

Intraseasonal Ocean Surface Variability Response to the Madden-Julian Oscillation: A Comparative Study of the Malacca Strait and the Indian Ocean

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Abstract

The Madden-Julian Oscillation (MJO) is the dominant mode of tropical intraseasonal variability, strongly modulating atmospheric convection and upper-ocean conditions across the Maritime Continent. However, its influence on narrow semi-enclosed straits relative to adjacent open-ocean regions remains insufficiently understood. This study investigated phase-dependent atmospheric and ocean-surface responses to active MJO events in the Malacca Strait (MS) and eastern Indian Ocean (IO) using daily ERA5 reanalysis and Copernicus Marine Service data for 2000-2025. Variables were interpolated onto a common $0.25^\circ \times 0.25^\circ$ grid, converted to daily anomalies, and classified into eight MJO phases using the OLR-based MJO Index (OMI). Power spectral density and phase composite analyses were applied to outgoing longwave radiation (OLR), surface wind, precipitation, sea surface temperature (SST), sea surface salinity (SSS), and significant wave height (SWH). Both regions exhibited dominant OLR variability at 43-45 days, with stronger spectral power and more coherent convective signals found in the eastern IO. During phases 4-6, enhanced convection was associated with negative OLR anomalies, stronger westerly winds, and increased precipitation, whereas these responses were weaker within the MS. SST shifted from positive anomalies during phases 1-3 to negative anomalies during phases 5-7, while SSS freshening occurred earlier and more extensively in the eastern IO. SWH also increased more strongly in the eastern IO. These findings demonstrate that the semi-enclosed MS spatially modulates and attenuates MJO-related atmosphere-ocean responses, with implications for subseasonal marine monitoring and forecasting across the Maritime Continent.

Keywords: Intraseasonal variability; Maritime continent; Ocean surface anomalies; Outgoing longwave radiation; Phase composite analysis.

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Introduction

The Madden-Julian Oscillation (MJO) is known as the dominant mode of tropical intraseasonal variability, with convective activity that typically develops over the Indian Ocean (IO) and dissipates over the western Pacific with an average speed of ~ 5 m/s, characterized by eastward-propagating convective disturbances on a

timescale of approximately 30-90 days (Barret et al., 2021; Worku et al., 2020; Lumbangaol & Yu, 2026; Marshall et al., 2015). Its propagation is divided into eight phases according to the geographical position of the main convective envelope (Kiladis et al., 2014; Da Silva & Matthews, 2021). As one of the primary drivers of tropical climate variability, the MJO modulates atmospheric circulation,

cloudiness, precipitation, and surface wind over the Indo-Pacific region (Xavier et al., 2014; Da Silva & Matthews, 2021). These atmospheric variations strongly influence ocean surface conditions through changes in turbulent heat fluxes, wind-induced mixing, freshwater input from precipitation, and wave generation (Karłowska et al., 2024; Baeda et al., 2019; DeMott et al., 2015). Consequently, variables such as outgoing longwave radiation (OLR), surface wind, precipitation, sea surface temperature (SST), sea surface salinity (SSS), and significant wave height (SWH) exhibit pronounced intraseasonal variability associated with MJO activity (Baeda et al., 2019; DeMott et al., 2015; Marshall et al., 2015; Hilmi et al., 2018; Ikuyajolu et al., 2024).

Previous studies have demonstrated that enhanced MJO convection is typically associated with negative OLR anomalies, intensified surface winds, increased precipitation, upper-ocean cooling, sea-surface freshening, and stronger wave activity. Conversely, suppressed convective phases are generally associated with positive OLR anomalies, weaker winds, reduced rainfall, and gradual recovery of upper-ocean thermal conditions (Lumbangaol & Yu, 2026; Savarin & Chen, 2022; Jiang et al., 2020). Numerous observational, reanalysis, and numerical modeling studies have investigated these responses in different tropical basins, including the IO, western Pacific, and the MC (DeMott et al., 2015; Du et al., 2025; Bi & Yuan, 2026). Nevertheless, most previous research has focused on individual atmospheric and oceanic variables, specific MJO events, or broad ocean basins rather than assessing the multiple atmosphere-ocean variables simultaneously over contrasting marine environments.

The MC consists of numerous islands, shallow marginal seas, narrow straits, and adjacent open oceans. The Malacca Strait

(MS) is a shallow, semi-enclosed waterway with restricted fetch, strong tidal mixing, and substantial influence from the surrounding landmasses (Lee et al., 2019; Zhao et al., 2025), while the adjacent eastern IO is a broad open ocean directly exposed to large-scale atmospheric forcing (Azuga et al., 2020; Napitupulu et al., 2022; Thomas et al., 2024). Their contrasting bathymetry, coastline geometry, and water exchange may produce different magnitudes, spatial patterns, and timing of SST, SSS, and SWH responses (Renkl et al., 2024), yet direct quantitative comparisons of atmospheric forcing and ocean-surface responses across all eight MJO phases remain limited. These two regions were selected because their close geographic proximity but markedly different bathymetric and geographical settings provide a suitable natural comparison for assessing how the same large-scale MJO forcing is modified across semi-enclosed and open-ocean environments. Hence, it is still unclear to what extent the open ocean response observed in the eastern IO can be applied to the semi-enclosed MS, where shallow bathymetry, surrounding landmasses, restricted fetch, and water exchange with adjacent seas may modify MJO-related SST, SSS, and SWH responses.

To address this gap, six atmospheric and oceanic variables, namely OLR, surface wind, precipitation, SST, SSS, and SWH, were examined through phase-based composite analysis across MJO phases 1-8, using daily ERA5 reanalysis and Copernicus Marine Service salinity data for 2000-2025. ERA5 was selected for the atmospheric variables and SST because of its consistent long-term daily coverage and $0.25^\circ \times 0.25^\circ$ spatial resolution, while Copernicus Marine was used for SSS because daily salinity data were available for the study period. To ensure consistency among the datasets, all variables were interpolated to a common $0.25^\circ \times 0.25^\circ$ grid prior to analysis. By directly comparing a

semi-enclosed strait with an open ocean environment, this study aimed to determine how regional geographical and oceanographic conditions shape the magnitude, spatial pattern, and timing of MJO-related variability.

Materials and Methods

Study Area

The study area covered the Malacca Strait and the adjacent Indian Ocean off Sumatra, within approximately 95.5-104°E and 0-6°N (Figure 1). The open Indian Ocean (IO)

domain was defined within this bounding box and, after ocean masking, covered approximately 127,533.26 km² and contained 147 OLR grid cells. The open IO domain is indicated by the green boundary, while the MS is indicated by the red boundary. The bathymetric gradient shows that most of the MS is very shallow, generally less than 100 m deep, whereas depth increases rapidly toward the western IO, exceeding 5,000 m in the deepest offshore area. The bathymetric contours illustrate the transition from the shallow waters around Sumatra and the offshore islands to the deep open ocean basin.

