required for TC formation (Tory and Dare, 2015). Long-term climatological data (Fig. 1b) show that the Savu Sea typically maintains SSTs above 28 °C, indicating that the region meets the thermal requirements for cyclogenesis. In 2021, SSTs were exceptionally high, frequently exceeding 29 °C, which resulted in a substantial thermal energy surplus that facilitated the rapid intensification of the cyclone.

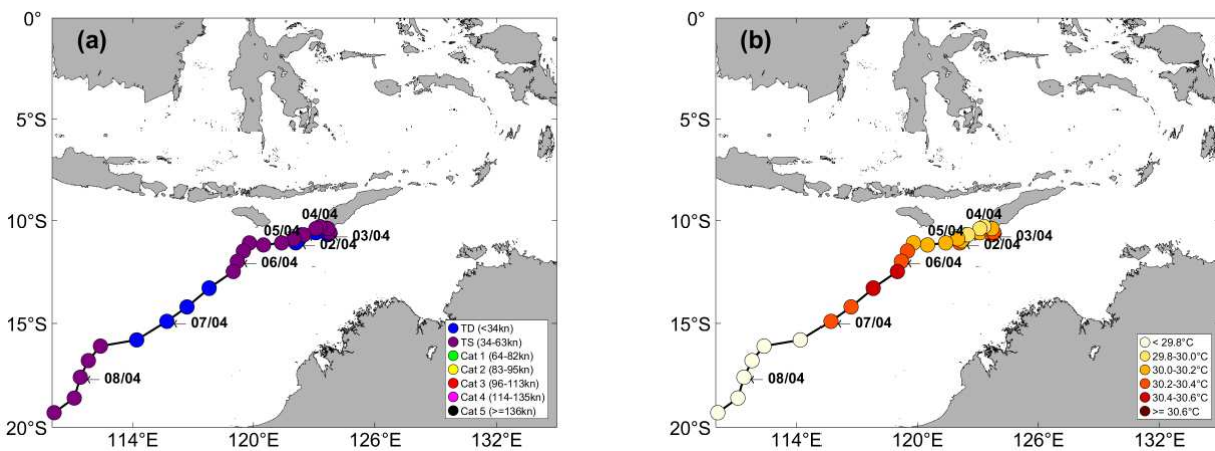


Fig. 4. Trajectory of TC Seroja from 2 to 7 April 2021 in the Savu Sea and adjacent waters. **(a)** Intensity categories of TC Seroja are indicated by colored circles, with each category defined by maximum sustained wind speed (knots) as shown in the legend. **(b)** SST along the track of TC Seroja.

The temporal response to the cyclone's movement was assessed by examining the evolution of MHW and MCS along the trajectory of TC Seroja, as shown in Fig. 5. In the Savu Sea, the presence of TC Seroja from 2 to 6 April led to a marked decrease in SST to approximately 27 °C, which initiated a pronounced MCS event (indicated by the blue shading). As a result, no MHW events were detected in the months preceding of following the cyclone. This absence is significant, given that the Savu Sea has consistently experienced MHW events

252 during the MAM season over the past five years (2020–2024) (Fig. S1). Typically, these events are promoted
 253 by the low climatological wind speeds that characterize this transitional period (Fig. 2c). However, 2021
 254 represented an exception; suppression of MHWs began in late January, attributed to atmospheric pre-
 255 conditioning by intensified winds (Fig. 3b). These winds likely enhanced latent heat transfer, thereby inhibiting
 256 MHW formation (Ningsih et al, 2025). Furthermore, the double vortex mechanism described by Yulihastin et
 257 al. (2023) produced wind speeds of approximately 6–8 m/s, providing mechanical forcing that further
 258 conditioned the upper ocean and limited heat accumulation. Following the cyclone's passage, residual cooling
 259 from the MCS served as a thermal buffer, preventing the re-emergence of MHWs. In contrast, as TC Seroja
 260 entered the Indian Ocean after 7 April, MHW events were observed along its path. These pre-existing heatwaves
 261 supplied the thermal energy required to sustain the cyclone's intensity (Fig. 5).



