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Seasonal Controls of Atmospheric Moisture on Tropical Precipitation Anomalies

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Abstract

Inter-annual precipitation variability across tropical regions is driven by complex interactions between large-scale atmospheric circulation and local processes, yet the relative contributions of key moisture budget components remain insufficiently quantified. This study examines seasonal contrasts between DJF and JJA in the Tropical Region using a moisture budget framework, with northern Sumatra, Indonesia, as a representative tropical case study. By using 36 years (1981–2016) of ERA-Interim data, wet and dry years are identified based on standardized precipitation anomalies, with statistical significance assessed using a Student's t-test. Composite analyses show that anomalous vertical moisture transport associated with vertical velocity anomalies (-⟨ω^' ∂_p q ̅⟩) is the dominant contributor in both seasons. However, its magnitude is weaker during DJF, indicating less coherent upward motion and weaker coupling between the large-scale circulation and convection than during JJA. In JJA, enhanced large-scale circulation strengthens moisture convergence and divergence, producing more organized convection. In contrast, DJF exhibits weaker circulation and a larger residual, suggesting stronger influences of transient and nonlinear processes. These findings highlight seasonal asymmetry in precipitation controls and provide insights applicable to tropical climate variability.

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Introduction

Understanding precipitation variability is essential for improving understanding of the global hydrological cycle, especially in tropical regions, where atmospheric processes are highly dynamic and closely linked to the ocean [1]. The Indonesian Maritime Continent (IMC) is one of the most active regions of deep convection and intense precipitation in the world [2]. As a major heat source that drives large-scale atmospheric circulation, including the Walker circulation, and contributes to the global energy balance. The IMC lies between the tropical western Pacific and the eastern Indian Ocean. This position exposes it to complex interactions among major climate drivers such as the El Niño–Southern Oscillation (ENSO), monsoon systems, and ocean–atmosphere coupling processes [3-5]. These large-scale interactions are fundamental components of the global hydrological cycle and are closely linked to atmospheric moisture transport processes [6, 7]. Therefore, studying precipitation variability over the IMC is important for both regional climate understanding and improving global climate models, especially for predicting extreme hydro-meteorological events.

Despite many studies on precipitation variability in Indonesia, most research has focused on Java Island. This focus is mainly due to the availability of dense observation networks and long-term high-quality data [8, 9]. As a result, precipitation patterns in Java are well understood. However, this creates an imbalance in regional studies. Other large islands, such as Sumatra, receive less attention. This is caused by limited rain-gauge stations, inconsistent datasets, and poor spatial coverage. These limitations restrict detailed climatological analysis, especially in regions with complex terrain. Northern Sumatra is one such area where topography and coastal influences play an important role. The lack of studies in this region leaves a major gap in understanding precipitation variability. More importantly, this gap is not only related to data scarcity but also to the limited understanding of how unique regional physical processes, including the interaction between steep orography (Bukit Barisan), strong land–sea breeze circulations along the western coast, and their coupling with large-scale modes such as the Walker circulation and monsoonal flow, modulate vertical moisture transport, convergence, and convective development in ways that are distinct from other regions of the Maritime Continent [3, 10, 11].

Northern Sumatra exhibits complex precipitation patterns due to its diverse geography, including coastal plains, mountain ranges, and proximity to the ocean. These factors produce semi-monsoonal, bimodal, and non-seasonal rainfall regimes [3]. The Bukit Barisan Mountains enhance rainfall on the windward side through orographic lifting, while creating rain shadow effects on the leeward side. Coastal processes, such as land–sea breeze circulation, also influence daily rainfall, particularly along the western coast [12]. Seasonal variability further modulates precipitation, with strong anomalies during JJA and DJF that can trigger hydro-meteorological hazards [13]. Intraseasonal variability, especially the Madden–Julian Oscillation (MJO), plays a key role during DJF [14]. Furthermore, the interaction between steep orography, coastal circulations, and large-scale climate modes is likely to produce distinct vertical moisture transport and convergence structures that differ from other regions within the Maritime Continent [10, 11]. This suggests that the moisture budget characteristics in northern Sumatra may exhibit unique seasonal behavior that cannot be generalized from studies conducted in other regions, such as Java. These conditions highlight the need for a detailed and process-based study of precipitation variability in this region.

The relative roles of large-scale climate drivers such as the Indian Ocean Dipole (IOD), ENSO, and monsoon systems in shaping precipitation variability over northern Sumatra remain unclear. Previous studies have highlighted differing dominant controls, with some emphasizing the role of monsoonal circulation in shaping seasonal precipitation, while others point to ENSO and IOD as key drivers of interannual variability [5]. These processes are closely linked to broader tropical circulation systems and monsoon dynamics that regulate large-scale precipitation patterns [15, 16]. These inconsistencies suggest that precipitation variability in this region is governed by complex interactions among multiple atmospheric processes rather than a single dominant factor. Moreover, the influence of these processes is likely to vary seasonally, particularly between the boreal summer (JJA) and boreal winter (DJF). However, a clear quantitative attribution of these processes, particularly their relative contributions to the atmospheric moisture budget across seasons, remains lacking [1, 7, 11]. This represents a key scientific gap in understanding the dynamical controls of precipitation variability over northern Sumatra.

