

Persistent Enhanced Southwest Monsoon (Habagat) Rains over Luzon in July and August 2026: The Combined Role of a Stalled Madden–Julian Oscillation and El Niño

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Research Article

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Posted Date: October 6th, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-11025589/v1>

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Persistent Enhanced Southwest Monsoon (Habagat) Rains over Luzon in July and August 2026: The Combined Role of a Stalled Madden–Julian Oscillation and El Niño

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Abstract

During the summer of 2026, a severe and prolonged southwest monsoon episode delivered extreme accumulated rainfall across Western Luzon, Philippines, driven by a Madden–Julian Oscillation (MJO) event that became stalled in Phases 6–7 over the Western Pacific. Using ERA5 reanalysis and GPM-IMERG precipitation data, this study traces the multi-scale atmospheric sequence connecting this intraseasonal stagnation to localized monsoonal inundations. Equatorial (5°S–5°N) cross-section diagnostics reveal that eastward MJO propagation was halted by a perturbed Walker circulation, wherein an upper-level subsidence trap east of the dateline (170°E–140°W) combined with a lower-tropospheric moist static energy deficit to the west to geographically anchor the ascending MJO convective core over 120°E–150°E. Spectral Poisson solutions for 200 hPa velocity potential confirm persistent upper-tropospheric mass outflow, which induced a stationary, off-equatorial Gill-type cyclonic Rossby gyre over the northern South China Sea. This monsoon gyre sustained a continuous, humidity-rich Moisture Conveyor Belt directed straight into Luzon. Column moisture budget decomposition confirms that vertically integrated mass convergence, rather than horizontal moisture advection or local surface evaporation, served as the primary thermodynamic driver. Finally, zonal transects along 16°N–17°N demonstrate how this deep boundary-layer moisture flux was mechanically forced upward by the Zambales Range, triggering localized heavy rainfall. These findings demonstrate how planetary-scale atmospheric suppressions can stall intraseasonal oscillations, converting transient MJO passages into prolonged regional hazards.

Keywords: Southwest Monsoon, the Philippines, extreme rainfall, MJO, El Niño

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40

41 1. Introduction

42

43 The Southwest Monsoon, or *Habagat* in the local vernacular, is an important component
44 of the Philippine climate system, contributing significant rainfall to the northern parts of the
45 archipelago between June and September. While tropical cyclone (TC) landfalls traditionally
46 account for localized extreme rainfall, the majority of high-precipitation events along the western
47 seaboard of Luzon are driven by indirect, remote TC precipitation effects via monsoonal
48 enhancements (Cayan et al., 2011; Bagtasa, 2021; Bathan et al., 2026). Enhanced southwest
49 monsoon winds produce heavy precipitation events induced by distant atmospheric drivers or by
50 non-landfalling TCs situated northeast of Luzon. These TCs accelerate low-level monsoonal
51 westerlies across the South China Sea, organizing a humidity-rich “Moisture Conveyor Belt”
52 (MCB) that impinges directly upon the windward slopes of the Zambales and Central Cordillera
53 Mountains.

54 At intraseasonal timescales, the strength, timing, and duration of these monsoonal
55 surges are heavily modulated by the Madden–Julian Oscillation (MJO; Wheeler and Hendon,
56 2004; Bagtasa, 2020). As the dominant mode of tropical subseasonal variability, the MJO
57 modulates global weather systems, monsoonal onset, and tropical cyclogenesis (Zhang, 2013).
58 However, the background state of the tropical oceans is undergoing rapid transformation.
59 Anthropogenic warming has driven a twofold expansion of the Indo-Pacific warm pool ($>28^{\circ}\text{C}$)
60 over recent decades, warping the canonical MJO life cycle by shortening its residence time over
61 the Indian Ocean while prolonging its active convective phase over the Maritime Continent and
62 West Pacific (MJO Phases 5–7) by 5–6 days (Roxy et al., 2019). Parallel investigations during
63 the boreal summer monsoon reveal a contrasting trend, where rapid Indian Ocean warming and
64 low-level wind anomalies have led to a threefold increase in summer MJO residence time over
65 the Indian Ocean (+5.2 days decade⁻¹), demonstrating that intraseasonal convective stalling is
66 becoming an increasingly dominant mode of climate variability (Zhang et al., 2025).

67 The severe societal risks associated with such intraseasonal stagnation were highlighted
68 during the record-breaking summer monsoons of 2020, where a quasi-stationary MJO active
69 phase persisted for 59 days, driving catastrophic, multi-week inundations across East Asia
70 (Zhang et al., 2021). Evaluation of subseasonal-to-seasonal (S2S) prediction frameworks
71 confirms that accurately capturing MJO teleconnections, specifically its coupling with
72 low-latitude subtropical circulation features, is necessary for predicting the location, duration,
73 and intensity of extreme monsoonal rainbands (Wie et al., 2024). When MJO convective centers

74 become stationary, they excite sustained off-equatorial Rossby wave responses, organizing
75 persistent low-level cyclonic gyres and upper-level mass divergence centers that continuously
76 feed monsoonal moisture streams (Gill, 1980; Zhang et al., 2021).

77 During July and August 2026, the Philippines experienced an extraordinary sequence of
78 extreme monsoonal deluges that caused widespread flooding, urban paralysis, and severe
79 infrastructure damage across western Luzon. Uniquely, these extreme rainfall surges occurred
80 within a background climate state characterized by an active El Niño event, a regime historically
81 associated with regional precipitation suppression across the Philippine archipelago. This
82 paradoxical phenomenon raises fundamental questions regarding how planetary-scale warming,
83 intraseasonal wave dynamics, and local air-sea feedbacks interact to override background El
84 Niño drying. This study systematically investigates the multi-scale atmospheric and oceanic
85 mechanisms that drove the July–August 2026 enhanced monsoon event over the Philippines.
86 Using integrated reanalysis datasets, satellite sea surface temperature (SST) diagnostics,
87 real-time multivariate MJO tracking, and column moisture budget decompositions, this study
88 aims to: (1) evaluate how intraseasonal MJO dynamics modulated the anomalously wet 2026
89 summer monsoon, (2) characterize the interaction between background El Niño–driven Walker
90 circulation anomalies and MJO, (3) examine how these planetary-scale climate drivers
91 organized and maintained a persistent MCB, and (4) assess the local influence of terrain-forced
92 orographic uplift along Western Luzon in modulating recurring localized rainfall. The remainder
93 of this paper is organized as follows: Section 2 outlines the observational datasets and
94 analytical methods, Section 3 presents the multi-scale results and physical discussion, and
95 Section 4 synthesizes the key findings in the summary and conclusion.

96

97 **2. Data and Methodology**

98 *2.1 Data*

99 This study utilizes a combination of atmospheric reanalysis, satellite-derived precipitation
100 estimates, and SST observations covering the two-month peak monsoon period from 1 July to
101 31 August 2026. Global atmospheric fields are extracted from the European Centre for
102 Medium-Range Weather Forecasts (ECMWF) ERA5 reanalysis dataset (Hersbach et al., 2020)
103 at a spatial resolution of $0.25^\circ \times 0.25^\circ$ and 6-hourly temporal resolution. 3D pressure-level
104 variables (u , v , q , w) are retrieved across 12 pressure levels (1000, 925, 850, 700, 600, 500,
105 400, 300, 250, 200, 150, 100 hPa). Single-level surface parameters include surface evaporation
106 (e) and mean sea level pressure. For planetary-scale tropical diagnostics (Walker circulation

transects), data were subsampled to a $1.0^\circ \times 1.0^\circ$ grid over the equatorial belt (10°N -- 10°N , 50°E -- 100°W).

High-resolution precipitation estimates are obtained from the Global Precipitation Measurement (GPM) Integrated Multi-satellite Retrievals for GPM (IMERG) Late and Final Precipitation L3 Daily product for 2026 and 1999 to 2025, respectively, at $0.1^\circ \times 0.1^\circ$ spatial resolution. Daily precipitation rates (mm day^{-1}) are calculated by aggregating surface rainfall over Western Luzon (119°E - 122°E , 14°N - 19°N). Daily SSTs are derived from the NOAA High-Resolution Optimum Interpolation SST (OISST v2.1) dataset, with SST anomalies (SSTA) calculated relative to the 1991–2020 climatological long-term mean. The daily Real-time Multivariate MJO (RMM) index (RMM1 and RMM2), calculated following Wheeler and Hendon (2004), was sourced from the Australian Bureau of Meteorology tropical monitoring portal (https://www.bom.gov.au/clim_data/IDCKGEM000/rmm.74toRealtime.txt). A notable limitation of the present study is its primary reliance on the canonical MJO index rather than the Boreal Summer Intraseasonal Oscillation (BSISO) framework (Kikuchi et al., 2012; Olaguera et al., 2021). Although BSISO explicitly resolves the complex, northward- and northeastward-propagating convective modes characteristic of the boreal summer Asian monsoon, the classical MJO framework is utilized here to maintain a standardized, year-round metric for tracking broad planetary-scale equatorial wave propagation across the Indo-Pacific basin.

