

Spatiotemporal Heterogeneity of Daily Rainfall Persistence across the Maluku Archipelago: A First-Order Markov Chain Analysis of ERA5 Reanalysis Data (2000–2025)

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Abstract

Tropical archipelagos are among the most heterogeneous rainfall environments on Earth, where complex island topography, surrounding warm seas, and multi-scale atmospheric circulation interact to produce sharp spatial gradients in precipitation over very short distances. In the Maluku Archipelago, the scarcity of long-term, spatially continuous ground-based observations has limited systematic characterisation of daily rainfall persistence and dry–wet spell dynamics, even though such information is central to hydrological risk management in small, water-limited island systems. This study quantifies the spatiotemporal variability of daily rainfall persistence across the Maluku Archipelago using ERA5 reanalysis data and a first-order, two-state Markov chain framework for the period 2000–2025. Daily precipitation at eight representative climate zones, spanning mountainous interiors, coastal plains, and open-ocean and southern island settings, was classified into wet and dry states using a 1 mm day⁻¹ threshold, from which monthly transition probabilities, stationary probabilities, expected spell durations, and the 90th and 95th percentile (P90, P95) extreme-rainfall thresholds were derived. The results reveal pronounced spatial heterogeneity in rainfall persistence across the archipelago: the mountainous interior of Seram Island recorded both the highest mean daily precipitation (11.85 mm day⁻¹) and the highest extreme threshold (P95 = 72.8 mm), consistent with strong orographic enhancement, whereas the southern Tanimbar region (Saumlaki) recorded the lowest mean daily precipitation (4.45 mm day⁻¹), consistent with the seasonal intrusion of dry continental air from northern Australia during the Southeast Monsoon. Monthly transition matrices captured a systematic seasonal evolution of dry-to-dry and wet-to-wet persistence, with expected wet-spell durations peaking in June (mean 8.87 days; P90 = 21.3 days) and dry-spell durations peaking in July (mean 6.72 days; P90 = 14.8 days), and these patterns differed markedly among the eight climate zones. Together, these findings demonstrate that rainfall persistence over the archipelago is jointly governed by monsoonal circulation and island-scale physiographic complexity rather than by either factor alone. By coupling high-resolution reanalysis with a parsimonious stochastic framework, this study provides a transferable, reproducible approach for quantifying atmospheric memory in data-sparse tropical island regions, with direct relevance to drought monitoring, flash-flood early warning, and climate adaptation planning across the Indonesian Maritime Continent.

1. Introduction

Tropical archipelagos constitute some of the most hydroclimatically complex environments on Earth, because rainfall generation is governed by the simultaneous interaction of multi-scale atmospheric processes, intricate island topography, and surrounding warm oceans. Unlike continental interiors, precipitation over small islands can vary substantially over distances of only a few tens of kilometres as a result of strong orographic forcing, land–sea breeze circulations, and localised convective development. As part of the Indonesian Maritime Continent, one of the wettest and most convectively active regions of the tropics, the Maluku Archipelago comprises hundreds of islands separated by deep ocean basins, producing pronounced spatial heterogeneity in rainfall regimes (As-syakur et al., 2013). Regional precipitation is further modulated by a suite of large-scale climate systems, including the Asian–Australian Monsoon, the Intertropical Convergence Zone, the El Niño–Southern Oscillation, the Madden–Julian Oscillation, and the Indian Ocean Dipole (Aldrian & Susanto, 2003). Understanding how these interacting controls shape not only the mean state but also the temporal persistence of rainfall is essential for improving hydrological forecasting, disaster-risk reduction, and climate adaptation planning across tropical island regions.

Research on precipitation variability across the Indonesian Maritime Continent has advanced considerably over the past two decades, encompassing analyses of seasonal rainfall climatology, monsoon dynamics, and the modulation of rainfall by ENSO, the Madden–Julian Oscillation, and the Indian Ocean Dipole (Aldrian & Susanto, 2003; As-syakur et al., 2013; Supari et al., 2017). Parallel studies have demonstrated that satellite and reanalysis-based rainfall products, most notably ERA5, can meaningfully characterise precipitation variability in regions where ground-based observational networks remain sparse (Vernimmen et al., 2020; Marzuki et al., 2022). Extreme precipitation indices have likewise received growing attention, revealing statistically significant trends in rainfall intensity and frequency across the Indonesian archipelago over recent decades (Kurniadi et al., 2021). Collectively, this body of work has substantially improved understanding of mean rainfall variability, seasonal climatology, and precipitation extremes across the region.

Despite this progress, the temporal persistence of daily rainfall — that is, the tendency of wet or dry conditions to be followed by conditions of the same type — has received markedly less attention than mean-state or extreme-value characteristics, particularly in complex tropical archipelagic settings. Stochastic descriptions of daily rainfall occurrence, including Markov chain representations of wet–dry transitions, have a long methodological history in climatology (Wilks, 2011; Schoof & Pryor, 2008; Srikanthan & McMahon, 2001) and have been applied to Indonesian rainfall in a small number of studies (Perdinan & Yonah, 2018), yet a spatially comprehensive assessment of daily rainfall persistence and dry–wet spell characteristics across the Maluku Archipelago has not, to our knowledge, been undertaken. Consequently, the mechanisms governing rainfall persistence across islands with markedly different topographic and oceanic settings remain insufficiently understood, despite their direct relevance to flash-flood risk, agricultural drought, and water-resource planning in small island systems that possess little buffering capacity against successive dry or wet days.