To address this gap, a moisture budget framework provides a robust diagnostic tool to quantify the relative roles of key atmospheric components, including horizontal moisture advection, vertical motion, specific humidity, and evaporation [1]. Based on the findings of Darmawan et al. (2021), which highlight the importance of vertical motion and low-level wind anomalies during JJA, this study extends the analysis to include both JJA and DJF seasons [17]. This study offers a novel contribution by providing a seasonally comparative and process-based quantification of moisture budget components, thereby clarifying how atmospheric dynamics differently control precipitation anomalies between boreal summer and winter. This research aims to compare the dominant atmospheric drivers of precipitation anomalies over northern Sumatra and to clarify how their contributions vary across seasons (DJF and JJA) using the Moisture Budget approach [1].

Data and Method

Description of the Study Area

Aceh Province, situated at the northern tip of Sumatra Island, extends from 95°E to 98°E and 2°N to 6°N, covering an area of approximately 58,377 km² (Figure 1). It lies between the Andaman Sea, the Indian Ocean, and the Strait of Malacca, placing it within a complex maritime environment. Its topography is dominated by the Bukit Barisan mountain range, with elevations reaching about 3,782 msl, which contributes to pronounced spatial variability in climate. Climatologically, northern Sumatra exhibits a semi-monsoonal precipitation pattern, with two main rain seasons in March-April-May (MAM) and September–October-November (SON), and relatively drier periods in DJF and JJA [3]. These seasonal variations are linked to monsoonal circulation, with transitional periods characterized by increased atmospheric instability and precipitation variability [18].

Data used

This study employs monthly reanalysis data from the ERA-Interim dataset developed by the European Centre for Medium-Range Weather Forecasts (ECMWF) as the primary source for diagnostic analysis. The dataset spans a 36-year period from 1981 to 2016 and has a spatial resolution of 0.125° × 0.125°. To maintain consistency in both temporal and spatial domains, precipitation analysis is mainly based on ERA-Interim data. In addition, several meteorological and moisture budget variables are derived from the same dataset. These include surface latent heat flux (J/m^2), daily precipitation (mm/day), horizontal wind components (*u* and *v*; m/s), specific humidity (kg/kg), and vertical velocity (Pa/s) expressed in pressure coordinates. To incorporate terrain influence, topographic information is obtained from the Shuttle Radar Topography Mission (SRTM), which has a spatial resolution of 30 meters.

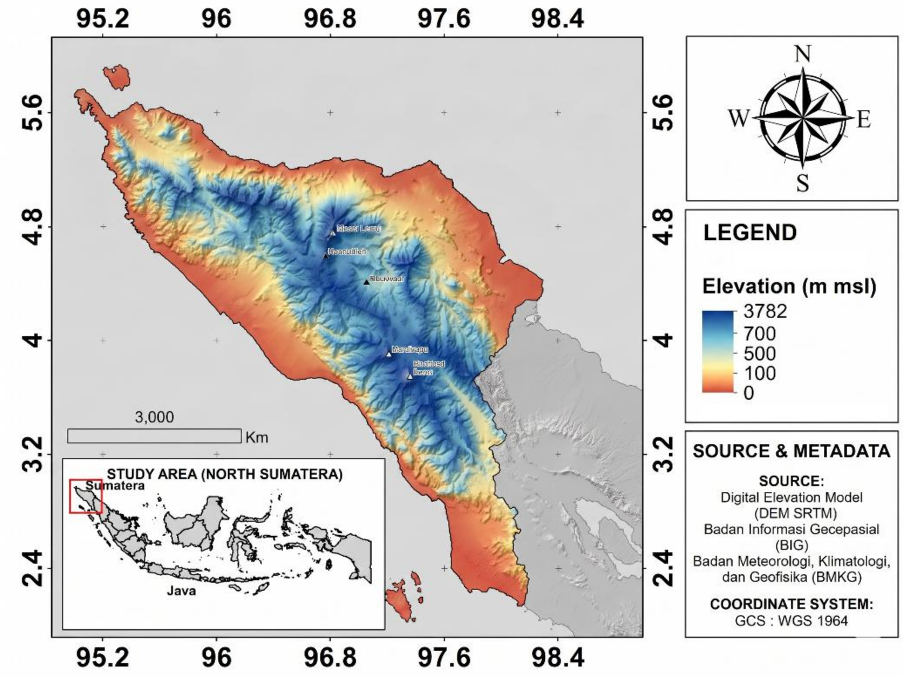

Figure 1. Elevation map of northern Sumatra (Aceh) and the Bukit Barisan range. Inset shows the study area in Indonesia.