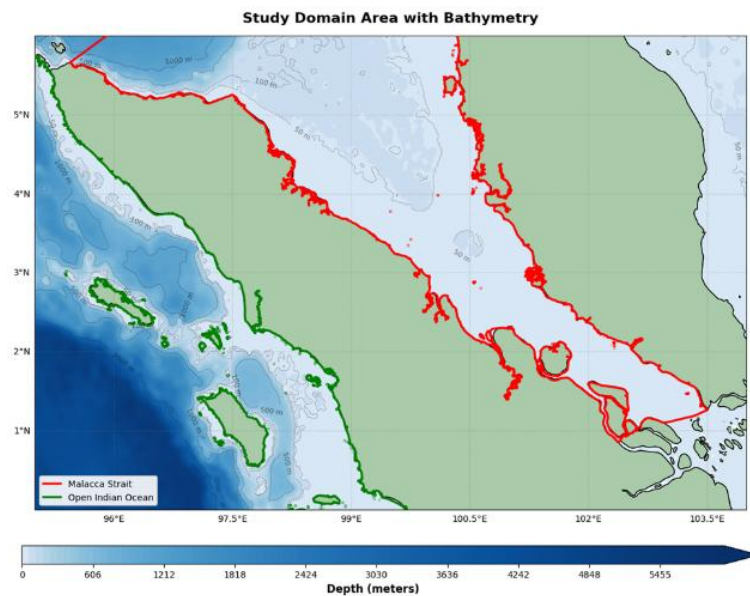


Figure 1. Map of study area and bathymetry of the Malacca Strait and the adjacent Indian Ocean, showing the regional masks used in the study.

Data Sources & Preprocessing

Daily atmospheric and ocean-surface data were collected for the period January 2000–December 2025. ERA5 reanalysis at a horizontal resolution of $0.25^\circ \times 0.25^\circ$ was used to obtain top net thermal radiation (TNR), 10-m zonal and meridional wind components, total precipitation, and sea surface temperature (SST), whereas significant wave height (SWH) was available at a coarser resolution of $0.5^\circ \times 0.5^\circ$ (Hersbach et al., 2020). To ensure spatial consistency among all variables, the SWH fields were interpolated onto the common $0.25^\circ \times 0.25^\circ$ analysis grid using

bilinear interpolation prior to subsequent analyses.

OLR was derived from the ERA5 top net thermal radiation field. Because ERA5 defines top net thermal radiation as positive downward, whereas OLR is conventionally expressed as upward longwave flux, the sign was reversed prior to analysis according to the standard ECMWF convention by (Hersbach et al., 2020) and written as follows:

$$OLR = -TNR \quad (1)$$

where TNR is the ERA5 top net thermal radiation W/m^2 . This sign reversal converts

the ERA5 downward-positive convention into the standard meteorological convention for OLR, in which larger positive values represent greater outgoing longwave radiation emitted from the Earth-atmosphere system to space.

Daily sea surface salinity (SSS) was obtained from the Copernicus Marine Service and interpolated onto the common $0.25^\circ \times 0.25^\circ$ analysis grid to match the ERA5 products. Daily principal components and amplitudes of the OLR-based Madden-Julian Oscillation Index (OMI) were used to identify active MJO conditions and classify each day into one of the eight MJO phases following Kiladis et al. (2014). All datasets were spatially subset to the MS and IO domains before further analysis.

The state of the MJO was classified using the OMI developed by Kiladis et al. (2014) and computed following the open-source implementation of Hoffmann et al. (2021). The OMI is derived from an empirical orthogonal function (EOF) analysis of 20-96-day bandpass-filtered OLR anomalies averaged over 20°S - 20°N , producing two leading principal components (PC1 and PC2) that describe the amplitude and propagation of the MJO.

Following Wheeler & Hendon (2004) and Kiladis et al. (2014), the daily MJO amplitude (A) was calculated as:

$$A = \sqrt{PC1^2 + PC2^2} \quad (2)$$

where A represents the strength of the MJO signal.

The MJO phase was determined from the angular position of the two principal components in the PC1-PC2 phase space (Wheeler & Hendon, 2004),

$$\theta = \text{atan2}(PC1, PC2) \quad (3)$$

where θ is the phase angle measured counterclockwise from the positive PC1 axis.

The phase angle (θ) was subsequently divided into eight equal 45° sectors, corresponding to the eight canonical MJO phases defined by Wheeler & Hendon (2004) and Kiladis et al. (2014), using the floor discretization function (Hoffmann et al., 2021) and is written as follows:

$$\text{Phase} = \left\lfloor \frac{\theta + 180^\circ}{45^\circ} \right\rfloor + 1, \quad (4)$$

($1 \leq \text{Phase} \leq 8$),

where the phase index is wrapped cyclically such that values exceeding Phase 8 return to Phase 1.

Following the standard practice, only days with OMI amplitude ≥ 1 were classified as active MJO events, whereas days with amplitude < 1 were excluded to avoid contamination from weak or poorly defined MJO conditions. Although the multivariate Real-time Multivariate MJO (RMM) index (Wheeler & Hendon, 2004) remains widely used, the OMI was selected because it is derived solely from OLR observations, making it more directly linked to the convective and radiative processes investigated in this study.

Power Spectral Density (PSD) Analysis

PSD analysis was performed to identify the dominant temporal variability of regional-mean OLR anomalies associated with the MJO. The PSD was estimated using Welch's method (Welch, 1967), as implemented in the *scipy.signal.welch* function of the SciPy scientific computing library (Virtanen et al., 2020). Welch's method with the window length of 1024 days; overlap percentage of 50%, and the window type Hann window may improve the statistical stability of spectral estimates by dividing the time series into overlapping segments, applying a window function to each segment, computing the modified periodogram of every segment, and averaging the resulting spectra to reduce the variance inherent in the classical periodogram. The resulting frequency spectrum was converted to oscillation periods. Spectral peaks within the 30-90-

day band were interpreted as characteristic signatures of the MJO variability.

Phase Composite and Regional Mean Analysis

Prior to the composite analysis, daily anomaly fields were computed to isolate the intraseasonal variability. The climatological reference period used for this formulation was 2000 to 2025. Daily climatologies were first established by calculating the long-term average for each specific day of the year across the entire 26-year period. Daily anomaly fields were then formulated by subtracting this day-of-year climatological mean from the raw daily observations. Once the anomalies were calculated, they were grouped according to the eight OMI phases to characterize the atmospheric and oceanic conditions associated with each active MJO phase. Composite maps were subsequently obtained by averaging all daily anomaly fields belonging to the same phase, following standard climate composite techniques (Wheeler & Hendon, 2004; Wilks, 2011).

$$\bar{X}'_p(i, j) = \frac{1}{N_p} \sum_{k=1}^{N_p} X'_k(i, j) \quad (5)$$

where $\bar{X}'_p(i, j)$ is the composite anomaly for phase p , N_p is the number of active MJO

days assigned to that phase, and $X'_k(i, j)$ is the anomaly field on the k -th day.

To quantify the temporal evolution within each study region, regional mean anomalies were calculated by averaging all grid cells within the MS and eastern IO domains (von Storch & Zwiers, 1999; Wilks, 2011),

$$\bar{X}'_R(t) = \frac{1}{N_R} \sum_{i=1}^{N_R} X'_i(t) \quad (6)$$

where N_R is the number of grid cells within region R . The regional means were subsequently averaged by MJO phase to compare the magnitude and evolution of atmospheric and ocean-surface responses between the two domains.

Results and Discussion

Distribution of Active MJO Days

The analysis of the 2000–2025 period identifies a total of 5,513 active MJO days, revealing significant variations in occurrence among the eight phases. The highest concentration was found in phase 5, which accounted for 796 days (14.4% of the total), closely followed by phase 4 (787 days, 14.3%) and phase 8 (784 days, 14.2%). Conversely, the lowest count occurred in phase 6, representing just 552 days (10.0%), as depicted in Figure 2.