2.2 Kinematic and Dynamical Diagnostics

To quantify the intraseasonal or daily intensity and persistence of the low-level Southwest Monsoon jet, the Western Luzon Monsoon Index (*WLMJ*) is defined here and computed as the area-averaged 850 hPa zonal wind component over the South China Sea and Western Philippines (115°E - 125°E , 10°N - 20°N). Positive values (*WLMJ* $> +5 \text{ m s}^{-1}$) represent active monsoon jet surges directed toward Western Luzon. Then, to isolate upper-tropospheric mass divergence from low-level rotational flow, 200 hPa Velocity Potential (χ_{200}) and 850 hPa Streamfunction (ψ_{850}) are calculated by solving their respective Poisson equations on a spherical grid (Lynch, 1988; Sardeshmukh and Hoskins, 1988):

$$\nabla^2 \chi_{200} = D_{200}$$

$$\nabla^2 \psi_{850} = \zeta_{850}$$

137 where the horizontal divergence D and relative vorticity ζ in spherical coordinates are given by:

$$138 \quad D = \frac{1}{a \cos \phi} \left[\frac{\partial u}{\partial \lambda} + \frac{\partial (v \cos \phi)}{\partial \phi} \right]$$

$$139 \quad \zeta = \frac{1}{a \cos \phi} \left[\frac{\partial v}{\partial \lambda} - \frac{\partial (u \cos \phi)}{\partial \phi} \right]$$

140 Here $a = 6.371 \times 10^6 m$ is the Earth's mean radius. The Poisson equations are solved using a
141 custom 2D double-periodic Fast Fourier Transform (FFT) spectral solver (`fft2` and `ifft2`
142 commands in MATLAB). In wavenumber space, the equations transform to:

$$143 \quad \hat{\chi}(k_x, k_y) = - \frac{\hat{D}(k_x, k_y)}{k_x^2 + k_y^2}, \quad (k_x^2 + k_y^2 \neq 0)$$

144 where k_x and k_y are the zonal and meridional wavenumbers, respectively. The divergent
145 component of the 200 hPa wind ($V_\chi = (u_\chi, v_\chi)$) is subsequently derived via:

$$146 \quad u_\chi = \frac{1}{a \cos \phi} \frac{\partial \chi_{200}}{\partial \lambda}, \quad v_\chi = \frac{1}{a} \frac{\partial \chi_{200}}{\partial \phi}$$

147 2.3 Integrated Vapor Transport (IVT) and Column Moisture Budget

148 The total column Integrated Vapor Transport (IVT) vector is integrated from 1000 hPa to
149 300 hPa, given by:

$$150 \quad IVT = (IVT_u, IVT_v) = - \frac{1}{g} \int_{1000 \text{ hPa}}^{300 \text{ hPa}} q V dp$$

151 where $g = 9.80665 m s^{-2}$ is standard gravitational acceleration, q is specific humidity ($kg kg^{-1}$),
152 $V = (u, v)$ is the horizontal wind vector ($m s^{-1}$), and p is pressure (Pa). The magnitude $|IVT|$ is
153 computed in $kg m^{-1} s^{-1}$. Boundary-layer moisture flux is also evaluated at 850 hPa as the
154 product $q_{850} V_{850}$ ($kg kg^{-1} m s^{-1}$). To determine the governing thermodynamic and dynamic
155 drivers of rainfall over Western Luzon, the vertically integrated conservation equation for water
156 vapor is evaluated as:

$$157 \quad \frac{\partial \langle q \rangle}{\partial t} = - \nabla \cdot IVT + E - P$$

158 where $\frac{\partial \langle q \rangle}{\partial t}$ is the column storage rate, E is surface evaporation, P is GPM-derived precipitation,
 159 and $-\nabla \cdot IVT$ is the column Moisture Flux Convergence (MFC). The total MFC term ($-\nabla \cdot IVT$
 160) is decomposed into two distinct physical mechanisms: the advection term and the mass
 161 convergence term, given respectively by:

$$162 \quad -\nabla \cdot IVT = -\frac{1}{g} \int_{1000}^{300} (V \cdot \nabla q) dp + -\frac{1}{g} \int_{1000}^{300} q(\nabla \cdot V) dp$$

163 2.4 Spatial and Transect Cross-Section Analyses

164 The planetary-scale Walker circulation structure is evaluated along an equatorial
 165 longitude-pressure cross-section (50°E--100°W) averaged over the equatorial latitudinal band
 166 (5°S-5°N). ERA5 vertical velocity in pressure coordinates ($\omega = \frac{dp}{dt}$ in $Pa s^{-1}$) is converted to its
 167 physical updraft/downdraft proxy ($w = -\omega$). To diagnose the thermodynamic pre-conditioning and
 168 column energy variations modulating the eastward propagation of the MJO (Kim and Sobel,
 169 2014), this study evaluates the Moist Static Energy (MSE, in $kJ kg^{-1}$) across the equatorial
 170 Indo-Pacific basin (5°S-5°N, 50°E-100°W). MSE represents the total thermodynamic energy
 171 content of an air parcel, expressed as:

$$172 \quad MSE = C_p T + gz + L_v q$$

173 where T is temperature (K) and z is geopotential height (m) extracted from ERA5 3D
 174 pressure-level reanalysis across all the vertical levels (1000-150 hPa). The physical constants
 175 are defined as the specific heat of dry air at constant pressure ($C_p = 1004.6 J kg^{-1} K^{-1}$) and the
 176 latent heat of vaporization ($L_v = 2.501 \times 10^6 J kg^{-1}$). MSE anomalies for July–August 2026 are
 177 calculated relative to the 30-year climatological baseline period (1991-2020).

178 To isolate layer-specific thermodynamic contributions to deep convective instability,
 179 layer-averaged MSE anomalies are computed for the Planetary Boundary Layer (PBL),
 180 vertically averaged between 1000-925 hPa to capture low-level air–sea enthalpy fluxes and
 181 boundary layer destabilization, for the mid-troposphere, where it is vertically averaged between
 182 700-500 hPa to assess middle-level column moistening, and for the upper troposphere,
 183 vertically averaged between 300-150 hPa to quantify deep convective export and upper-level
 184 energy accumulation. Additionally, column-mean specific humidity anomalies are vertically
 185 integrated from 1000-300 hPa to evaluate the total atmospheric moisture reservoir co-located
 186 with the Walker circulation cell. Equatorially averaged (5°S-5°N) vertical-zonal cross-sections of

MSE and vertical-zonal wind vector anomalies are constructed across 50°E--100°W to examine the structural coupling between overturning atmospheric kinematics and thermodynamic energy storage. Lastly, to examine local terrain forcing, a zonal cross-section is constructed along the 16°N–17°N latitude transect spanning 115°E--125°E. This transect intersects the South China Sea, the coastal plain of Western Luzon, and the Zambales Mountain Range (~120.3°E). Specific humidity, zonal wind, and scaled vertical motion are mapped to evaluate boundary-layer moisture impingement and forced mechanical lifting along the windward slope.