Methods

Most data processing was performed using the NCAR Command Language (NCL) [19]. The methodology adopted in this study comprises four main stages. First, the spatial variability of precipitation across Indonesia, with particular emphasis on Sumatra, was examined using composite analysis based on a 36-year ERA-Interim dataset (1981–2016). The analysis incorporates key atmospheric variables, including precipitation (P) , horizontal wind (v) components, and specific humidity (q). To ensure the robustness of the dataset, ERA-Interim precipitation was further validated through comparison with rain gauge observations and CHIRPS data [17, 20]. Second, dry and wet years during June–July–August (JJA) were identified using normalized precipitation anomalies relative to the 1981–2016 climatology, with thresholds set at ± 0.8 standard deviations to increase the sample size [21]. Third, a student's t-test was used for calculating the significance level, assuming a null hypothesis of equal means (H_0: $\mu_1 = \mu_2$). Finally, the physical processes governing precipitation anomalies were analyzed through a vertically integrated moisture budget approach based on the framework introduced by Chou et al. (2009)[1].

$$\boldsymbol{P'} = -\langle \bar{\boldsymbol{\omega}} \boldsymbol{\partial_p q'} \rangle - \langle \boldsymbol{\omega' \partial_p \bar{q}} \rangle - \langle \boldsymbol{v} \,.\, \boldsymbol{\nabla q} \rangle' + \boldsymbol{E'} + \boldsymbol{residual\_q} \tag{1}$$

$$\boldsymbol{P'} = -\langle \bar{\boldsymbol{\omega}} \boldsymbol{\partial_p q'} \rangle - \langle \boldsymbol{\omega' \partial_p \bar{q}} \rangle - \langle \bar{\boldsymbol{v}} .\, \boldsymbol{\nabla q'} \rangle - \langle \boldsymbol{v'} .\, \boldsymbol{\nabla \bar{q}} \rangle + \boldsymbol{E'} + \boldsymbol{residual\_q} \tag{2}$$

Here, the overbar ($\bar{}$) denotes the climatological mean, defined over the period 1981–2016, while the prime (′) indicates anomalies relative to this mean. In this framework, $\boldsymbol{E}$, $\boldsymbol{\omega}$, $\boldsymbol{v}$, and $\boldsymbol{q}$ represent evaporation, vertical pressure velocity, horizontal wind vector, and specific humidity, respectively. The residual term ($\boldsymbol{residual\_q}$) accounts for nonlinear transient eddy contributions, which are typically small and often neglected. The moisture budget consists of five main components (Equation 1). Precipitation anomalies are primarily balanced by contributions from vertical moisture transport associated with both mean ($\overline{\boldsymbol{\omega}}$) and anomalous ($\boldsymbol{\omega'}$) vertical motion, horizontal moisture advection, evaporation anomalies, and the residual term. All terms are converted into units of energy by incorporating the heat of latent per unit mass. Precipitation (P) was represented by W/m² and can be changed into mm/day [29]. In this study, the vertical integration is performed from 1000 to 300 hPa, where ⟨ ⟩ denotes mass-weighted vertical integration over this pressure range.

$$\langle \boldsymbol{X} \rangle = \boldsymbol{g}^{-1} \int_{1000}^{300} \boldsymbol{X} d\boldsymbol{p} \tag{3}$$

Here $\boldsymbol{g}$ denotes gravitational acceleration. In this study, the atmospheric column uses 300 hPa as the upper limits [22]. In the fifth step, velocity potential in the upper part of the troposphere is used to define the large-scale upward motion [39]. In tropical regions, wind fields are often used to describe synoptic conditions instead of pressure or geopotential height. Based on Helmholtz's theorem, any wind field can be decomposed into a non-divergent component ($\boldsymbol{V_\psi}$) and a divergence-dominated (curl-free) component ($\boldsymbol{V_e}$), where $\boldsymbol{\nabla} \cdot \boldsymbol{V_\psi} = \boldsymbol{0}$ and $\boldsymbol{\nabla} \times \boldsymbol{V_e} = \boldsymbol{0}$. These components are represented by the velocity potential and stream function (ψ), which are widely used in tropical weather analysis. For a two-dimensional flow, the non-divergent wind can be described using the stream function ($\boldsymbol{\psi}$).

$$\mathbf{v}_\psi = -\frac{\partial \psi}{\partial \mathbf{x}} \qquad \boldsymbol{u_\psi} = \frac{\partial \boldsymbol{\psi}}{\partial \boldsymbol{y}} \tag{4}$$

Result and Discussions

Identification of DJF Wet and Dry Years

In this study, DJF precipitation anomalies for the period 1981–2016 are used to classify years as wet or dry, as illustrated in Figure 2. Based on this classification, eight wet years (1983, 1986, 1988, 1999, 2004, 2008, 2009, and 2016) and eight dry years (1982, 1990, 1997, 1998, 2000, 2002, 2003, and 2007) are identified. Figure 1 indicates that the amplitude of precipitation anomalies in wet years is broadly similar to that in dry years, suggesting a balanced variability during DJF. This pattern implies that, unlike JJA, extreme anomalies in DJF are not strongly biased toward either wet or dry conditions, reflecting a more stable, symmetric climatological behavior in the boreal winter season.

