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Transect Analysis of Orographic Precipitation in the Mount Rinjani Region: Case Study of the Sembalun Valley

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Abstract: Rainfall distribution in mountainous regions is powerfully shaped by orography, yet detailed spatial understanding in Indonesia remains limited. This study examines orographic precipitation patterns and rain-shadow effects on Mount Rinjani using two main transects, west–east (WE) and north–south (NS), intersecting the Sembalun Valley. As a representative leeward site, Sembalun is the focal point of analysis, with attention to rainfall variability across timescales and the occurrence of extreme events. Daily rainfall data (~1 km resolution) from CHELSA-W5E5, spanning 1979–2016, were analysed. Results reveal sharp contrasts between windward and leeward slopes. Along the WE transect, rainfall rises toward the summit and declines steeply eastward into Sembalun, producing a structured leeward gradient of 22.6 mm per 100 m compared with a more variable 9.0 mm per 100 m on the windward side. Seasonal analysis highlights December–February as the peak rainfall period due to orographic enhancement, whereas shifting monsoonal winds shift the positions of the windward and leeward slopes along the NS transect. Extreme event analysis reveals that over 38 years, more than 25 days exceeded 50 mm on the western slope, while the east recorded far fewer. These findings confirm classical orographic uplift theory while demonstrating its modulation by monsoonal circulation in a tropical island context. They underscore the role of topography in shaping both overall rainfall patterns and precipitation extremes, with implications for hazard risk, irrigation, and tourism in Sembalun. The study provides a scientific basis for climate adaptation, water conservation, and sustainable land-use in the Rinjani region.

Keywords: Orographic Precipitation, Elevation–Precipitation Gradient, Monsoonal Circulation, Transect Analysis, Mount Rinjani

Introduction

Precipitation is a key element of the global climate system, playing an essential role in sustaining ecosystems, agricultural productivity, and water availability, particularly in mountainous regions (Mamenun et al., 2014). In areas with complex topography, the spatial distribution of rainfall is strongly influenced by orographic precipitation processes, in which moist air masses are forced upward by mountain slopes, undergo cooling, and subsequently condense to produce rainfall. This process generally results in high rainfall on the windward side and a significant reduction on the leeward side, a phenomenon known as the rain shadow effect (Roe, 2005).

Mount Rinjani and its surrounding protected areas form the most critical watershed ecosystem for Lombok Island, sustaining over half a million people across more than 80 villages that depend on forest-derived water resources (Astawa, 2002). The mountain's steep relief and mixed tropical and savanna vegetation define the island's hydrological balance, biodiversity, and socio-economic landscape, creating a setting where orographic effects play a crucial role in shaping water availability and land-use patterns. Recent studies have highlighted the increasing pressure on these resources from tourism expansion, land conversion, and climatic variability (Mahrup et al., 2021). Geodiversity mapping further identifies Rinjani and Sembalun as critical hotspots within the UNESCO Rinjani–Lombok Global Geopark, where geological richness supports both ecosystem services and local livelihoods (Harbowo et al., 2025). Recent assessments of the Government Strategy for Sembalun Tourism Destination emphasize that the valley is now positioned within the Mandalika–Senggigi–Sembalun development triangle, yet still faces significant challenges in spatial coordination, water infrastructure, and sustainable agriculture (Hadi et al., 2025). Limited amenities, uneven access to irrigation, and competition for land between farming and tourism reflect the broader tension between economic growth and ecological carrying capacity. These interlinked pressures underscore the strategic relevance of orographic precipitation studies for guiding regional planning, particularly in designing water-resource management and climate-adaptive tourism strategies in the Sembalun region.