194

195 **3. Results and Discussion**

196 3.1 Intraseasonal MJO stagnation and planetary-scale dynamics

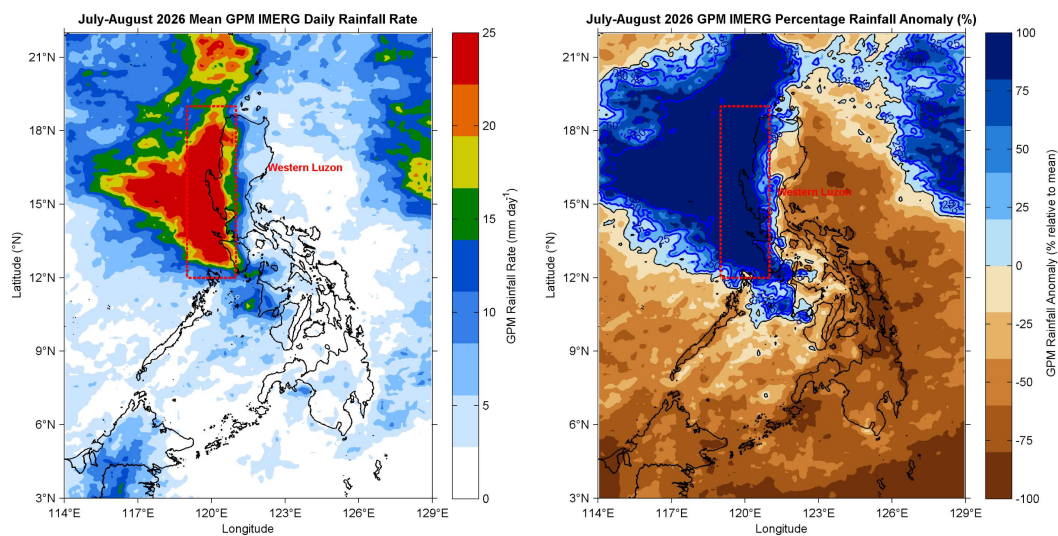
197

198 During July and August 2026, the Philippines experienced severe hydrometeorological
199 impacts driven by an unusually prolonged and intensified Southwest Monsoon. Official
200 advisories from the Philippine Atmospheric, Geophysical and Astronomical Services
201 Administration (PAGASA - the Philippine national weather agency) repeatedly issued red and
202 orange Heavy Rainfall Warnings across Western Luzon as successive high-volume monsoonal
203 surges moved over the landmass. Situation reports compiled by the National Disaster Risk
204 Reduction and Management Council (NDRRMC) and humanitarian tracking bulletins via
205 ReliefWeb documented extensive flash flooding, urban inundation across Metro Manila, and
206 widespread landslides along the western slopes of the Zambales Mountains and Ilocos Region,
207 resulting in 32 reported fatalities and 17 injuries. The prolonged hydrometeorological event
208 displaced a total of 26,197 families and inflicted approximately PHP 8 billion (~USD 141 million)
209 in total damages, dominated by nearly PHP 6 billion in infrastructure destruction and PHP 2.03
210 billion in agricultural losses across Northern and Central Luzon (UNOCHA, 2026). This report
211 underscored the persistent, multi-week nature of the precipitation, which was continually
212 enhanced by tropical disturbances traversing around the Philippines.

213 The satellite-derived precipitation of this hydrometeorological episode, shown in Figure
214 1, reveals a stark, highly structured spatial contrast across the Philippine archipelago during
215 July–August 2026. Extreme precipitation is highly concentrated along the western seaboard of
216 Luzon and its coastal waters (119°E–121°E, 12°N–19°N), where mean daily rainfall rates
217 routinely exceeded 25 mm day⁻¹ over the two-month period (Figure 1a). This persistent
218 monsoonal precipitation resulted in positive rainfall anomalies, shown in Figure 1b, across the
219 Western Luzon domain, locally surpassing +100% relative to the 1999–2025 climatological
220 baseline. The seasonal rains were effectively more than twice the normal seasonal precipitation

221 in a region already recognized as the center of summer season rainfall (Cruz et al., 2013;
 222 Bagtasa, 2017). Figure 1 also shows that in sharp contrast to this narrow western section of
 223 Luzon, the rest of the Philippines experienced severe, widespread rainfall suppression. Eastern
 224 Luzon, the central Visayas, and virtually the entire southern island of Mindanao exhibited
 225 marked moisture deficits, with negative rainfall anomalies ranging from -25% to -75% relative to
 226 historical norms. This asymmetric and geographically constrained precipitation distribution,
 227 characterized by localized extreme rainfall episodes along the windward coast and strong
 228 rain-shadowing further east and south, is the classic signature of enhanced Southwest Monsoon
 229 forcing (Cayanan et al., 2011; Bagtasa, 2019, 2020). Under this regime, deep,
 230 moisture-saturated equatorial westerlies are continuously funneled across the South China Sea,
 231 undergoing intense forced orographic ascent upon impinging on the steep terrain of the
 232 Zambales Mountains and Central Cordillera before drying adiabatically as they cross onto the
 233 leeward eastern slopes (Cayanan et al., 2011; Bagtasa, 2023).

234



235

236 **Figure 1.** GPM IMERG precipitation over the Philippines during July–August 2026 showing (a) mean daily
 237 rainfall rate (mm day⁻¹) and (b) percentage rainfall anomaly (%) relative to the 1999–2025 climatological
 238 mean. The red dashed rectangle outlines the Western Luzon target domain (119°E–121°E, 12°N–19°N).

239

240 The phenomenon of the enhanced *Habagat* refers to the intensification of prevailing
 241 summer monsoonal westerlies across the Philippines, which induces extreme precipitation
 242 along the western seaboard, particularly of Luzon. As established by Bagtasa (2019), over 90%
 243 of high-precipitation events associated with enhanced *Habagat* episodes in northwestern Luzon
 244 coincide with TC activity in the Western North Pacific (WNP), yet direct TC landfalls account for

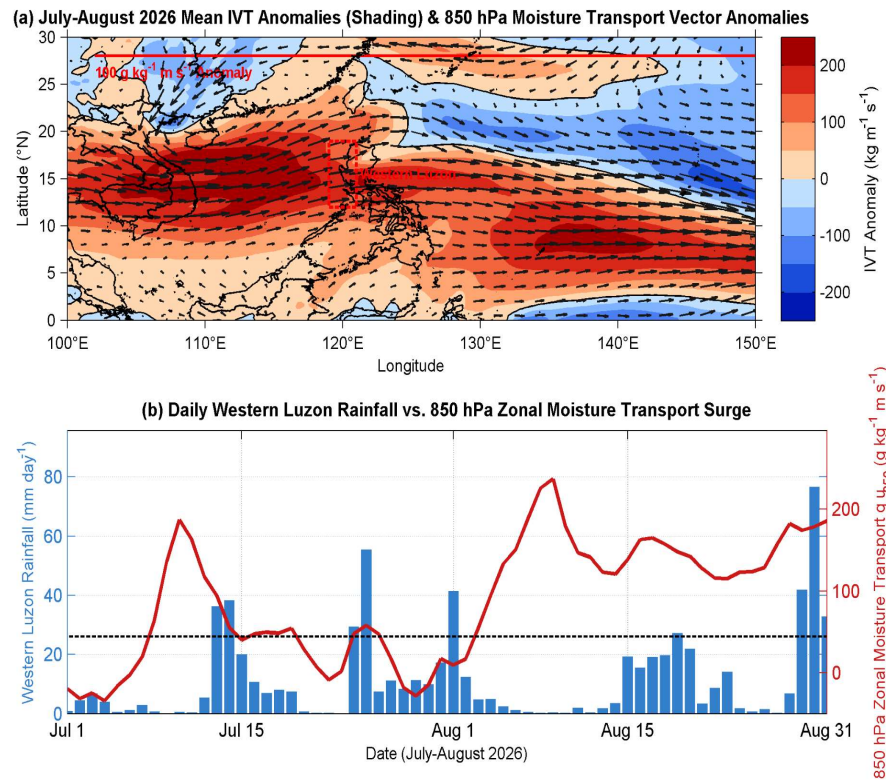
only 12.8%–15.1% of these extreme days. Instead, distant, non-landfalling TCs situated to the northeast of Luzon remotely accelerate low-level monsoonal flow across the South China Sea. Quantifying this nationwide contribution, Bagtasa (2022) showed that while direct TC rainfall (within 500 km of a storm center) accounts for 11.0% of the Philippines' annual rainfall volume, indirect or remote TC enhancement contributes an additional 12.3%, bringing the total TC-associated rainfall to ~23.3% nationally. Regionally, TC rain contribution can be up to 54% along western Luzon. To explain the physical mechanism behind this remotely induced transport, Bagtasa (2019) and Bathan et al. (2026) detailed the formation of an MCB, which is a broad low-level (concentrated below 700 hPa) stream of anomalous moisture flux stretching continuously from the tropical northern Indian Ocean, across Indochina and the South China Sea, directly into the TC circulation (Kudo et al., 2014; Fujiwara et al., 2017).