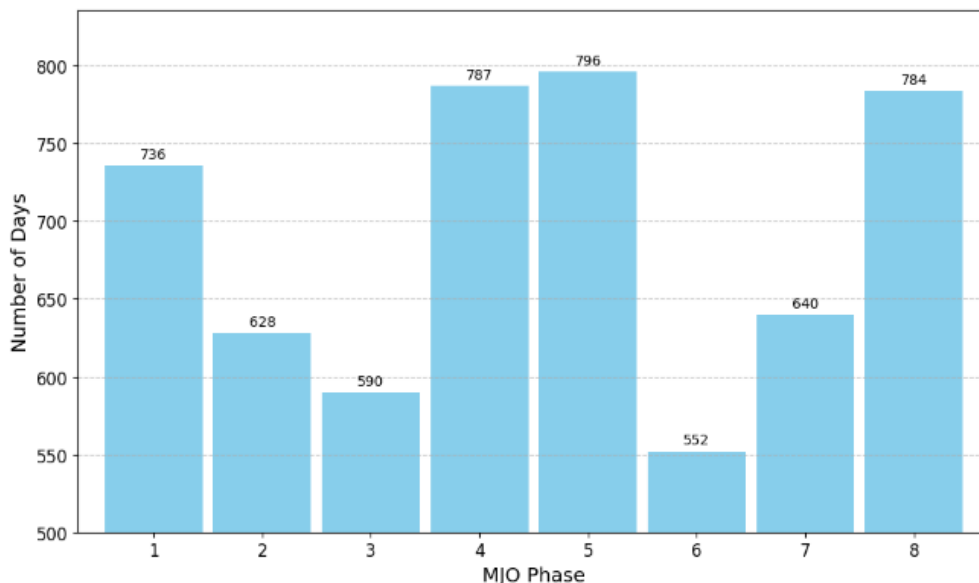


Figure 2. Number of Active MJO days in phases 1-8 during 2000-2025.

This phase-to-phase variation in active-day counts highlights differences in the occurrence and persistence of active MJO conditions. However, we acknowledge that the number of active days alone cannot directly represent propagation speed, as these totals are influenced by a combination of multiple factors, including event duration, overall event frequency, and amplitude persistence. MJO propagation is heavily dependent on coupled large-scale circulation and moist convective processes (Adames et al., 2017). Therefore, while the relatively high number of active days observed in phases 4–5 aligns with the longer residence times over the Maritime Continent reported by Yadav & Straus (2017), who found that events can stall or propagate slowly in this region, this metric alone only suggests, rather than directly proves, variations in propagation speed across our study period.

Intraseasonal Outgoing Longwave Radiation (OLR) Variability

PSD analysis shows clear intraseasonal variability in the regional-mean OLR anomaly for both the MS and the adjacent IO, with both regions peaks at approximately 43–45 days (Figure 3). The IO reached a maximum spectral power at about 39–43 days ($\text{PSD} \approx 39$), while the MS peaked over a broader 26–44-day band with lower power ($\text{PSD} \approx 25$). This difference indicates that the regional convective signal was stronger and more coherent over the open IO, although the weaker spectral power in the MS does not imply an absence of MJO-related variability; the intraseasonal signal remains detectable but is less pronounced in the regional OLR variance.

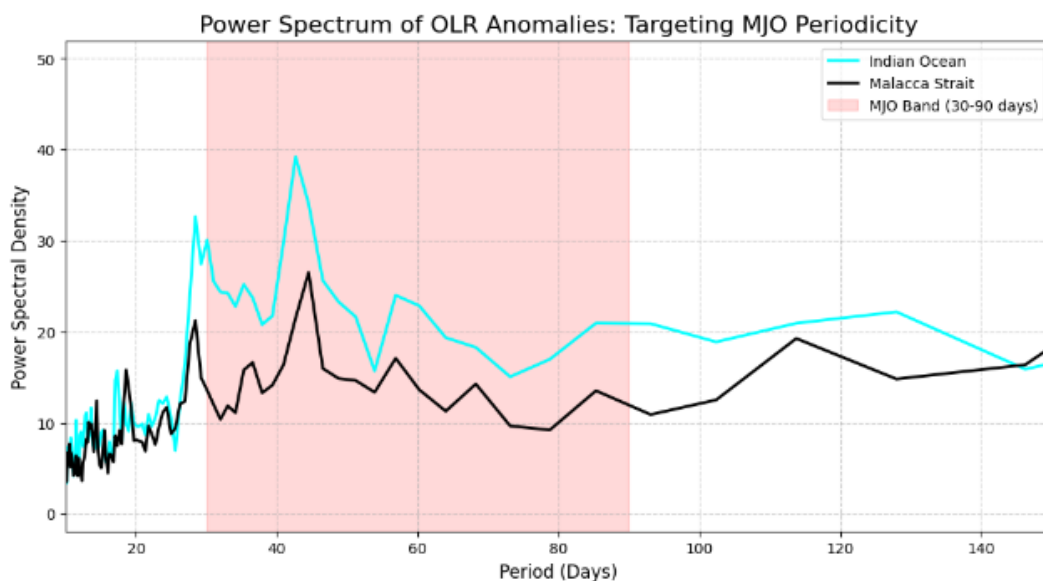


Figure 3. PSD plot of regional-mean OLR anomalies over the Malacca Strait (black) and the Indian Ocean (cyan) during 2000–2025. The shaded area represents the 30–90-day MJO intraseasonal period.

The dominant 43–45 days period found in this study was consistent with the established temporal characteristics of the MJO, found by Lin (2022), which showed that tropical wavenumber-frequency spectra commonly exhibited enhanced MJO power within the 30–60-day range, particularly in large-scale OLR and zonal-wind variability. Similarly, research by Neena et al. (2022) analyzed the OLR and

atmospheric circulation data spanning from 1979–2019 and revealed that the wavenumber-frequency analysis identified MJO-related convective variability within the 30–90 day period. The spatial distribution of MJO-filtered OLR variance showed pronounced activity over the IO and several other tropical ocean basins. Among the three regional domains examined, the IO exhibited the largest

standard deviation of the regional MJO index, indicating stronger MJO-related convective variability than in the selected Pacific and Atlantic domains. In addition, the comparatively strong MJO-related OLR variability over the Indian Ocean is consistent with the large amplitude of MJO-filtered OLR anomalies and the strong tropospheric convection-circulation coupling reported for this region. Previous studies also show that MJO evolution involves interactions among column moisture, large-scale circulation, cloud processes, and surface turbulent fluxes, although no single process can be identified as the sole cause of the larger spectral power observed in the present study (Kim et al., 2018; Jiang et al., 2020; Neena et al., 2022).

OLR and Surface-Wind Response during MJO Active Phase in Malacca Strait and Indian Ocean

OLR represents the thermal infrared energy emitted by the Earth-atmosphere system to space. Because deep convective clouds

have cold, high tops that emit less longwave radiation, negative OLR anomalies are a standard proxy for enhanced deep convection, while positive anomalies indicate suppressed convection. Phase composites of OLR can consequently describe the location, strength, and temporal evolution of MJO-related convection (Barrett et al., 2021; Zheng et al., 2024; Veerbhan & Kumar, 2025).