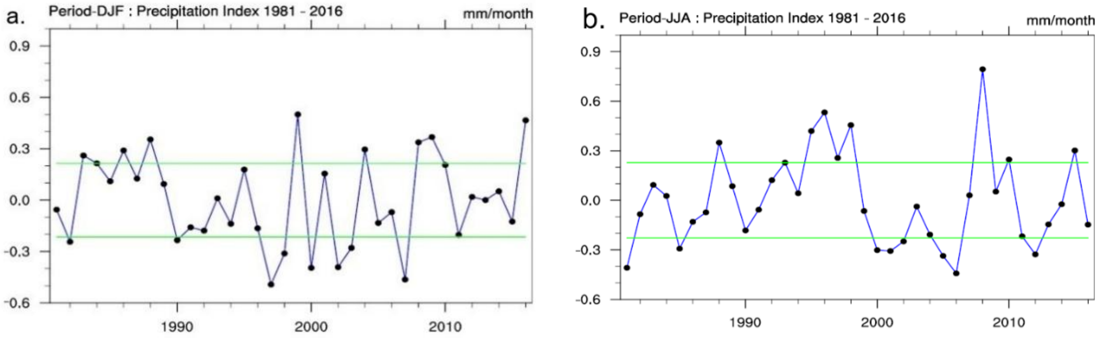

Figure 2. Time series of the standardized precipitation anomaly index (z-score) over northern Sumatra for 1981–2016 derived from ERA-Interim data, shown for (a) DJF and (b) JJA. Green lines denote the ±0.8 thresholds (in standardized units) used to classify wet and dry years.

Statistical Validation of Wet and Dry Year Classification

To validate the classification of wet and dry years, a student's t-test was applied for DJF and JJA (Figure 3). Hatched areas indicate precipitation anomalies significant at the 10% level. During DJF, northern Sumatra exhibits weak and spatially inconsistent anomalies, with values generally close to neutral in both wet and dry years, indicating limited deviation from climatology. In contrast, JJA shows a much stronger and more coherent signal, with significant positive anomalies in wet years and negative anomalies in dry years, reflecting enhanced and suppressed convection, respectively [17]. This contrast suggests that precipitation variability is more robust and strongly controlled by large-scale processes during JJA, while DJF variability is weaker and more influenced by local factors.