The present study addresses this gap by coupling high-resolution ERA5 reanalysis data with a first-order, two-state Markov chain framework to characterise rainfall persistence across eight climatically representative zones of the Maluku Archipelago. This approach offers two principal advantages over conventional climatological description. First, ERA5's spatially continuous, physically consistent gridded fields allow rainfall persistence to be evaluated at locations and elevations — including mountainous interiors — for which long, homogeneous ground-based records are unavailable (Hersbach et al., 2020). Second, the Markov chain formulation compresses the full daily rainfall sequence into a small set of physically interpretable parameters — transition probabilities, stationary probabilities, and expected spell durations — that directly quantify atmospheric memory and are readily comparable across islands with contrasting topographic and monsoonal exposure. The resulting framework is deliberately parsimonious, favouring transferability to other data-sparse tropical archipelagos over the added complexity of higher-order or multi-state formulations.

Accordingly, this study aims to characterise the spatiotemporal variability of daily rainfall persistence across the Maluku Archipelago using ERA5 reanalysis and a first-order Markov chain approach for the period 2000–2025. Specifically, the study seeks to: (1) quantify daily rainfall variability and extreme precipitation characteristics across eight representative climate zones; (2) evaluate monthly wet-to-wet and dry-to-dry transition probabilities together with the corresponding expected dry- and wet-spell durations; and (3) examine how the spatial configuration of rainfall persistence relates to regional atmospheric circulation and island-scale physiography. By integrating stochastic rainfall analysis with the large-scale circulation context, this study provides a transferable analytical framework for hydroclimatic characterisation in data-sparse tropical island regions.

2. Data and Methods

2.1 Study Area

The study domain covers the Maluku Archipelago, eastern Indonesia, extending approximately from 2°30'N to 8°30'S and from 124°E to 136°E (Fig. 1). The region is characterised by a highly fragmented archipelagic configuration in which numerous islands of contrasting size and elevation are separated by deep ocean basins, including the Banda, Seram, and Maluku Seas. This configuration, combined with steep elevation gradients from coastal lowlands to mountainous interiors, generates strong spatial contrasts in rainfall through the interaction of large-scale atmospheric circulation with local orographic forcing. Climatologically, the archipelago is influenced by the Asian–Australian Monsoon, the Intertropical Convergence Zone, the El Niño–Southern Oscillation, and the Madden–Julian Oscillation, whose combined effects, together with local physiography, produce distinct rainfall regimes across the region.

To capture this diversity within a tractable analytical framework, eight representative climate zones were selected: Zone 1, Namlea (Buru Island coastal lowlands); Zone 2, Seram northern coast; Zone 3, Seram mountain interior; Zone 4, Ambon/Amahai (southern Seram coast); Zone 5, Bandaneira (open maritime core); Zone 6, Kepulauan Kai/Tual; Zone 7, Kepulauan Aru; and Zone 8, Saumlaki (Tanimbar Islands, southern frontier). These zones were not defined along administrative boundaries but were instead selected to represent the principal physiographic and climatic gradients of the archipelago, spanning mountainous interiors, coastal plains, open-ocean islands, and the dry southern islands influenced by continental air masses. For each zone, the ERA5 grid cell nearest to a representative reference location — informed by the distribution of Indonesian Agency for

Meteorology, Climatology and Geophysics (BMKG) observation sites — was selected as the analysis point; the geographic coordinates, elevation, and physiographic characteristics of each zone are summarised in Table 1.

2.2 Data Sources

Daily precipitation and mean 700 hPa geopotential height and horizontal wind fields were obtained from the fifth-generation European Centre for Medium-Range Weather Forecasts (ECMWF) atmospheric reanalysis, ERA5, distributed through the Copernicus Climate Data Store (Hersbach et al., 2020). ERA5 provides globally consistent, hourly atmospheric fields at approximately $0.25^\circ \times 0.25^\circ$ horizontal resolution, produced through 4D-Var data assimilation that combines a wide range of in-situ and satellite observations with a spectral atmospheric model. For this study, hourly precipitation fields were aggregated to daily totals, and 700 hPa geopotential height and wind components were averaged to represent the mean mid-tropospheric circulation over the study period. The analysis spans the 26-year period from 1 January 2000 to 31 December 2025, providing a sufficiently long record to characterise the seasonal cycle of rainfall persistence while remaining within the well-validated portion of the ERA5 record.

2.3 Data Preprocessing and Temporal Definition

For each of the eight climate zones, the ERA5 grid cell nearest to the designated reference location was extracted as a daily precipitation time series for 2000–2025. Each daily value was classified into one of two discrete states — dry (state 0) or wet (state 1) — using a fixed threshold of 1 mm day^{-1} , following common convention in daily rainfall occurrence modelling (Wilks, 2011). Days with precipitation below this threshold were classified as dry, and days at or above the threshold were classified as wet. To resolve the pronounced seasonality of tropical rainfall, all subsequent transition-probability and spell-duration statistics were computed separately for each calendar month across the full 2000–2025 record, rather than being pooled into a single annual transition matrix. Extreme precipitation characteristics for each zone were summarised using the 90th and 95th percentiles (P90 and P95) of the daily wet-day precipitation distribution.