OLR and surface-wind composites (Figure 4) show a transition from suppressed convection during phases 1-3 to enhanced convection during phases 4-6. The IO generally exhibits stronger OLR anomalies than the MS, with the strongest negative anomalies occurring during the enhanced-convection phases. In phase 6, both regions show strong negative anomalies, reaching approximately -13.88 W/m^2 . The convective signal weakens during phase 7 and reverses to positive anomalies in phase 8, while the surface-wind circulation changes markedly between phases 1-3 and 4-6.

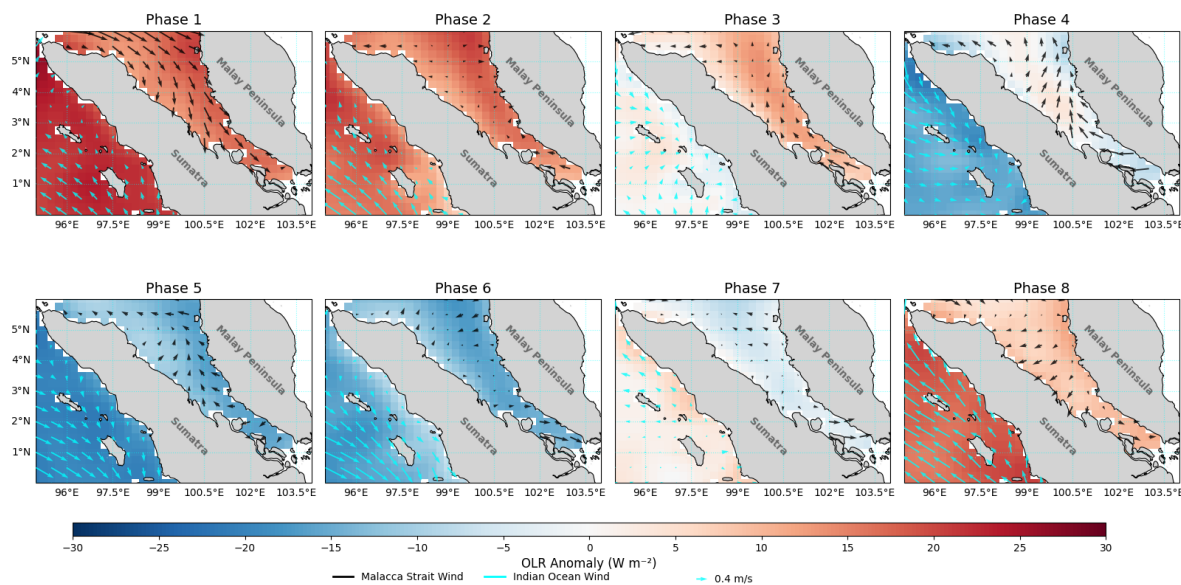


Figure 4. Spatial composites of OLR and 10-m surface-wind anomalies. Black vectors represent the Malacca Strait and cyan vectors represent the Indian Ocean during active MJO phases 1-8 for 2000-2025.

The shifting from positive OLR anomalies in phases 1-3 to negative anomalies in phases 4-6 (as depicted in Figure 5) represents the eastward development of the MJO convective system from the eastern

Indian Ocean toward the western MC. The earlier decrease in OLR over the IO during phase 3, followed by stronger negative anomalies during phases 4-5, suggested that enhanced convection initially intensified

over the open ocean before extending toward the Malacca Strait. Kang et al. (2022) reported a similar phase evolution over the southern MC, where low-level zonal wind convergence strengthened during phase 4, while upward motion and precipitation peaked in phase 5. Westerly

lower-tropospheric wind anomalies also accompanied the phase 5 precipitation increase. Therefore, the strongest negative OLR anomaly observed during phase 5 is consistent with the established sequence from low-level convergence to intensified deep convection.

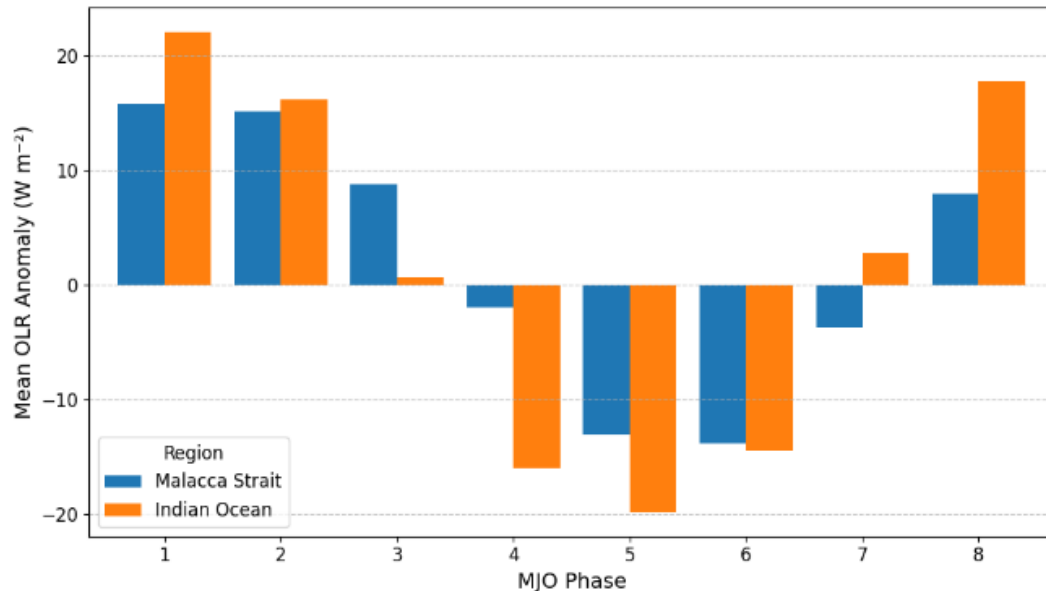


Figure 5. Regional-mean OLR anomaly during MJO phases 1-8. Bars represent the spatially averaged OLR anomalies for each regional domain. Positive values indicate suppressed convection, whereas negative values indicate enhanced convection.

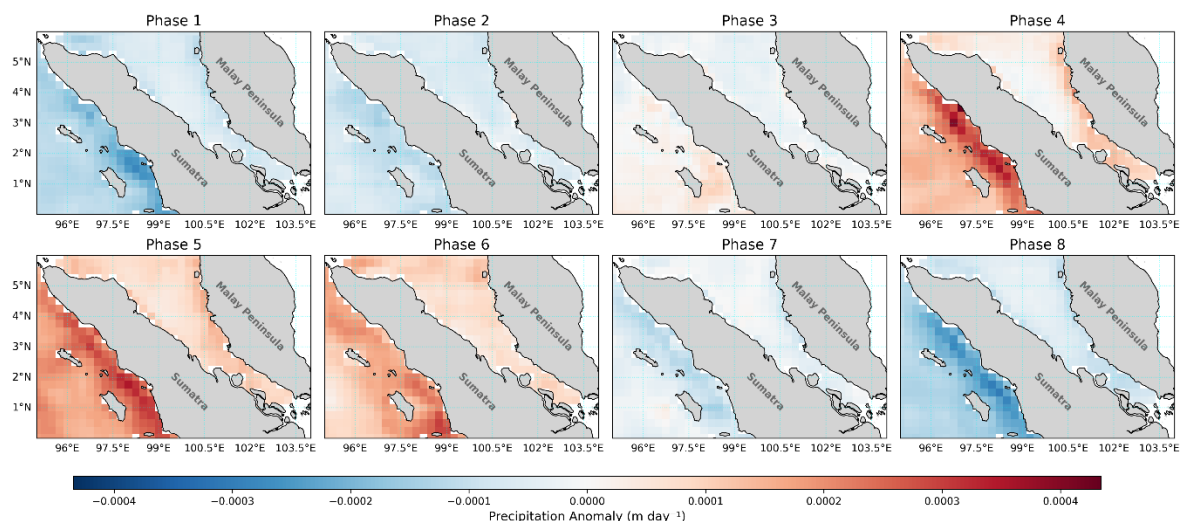


Figure 6. Spatial composite precipitation anomalies during MJO phases 1-8 over the Malacca Strait and the adjacent Indian Ocean during active MJO phases 1-8 for 2000-2025.