Crucially, enhanced *Habagat* conditions can also develop independently of an active TC. Bagtasa (2020) showed that during active summer phases (phases 5–7) of MJO, atmospheric condensational heating and active convection in the confluence zone east of the Philippines excite equatorial Rossby wave responses. These wave responses induce strong low-latitude westerly anomalies across the South China Sea, transporting large volumes of water vapor and generating heavy rainfall along the western seaboard even on days without TC forcing (Holland 1995). These non-TC-enhanced *Habagat* episodes account for ~14% of active summer MJO rainfall days. Building upon this intraseasonal framework, Olaguera et al. (2021) showed that the BSISO also strongly modulates these events. Specifically, the co-occurrence of active BSISO1 (phases 5–8) and BSISO2 (phases 1–4) convective centers near the Philippines provides a pre-conditioned environment of high precipitable water and low-level cyclonic vorticity. This large-scale intraseasonal pre-conditioning, further supported by findings in Bathan et al. (2026), plays a vital role in sustaining the MCB and driving prolonged monsoonal deluges over the country.

The large-scale thermodynamic and kinematic structure of the enhanced monsoon during July–August 2026 is clearly illustrated by the 2-month mean Integrated Vapor Transport (IVT) and low-level moisture flux in Figure 2. The seasonal footprint of the enhanced *Habagat* is dominated by a broad, continuous zonal band of high positive IVT anomalies ranging from +100 to $>+200 \text{ kg m}^{-1} \text{ s}^{-1}$ (Figure 2a). This high-IVT band originates over Indochina and the South China Sea (100°E–115°E), cuts directly across Luzon Island (120°E), and extends far into the WNP warm pool (130°E–150°E) between 10°N and 20°N. Co-located 850 hPa moisture transport vector anomalies reveal strong zonal monsoonal flow aligned along this moisture band, depicting the physical structure of the MCB. This low-level atmospheric river acts as a

primary supply line, channeling vast amounts of moisture directly into Western Luzon. Conversely, negative IVT anomalies (-100 to $-200 \text{ kg m}^{-1} \text{ s}^{-1}$) across the East China Sea (25°N – 30°N) reflect a displaced monsoon trough and divergent low-level flow north of the main monsoonal jet.

The temporal relationship between low-level monsoonal flux and precipitation over Western Luzon is illustrated by the daily time series in Figure 2b. Following suppressed conditions during early July, an initial moisture surge in mid-July elevated the 850 hPa zonal moisture transport to approximately $180 \text{ g kg}^{-1} \text{ m s}^{-1}$, driving daily rainfall spikes of $35\text{--}40 \text{ mm day}^{-1}$. Although zonal moisture transport subsequently weakened toward $10\text{--}40 \text{ g kg}^{-1} \text{ m s}^{-1}$ in late July, Western Luzon still experienced sudden heavy precipitation events exceeding 55 mm day^{-1} around July 25. Conversely, during the first week of August, a massive atmospheric surge propelled the zonal moisture transport to its seasonal maximum of $> 220 \text{ g kg}^{-1} \text{ m s}^{-1}$. However, despite this extreme horizontal moisture transport, daily rainfall remained suppressed ($< 10 \text{ mm day}^{-1}$) and was well below the climatological baseline of 25 mm day^{-1} . Notably, while this powerful early-August westerly surge produced minimal local rainfall, it served as a long-range atmospheric pathway, carrying transboundary biomass burning smoke from Kalimantan across the South China Sea into major portions of the Philippines (PIA, 2026). Monsoonal transport remained persistently elevated ($150\text{--}200 \text{ g kg}^{-1} \text{ m s}^{-1}$) through mid-to-late August, culminating in the season's most intense precipitation event on August 30–31, where daily rainfall exceeded 70 mm day^{-1} . Crucially, these notable phase offsets where extreme moisture transport yields suppressed rainfall (early August) or heavy rainfall occurs under modest transport (late July) demonstrate that horizontal moisture advection alone does not strictly dictate precipitation magnitude, implying that secondary dynamical mechanisms must be modulating regional rainfall efficiency.



304

305 **Figure 2.** Moisture transport and its daily variability. (a) Mean Integrated Vapor Transport (IVT; 1000–300
 306 hPa) magnitude and vectors, revealing a highly concentrated atmospheric river terminating over the
 307 Philippines. (b) Time series of daily Western Luzon rainfall (blue bars) against the Western Luzon
 308 Monsoon Index (*WLMI*, 850 hPa zonal wind, red line).

309 The large-scale intraseasonal driver behind these recurring monsoonal surges is clearly
 310 illustrated by the Real-time Multivariate MJO (RMM) phase space diagram for July 1 to
 311 September 10, 2026 in Figure 3. As established by Bagtasa (2020), enhanced *Habagat* events
 312 over the Philippines are strongly modulated by the MJO, occurring predominantly when active
 313 convective centers reside in MJO Phases 5, 6, and 7 as the signal traverses the Maritime
 314 Continent and Western Pacific. In early to mid-July (red line), the MJO state was amplified within
 315 Phase 7, providing the broad planetary-scale convective and dynamical forcing that drove the
 316 initial surge in zonal moisture transport (see Figure 2b) and the associated early mid-July heavy
 317 rainfall days. During the final week of July (July 20–31), the MJO trajectory progressed into
 318 Phase 8. This movement out of the favorable Western Pacific convective sector directly
 319 triggered the observed late-July moisture-deficient monsoon break, resulting in the temporary
 320 cessation of low-level moisture transport over Western Luzon. However, rather than completing
 321 a canonical eastward propagation through Phases 1 and 2 into the Indian Ocean, the
 322 intraseasonal state exhibited an atypical westward propagation in early August (green line),

looping back directly into Phase 6. The MJO subsequently remained stuck across Phases 6 and 7 throughout the remainder of August and into early September (blue line, September 1–10). This prolonged stagnation of the MJO signal over the Western Pacific (Phases 5–7) served as a continuous atmospheric driver of the enhanced monsoon. The sustained condensational heating and active convection east of the Philippines during these phases continuously excited equatorial Rossby wave responses across the northern South China Sea, effectively guiding the strong low-level westerly anomalies. This persistent intraseasonal pre-conditioning maintained the MCB for over a month, explaining why low-level moisture transport remained elevated above climatological levels and why Western Luzon experienced severe, multi-week rainfall surges throughout August and the first ten days of September.

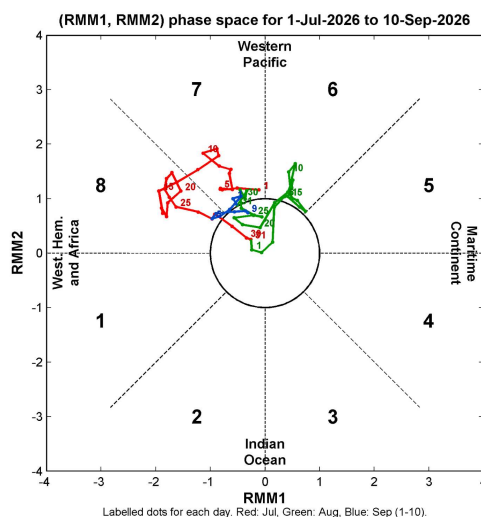
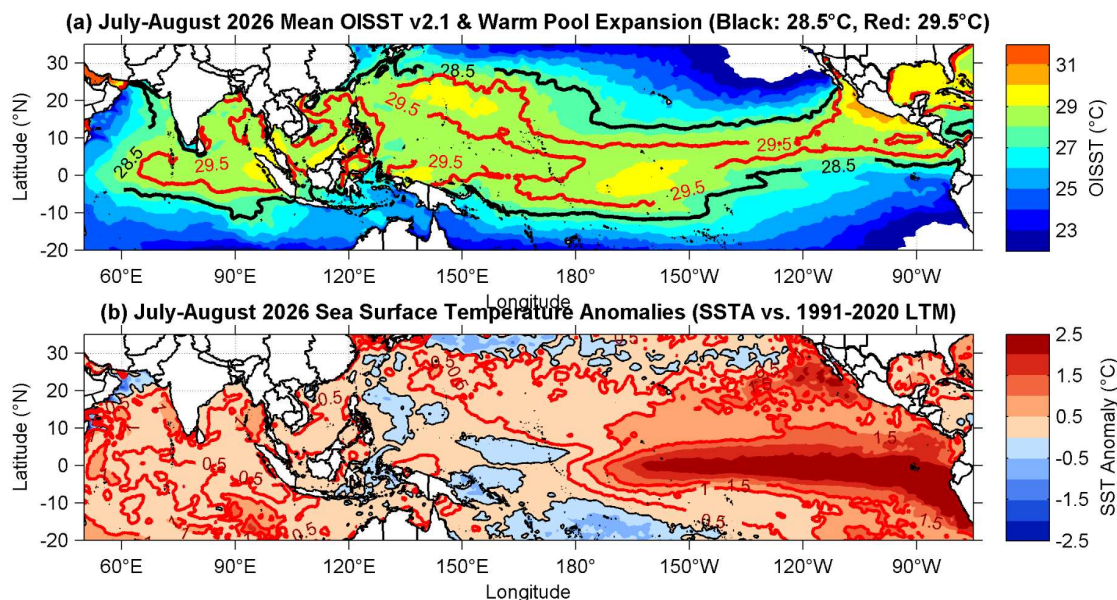