Fig. 5. Temporal evolution of MHWs and MCSs along the track of TC Seroja from 2 to 10 April 2021. Each panel (a–i) presents the daily SST (black line) at a specific location along the TC Seroja trajectory. The green solid line indicates the daily climatological mean. The red and blue dashed lines represent the 90th and 10th percentiles, respectively. Red shading highlights MHWs (SST above the 90th percentile), while the blue shading highlights MCSs (SST below the 10th percentile). The vertical magenta line indicates the date of TC Seroja's passage at each location.

262 To elucidate the atmospheric drivers and vertical transport mechanisms underlying these oceanic responses,
 263 the spatio-temporal patterns of wind speed at 850 hPa, OLR, and EPV were analyzed before, during, and after
 264 the phases of TC Seroja (Figs. 6–8). The wind speed patterns at the 850 hPa level clearly demonstrate the
 265 cyclogenesis process (Fig. 6). A distinct cyclonic circulation developed over the Savu Sea on 1 April and reached
 266 maximum intensity by 4 April. During this period, maximum wind speeds exceeded 25 m/s, in contrast to the
 267 eye of the storm, where wind speeds remained below 5 m/s. This spatial distribution, characterized by a high-
 268 velocity wind ring encircling a calm center, is a defining feature of TC structure, as reported in previous studies
 269 (Yulihastin et al. 2023; Latos et al. 2023). From 6 April onward, the core of these high-velocity winds shifted
 270 southwestward toward the Indian Ocean. By 8 and 9 April, wind speeds in the Savu Sea had returned to values
 271 of approximately 5–10 m/s.