The larger negative OLR anomalies over the IO during phases 4-5 are consistent with enhanced MJO convection over the eastern IO and western MC. Karlowska et al. (2024) and Barrett et al. (2021) similarly reported enhanced convection and stronger negative OLR anomalies over the eastern

IO during active MJO phases, before the MJO propagated into the MC. However, these studies did not specifically examine the MS or quantify the difference in OLR response between the open ocean and the strait. The present results further show that the OLR response in the MS was weaker

and more spatially heterogeneous than in the IO. During phases 4 and 5, the spatial standard deviation of OLR anomalies was 3.76 and 2.41 W/m^2 in the MS, compared with 1.66 and 1.06 W/m^2 in the IO, respectively. The larger spatial variability in the MS indicates a less uniform convective response, which may contribute to the weaker regional-mean anomaly through spatial cancellation. This contrast suggests that the MJO-related OLR response observed over the open IO may not be directly representative of the response within the semi-enclosed MS.

Response of Precipitation during MJO Active Phase in Malacca Strait and Indian Ocean

The spatial composites in Figure 6 showed a clear phase-dependent evolution of precipitation anomalies over the IO and MS. Negative anomalies dominated phases 1-2, followed by increasing rainfall during phases 4-6, with the strongest and most extensive positive anomalies over the eastern IO and western waters of Sumatra. A two-tailed Student's t-test confirms that these positive precipitation anomalies across phases 4-6 are highly statistically significant ($p < 0.001$) for both regional domains. It indicates a robust MJO-driven convective signal. Precipitation decreased again during phases 7-8. Compared with the IO, the MS generally showed weaker and less spatially continuous anomalies.

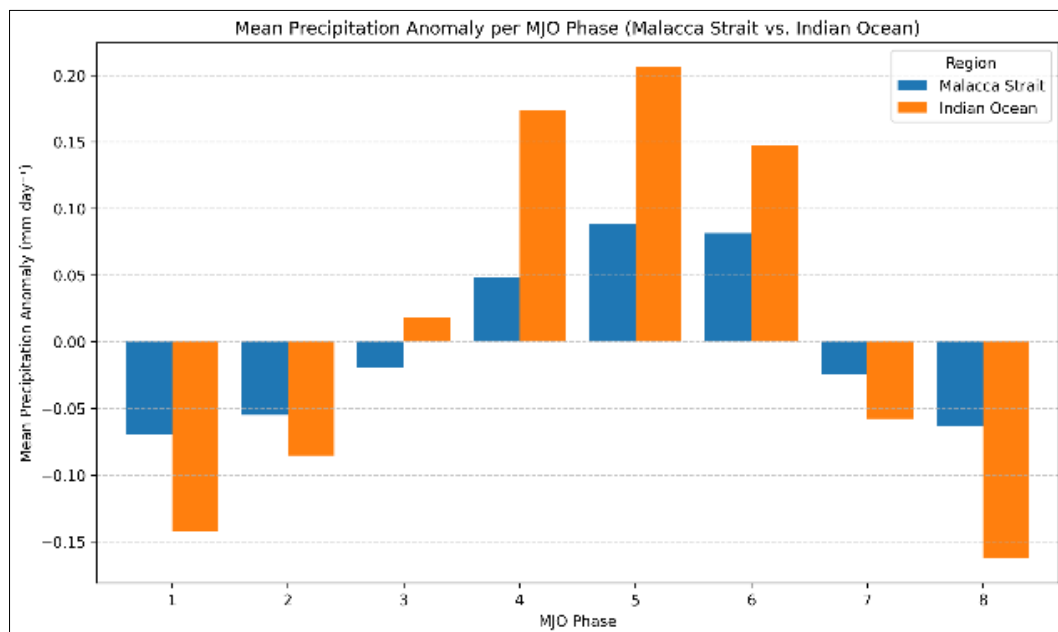


Figure 7. Regional-mean precipitation anomaly during MJO phases 1-8. Bars represent the spatially averaged precipitation anomalies for each regional domain.

Figure 7 confirmed a similar sequence of patterns in both regions, although the IO consistently showed larger amplitudes than the MS. The IO experienced a pronounced rainfall peak in phase 5, more than twice as large as that in the MS. Conversely, dry anomalies during phase 8 were also substantially stronger over the open ocean. The divergence in phase 3, where the IO showed a weak positive anomaly while the MS remained slightly negative, marked the

earliest onset of the wet phase over the open water.

The positive precipitation anomalies during phases 4-6 are in line with the enhanced oceanic rainfall reported over the western MC during active MJO conditions. Kim et al. (2022) found that oceanic precipitation increased during phases 4-5, with the largest ocean-to-land precipitation ratio occurring in phase 5. In contrast, precipitation weakened during phases 1-2 and 7-8, when the active MJO convection

was located outside the study region. The corresponding negative OLR anomalies during phases 4–6 provide additional evidence of greater high-cloud cover and deep convective activity during the wetter phases, whereas positive OLR anomalies coincided with reduced precipitation during the suppressed phases.

The larger precipitation anomalies over the IO were consistent with the stronger moisture sensitivity of oceanic rainfall reported by Chen et al. (2021). In phase 5, the IO anomaly was more than twice that over the MS, although both regions followed a similar phase evolution. The weaker MS response may reflect the influence of nearby landmasses, coastal circulation, and the diurnal cycle, which were not separated in previous analyses of phases 4–5 over the western MC (Kim et al., 2022). Therefore, precipitation responses observed over the open IO may not directly represent rainfall variability within the MS during active MJO phases.

Response of Sea Surface Temperature (SST) during MJO Active Phase in Malacca Strait and Indian Ocean

SST is a critical indicator of air-sea interaction during MJO episodes because differences in cloud cover, surface winds, and air-sea heat fluxes can modify the upper-ocean heat balance (Karlowska et al., 2024). Spatial composites (Figure 8) showed positive SST anomalies through phases 1–4, which reach their largest extent over the IO in phases 2–3 before weakening by phase 4, especially in the MS. Negative anomalies then emerged across both regions in phases 5–7, with the most extensive cooling observed over the IO in phase 6, followed by a peak cooling response over the MS in phase 7. This indicates a one-phase lag in the peak SST cooling response of the MS relative to the

IO. The cooling anomalies gradually weakened during phases 7–8.