Mount Rinjani on Lombok Island, West Nusa Tenggara, provides a clear example of how orographic precipitation influences local ecosystem structure. Its western slopes are dominated by dense tropical forests (Suripto & Maulidan, 2021), while its eastern side, particularly the Sembalun Valley, is characterized by drier open savanna (**Figure 1**). This vegetation contrast suggests the presence of a sharp spatial rainfall gradient driven by topographic differences, making the area highly relevant for the analysis of localized orographic precipitation (Alfiandy et al., 2020). In this study, Sembalun was selected as the focal area because its savanna landscape indicates potential rain-shadow conditions on the leeward side of Rinjani, as shown in **Figure 1**. This research aims to verify that assumption by quantifying precipitation gradients and extreme rainfall events.

Figure 1. Satellite image of Mount Rinjani, Lombok Island, Indonesia, highlighting the summit crater and the Sembalun Valley on the eastern slope. Vegetation contrasts are evident, with dense tropical forest dominating the western slopes (dark green) and drier savanna characterizing the eastern slopes (yellowish tones). The locations of Mount Rinjani's summit and the Sembalun Valley are annotated as focal sites for the transect-based precipitation analysis.
Source: Google Earth Pro, 2025 imagery

Although orographic precipitation has been extensively studied globally, including detailed investigations in the Alps (Foresti & Pozdnoukhov, 2011), the Andes (Viale & Garreaud, 2015), and tropical islands such as Dominica (Smith et al., 2009), comparable high-resolution analyses in tropical Indonesia remain scarce. These studies have collectively demonstrated that mountainous terrain can drive steep precipitation gradients, enhance convective activity on windward slopes, and generate well-defined rain-shadow zones. For instance, Smith et al. (2009) reported orographic enhancement factors of 2-8 in Dominica due to terrain-forced lifting under persistent trade winds, while Roe et al. (2003) highlighted how orographic precipitation patterns shape mountain morphology. Despite such insights, the absence of similarly detailed and localized studies in Indonesia limits the development of a robust spatial understanding of climate. This research gap limits the availability of reliable local climate information that is essential for land-use planning, climate change adaptation, and drought risk mitigation in mountainous regions.

With increasing climate variability and pressures on natural resources, studies evaluating the relationship between elevation and rainfall distribution are becoming more critical. In this context, spatial transect approaches are effective methods for quantitatively identifying orographic precipitation patterns and the impacts of rain shadows. This research aims to analyse rainfall distribution along two principal transects (west–east and north–

south), selected to align with the dominant north-westerly monsoon winds carrying moisture from the Java Sea to Lombok Island (Mahrup & Idris, 2018). These wind patterns are thought to play an essential role in determining the positions of windward and leeward slopes on Mount Rinjani. Therefore, analysis of these two transects is expected to provide a more comprehensive representation of orographic precipitation mechanisms in the Sembalun Valley, using high-resolution rainfall data (30 arc-seconds, ~1 km) from the CHELSA-W5E5 dataset (Karger et al., 2022).

This study represents one of the first high-resolution transect-based analyses of orographic precipitation in Indonesia. By integrating fine-scale climate data with a spatial transect approach, it provides new insight into how monsoonal circulation and mountain topography interact to shape rainfall gradients and rain-shadow effects in a tropical island setting. Beyond its academic significance, the study also holds practical relevance, as its findings can inform strategies to strengthen the resilience of Sembalun's horticultural agribusiness, which relies heavily on water availability, and to improve risk management for Rinjani mountain tourism. Thus, the research contributes directly to the sustainability of the local economy and livelihoods in the Rinjani highlands.

Methods

Study Location and Scope

This research was conducted in the Mount Rinjani area, Lombok Island, West Nusa Tenggara, with a focus on the Sembalun Valley on the eastern side of the mountain. This region represents a striking ecological transition zone, where tropical forests dominate the western slopes, while the eastern side, particularly around Sembalun, is characterized by dry savanna. This contrast makes the Rinjani region highly relevant for study in the context of orographic precipitation influenced by topography and monsoonal wind directions. Two transects were designed to cross Mount Rinjani, directly intersecting Sembalun as the leeward reference point. All key metrics, such as extreme rainfall days and frequency of >50 mm per day at ~1 km grid resolution, were analysed through Sembalun to ensure consistency when comparing windward and leeward conditions across seasons.