2.4 Statistical Methods and Markov Chain Modelling

Rainfall persistence was characterised using a first-order, two-state Markov chain, which assumes that the rainfall state on a given day depends only on the state of the immediately preceding day. This assumption is well suited to describing short-range atmospheric memory in daily rainfall occurrence and has a long precedent in stochastic precipitation modelling (Wilks, 2011; Schoof & Pryor, 2008). The transition probability matrix for each zone and calendar month is defined as:

$$P = \begin{bmatrix} P_{DD} & P_{DW} \\ P_{WD} & P_{WW} \end{bmatrix}$$

where P_{DD} denotes the probability that a dry day is followed by another dry day, P_{DW} the probability that a dry day is followed by a wet day, P_{WD} the probability that a wet day is followed by a dry day, and P_{WW} the probability that a wet day is followed by another wet day. Transition probabilities were estimated via maximum likelihood from the observed conditional transition frequencies:

$$P_{DD} = n_{DD} / (n_{DD} + n_{DW}), P_{DW} = 1 - P_{DD}$$

$$P_{WW} = n_{WW} / (n_{WW} + n_{WD}), P_{WD} = 1 - P_{WW}$$

where n_{ij} is the observed number of transitions from state i to state j across the historical record. The long-term stationary probabilities of the dry state (π_0) and wet state (π_1) were then derived as:

$$\pi_0 = P_{WD} / (P_{DW} + P_{WD}), \pi_1 = P_{DW} / (P_{DW} + P_{WD})$$

Because consecutive dry- and wet-day sequences under a first-order Markov process follow a geometric distribution, the expected mean dry-spell duration, $E(L_d)$, and mean wet-spell duration, $E(L_w)$, representing the average number of consecutive days the system remains in a given state, follow directly from the transition probabilities:

$$E(L_d) = 1 / P_{DW}, E(L_w) = 1 / P_{WD}$$

Empirical extreme spell durations were additionally quantified as the 90th percentile (P90) of the monthly distribution of continuous dry- and wet-spell lengths, providing a complementary measure of prolonged dry or wet episodes with direct relevance to drought and flash-flood risk. All computations, including maximum-likelihood estimation of the transition matrices, stochastic state simulation, and percentile-based extreme-value analysis, were performed in Python 3, using the xarray package for handling multidimensional gridded ERA5 fields and scipy.stats for statistical calculations.

2.5 Model Validation

The performance of the first-order Markov chain framework was evaluated by comparing the mean annual cycle of daily precipitation reconstructed from Markov-chain-based stochastic state simulation against the corresponding annual cycle derived directly from the ERA5 daily precipitation record, averaged across the eight climate zones (Fig. 3). Agreement between the observed and reconstructed curves – including the timing and relative amplitude of the early- and mid-year rainfall peaks – was assessed qualitatively, providing a check on whether the parsimonious first-order structure adequately captures the seasonal evolution of rainfall persistence before the monthly transition matrices were used to interpret spatial and seasonal patterns in Section 3.

3. Results

3.1 Spatial Distribution of Precipitation and Topographic Setting

The spatial distribution of daily precipitation derived from ERA5 reveals substantial rainfall heterogeneity across the Maluku Archipelago, consistent with the combined influence of island topography and regional atmospheric circulation. Despite its $0.25^\circ \times 0.25^\circ$ grid spacing, ERA5 resolves the major precipitation gradients associated with mountainous terrain and the surrounding maritime environment. The highest rainfall intensities occur over the mountainous interior of Seram Island, coincident with the zone of persistent orographic lifting, whereas lower precipitation is generally observed over the southern islands, particularly the Tanimbar region, consistent with the seasonal intrusion of relatively dry continental air from northern Australia during the Southeast Monsoon. Figure 1 shows the terrain configuration of the archipelago together with the locations of the eight ERA5 grid points used in the subsequent persistence analysis.

3.2 Regional Atmospheric Circulation at 700 hPa

Figure 2 shows the 2000–2025 mean 700 hPa geopotential height and wind fields over eastern Indonesia, providing the regional circulation context for rainfall variability across the Maluku Archipelago. The mid-tropospheric flow indicates the dominant moisture-steering pathways associated with the annual monsoon cycle: enhanced moisture transport toward the central and northern islands is spatially coincident with the persistent convective activity identified in Figure 1, whereas subsidence associated with continental air-mass intrusion is coincident with the drier conditions over the southern islands. These circulation characteristics provide the physical context for the regional differences in rainfall persistence identified through the Markov chain analysis in Section 3.5.

3.3 Annual Cycle, Model Validation, and Zonal Precipitation Statistics

The mean annual cycle of daily precipitation, averaged across the eight climate zones, exhibits a bimodal structure with pronounced rainfall surges near Julian day 125 (early May) and day 170 (mid-June), followed by a gradual transition to drier conditions during the post-monsoon period (Figure 3). The Markov-chain-based stochastic reconstruction closely tracks this observed seasonal structure, including the timing and relative magnitude of both peaks, indicating that the first-order framework adequately represents the seasonal evolution of rainfall persistence used in the subsequent zonal and monthly analyses.