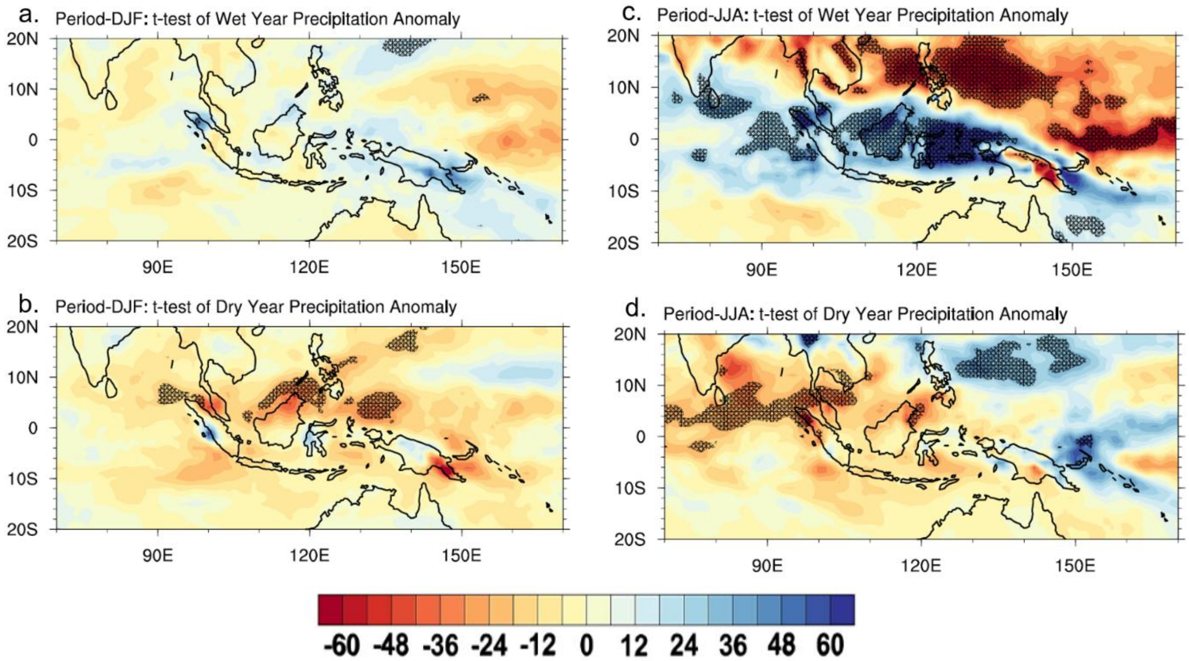

Figure 3. Composite precipitation anomalies (mm/month) for DJF: (a) wet years and (b) dry years; and for JJA: (c) wet years and (d) dry years. Hatched areas indicate statistically significant anomalies at the 10% level.

Moisture Budget Drivers

This study examines the moisture budget during wet and dry conditions in the DJF and JJA seasons using the framework of Chou et al. (2009)[1].

During the Wet Years

The moisture budget during wet years reveals clear seasonal differences between DJF and JJA over northern Sumatra (Figure 4). In DJF, precipitation anomalies are moderately positive (18.18 W/m^2) and are mainly balanced by vertical moisture transport associated with anomalous upward motion ($-\langle \boldsymbol{\omega}' \boldsymbol{\partial}_{\boldsymbol{p}} \bar{\boldsymbol{q}} \rangle \approx 15.65$ W/m^2). This indicates that vertical velocity anomalies enhance moisture convergence and support convection, although the overall signal remains relatively weak [1]. In contrast, JJA exhibits much stronger precipitation anomalies (27.58 W/m^2), indicating more intense convective activity. The dominant contribution comes from vertical moisture transport driven by anomalous vertical motion ($-\langle \boldsymbol{\omega}' \boldsymbol{\partial}_{\boldsymbol{p}} \bar{\boldsymbol{q}} \rangle \approx 52.04$ W/m^2), highlighting the key role of upward motion in regulating tropical rainfall [1]. However, this strong contribution is partly offset by a negative residual term (−20.23 W/m^2), which reflects the influence of unresolved transient or nonlinear processes [23]. The residual term exhibits a clear seasonal and regime-dependent behavior, indicating the role of unresolved transient and nonlinear processes in modulating precipitation anomalies. During JJA of wet years, the large negative residual partly offsets the strong contribution from vertical moisture advection, suggesting that sub-seasonal variability and nonlinear convective processes act to reduce the intensity of large-scale dynamically driven precipitation [23].

Overall, vertical motion ($\boldsymbol{\omega}'$) is the primary driver of precipitation anomalies in both seasons, but its effect is much stronger during JJA. This suggests stronger control by large-scale atmospheric circulation in JJA, whereas DJF variability is weaker and exhibits reduced spatial and temporal coherence, reflecting the superposition of multiple interacting processes, including intraseasonal variability and monsoonal convection. [29]. During DJF in wet years, convection over the Maritime Continent is strongly influenced by the Madden–Julian Oscillation (MJO), which introduces high intraseasonal variability and results in more scattered, less organized moisture convergence [15]. In addition, active monsoonal convection during this season tends to homogenize rainfall, thereby reducing the relative impact of anomalous vertical motion [11]. As a result, the coupling between large-scale circulation and convection is relatively weak, and vertical velocity anomalies contribute less efficiently to precipitation variability. In contrast, during JJA, precipitation variability is more strongly controlled by inter-annual climate models such as ENSO and the Indian Ocean Dipole (IOD), which enhance low-level wind anomalies and promote large-scale moisture convergence over the region. This leads to more persistent and spatially coherent upward motion, allowing vertical velocity anomalies to play a more dominant role. Consequently, convection becomes more tightly coupled with large-scale circulation, resulting in stronger and more organized precipitation responses compared to DJF.