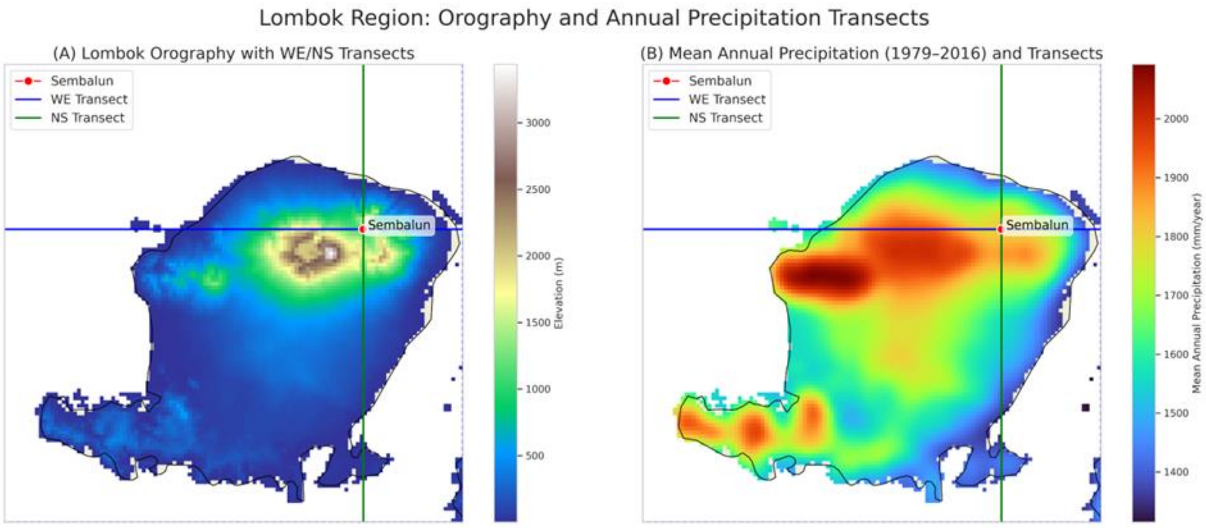

Figure 2. Orography and mean annual precipitation of Lombok Island. (a) Elevation map highlighting Mount Rinjani and the Sembalun Valley, with the west–east (blue) and north–south (green) transects intersecting at Sembalun (red marker). (b) Mean annual precipitation (1979–2016) from CHELSA-W5E5 data, showing enhanced rainfall on the windward slopes and a pronounced rain shadow across the Sembalun region. Data Source: CHELSA-W5E5 (Karger et al., 2022); figure processed by the authors

To identify the spatial distribution of precipitation, two main transects were applied: the west–east (WE) transect and the north–south (NS) transect. **Figure 2** presents the orographic map of Lombok Island, showing the location of the Sembalun station and the two transect lines that cross Mount Rinjani's slopes orthogonally. The selection of transect directions considered the area's complex topography and the dominant northwesterly monsoon winds that transport moisture from the Java Sea to Lombok Island.

Data and Sources

This study employed daily precipitation data from the CHELSA-W5E5 v1.0 dataset, which statistically downscales the W5E5 reanalysis for the Inter-Sectoral Impact Model Intercomparison Project (ISIMIP3a) (Karger et al., 2022). The dataset provides global coverage at 30 arc-seconds (~1 km) spatial resolution for 1979–2016, making it particularly valuable for hydrometeorological analysis in complex mountain terrain (Karger et al., 2023).

The precipitation fields in CHELSA-W5E5 are corrected using the CHELSA v2.1 algorithm, which explicitly accounts for orographic processes. Three main mechanisms are implemented. First, windward–leeward corrections enhance precipitation on windward slopes and reduce it on leeward slopes, simulating rain-shadow effects. Second, wind exposure corrections quantify the angular relationship between slope aspect and near-surface wind vectors from ERA5 to refine rainfall distribution. Third, orographic convection corrections adjust precipitation by incorporating local lapse rates and elevation, capturing enhanced adiabatic cooling and convective uplift at higher altitudes. These corrections are applied using high-resolution slope, aspect, and elevation data from the GMTED2010 digital elevation model (Karger et al., 2017, 2021, 2023).