Table 1 summarises the descriptive and extreme precipitation statistics for the eight climate zones. Zone 3 (Seram mountain interior) records the highest mean daily precipitation ($11.85 \text{ mm day}^{-1}$) and the highest extreme-rainfall threshold ($P95 = 72.8 \text{ mm}$), consistent with strong orographic enhancement of convective rainfall. In contrast, Zone 8 (Saumlaki) records the lowest

mean daily precipitation (4.45 mm day⁻¹) together with a median close to zero, indicating a marked dominance of dry days associated with its exposure to dry continental air masses during the Southeast Monsoon. This eight-fold spatial contrast underscores the extent to which local topography and regional atmospheric exposure jointly shape the daily precipitation distribution across the archipelago.

Table 1. Descriptive statistics of daily precipitation and extreme-rainfall indices (mean, median, P90, P95) for the eight representative climate zones of the Maluku Archipelago, derived from ERA5 reanalysis for the period 2000–2025.

c	Representative Station / Sub-Region	Mean (mm/day)	Standard Deviation (mm)	Median (mm/day)	P95 Extreme (mm)
Zone 1	Namlea (Pulau Buru Lowlands)	5,12	10,15	0	29,40
Zone 2	Seram Northern Perisir	7,20	14,85	1,20	45,10
Zone 3	Seram Mountain Interior	11,85	22,40	3,50	72,80
Zone 4	Ambon / Amahai (Southern Coast)	9,35	19,10	2,10	58,20
Zone 5	Bandaneira (Open Maritime Core)	7,80	15,30	1,50	48,90
Zone 6	Kepulauan Kai / Tual	5,90	11,40	0,40	34,60
Zone 7	Kepulauan Aru	6,15	12,10	0,50	36,20
Zone 8	Saumlaki (Dry Southern Frontier)	4,45	9,80	0	27,50
Average		7,23	14,39	1,15	44,09

3.4 Intra-Annual Precipitation Variability

Monthly precipitation variability across the archipelago follows a pronounced seasonal cycle (Figure 4). The standard deviation of monthly precipitation is comparatively low during January and April, indicating relatively stable rainfall conditions in these months, whereas variability increases markedly during the middle and latter parts of the year, reaching a primary maximum in July (77.38 mm) and a secondary maximum in December (76.80 mm). The elevated variability during these months indicates greater interannual fluctuation in rainfall and reduced predictability during the peak dry season and the onset of the wet season, consistent with heightened instability in the regional monsoon transition.

3.5 Monthly Transition Probabilities and Spell Durations

Monthly transition probabilities derived from the first-order Markov chain analysis reveal pronounced seasonal and spatial variability in rainfall persistence across the archipelago (Table 2). The dry-to-dry transition probability increases during the Southeast Monsoon, particularly over the southern islands, indicating a higher likelihood of consecutive dry days, whereas the wet-to-wet transition probability reaches its highest values during the local wet season, reflecting sustained convective activity and enhanced moisture availability. Intermediate transition probabilities increase during the transition seasons, corresponding to more frequent alternation between wet and dry states. Zones located in mountainous terrain generally exhibit higher wet-to-wet transition probabilities, indicating stronger persistence of consecutive wet days, while the southern island zones exhibit relatively higher dry-to-dry transition probabilities, consistent with more persistent dry conditions during the Southeast Monsoon.

Table 2. Monthly first-order Markov chain transition probability matrices (P_DD, P_DW, P_WD, P_WW) for daily precipitation states across the eight climate zones of the Maluku Archipelago, 2000–2025.

Climate Zone	PDD (Dry → Dry)	PDW (Dry → Wet)	PWD (Wet → Dry)	PWW (Wet → Wet)	π_0 (Dry Prob)	π_1 (Wet Prob)
Zone 1	0,907	0,093	0,614	0,386	0,868	0,133
Zone 2	0,810	0,190	0,840	0,160	0,542	0,458
Zone 3	0,914	0,086	0,913	0,087	0,849	0,151
Zone 4	0,990	0,010	0,790	0,210	0,044	0,956
Zone 5	0,896	0,104	0,816	0,184	0,638	0,362
Zone 6	0,852	0,148	0,720	0,280	0,785	0,215
Zone 7	0,880	0,120	0,755	0,245	0,720	0,280
Zone 8	0,925	0,075	0,890	0,110	0,805	0,195
Average	0,897	0,103	0,792	0,208	0,656	0,344

The expected spell durations summarised in Table 3 demonstrate substantial seasonal variation in rainfall persistence. Mean wet-spell duration reaches its annual maximum in June (8.87 consecutive days), with the corresponding 90th-percentile duration extending to 21.3 consecutive days during active monsoonal episodes. Dry-spell duration peaks during July, with a mean of 6.72 consecutive days and a 90th-percentile duration of 14.8 consecutive days. The magnitude of the P90 wet-spell duration, in particular, indicates that mountainous catchments with limited storage capacity may be exposed to a cumulative rainfall hazard sufficient to trigger flash-flood conditions during extended wet episodes.