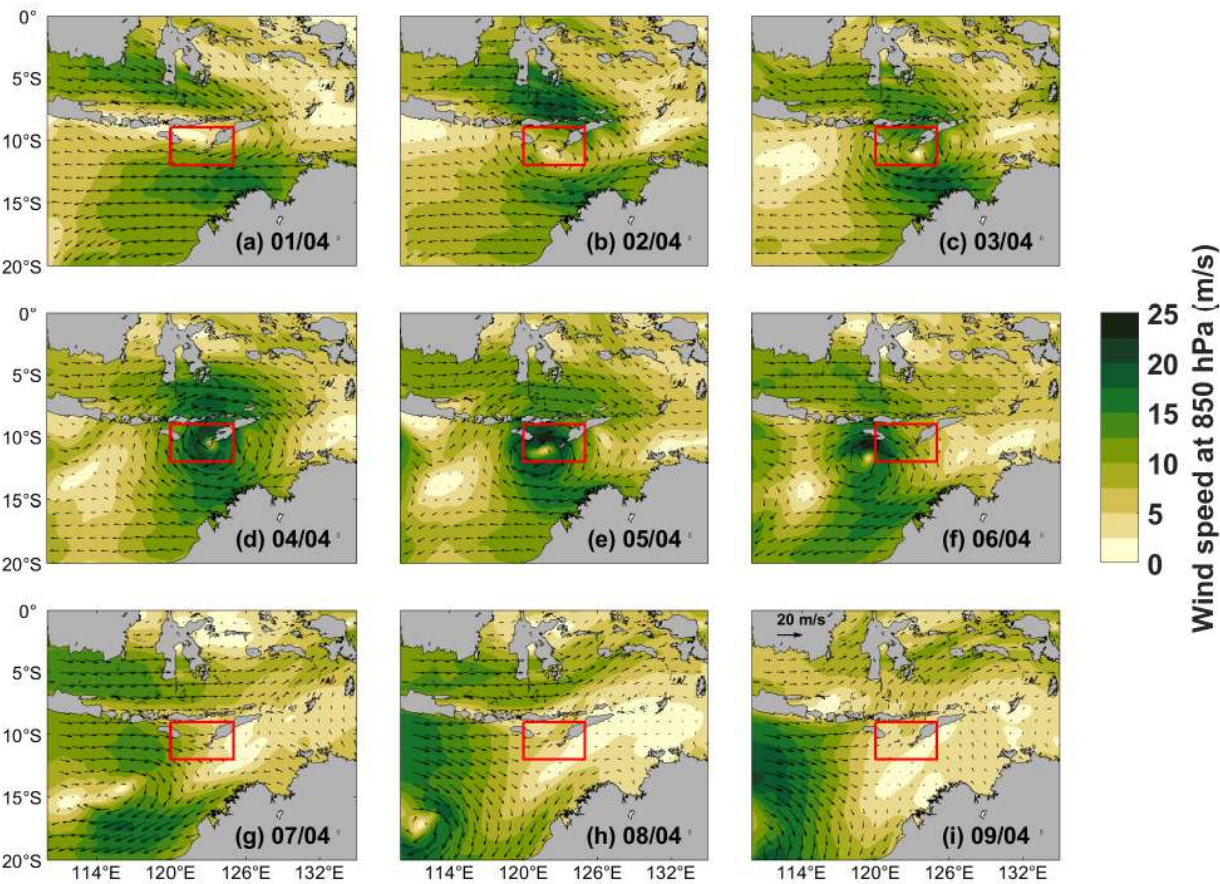


Fig. 6. Spatial evolution of wind speed at 850 hPa before, during, and after TC Seroja (1–9 April 2021). Panels (a–i) present daily averaged wind speed (shaded, m/s) and wind vectors (arrows) at the 850 hPa level. The red box delineates the Savu Sea region, which is the primary focus of this study.

OLR was analyzed as a proxy for deep convective activity. Negative OLR values are associated with dense cloud cover and vigorous storm development, serving as a reliable indicator of TC intensification (Dutheil et al, 2024). The spatial distribution of OLR exhibited a distinct evolutionary pattern during the study period (Fig. 7). Convective initiation was observed over the Savu Sea on 1 April, reaching peak intensity by 4 April, with values dropping below -120 W/m^2 . This convective peak coincided with the maximum 850 hPa wind speed observed on the same date (Fig. 6), confirming the synchronization between convective activity and wind intensity. Following 6 April, the convective core migrated southwestward toward the Indian Ocean. As a result, OLR values over the Savu Sea gradually increased, indicating a transition to clear-sky conditions as the cyclone exited the region.