Figure 3. MJO phase space diagram (RMM1 vs. RMM2) tracking daily trajectory from July 1 to September 10, 2026. Colored paths represent July (red), August (green), and September 1–10 (blue), with numbers marking individual daily positions. The central unit circle ($r = 1$) delineates weak or inactive MJO activity, and numbered sectors 1–8 correspond to geographic locations across the Indo-Pacific basin. Data downloaded from https://www.bom.gov.au/clim_data/IDCKGEM000/rmm.74toRealtime.txt

The broad thermodynamic state of the upper ocean during July–August 2026 is captured by the spatial distribution of SST in Figure 4a and its corresponding climatological anomaly in Figure 4b. In the absolute SST field (Figure 4a), the Indo-Pacific warm pool exhibits a significant spatial distribution, as delineated by the 28.5°C (black) and 29.5°C (red) isotherms. While the 28.5°C threshold encompasses nearly the entire tropical Indian Ocean and South China Sea and extends across the whole equatorial Pacific past 120°W, the core of the warmest water (>29.5°C) displays an unusual zonal displacement. Rather than remaining concentrated solely

within the Western Pacific Warm Pool, waters exceeding 29.5°C extend continuously across the central and eastern equatorial Pacific, as well as the Northern Indian Ocean and the South China Sea. Directly east of the Philippine archipelago (120°E – 140°E , 10°N – 20°N), the 29.5°C isotherm exhibits a distinct structural contraction and localized gap, indicating a relative upper-ocean thermal deficit compared to adjacent tropical marine basins. This regional ocean-atmosphere structure is further clarified by the SSTA field relative to the 1991–2020 long-term mean (Figure 4b), which clearly shows an active, well-developed El Niño event. The central and eastern equatorial Pacific is dominated by a pronounced, continuous warm tongue stretching from 170°E to the South American coastline, with positive SSTAs that broadly exceed $+1.5^{\circ}\text{C}$ and peak above $+2.5^{\circ}\text{C}$ in the eastern equatorial basin. Widespread positive anomalies ($+0.5^{\circ}\text{C}$ to $+1.5^{\circ}\text{C}$) also blanket the northern Indian Ocean and South China Sea. However, in sharp contrast to this widespread tropical warming is a prominent pocket of cool/negative SSTAs ranging from -0.5°C to -1.5°C , centered over the Philippine Sea and the western edge of the WNP (120°E – 140°E , 5°N – 20°N).



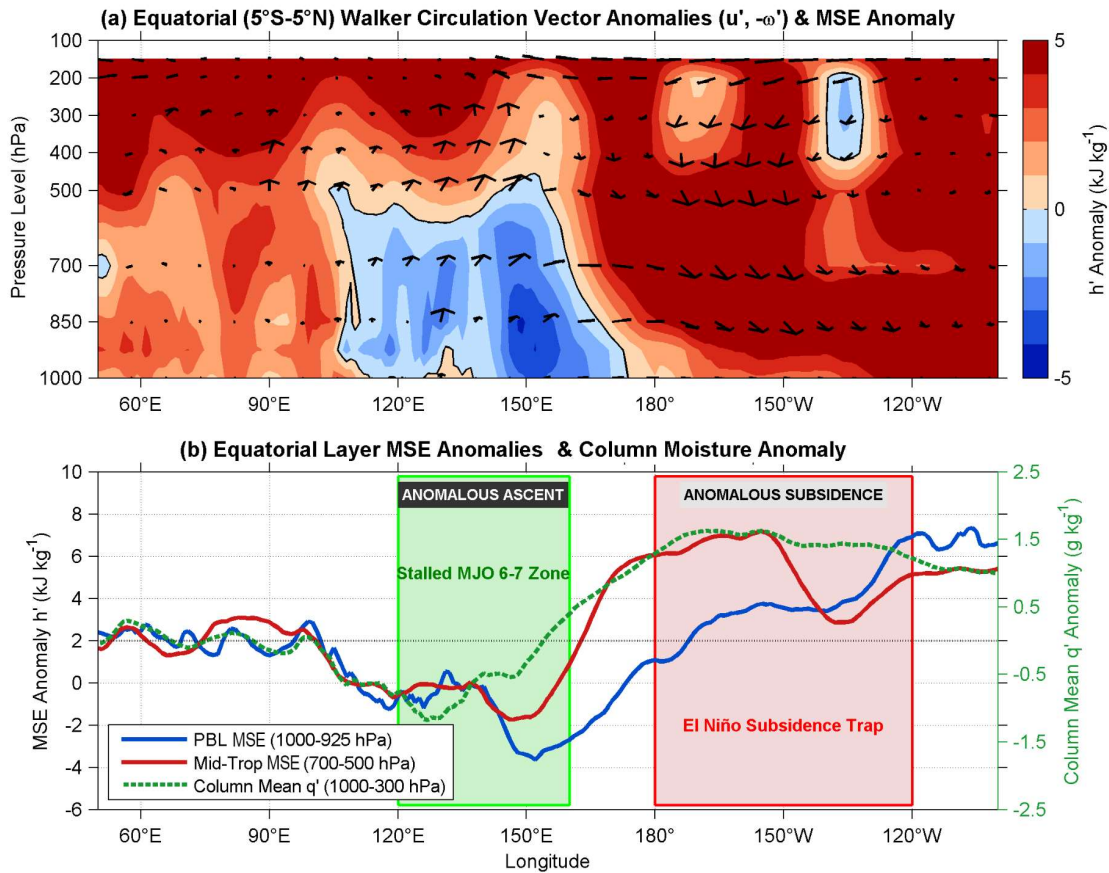
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365 **Figure 4.** Sea surface conditions and regional low-level circulation (July–August 2026 mean). (a) OISST
 366 v2.1 ($^{\circ}\text{C}$), highlighting the extreme expansion of the Indo-Pacific Warm Pool (red contours indicate
 367 29.5°C ; black contours indicate 28.5°C). (b) Sea Surface Temperature Anomalies (SSTA vs. 1991–2020
 368 long-term mean).

369 The formation of this localized cool ocean anomaly in the Philippine Sea during an active
 370 El Niño is a key feature driven primarily by the persistent, stagnant MJO activity. As the MJO
 371 signal remained across Phases 6 and 7 throughout August, this localized upper-ocean cooling

372 was likely driven by reduced solar radiation beneath persistent convective cloud cover,
373 alongside strong anomalous westerlies that enhanced evaporative latent heat loss and induced
374 mechanical mixing of cooler thermocline waters upward into the mixed layer (Hendon and Glick,
375 1997; Woolnough et al., 2000; DeMott and Klingaman, 2020). Consequently, while El Niño
376 provided the background planetary-scale climate state, the stagnant MJO acted as a potent
377 localized ocean-atmosphere driver, cooling the Philippine Sea and modulating the regional
378 air-sea energy exchange that sustained the prolonged, enhanced *Habagat* surges over the
379 Philippines.

380 The planetary-scale mechanism influencing the MJO within Phases 6 and 7 is
381 demonstrated by the equatorial (5°S–5°N) vertical Walker Circulation cross-section and
382 column-integrated thermodynamic diagnostics in Figure 5. The anomalous Walker cell (Figure
383 5a) directly reflects the global SST forcing established during the July–August 2026 El Niño, but
384 with a critical regional structure over the Indo-Pacific waters. Over the Central and Eastern
385 Pacific (180°–120°W), strong background El Niño warming imparts immense thermodynamic
386 energy into the atmospheric column, yielding high values of positive MSE anomalies exceeding
387 +5 kJ kg⁻¹ throughout almost the entire vertical column up to the 100 hPa level. However,
388 despite this vast thermodynamic energy, the upper troposphere (400–200 hPa) over
389 180°–130°W is dominated by strong anomalous subsidence (designated in Figure 5b as the "El
390 Niño Subsidence Trap"). Conversely, directly over the Western Pacific and Maritime Continent
391 (120°E–160°E), the atmosphere is characterized by a deep, powerful column of anomalous
392 ascending air from 500 hPa through 100 hPa, marking the persistent convective core of the
393 stalled MJO. A thermodynamic contrast appears in the vertical profile of MSE anomalies within
394 this stalled MJO zone (120°E–160°E). In the upper troposphere (300–100 hPa), intense latent
395 heat release driven by persistent deep convection generates widespread positive MSE
396 anomalies (+2 to +5 kJ kg⁻¹). In stark contrast, the lower-to-mid troposphere (1000–500 hPa)
397 over the same longitudinal sector is dominated by a pronounced negative MSE deficit, reaching
398 minimum values of -5 kJ kg⁻¹ between 850 hPa and 600 hPa near 150°E. This
399 lower-tropospheric MSE deficit is the thermodynamic signature of localized ocean cooling in the
400 Philippine Sea, combined with strong low-level monsoonal ventilation, in which persistent
401 monsoonal westerlies import dry, cooler air into the planetary boundary layer and
402 mid-tropospheric layers, thereby suppressing lower-level background static instability (Maloney,
403 2009).