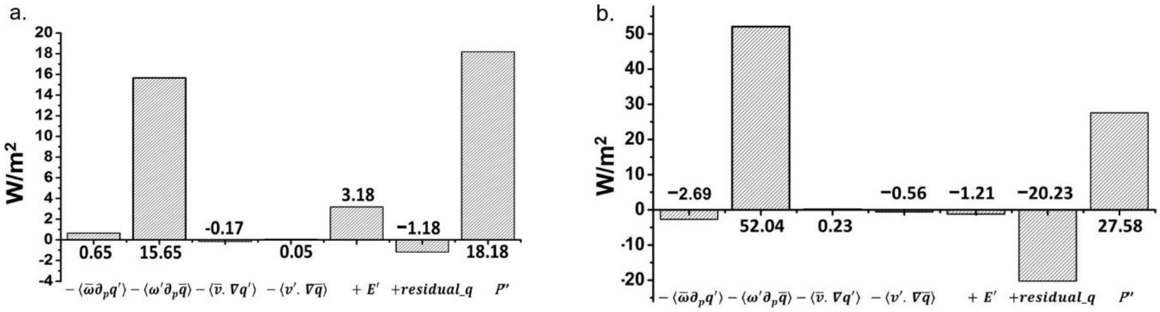

Figure 4. Contributions of moisture budget components to precipitation anomalies during wet years over northern Sumatra for 1981–2016, shown for (a) DJF and (b) JJA. The analysis is limited to land areas with terrain correction and covers the domain 2°N–6°N and 95°E–98°E. Values are expressed in W/m².

During the Dry Years

The moisture budget during dry years shows a clear suppression of precipitation over northern Sumatra, with distinct differences between DJF and JJA (Figure 5). In DJF, precipitation anomalies are slightly negative (−4.00 W/m²) and are mainly linked to reduced vertical moisture transport ($-\langle\boldsymbol{\omega}'\boldsymbol{\partial}_{\boldsymbol{p}}\bar{\boldsymbol{q}}\rangle \approx -16.63$ W/m²), indicating anomalous subsidence that suppresses convection [24]. However, this drying effect is partly offset by a large positive residual term (16.22 W/m²), which suggests contributions from transient or unresolved processes [23]. During DJF of dry years, the positive residual offsets the drying effect associated with anomalous subsidence, implying that transient disturbances and local-scale processes partially mitigate the suppression of convection. These results highlight that, while large-scale vertical motion provides the primary control on precipitation anomalies, unresolved processes play a compensating role, reducing the net anomaly in both wet and dry regimes. The horizontal advection and evaporation play only minor roles, confirming that vertical motion dominates the moisture budget during this season. In JJA, the drying signal is stronger and more coherent. Precipitation anomalies become more negative (−17.05 W/m²), largely controlled by enhanced subsidence ($-\langle\boldsymbol{\omega}'\boldsymbol{\partial}_{\boldsymbol{p}}\bar{\boldsymbol{q}}\rangle \approx -18.35$ W/m²), which strongly suppresses convective activity. Unlike DJF, the residual term is also negative (−2.70 W/m²), reinforcing the drying signal. Other components remain small. Overall, vertical velocity anomalies are the main driver of precipitation deficits in both seasons. Their impact is more consistent and pronounced in JJA, reflecting stronger control by large-scale circulation, while DJF variability is weaker and influenced by compensating processes. This seasonal contrast can be explained by differences in large-scale climate forcing. During DJF, intraseasonal variability associated with the Madden–Julian Oscillation (MJO) and active monsoonal convection tends to disrupt persistent subsidence, leading to a weaker and less organized drying signal [14, 15]. In contrast, during JJA, dry conditions are more strongly linked to large-scale circulation anomalies associated with ENSO and the Indian Ocean Dipole (IOD), which induce anomalous subsidence and suppress moisture convergence over the region [4, 5]. These large-scale modes enhance atmospheric stability and reduce convective activity, resulting in a stronger, more spatially coherent drying signal than in DJF.

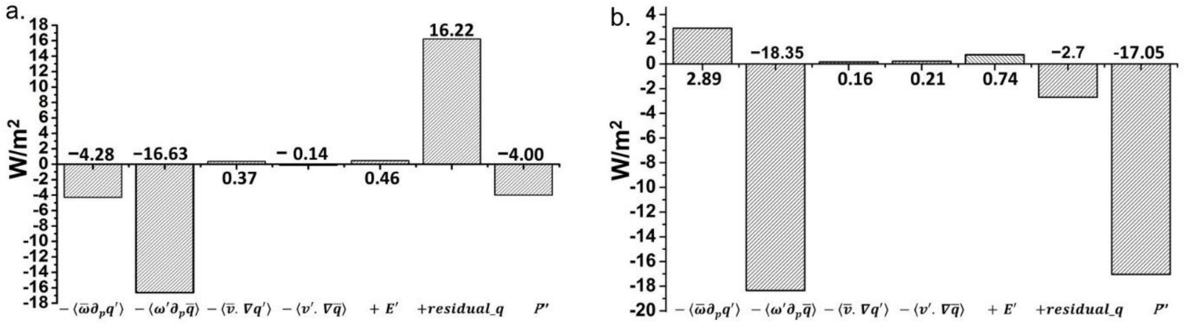

Figure 5. Contributions of moisture budget components to precipitation anomalies during dry years over northern Sumatra for 1981–2016, shown for (a) DJF and (b) JJA. The analysis is limited to land areas with terrain correction and covers the domain 2°N–6°N and 95°E–98°E. Values are expressed in W/m^2.