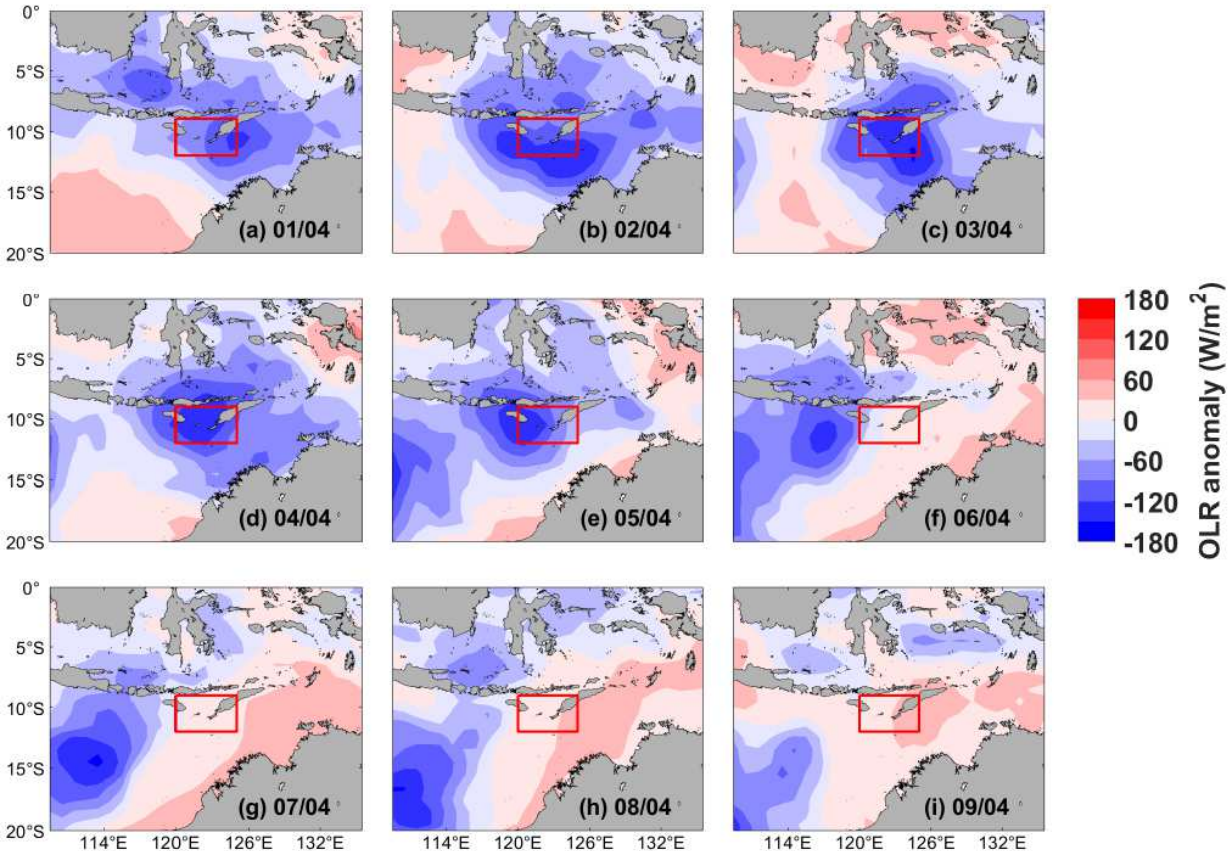


Fig. 7. Spatial evolution of OLR (W/m^2) before, during, and after TC Seroja (1–9 April 2021). Panels (a–i) present anomaly OLR (shaded, W/m^2). The red box indicates the Savu Sea region, which is the primary focus of this study.

Fig. 8 presents the spatio-temporal evolution of EPV, highlighting storm-induced upwelling and downwelling processes. On April 1, prevailing westerly winds (black arrows) moved from west to east, generating surface currents that were deflected to the left by the Coriolis effect (magenta arrows). This deflection resulted in the divergence of surface waters, which initiated upwelling and bringing cooler water from deeper layers to the surface. Upwelling reached its peaked-on April 4, as evidenced by EPV values exceeding $20 \times 10^{-5} \text{ m/s}$, marking the period of most intense upwelling (Fig. 8). These results correspond with observations on April 4, when 850 hPa wind speeds attained their maximum ($>25 \text{ m/s}$, Fig. 6) and OLR reached its minimum ($<50 \text{ W/m}^2$, Fig. 7). The simultaneous occurrence these parameters indicates strong air-sea interaction. Intense cyclonic wind stress at 850 hPa generated significant divergence of surface waters. According to the principle of mass continuity, this divergence brought cold water from deeper layers to the surface, as shown by high positive EPV values. Mechanical forcing intensified with deep convection (low OLR), which increased the storm's strength. Strong positive EPV remained in the Savu Sea until April 6, then declined to near zero as the cyclone exited the region.