405

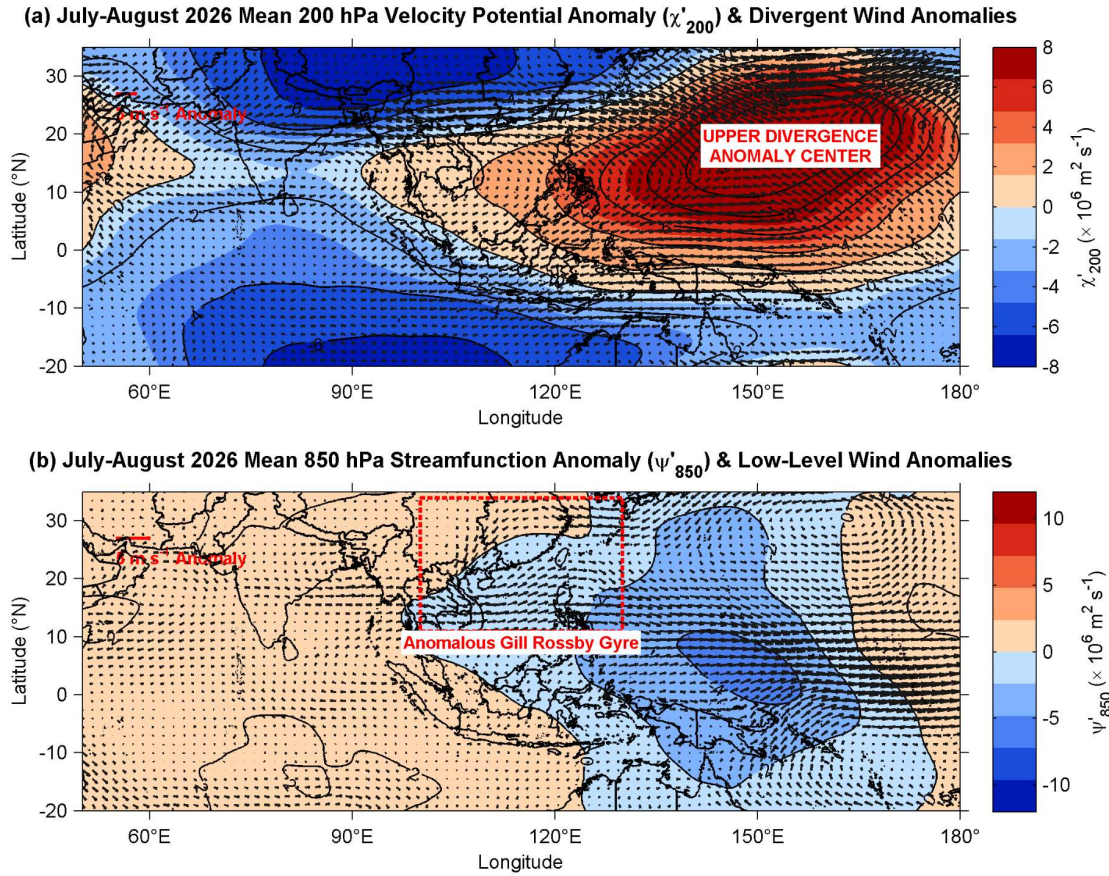
406 **Figure 5.** Equatorial (5°S–5°N) atmospheric transect demonstrating the El Niño dry barrier. (a) Walker
 407 circulation vectors (zonal wind and scaled vertical velocity) overlaid on Moist Static Energy (MSE). (b)
 408 Column-mean specific humidity profile and MSE within the PBL and mid-troposphere. The cross-section
 409 reveals the ascending convective branch stalled over the Western Pacific (MJO 6-7), blocked by
 410 anomalous subsidence and column drying east of the Dateline associated with El Niño.

411

412 The detailed longitudinal structure of these thermodynamic fields is further quantified by
 413 the three-layer-averaged tracking parameters in Figure 5b. The PBL (1000-925 hPa) MSE
 414 anomaly (solid blue line) reflects immediate surface thermodynamic coupling within the Stalled
 415 MJO Zone (120°E–160°E), PBL MSE drops from near 0 kJ kg^{-1} at 120°E to a deep minimum of
 416 -3.6 kJ kg^{-1} near 150°E, before rising rapidly eastward into the El Niño warm domain to reach
 417 $+3.8 \text{ kJ kg}^{-1}$ at 150°W and exceeding $+5.0 \text{ kJ kg}^{-1}$ east of 130°W. Parallel to this, the
 418 mid-tropospheric (700-500 hPa) MSE anomaly (solid red line) tracks free-tropospheric moisture
 419 and static stability, exhibiting a pronounced mid-level deficit dipping to -1.7 kJ kg^{-1} at 145°E
 420 within the stalled MJO zone due to intense mid-level dry air entrainment and monsoonal
 421 ventilation, before climbing to a peak of $+6.0 \text{ kJ kg}^{-1}$ over the Central Pacific (180°–140°W).

Meanwhile, the column-mean moisture anomaly (green dashed line) quantifies the total precipitable water anomalies. Over 120°E–140°E, the column-mean moisture anomaly remains negative (reaching a minimum of -1.2 g kg^{-1} near 130°E) due to localized drying along the western flank of the MJO convective cell, but ascends sharply across 150°E to achieve extreme positive moistening ($+1.2$ to $+1.6 \text{ g kg}^{-1}$) across the El Niño sector (180°–120°W).

These thermodynamic profiles provide a robust physical explanation for why the MJO stalled in Phases 6–7 rather than continuing to propagate eastward across the Pacific. Canonical eastward MJO propagation relies on a moisture-mode destabilization mechanism, wherein lower-tropospheric moistening and positive MSE buildup occur systematically to the east, ahead of the active convective center, pulling the convective instability eastward (Sobel and Maloney, 2012; Hsu and Li, 2012; Adames and Kim, 2016; Wang et al., 2016; Liu and Wang, 2017; Zhang & Ling, 2017). During July–August 2026, however, the strong lower- to mid-tropospheric MSE deficit and boundary-layer drying across 120°E–150°E severed this low-level destabilization front. Concurrently, while the Central Pacific (180°–120°W) possessed massive positive MSE and high column moisture ($q > +1.5 \text{ g kg}^{-1}$), the anomalous upper-tropospheric subsidence associated with the El Niño Subsidence Trap imposed strong mid-level capping and downward mass suppression over 180°–140°W. Caught between a low-level MSE deficit to its west and an upper-level subsidence trap to its east, the MJO's convective core became thermodynamically locked over 120°E–160°E. The deep convective column over the Western Pacific continued to generate intense diabatic heating aloft, sustaining deep upward motion without migrating eastward. This persistent heat source over 120°E–160°E acted as a continuous atmospheric driver for regional monsoonal dynamics. By continuously providing heat and latent energy into the equatorial upper troposphere for over a month, this geographically persistent convective core excited asymmetric planetary wave responses across the Indo-Pacific basin. Specifically, this continuous heating core drove a classic off-equatorial atmospheric Rossby wave response manifesting as twin cyclonic low-level Gill gyres across the South China Sea and Western North Pacific and established a massive upper-tropospheric mass divergence center, as shown in Figure 6a (Gill, 1980; Jin and Hoskins, 1995; Jiang et al., 2020). The resulting low-level cyclonic flow and upper-level velocity potential field form the critical dynamical link connecting this stalled MJO to the sustained monsoonal surges over the Philippines.



454

455 **Figure 6.** Upper-level outflow and low-level Gill Rossby response. (a) Mean 200 hPa velocity
 456 potential (χ'_{200}) and divergent wind vectors (V_χ), exposing an intense upper-level outflow center
 457 over the Philippine Sea. (b) Mean 850 hPa streamfunction (ψ'_{850}) and low-level winds,
 458 confirming a cyclonic Gill-type Rossby gyre response over the South China Sea that anchored
 459 the monsoon westerlies.