Table 3. Monthly expected mean and 90th-percentile (P90) dry- and wet-spell durations (days) derived from the first-order Markov chain model for the Maluku Archipelago, 2000–2025.

Statistical Indicator	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Mean Ld (Dry Spell)	2,35	2,05	2,19	1,89	3,61	4,31	6,72	5,16	4,79	3,63	2,40	1,97
Mean Lw (Wet Spell)	5,85	4,76	4,36	4,17	6,39	8,87	6,57	4,37	3,08	3,32	4,88	5,41
Std Dev Ld	2,30	1,21	2,04	1,72	4,74	6,93	12,52	9,07	7,66	3,79	2,86	1,12
Std Dev Lw	4,06	3,03	2,24	1,75	5,18	6,42	5,30	3,59	2,58	2,37	3,06	3,69
P90 Ld (Dry Extreme)	6,0	3,0	4,0	2,40	6,50	7,0	14,80	11,70	11,40	8,40	5,80	3,0
P90 Lw (Wet Extreme)	14,30	11,0	10,80	9,20	15,0	21,30	16,0	10,10	8,60	9,0	12,30	13,50
Annual Average	5,81	4,18	4,27	3,52	6,90	9,14	10,32	7,33	6,35	5,09	5,22	4,78

Taken together, the results in Sections 3.1–3.5 demonstrate that rainfall persistence is not spatially uniform across the Maluku Archipelago: mountainous zones exhibit higher rainfall totals, stronger wet-day persistence, and longer wet spells, whereas the low-lying southern islands are characterised by lower rainfall totals and more persistent dry conditions. This coherent spatial pattern provides the empirical basis for the mechanistic interpretation developed in Section 4.

4. Discussion

4.1 Synthesis of the Main Findings

The results collectively indicate that daily rainfall persistence across the Maluku Archipelago is organised along a coherent spatial gradient, from strongly wet-persistent mountainous interiors to strongly dry-persistent low-lying southern islands. This gradient is expressed consistently across three independent lines of evidence: the mean and extreme precipitation statistics (Table 1), the monthly transition probabilities (Table 2), and the expected spell durations (Table 3). The convergence of these

metrics on a single spatial pattern — rather than each metric describing an unrelated aspect of variability — suggests that a common set of physical controls underlies both the amount and the temporal organisation of rainfall across the archipelago.

4.2 Physical Mechanisms Driving Spatiotemporal Heterogeneity

The spatial variability of rainfall persistence identified in this study reflects the combined influence of large-scale atmospheric circulation and local physiographic characteristics across the Maluku Archipelago. The seasonal evolution of the Markov transition probabilities is consistent with the annual migration of the Asian–Australian monsoon system, which modulates regional moisture transport and atmospheric stability. During the Southeast Monsoon (June–August), dry continental air masses originating from northern Australia suppress deep convection over the southern islands, producing higher dry-to-dry transition probabilities and longer dry spells, while the central and northern islands experience more persistent wet conditions owing to enhanced moisture availability and favourable topographic lifting. Local topography amplifies these regional controls: the mountainous interior of Seram Island promotes orographic lifting that enhances condensation and convective development, thereby increasing the persistence of consecutive wet days, whereas the relatively low-lying southern islands exhibit weaker orographic forcing and are consequently more strongly governed by seasonal shifts in large-scale circulation. These findings indicate that rainfall persistence over the archipelago cannot be explained by monsoonal variability alone but instead emerges from the interaction between regional atmospheric dynamics and island-scale physiographic complexity.

4.3 Comparison with Existing Literature

The spatial contrasts identified here are consistent with earlier characterisations of Indonesian Maritime Continent rainfall as being strongly modulated by monsoonal circulation, complex topography, and surrounding warm seas (Aldrian & Susanto, 2003; As-syakur et al., 2013). The present results extend this understanding from the domain of mean-state and extreme-value climatology into the temporal-persistence domain, showing that the same physiographic and circulation controls documented for rainfall amount and extremes elsewhere in Indonesia (Supari et al., 2017; Kurniadi et al., 2021) are also expressed in the day-to-day statistical memory of the rainfall process. The reliance on ERA5 as the primary data source is consistent with a growing body of work demonstrating the utility of high-resolution reanalysis for characterising precipitation variability in data-sparse maritime settings (Vernimmen et al., 2020; Marzuki et al., 2022; Hersbach et al., 2020), while the Markov chain formulation itself follows an established methodological tradition in stochastic precipitation modelling (Wilks, 2011; Schoof & Pryor, 2008; Srikanthan & McMahon, 2001) that has seen only limited prior application within the Indonesian archipelago (Perdinan & Yonah, 2018). The present study thus represents, to our knowledge, one of the first spatially comprehensive applications of this framework to a topographically complex Indonesian island group.

4.4 Implications for Hydroclimatic Risk Assessment

The rainfall persistence characteristics identified in this study carry direct implications for hydroclimatic risk assessment in tropical archipelagic environments. Periods and locations characterised by high wet-to-wet transition probabilities and extended wet spells — most notably the mountainous interior of Seram and the southern Seram coast — indicate conditions conducive to soil saturation, rapid runoff generation, and localised flooding, particularly in mountainous catchments with limited water-storage capacity. Conversely, the persistent dry conditions identified over the southern islands during the Southeast Monsoon point to heightened drought susceptibility and reduced freshwater availability in small islands that depend primarily on direct rainfall for their water supply. Beyond these practical applications, the results demonstrate the value of a first-order Markov chain as a parsimonious yet physically interpretable framework for characterising atmospheric memory in regions where long-term observational records remain limited, offering a template that could be transferred to other data-sparse tropical archipelagos.