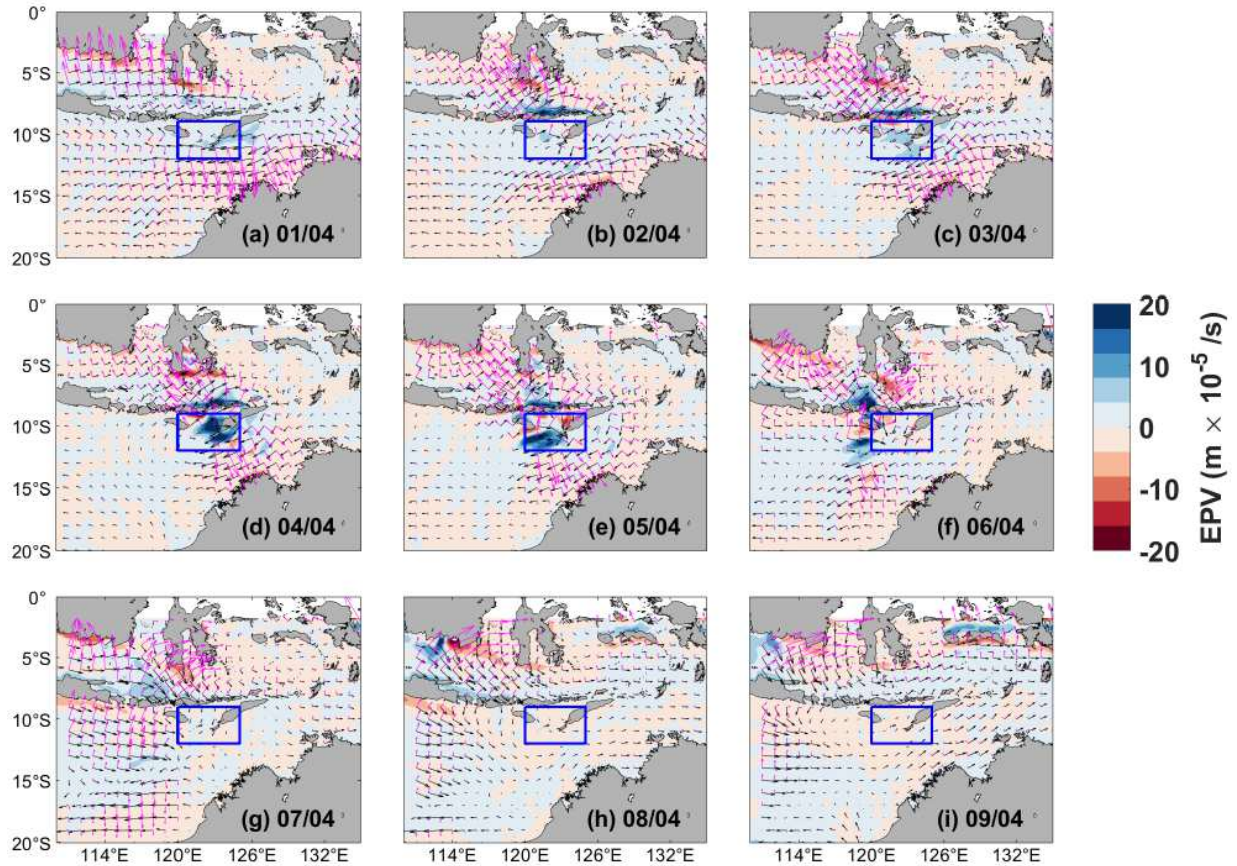


Fig. 8. Spatial evolution of EPV (m/s) before, during, and after TC Seroja (1–9 April 2021). Panels (a–i) present daily averaged EPV (shaded, m/s), wind stress vectors (black arrows), and Ekman transport (magenta arrows). Positive velocity represents upwelling, while negative velocity represents downwelling. The blue box delineates the Savu Sea region, which is the primary focus of this study.

3.4 MHW-MCS Dynamics and Local Forcing through Heat Budget Assessment

A mixed-layer heat budget analysis was conducted to identify the localized drivers of the observed cooling and the subsequent MCS event (Fig. 9). The results reveal a pronounced negative temperature tendency during the passage of TC Seroja, reaching $-0.4\text{ }^{\circ}\text{C/day}$ (Fig. 9a). This MLT cooling was primarily due to a substantial reduction in net surface heat flux, which decreased by $-0.12\text{ }^{\circ}\text{C/day}$ (Figs. 9a, 9c). The primary contributor to this deficit was the shortwave radiation flux (Fig. 9c), which declined sharply as a result of dense convective cloud cover associated with the cyclone (Fig. 7), thereby limiting solar heating of the sea surface. Concurrently, the latent heat flux intensified to $-0.13\text{ }^{\circ}\text{C/day}$ (Fig. 9c), driven by higher wind speeds (Fig. 3) that enhanced

301 evaporative cooling. In contrast, both sensible heat flux and longwave radiation showed minimal variation and
 302 remained relatively stable throughout the TC Seroja event.