Spatial distribution of velocity potential

To evaluate the role of vertical velocity anomalies as the main driver of precipitation variability, anomalies of velocity potential and divergent winds were analyzed at the upper (300 hPa) and lower (850 hPa) tropospheric levels for both wet and dry years, as presented in Figures 6 and 7.

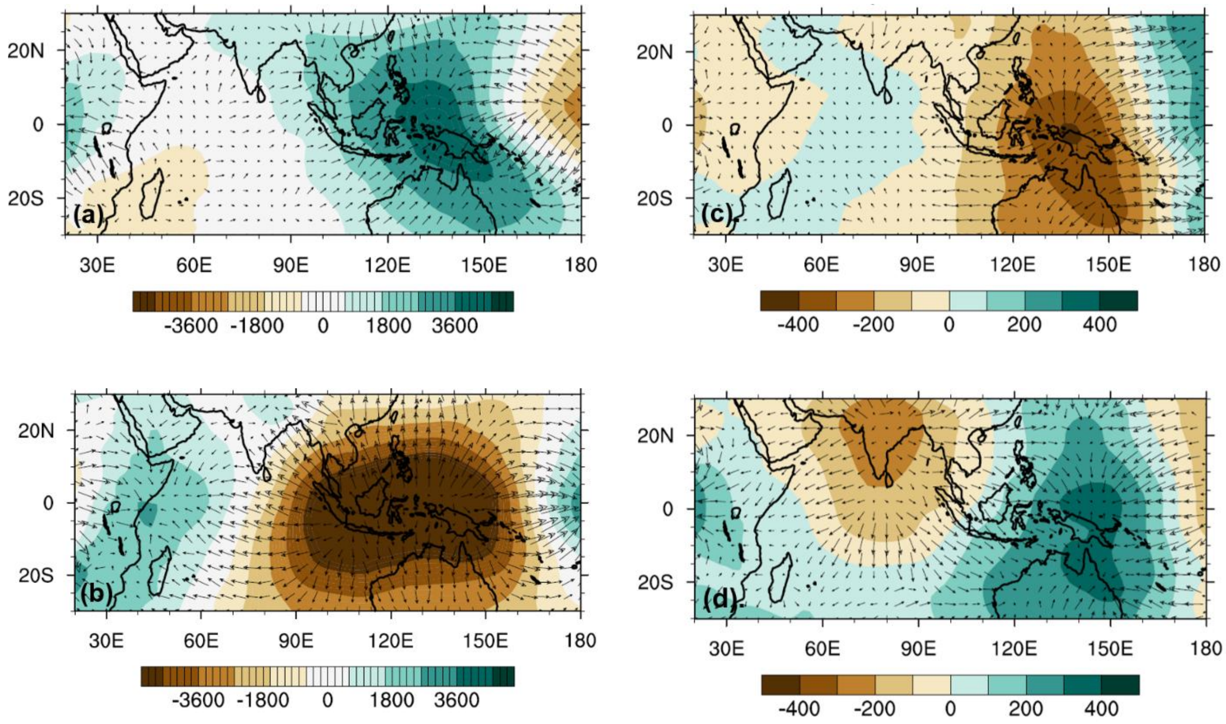

Figure 6. Spatial patterns of velocity potential anomalies (shaded; m^2/s) and divergent wind anomalies (vectors; m/s) during JJA at 850 hPa (a, b) and 300 hPa (c, d). Panels (a) and (c) represent wet years, while (b) and (d) correspond to dry years [17].

During JJA, the velocity potential exhibits a well-defined dipole structure between the eastern Indian Ocean and the western Pacific. At both 850 hPa and 300 hPa, a strong coupling between convergence and divergence is evident, indicating a robust, vertically coherent circulation system [25]. This structure reflects an intensified large-scale overturning circulation, characterized during wet years by enhanced low-level convergence and upper-level divergence, and by the opposite patterns during dry years [26]. Such an organized circulation is consistent with pronounced ascending (descending) motion anomalies over northern Sumatra, which strongly modulate precipitation variability [27, 28].

In contrast, during DJF, the velocity potential and divergent wind anomalies exhibit a dipole-like pattern, but with weaker magnitudes and reduced spatial coherence. The upper-level velocity potential generally exhibits an opposite sign relative to the lower level, indicating a vertically coupled circulation, although less organized than in JJA. Overall, the signal during DJF is weaker compared to JJA, suggesting a reduced influence of large-scale circulation. The divergence–convergence dipole in both seasons supports the development of anomalous low-level winds, which further modulate regional moisture transport. However, the stronger and more coherent circulation during JJA indicates a tighter coupling between large-scale dynamics and convection, whereas the weaker DJF signal implies a greater contribution from local and transient processes in controlling Precipitation variability.