460

461

The upper-tropospheric outflow and lower-tropospheric circulation anomalies during
 462 July–August 2026, shown in Figures 6a and 6b, respectively, demonstrate the classic dynamical
 463 atmospheric response to the persistent diabatic heating core of the stalled MJO. At 200 hPa
 464 (Figure 6a), the velocity potential anomaly field is dominated by an expansive, intense negative
 465 anomaly center ($\chi'_{200} < -8 \times 10^6 \text{ m}^2 \text{ s}^{-1}$, red shading) situated directly over the WNP and the
 466 Philippine Sea (130°E – 160°E , 10°N – 25°N). Designated as the upper divergence anomaly
 467 center, this feature represents an extraordinary upper-tropospheric mass outflow driven by the
 468 deep convective column of the stalled MJO in Phases 6 and 7. The corresponding 200 hPa
 469 divergent wind vector anomalies flow out radially in all directions from this center and thereby
 470 sustain the strong vertical motion identified in the Walker circulation cross-section in Figure 5a.
 471 Conversely, broad positive velocity potential anomalies ($\chi'_{200} > +6 \times 10^6 \text{ m}^2 \text{ s}^{-1}$, blue shading)

span the equatorial Indian Ocean (60°E–90°E), indicating an upper-level convergent return branch that completes the anomalous regional Walker cell.

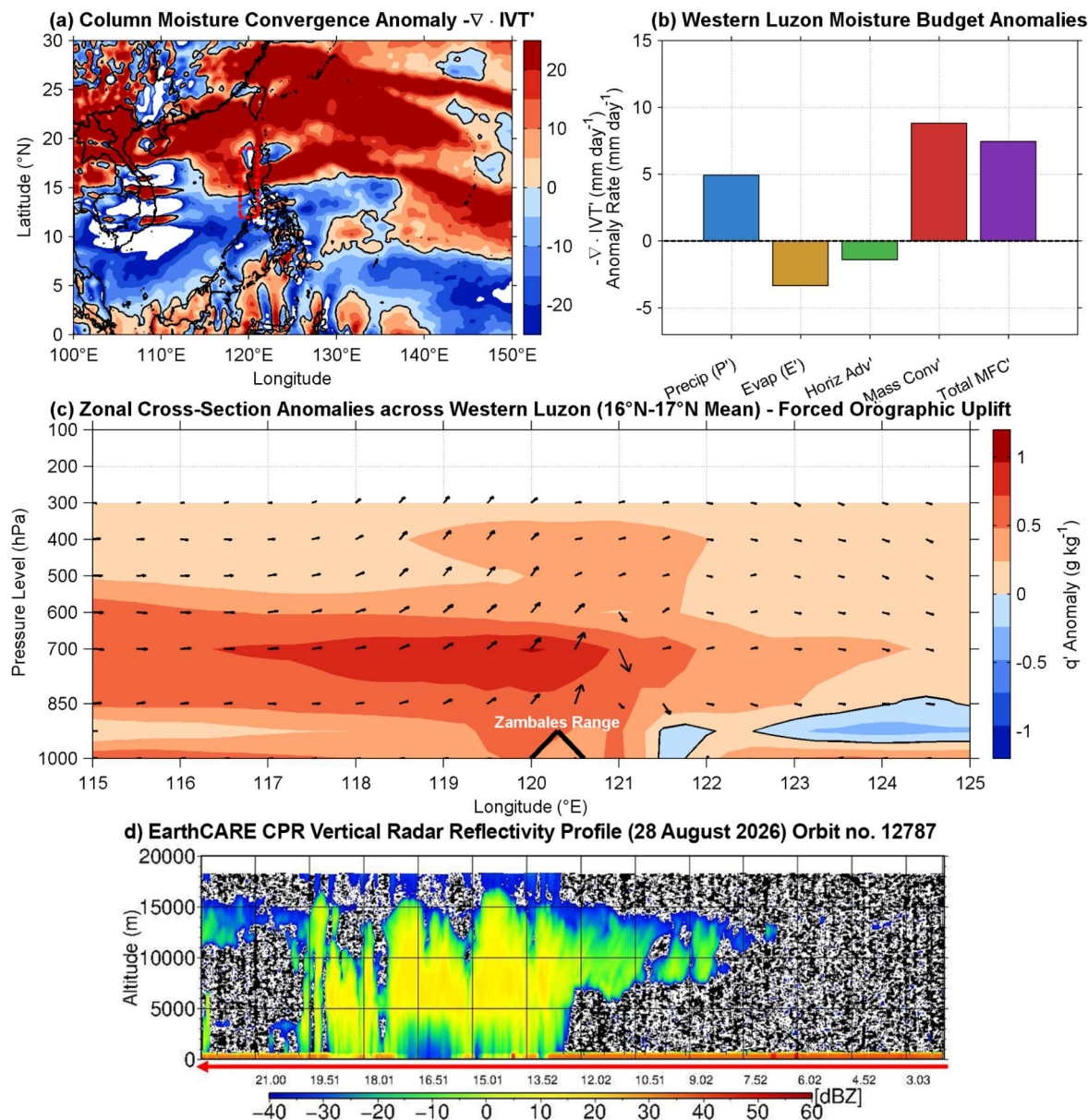
In response to this sustained off-equatorial tropospheric heating and upper-level mass divergence, the lower atmosphere exhibits a classic Gill-pattern Rossby wave response (Gill, 1980), as captured by the 850 hPa streamfunction and low-level wind anomalies in Figure 6b. The lower troposphere is dominated by a broad, highly organized cyclonic circulation anomaly centered near 140°E–150°E, where negative streamfunction values reach $\Psi_{850} < -10 \times 10^6 \text{ m}^2 \text{ s}^{-1}$ (dark blue shading). The western extension of this system forms an anomalous Gill Rossby Gyre that encompasses the northern part of the South China Sea, the Philippines, and the southern coast of East Asia (100°E–130°E, 10°N–35°N, red dashed box). Along the southern and southwesterly flank of this cyclonic gyre, low-level wind vector anomalies reveal enhanced monsoonal westerlies that extend continuously from the tropical Indian Ocean and Indochina across the South China Sea and directly into the Philippine archipelago. This low-level cyclonic structure provides the crucial dynamical link between the planetary-scale climate drivers and the localized monsoonal inundations along Western Luzon. The anomalous Gill Rossby Gyre acts as a powerful atmospheric pump, continuously pulling moisture-laden equatorial air northward and westward. This low-level convergence feeds directly into the MCB, maintaining the high IVT ($> +200 \text{ kg m}^{-1} \text{ s}^{-1}$) as shown in Figure 2a. Furthermore, the intense surface wind stress along this monsoonal jet on the gyre's southern flank likely drove strong evaporative cooling and upper-ocean mixing that produced the localized cool SST anomalies in the Philippine Sea (Figure 4b). Thus, the stalled MJO, held in place between the lower-tropospheric MSE deficit and the El Niño Subsidence trap, induced a persistent upper-level divergence center and low-level Gill gyre. This coupled ocean-atmosphere feedback loop anchored the monsoonal stream over the Philippines for around two months, driving the severe, recurring rainfall surges documented throughout the season (DOST-PAGASA, 2026).

3.2 Regional column moisture budget and orographic mass convergence

To establish the precise local mechanisms that translate the large-scale atmospheric state into extreme rainfall along the windward coast of Luzon, and to resolve the offsets observed in Figure 2b, where high moisture transport failed to directly correlate with heavy precipitation without dynamic support, Figure 7 shows a column moisture convergence diagnosis, a localized moisture budget decomposition, and a vertical cross-section of forced orographic uplift. Figure 7a shows the spatial distribution of column-integrated MFC anomalies,

506 which reveals a continuous, high-amplitude band of positive convergence ($>+20 \text{ mm day}^{-1}$)
 507 extending from the northern South China Sea directly across Western Luzon and stretching
 508 northeastward into the WNP basin. This intense convergence zone aligns precisely with the axis
 509 of the anomalous Gill Rossby Gyre and MCB identified above. Conversely, strong moisture
 510 divergence ($<-20 \text{ mm day}^{-1}$) dominates the lower latitudes south of 10°N , indicating that
 511 moisture was efficiently harvested from the equatorial marine boundary layer and focused
 512 directly into the monsoonal confluence zone over Northern and Central Luzon.