303 Within upper-ocean dynamics, horizontal heat advection had a limited yet measureable effect, with zonal and
 304 meridional components contributing nearly equally to the heat budget (Fig. 9d). The relative importance of these
 305 components varied temporally: meridional transport dominated prior to the onset of TC Seroja, whereas zonal
 306 advection became the primary driver following the cyclone's passage. Vertical entrainment contributed
 307 minimally throughout the period (Fig. 9a). These results suggest that, although ocean currents caused minor
 308 fluctuations, the marked MLT cooling was primarily driven by air-sea interaction forcing associated with the
 309 intensification of TC Seroja (Figs. 9a, 9c). This cooling was specifically associated with a substantial reduction
 310 in net shortwave radiation due to dense cyclonic cloud cover and an increased latent heat flux, resulting from
 311 the cyclone's high-velocity wind field (Fig. 9c).

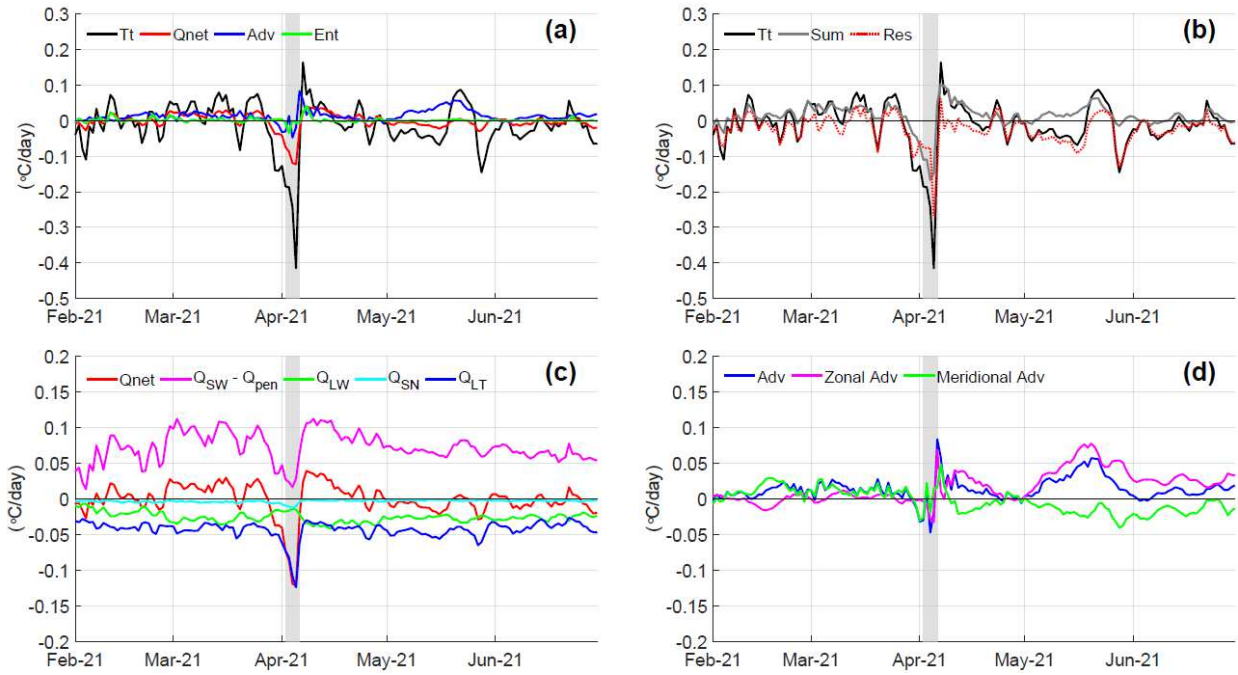


Fig. 9. Temporal evolution of MLT balance in the Savu Sea before, during, and after TC Seroja ($^{\circ}\text{C}/\text{day}$).