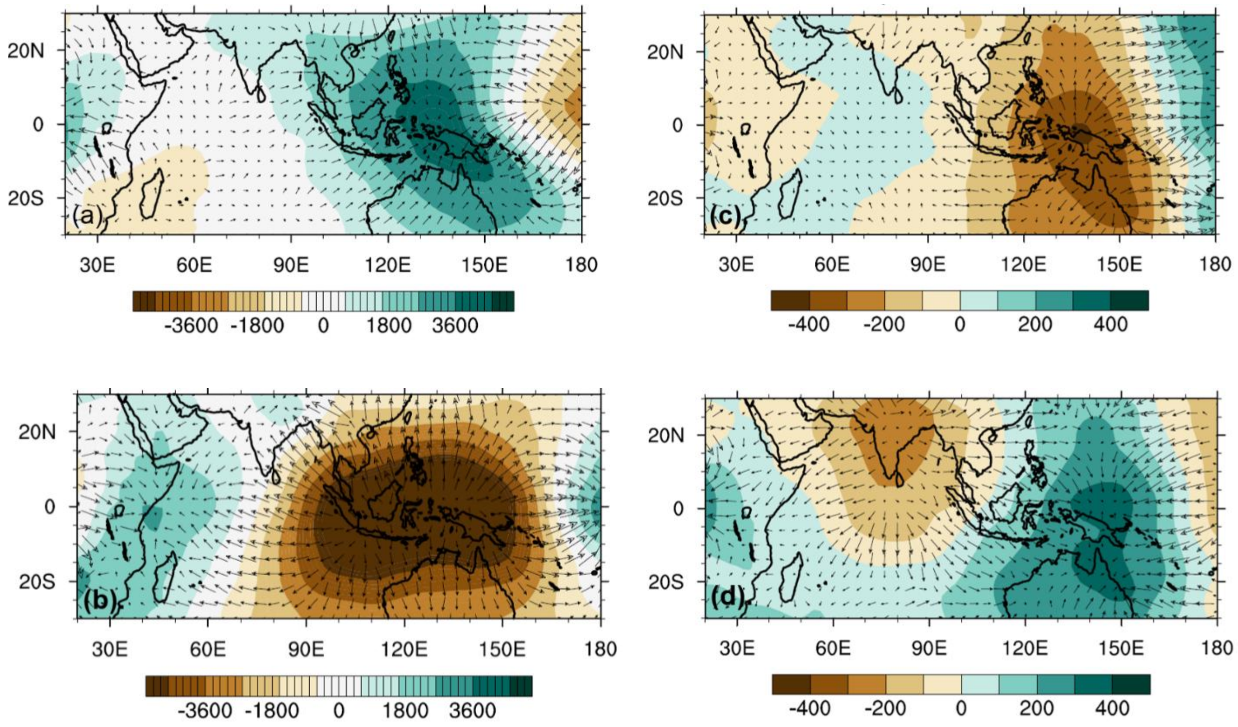

Figure 7. Spatial patterns of velocity potential anomalies (shaded; m^2/s) and divergent wind anomalies (vectors; m/s) during DJF at 850 hPa (a, b) and 300 hPa (c, d). Panels (a) and (c) represent wet years, while (b) and (d) correspond to dry years

Conclusion

Precipitation anomalies over northern Sumatra are primarily governed by anomalous vertical motion and associated moisture transport, with enhanced ascent (subsidence) producing wet (dry) conditions, confirming vertical motion as the dominant control across seasons. However, a clear seasonal contrast exists between DJF and JJA. During JJA, variability is strongly controlled by the large-scale atmospheric circulation, resulting in larger, more spatially coherent anomalies and tighter coupling between dynamics and convection. In contrast, DJF exhibits weaker and less coherent anomalies, reflecting weaker large-scale organization and reduced dynamical control. This contrast is further reflected in the residual term, which highlights the role of unresolved transient and nonlinear processes. In JJA of wet years, a large negative residual partly offsets strong vertical moisture advection, indicating that sub-seasonal variability and nonlinear convective processes dampen dynamically driven rainfall. Conversely, during DJF of dry years, a positive residual offsets subsidence-induced drying, suggesting that transient disturbances and local processes partially mitigate convection suppression. Overall, these residuals act as a compensating mechanism, reducing the magnitude of both wet and dry anomalies. The weaker DJF signal reflects the combined influence of multiple interacting processes, including intraseasonal variability, monsoonal convection, and land–sea interactions, which are not fully captured by seasonal mean diagnostics. As a result, precipitation variability in DJF is less organized and potentially less predictable, whereas JJA variability is more directly linked to large-scale forcing and thus more predictable. These findings highlight fundamental seasonal differences in precipitation controls, underscore the limitations of large-scale diagnostics for DJF, and have implications for improving seasonal forecasting, water resource management, and model representation of sub-seasonal processes under a changing climate.

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