Positive SST anomalies during phases 1–3 indicate warming before the development of strong convection, consistent with reduced cloud cover and weaker winds reported during the early MJO phases (Cui et al., 2024). SST remained slightly positive in phase 4 despite the onset of negative OLR and increased precipitation, suggesting a lagged ocean response to atmospheric forcing. SST subsequently became negative during phases 5–7, consistent with MJO-related cooling associated with reduced solar heating, evaporation, and mixing (Chandra et al., 2024). The evolution of negative SST anomalies reveals a distinct temporal lag between the two regional domains. Maximum cooling in the Malacca Strait peaked during phase 7, occurring one full phase later than the phase 6 peak observed over the open Indian Ocean. This delayed thermal response within the strait suggests that the local upper-ocean heat balance is not driven solely by instantaneous atmospheric forcing, but is instead modulated by complex regional oceanographic dynamics. Given the shallow bathymetry of the Malacca Strait, the water column is continuously subjected to intense tidal mixing. This strong vertical mixing can redistribute heat throughout the water column. Horizontal advection driven by coastal currents may continuously transport varying water masses from the adjacent Andaman and South China Seas. While a complete oceanic heat budget analysis would be necessary to quantify these individual driving factors, the combination of restricted coastal geometry, strong tidal mixing, and horizontal advection provides a highly plausible physical framework for the lagged SST response observed within the strait (Chen et al., 2014; Kurniawan et al., 2021).

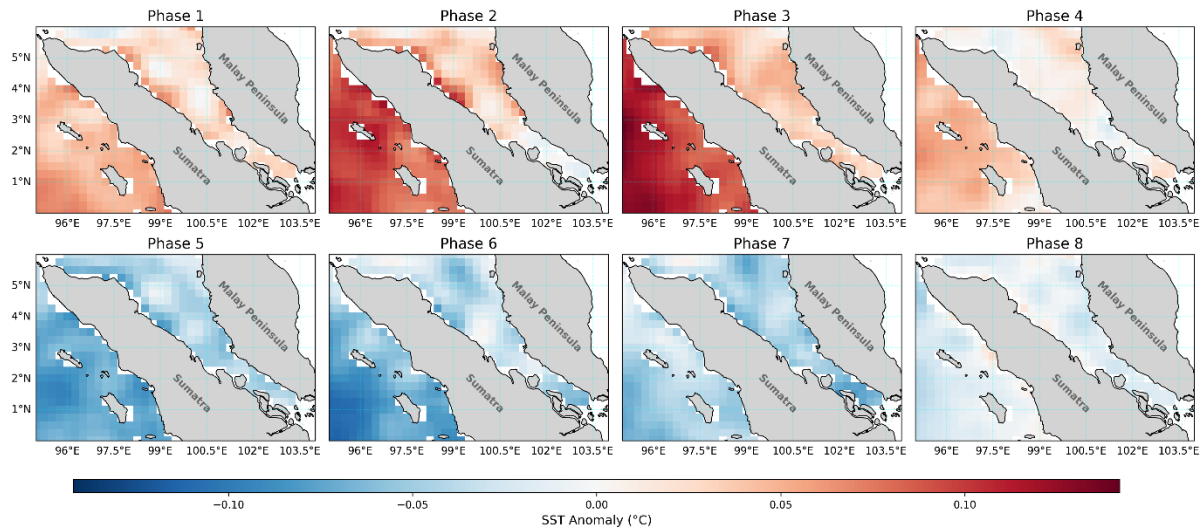


Figure 8. Spatial composites of sea surface temperature anomalies over the Malacca Strait and adjacent Indian Ocean during active MJO phases 1-8 for 2000-2025.

The regional means of SST, as depicted in Figure 9, confirmed that there is a shift from warming to cooling across MJO phases. The SST response exhibited a coherent warm-to-cool cycle across the MJO. Maximum warming was observed in phase 3 for both regions, but the amplitude over the IO was nearly three times that in the MS. The cooling phase extended from phases 5 to 7, with the strongest negative

anomaly over the IO occurring in phase 6. The MS cooling was consistently weaker and peaked later in phase 7, reflecting the combined effects of reduced wind fetch and shallower mixed-layer dynamics that dampened the thermal response. Overall, both regions displayed a similar warm-to-cool sequence, but the IO generally exhibited larger SST anomaly amplitudes.

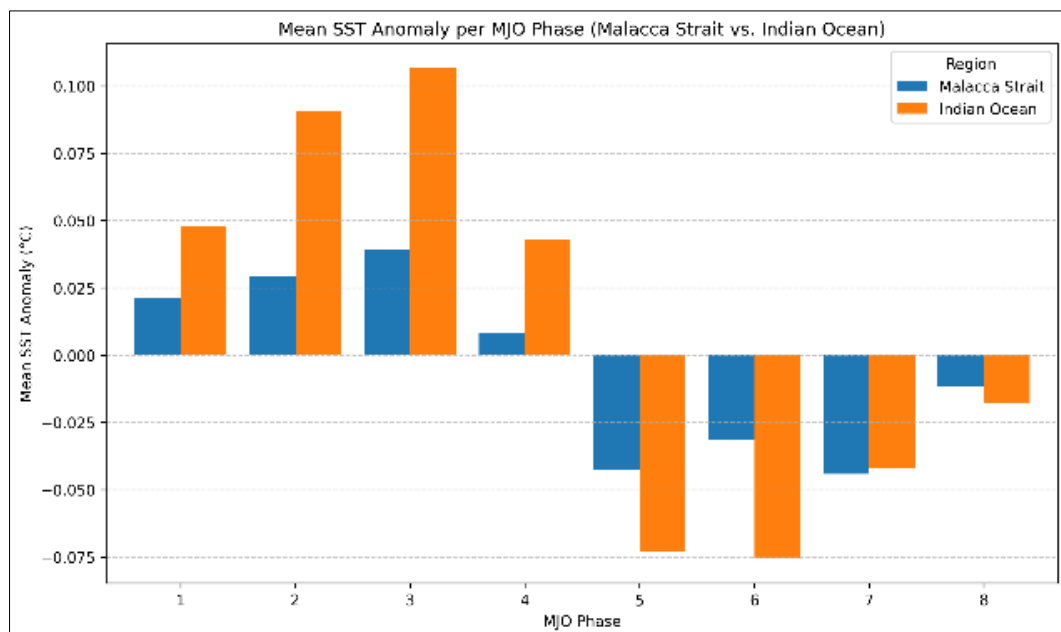


Figure 9. Regional-mean SST anomaly during MJO phases 1-8. Bars represent the spatially averaged SST anomalies for each regional domain.