(a) Temperature tendency (T_t ; black line), net air-sea heat flux (Q_{net} ; red line), horizontal advection (Adv ; blue line), and entrainment (Ent ; green line). **(b)** Temperature tendency (T_t ; black line), sum of MLT balance terms (grey line), and residual (red dashed line). **(c)** Decomposition of net air-sea heat flux

into net shortwave radiation (Q_{SW}) minus the shortwave penetration (Q_{pen} ; magenta line), net longwave radiation (Q_{LW} ; green line), net sensible heat flux (Q_{SN} ; cyan line), and net latent heat flux (Q_{LT} ; blue line). (d) Decomposition of horizontal advection into zonal advection (magenta line) and meridional advection (green line).

4. Conclusions

This study highlights the critical thermodynamic conditions that facilitated the development of TC Seroja in the Savu Sea. The long-term mean SST in this region consistently exceeds 28°C, which is significantly above the 26.5°C threshold required for tropical cyclogenesis, indicating a high inherent potential for cyclone formation. Additionally, a key finding is that the TCHP in 2021 was anomalously high compared to its climatological mean. It is proposed that this substantial subsurface heat reservoir served as a primary energy source, providing the essential fuel for TC Seroja's intensification within the Savu Sea basin.

Despite elevated TCHP, no MHW events were observed in the Savu Sea during TC Seroja. Instead, persistent MCS activity reduced SST to 27 °C. The suppression of MHWs was initiated by intensified pre-storm westerly winds and maintained by ongoing convective activity and cloud cover associated with the cyclone. These results extend previous research that has primarily emphasized atmospheric drivers, such as Kelvin waves, Rossby waves, and the MJO, as well as high SSTs and double vortices. By incorporating the oceanic perspective, particularly the influence of subsurface heat and the dynamics of MCSs and MHWs, this study offers a more comprehensive understanding of the complex ocean-atmosphere interactions governing the event. In the Savu Sea, the cyclone reached its peak on 4 April, with maximum wind speeds at 850 hPa exceeding 25 m/s, anomaly OLR reach -120 W/m² indicating deep convection, and EPV levels consistent with cyclone-induced upwelling.

Thermal fluctuations within the mixed layer were primarily controlled by local net surface heat flux rather than oceanic advection. Cooling of the MLT was attributed to a marked reduction in shortwave radiation resulting from dense cloud cover, along with substantial evaporative heat loss driven by extreme wind speeds. A thorough understanding of these complex ocean-atmosphere interactions is crucial for improving regional disaster mitigation strategies. By identifying the precursors to extreme weather events, particularly the function

of TCHP as an early warning indicator, this study offers valuable insights for enhancing predictive modeling and early warning systems. These advancements are essential for reducing the socio-economic impacts of future TCs. Further investigation is required to elucidate the specific mechanisms underlying pre-storm heat accumulation, with emphasis on the roles of oceanic advection and thermocline variability in sustaining elevated TCHP levels.

Data availability

OSTIA data are available from Copernicus Marine Service (<https://doi.org/10.48670/moi-00165>). GLORYS12V1 data can be accessed through the Copernicus Marine Service (<https://doi.org/10.48670/moi-00021>). ERA5 data are provided by the Copernicus Climate Change Service (C3S) Climate Data Store (<https://doi.org/10.24381/cds.adbb2d47>). IBTrACS data, documentation, and related information are accessible from 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

EB methodology, writing original draft, visualization; MFAI conceptualization, supervision, writing–review and editing; AB supervision, writing–review and editing; AS supervision, writing–review and editing; SS supervision; EY supervision; FM supervision.

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