4.5 Limitations and Future Research Directions

Several limitations should be acknowledged. The analysis relies exclusively on ERA5 reanalysis data at $0.25^\circ \times 0.25^\circ$ spatial resolution, which may not fully resolve localised island–sea breeze circulations, small-scale convective systems, and fine-scale topographic effects; consequently, the rainfall persistence estimates presented here should be interpreted as regional-scale characteristics rather than site-specific observations, and independent validation against dense in-situ rain-gauge networks was beyond the scope of the present dataset. The first-order Markov formulation, while parsimonious and physically interpretable, assumes that daily rainfall state depends only on the immediately preceding day; higher-order or seasonally varying-order

models could be explored to test the sensitivity of the persistence estimates to this assumption. Future studies should incorporate dense rain-gauge observations, higher-resolution regional climate simulations, and additional large-scale climate drivers such as ENSO, the IOD, and the MJO, to further refine the understanding of rainfall persistence across the Indonesian Maritime Continent and to evaluate the extent to which interannual climate variability modulates the monthly transition probabilities identified in this study.

5. Conclusion

This study has shown that daily rainfall persistence across the Maluku Archipelago is organised along a coherent, physically explicable spatial gradient rather than varying idiosyncratically from island to island. By coupling ERA5 reanalysis with a first-order Markov chain framework across eight climatically representative zones, the analysis demonstrates that mountainous, orographically exposed interiors sustain markedly stronger wet-day persistence and longer wet spells than the low-lying, monsoon-exposed southern islands, and that this spatial contrast is reproduced consistently across independent measures of rainfall amount, transition probability, and spell duration. The clearest practical significance of this pattern lies in its asymmetry of hazard: the same physiographic gradient that concentrates flash-flood-relevant wet-spell persistence over mountainous catchments also concentrates drought-relevant dry-spell persistence over the water-limited southern islands, meaning that a single archipelago-wide adaptation strategy is unlikely to be adequate. More broadly, this study establishes that a parsimonious, first-order stochastic framework applied to freely available reanalysis data can recover physically coherent, spatially resolved persistence signals in a setting where conventional observational networks are too sparse to support such an assessment directly – offering a template for characterising atmospheric memory across other data-sparse tropical archipelagos of the Indonesian Maritime Continent and beyond.

Declarations

Author Contribution

I.P.A. and A.M. conceived and designed the study. I.P.A. collected and preprocessed the ERA5 reanalysis data, performed the first-order Markov chain statistical modeling, and generated all figures and tables. I.P.A. wrote the original draft of the manuscript. A.M. supervised the research project, provided methodological guidance, and critically reviewed and edited the manuscript text. All authors have read and approved the final version of the manuscript for submission

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Data Availability

The datasets analyzed during the current study are available in the Copernicus Climate Data Store (CDS) repository. The hourly and daily precipitation data, as well as the mid-tropospheric geopotential height and wind field parameters from the ERA5 atmospheric reanalysis (2000–2025), can be publicly accessed and downloaded at <https://cds.climate.copernicus.eu/>. The processed Python scripts used for the maximum-likelihood estimation of the first-order Markov chain, stochastic state simulations, and the generation of transition probability matrices during this study are available from the corresponding author upon reasonable request.