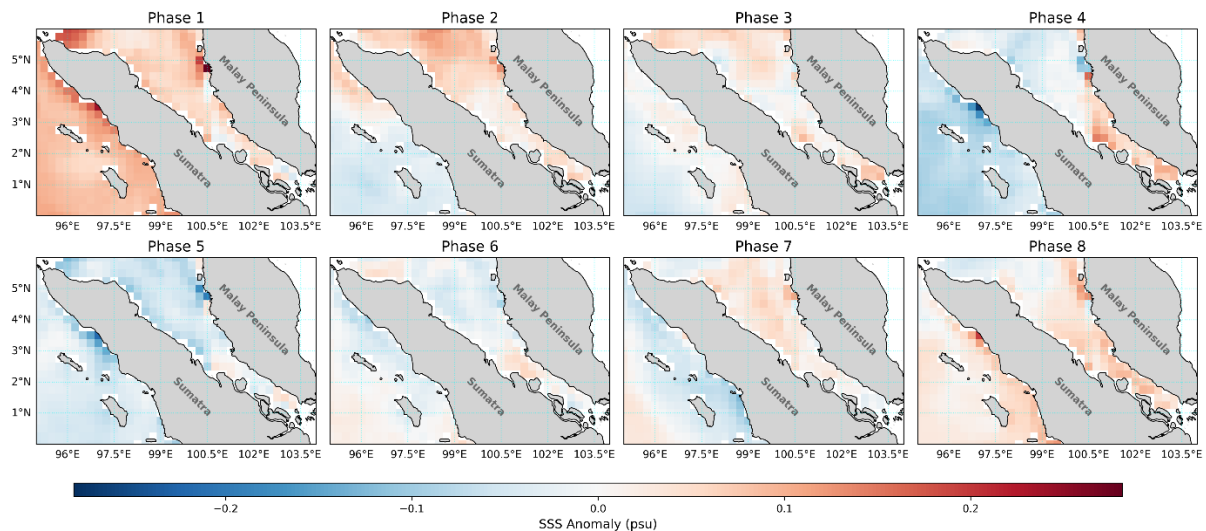


Figure 10. Spatial composites of sea surface salinity anomalies over the Malacca Strait and adjacent Indian Ocean during active MJO phases 1-8 for 2000-2025.

The narrow, shallow bathymetry of the strait likely strengthens tidal and wind-driven circulation, promoting upwelling and horizontal advection that dampen the surface thermal signal (Mandal et al., 2021), while net surface heat flux dominates the large-scale mixed-layer response and ocean advection becomes more important at smaller scales (Karlowska et al., 2024). The shallow water column in the strait also allows wind mixing to penetrate the full depth and distribute the heat over a smaller volume, further reducing the surface response compared with the deeper, more sensitive mixed layer of the open IO.

Sea Surface Salinity Response during MJO Active Phase in Malacca Strait and Indian Ocean

SSS reflects the surface freshwater balance, where positive anomalies indicate saltier conditions and negative anomalies indicate freshening (Yu, 2023). Spatial composites (Figure 10) showed positive anomalies in both regions during phase 1. During phases 2 and 3, the MS stayed mostly positive while the IO shifted slightly negative, and the most extensive IO freshening developed in phase 4, when the MS instead showed

adjacent positive and negative anomalies on its eastern and western sides. The low regional mean in phase 4 resulted from spatial heterogeneity (spatial standard deviation of 0.050 psu in the MS versus 0.026 psu in the IO), where these adjacent positive and negative anomalies largely canceled each other out. Negative anomalies were stronger across the MS in phase 5 as IO freshening weakened. Both regions show weak negative means in phase 6 (about -0.012 psu in the MS and -0.007 psu in the IO), and a clear contrast appeared in phase 7, with positive MS anomalies against continued IO freshening, before positive anomalies prevailed in both regions by phase 8.

Additionally, the regional mean of SSS over the IO shifted from a positive anomaly in phase 1 to negative anomalies during phases 2–7, with the strongest freshening occurred in phase 4 (Figure 11). The MS showed a less regular pattern, as positive anomalies weakened during phases 1–3, approached zero in phase 4, and became weakly negative during phases 5–6. The near-zero mean in phase 4 resulted from adjacent positive and negative anomalies that largely canceled each other in the regional average, as shown in Figure 10.

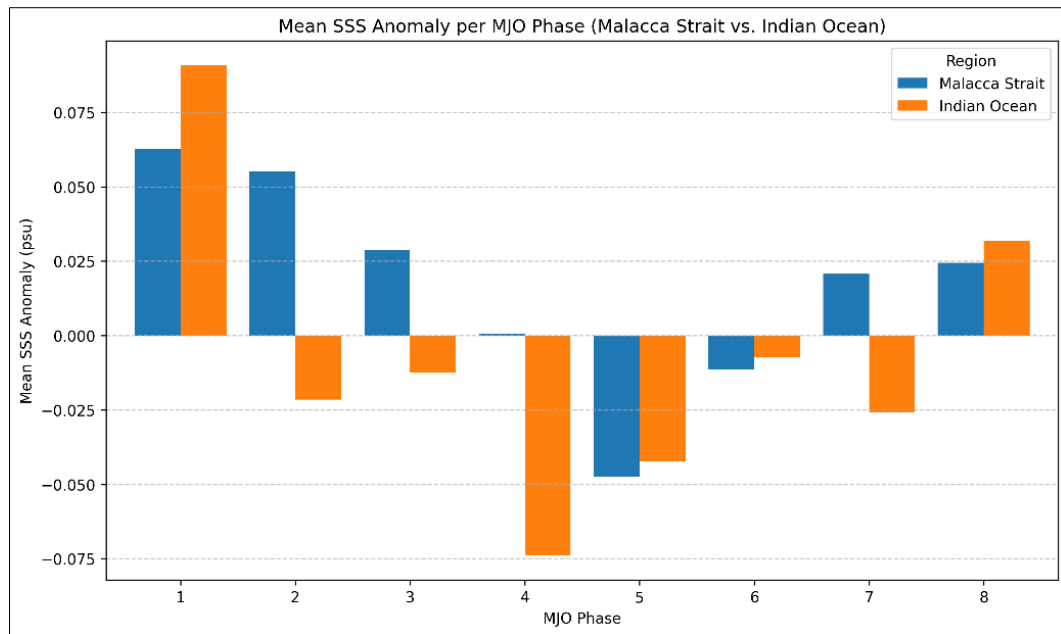


Figure 11. Regional-mean SSS anomaly during MJO phases 1-8. Bars represent the spatially averaged SSS anomalies for each regional domain.

These patterns generally followed variations in freshwater input and upper-ocean redistribution during the MJO cycle, where reduced precipitation in phases 1-2 limited surface freshening, while increased rainfall during the transition toward active convection deposited fresher, less dense water at the surface. Near-surface rain layers that developed during this transition and were later eroded by stronger wind mixing (Shackelford et al., 2024) are consistent with the IO freshening peak seen here in phase 4. The weaker and delayed

MS freshening signal, however, indicates that SSS is not solely controlled by precipitation. Horizontal advection and turbulent mixing jointly shape salinity variability in the equatorial IO (Chi et al., 2021), while MS salinity has separately been linked to water transport and inflow salinity (Zhao et al., 2025). The present comparison suggests that precipitation dominates the IO signal, whereas tidal mixing and exchange with adjacent water masses play a larger role in the MS.