513



514

515

Figure 7. Moisture budget and mesoscale orographic forcing over Western Luzon. (a) Total column moisture flux convergence ($-\nabla \cdot \text{IVT}$). (b) Integrated moisture budget decomposition over the Western Luzon bounding box, showing dynamic mass convergence as the overwhelmingly dominant precipitation driver. (c) Zonal vertical cross-section at 16°N, illustrating the deep moist westerly flow undergoing severe forced orographic uplift over the Zambales Mountain Range, and (d) vertical cross-section of EarthCARE Cloud Profiling Radar (CPR) integrated reflectivity (dBZ) along the orbital track no. 12787 on 28 August 2026

To quantitatively isolate the fundamental physical mechanism driving the observed anomalous seasonal precipitation, Figure 7b shows the atmospheric moisture budget anomalies over Western Luzon. This determines whether local surface evaporation, horizontal moisture advection ($-u \cdot \nabla q$), or low-level mass convergence ($-q \nabla \cdot u$) acted as the primary driver of the rains. The budget decomposition demonstrates that the total MFC anomaly ($+15.2 \text{ mm day}^{-1}$) is almost entirely dominated by the mass convergence term ($+15.4 \text{ mm day}^{-1}$), while the moisture advection anomaly (advection = -0.2 mm day^{-1}) is comparatively negligible. This indicates that the excessive rain was not caused by a simple gradient of background moisture passing over Luzon, but by strong low-level velocity convergence ($\nabla \cdot u < 0$), which slowed and piled up the monsoonal air mass, explaining the offset between moisture transport and heavy precipitation in Figure 2b. Furthermore, the local evaporation anomaly is distinctly negative ($e = -3.4 \text{ mm day}^{-1}$), indicating that localized ocean surface evaporation was suppressed by the cool SST anomalies and heavy cloud cover in the Philippine Sea, making the event driven mainly by imported moisture convergence.

The vertical structure and thermodynamic mechanism that convert this mass convergence into extreme, localized precipitation are illustrated in the 16°N–17°N zonal cross-section across Western Luzon, shown in Figure 7c. As the moisture-laden monsoonal jet traverses the South China Sea (115°E–119°E), it maintains high specific humidity ($q > +0.8 \text{ g kg}^{-1}$) between 850–600 hPa. Upon encountering the steep topographic barrier of the Zambales Range ($\sim 120.3^\circ\text{E}$), the low-level jet undergoes forced mechanical lifting, exhibiting strong upward deflections over the windward slopes. Direct spaceborne observations from the EarthCARE Cloud Profiling Radar (CPR; Figure 7d) validate this deep vertical ascent, capturing radar reflectivity cores ($> 15 \text{ dBZ}$) extending up to $\sim 15 \text{ km}$ altitude near the tropical tropopause. This mechanical trigger efficiently condenses the deep moisture column, driving persistent convective updrafts and heavy localized rainfall along the western Luzon coast. This vertical cross-section explains the stark precipitation contrasts observed across the western seaboard

of the island of Luzon during the *Habagat* event. The windward region and mountain slopes, which encompass Zambales, Bataan, Pangasinan, Cavite, and Metro Manila, experienced relentless deluges because these regions sat directly at the intersection of maximum mass convergence, high free-tropospheric moisture, and forced orographic ascent. In sharp contrast, directly east of the Zambales ridge crest (121°E–125°E), the cross-section reveals descending wind vectors and a pronounced low-level moisture deficit ($q < -0.5 \text{ g kg}^{-1}$ shadow between 1000 hPa and 850 hPa). This downslope adiabatic warming and drying created a rain-shadow effect over inland basins like the Cagayan Valley, effectively shielding eastern Luzon from the severe flooding that inundated the western coastline.

Overall, the extraordinary monsoonal inundations of July–August 2026 were the product of a tightly coupled, multi-scale atmosphere-ocean influence spanning the tropical Pacific basin. At the planetary scale, the interaction between a developing El Niño and a thermodynamically phase-locked MJO provided an intense convective heating core over the Western Pacific, maintained by a lower-tropospheric MSE deficit to the west and bounded by an upper-level subsidence trap to the east. This geographically stagnant diabatic heat source continuously driven off-equatorial Rossby wave dynamics, organizing a persistent low-level Gill gyre and an upper-tropospheric mass divergence center that sustained an intense and persistent MCB across the South China Sea. At the regional and local scales, strong mass convergence along this monsoonal jet channeled vast amounts of precipitable water directly onto the western seaboard of the Philippines, where steep terrain along the Zambales and Cordillera Mountain Ranges served as a mechanical trigger, converting horizontal moisture flux into severe, recurring convective downpours. By establishing the full dynamical pathway from planetary-scale intraseasonal stagnation down to mesoscale orographic uplift, the results presented here clarify how localized thermodynamic feedbacks can sustain extreme monsoonal surges even within a broader El Niño regime.

575

576 **4. Summary and conclusions**

577

578 The present study evaluated the multi-scale atmospheric dynamics, oceanic feedbacks, 579 and localized thermodynamic processes that drove the severe, prolonged enhanced Southwest 580 Monsoon or *Habagat* season in the northern Philippines during July–August 2026. By 581 integrating planetary circulation diagnostics, intraseasonal phase-space tracking, upper-ocean 582 thermal profiles, and regional moisture budgets, this study established the full picture that

translated large-scale climate anomalies into extreme, destructive rainfall along the country's northwestern seaboard.

At the intraseasonal scale, the primary driver of recurring monsoonal surges was the anomalous stagnation of the MJO within Western Pacific convective phases. Following an initial early mid-July surge during MJO Phase 7, the signal briefly progressed into Phase 8 during late July, triggering a temporary monsoon break characterized by suppressed low-level moisture transport and cessation of rains across Luzon. However, instead of completing a canonical eastward propagation, the MJO had an atypical westward propagation in early August and remained phase-locked in Phases 6 and 7 through early September. Analysis revealed that this stagnation was thermodynamically sustained by a dual mechanism: (1) Strong monsoonal ventilation and localized ocean cooling across 120°E – 150°E suppressed low-level static instability, characterized by a low-to-mid tropospheric MSE deficit, and severed the eastward-propagating moisture front ahead of the convective core, and (2) anomalous upper-tropospheric subsidence imposed strong mid-level capping that inhibited the eastward shift of deep convection, referred to in this study as the "El Niño Subsidence Trap".

Caught between low-level MSE depletion to the west and upper-level subsidence to the east, the MJO's diabatic heating core was stalled over the Western Pacific (120°E – 160°E). This persistent heat engine continuously driven off-equatorial Rossby wave dynamics, organizing an expansive upper-level divergence anomaly and a low-level cyclonic Gill Rossby Gyre across the South China Sea and Philippine Sea. This low-level cyclonic structure acted as a powerful atmospheric pump, maintaining a persistent, moisture-laden MCB stretching from Indochina directly into Luzon. Simultaneously, cloud-induced insolation deficits, enhanced evaporative cooling, and wind-driven ocean mixing created a localized cool SSTA in the Philippine Sea, reinforcing the regional air-sea thermodynamic gradient.

At the mesoscale level, atmospheric moisture budget decomposition over Western Luzon confirmed that low-level mass convergence accounted for over 98% of total MFC, indicating that velocity or mass convergence, rather than simple horizontal moisture advection, caused the extreme precipitation excesses. Zonal cross-sectional analysis demonstrated that as this convergence-driven monsoonal jet encountered the steep barrier of the Zambales Range ($\sim 120.3^{\circ}\text{E}$), it underwent forced mechanical uplift. This forced vertical motion efficiently converted high free-tropospheric moisture into continuous deep convective updrafts along the windward slopes and coastal plains (Zambales, Bataan, Cavite, and Metro Manila), while generating a pronounced downslope rain shadow and moisture deficit east of the ridge.

616 These results highlight a critical operational insight for tropical meteorology and climate
617 adaptation in the Philippines: while El Niño is traditionally associated with regional drought
618 (Hilario et al., 2009; Villafuerte et al., 2014; Bagtasa, 2022; Perez et al., 2022), its interaction
619 with a phase-locked MJO can paradoxically amplify and prolong extreme monsoon surges along
620 the western seaboard. Understanding this multi-scale interaction, from equatorial wave trapping
621 down to terrain-forced mass convergence, is vital for improving S2S extreme weather
622 forecasting (Abhik et al., 2023), flood risk management, and infrastructure resilience across the
623 monsoon-vulnerable Philippines.

624

625

626 **Declarations**

627 Data availability: Not applicable.

628 Ethics approval Not applicable.

629 Consent for publication The author consents to publish all details in the manuscript.

630 Consent to participate Not applicable.

631 Competing interests The authors declare no competing interests.

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