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Figures

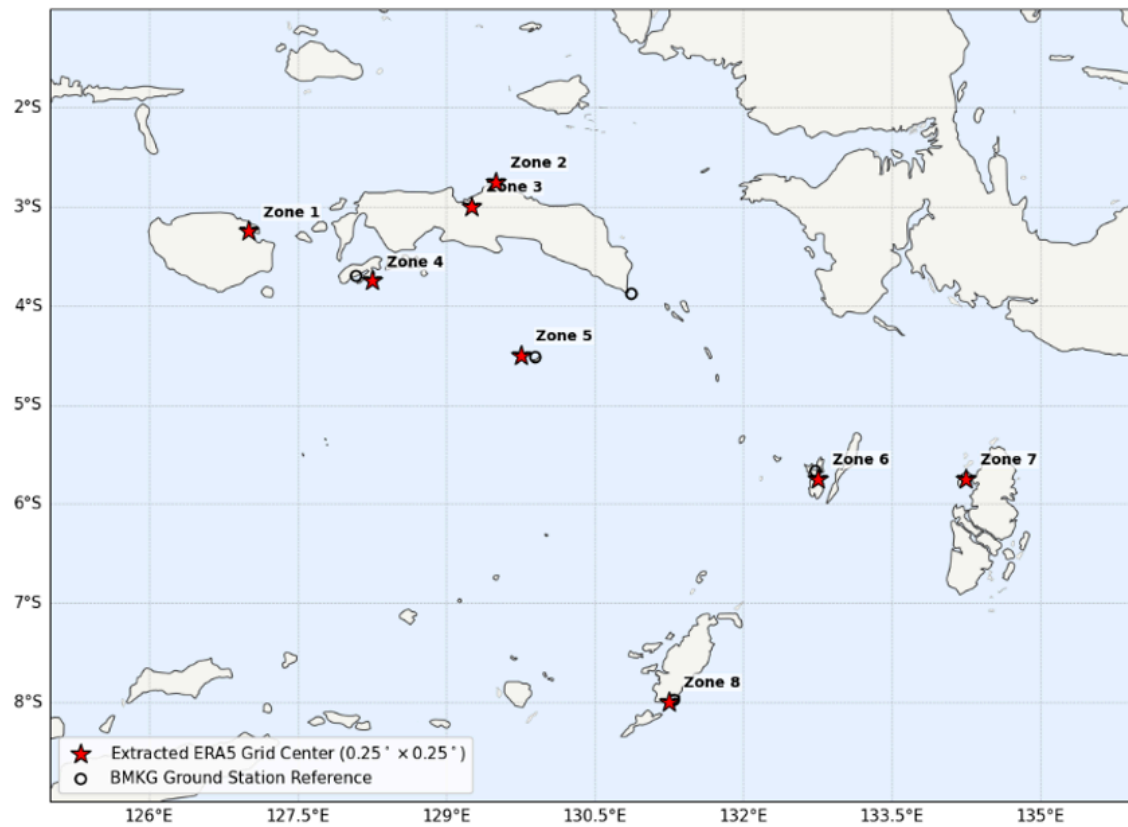


Figure 1. Spatial domain of the Maluku Archipelago and the locations of the eight analyzed climate zones.

Figure 1

Digital elevation map of the Maluku Archipelago showing the locations of the eight ERA5 grid-cell centres selected to represent the study's climate zones, overlaid on terrain contours highlighting the central mountain ranges of Seram and Buru islands.

**Pola Sirkulasi Atmosfer Level 700 hPa
dan Variasi Curah Hujan Harian di Maluku
Periode 2000-2025**

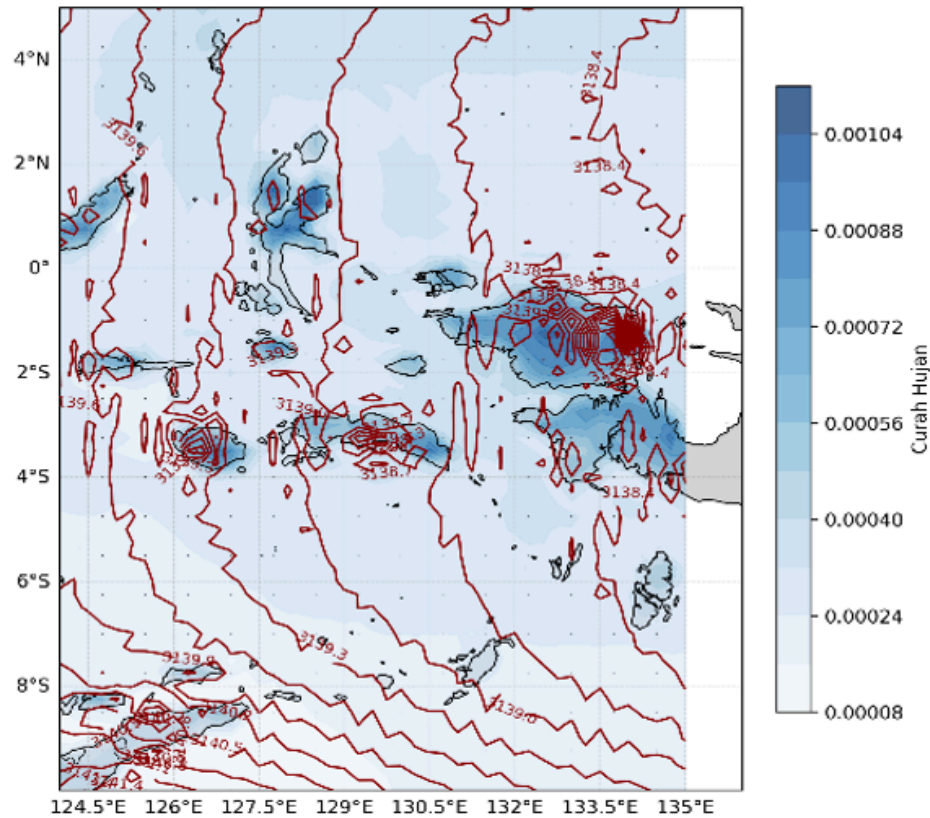


Figure 2

Mean 700 hPa geopotential height field (contours, gpm) and horizontal wind vectors over the Maluku Archipelago and surrounding eastern Indonesian seas, averaged over 2000–2025, illustrating the dominant mid-tropospheric steering flow associated with the Asian–Australian monsoon system.