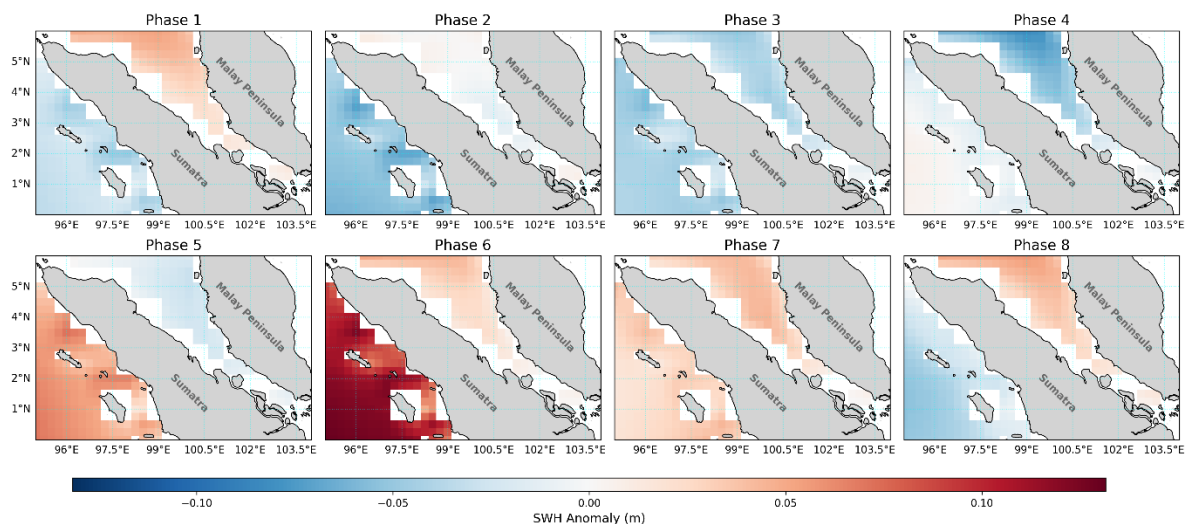


Figure 12. Spatial composites of significant wave height anomalies over the Malacca Strait and adjacent Indian Ocean during active MJO phases 1-8 for 2000-2025.

Significant Wave Height Response during MJO Active Phase in Malacca Strait vs Indian Ocean

The spatial composites in Figure 12 showed contrasting phase-dependent SWH responses over the IO and MS. During phase 1, positive anomalies occurred over much of the MS, whereas negative anomalies dominated the IO. Negative anomalies became more widespread during phases 2–4, with the strongest reduction

over the IO during phases 2–3 and over the MS during phase 4. The pattern changed during phase 5, when positive anomalies developed over the IO, while the MS remained weakly negative. Positive anomalies then expanded across both regions during phases 6–7, with the largest and most extensive increase over the IO in phase 6. A regional contrast returned in phase 8, when positive anomalies persisted over the MS, but negative anomalies reappeared over the IO.

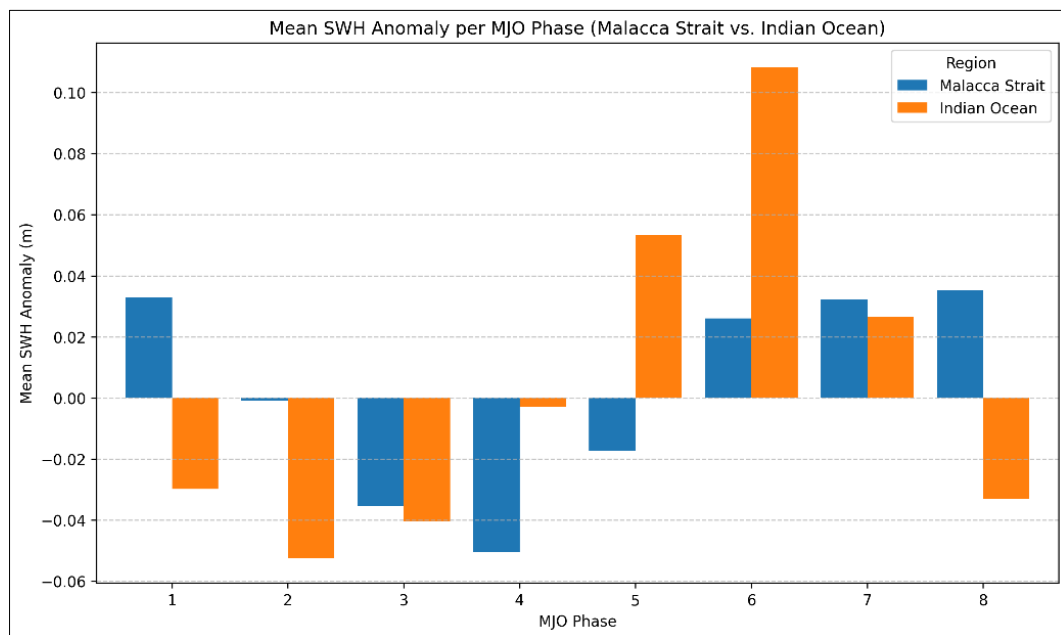


Figure 13. Regional-mean SWH anomaly during MJO phases 1–8. Bars represent the spatially averaged SWH anomalies for each regional domain.

The phase-dependent SWH response was closely associated with surface-wind forcing during the MJO cycle. The stronger IO response in phases 5–6 coincided with stronger wind anomalies in the preceding phases, which peaked in phases 4–5, representing a lag of approximately one phase or 5–7 days. Thus, the phase 6 SWH peak was likely related to accumulated wind forcing rather than an instantaneous response. Previous work has also reported MJO-related wave responses in the Riau Archipelago (Napitupulu et al., 2022). In contrast, the MS showed a weaker and less phase-coherent response, which may be partly related to its constrained wave environment and the effects of fetch, bathymetry, and topographic sheltering (Xu

et al., 2026). However, these factors were not directly evaluated in the present study.

The regional means in Figure 13 show that the SWH response differed between the IO and MS. A stronger positive response was observed in the IO, with a peak in phase 6, whereas a weaker and more variable response was observed in the MS, with positive anomalies present during phases 6–8. The stronger response in the IO may be associated with contributions from locally generated waves and remote swell, whereas the weaker response in the MS may be partly related to its restricted fetch and surrounding landmasses, which limit wave development (Gao et al., 2023). The broader and delayed response in the MS

indicates that the SWH response to MJO-related wind forcing differed between the semi-enclosed strait and the open IO.

Spatial averaging over the small, heterogeneous MS domain contributes to its reduced amplitude, since adjacent anomalies partly cancel (Mandal et al., 2021), but physical mechanisms, including fetch limitation, shallow bathymetry, and tidal mixing, also genuinely dampen the MJO signal in the strait. Distinguishing these contributions would require higher-resolution data.

Conclusion

This study found clear differences in MJO-related variability between the Malacca Strait (MS) and the eastern Indian Ocean (IO). Both regions showed intraseasonal OLR variability within the MJO timescale, but the IO exhibited stronger spectral power and atmospheric responses, particularly during the enhanced convection phases. The ocean-surface responses also differed between the two regions, with SST changing from warming during phases 1–4 to cooling during phases 5–7, reaching maximum cooling in phase 6 in the IO and one phase later, in phase 7, in the MS. SSS freshening and SWH responses were also stronger and more consistent in the IO than in the MS. Overall, the results show that the magnitude, spatial pattern, and timing of MJO-related variability differ between the open IO and semi-enclosed MS, indicating that regional geographical and oceanographic conditions shape the ocean-surface response to the MJO.

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Author Contribution

NAA contributed to conceptualization, methodology, formal analysis, investigation, visualization, project administration, writing the original draft, and reviewing and editing the manuscript. ADH contributed to conceptualization, data curation, software, formal analysis, visualization, and reviewing and editing the manuscript. BA contributed to supervision. RP contributed to validation. M contributed to supervision. II contributed to validation. R contributed to supervision and validation. All authors read and approved the final manuscript.

Conflict of Interest

The authors declare that there are no financial or personal relationships that could have influenced the research presented in this manuscript.

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