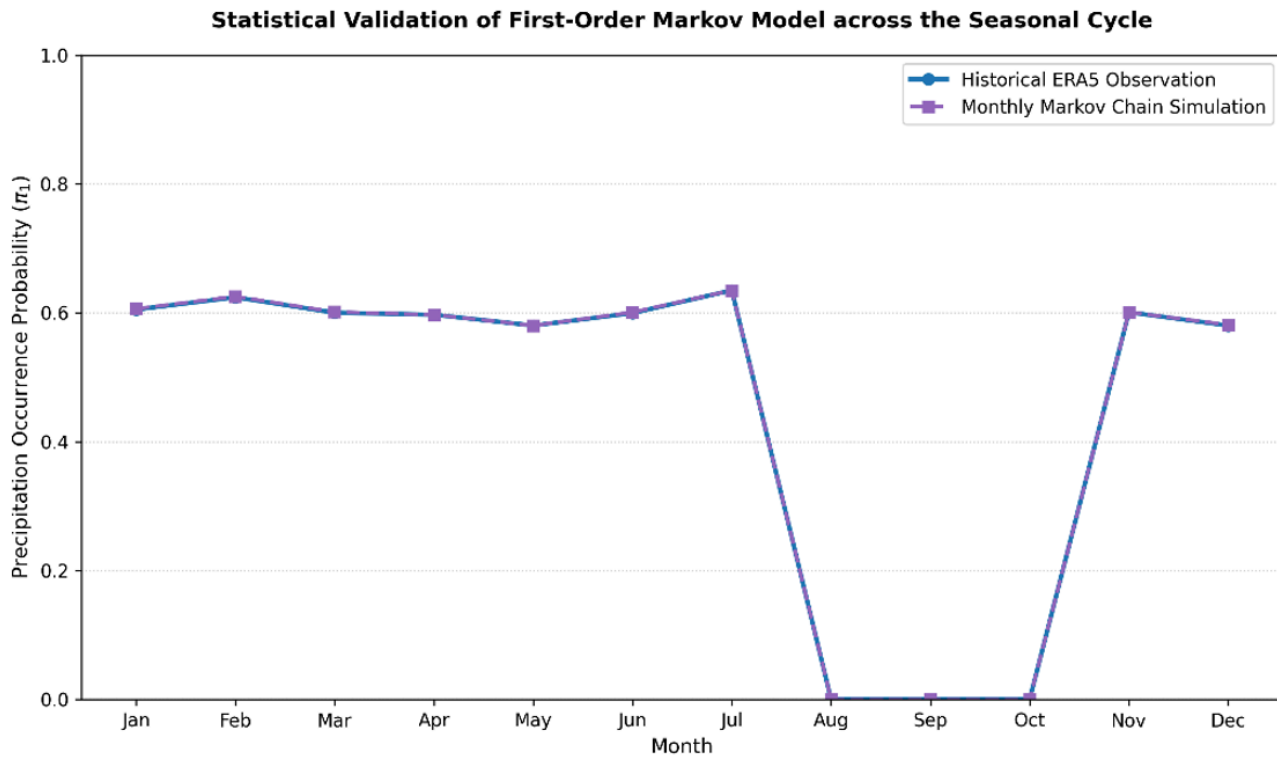


Figure 3

Observed (ERA5-derived) and Markov-chain-reconstructed mean annual cycle of daily precipitation (mm day^{-1}), averaged across the eight climate zones of the Maluku Archipelago, 2000–2025. The correspondence between the two curves indicates that the first-order Markov chain model reproduces the bimodal seasonal precipitation structure, including the early- and mid-year rainfall peaks.

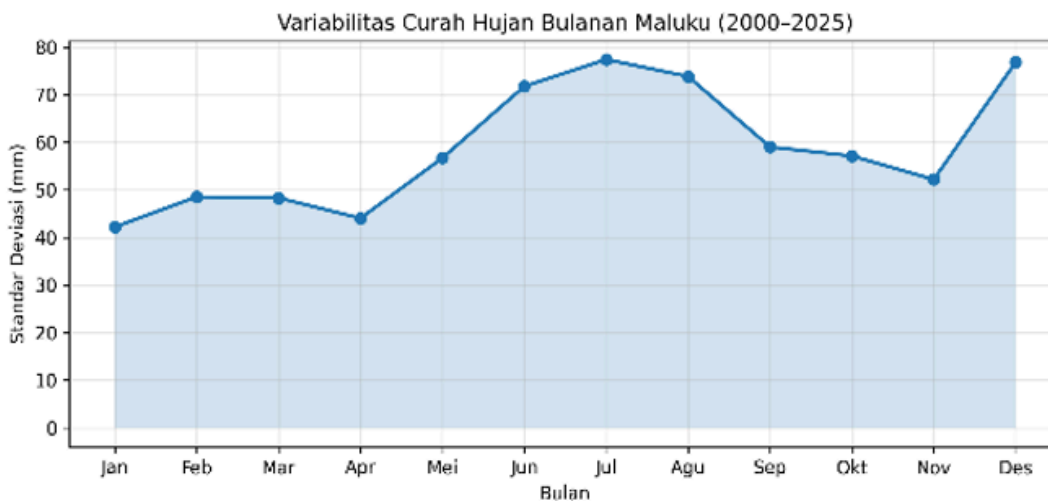


Figure 4

Monthly standard deviation of daily precipitation (mm), averaged across the eight climate zones of the Maluku Archipelago, 2000–2025, illustrating the intra-annual cycle of rainfall variability.