The main advantage of CHELSA-W5E5 lies in its ability to represent precipitation variability at kilometre scales, which is essential for capturing the steep orographic gradients of Mount Rinjani. The dataset is publicly available through the CHELSA data portal (https://chelsa-climate.org/) with the repository DOI provided by Karger et al. (2022) and methodological details documented in Karger et al. (2023).

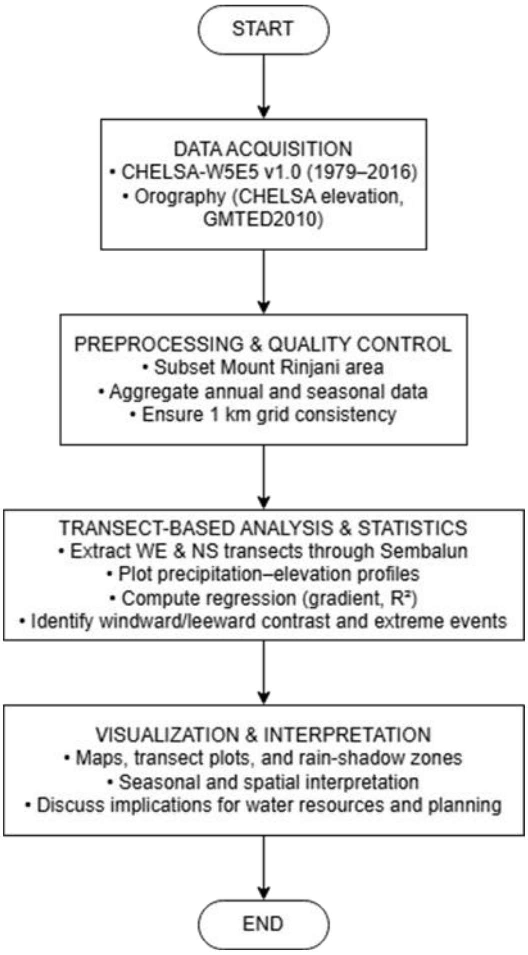

Figure 3. Flowchart summarizing the analytical workflow used in this study. The process includes four main stages: (1) data acquisition, (2) preprocessing and quality control, (3) transect-based spatial and statistical analysis, and (4) visualization and interpretation.

Analytical Procedures

The overall analytical framework of this study followed the sequential steps illustrated in **Figure 3**. The analytical procedures in this study began with the processing of daily precipitation data from CHELSA-W5E5 v1.0 at 1 km spatial resolution for the 1979–2016 period. This dataset was chosen for its ability to represent rainfall in complex terrain and for its systematic integration of orographic components. To maintain consistency across variables, elevation data were also taken from the CHELSA orographic dataset, which is specifically designed to improve topographic representation in high-resolution precipitation models.

Precipitation data were aggregated into annual, seasonal (DJF, MAM, JJA, SON), and climatological daily averages. Spatial analysis was carried out on the two main transects: the west–east (WE) transect at a fixed latitude of −8.36° and the north–south (NS) transect at a fixed longitude of 116.53°. Both were designed to cross Mount Rinjani and the Sembalun area. Precipitation distribution along each transect was plotted together with elevation to evaluate the spatial relationship between topography and rainfall patterns.

Linear regression was used to assess the relationship between elevation and precipitation, both overall and by separating windward and leeward sides based on their relative position to the topographic peak. The precipitation–elevation gradient (mm/100 m) and the coefficient of determination (R^2) were calculated for each slope and season. This analysis enabled the detection of orographic effects and seasonal variation in prevailing wind patterns. Changes in windward and leeward roles, particularly during the dry season (JJA and SON), were also identified, indicating shifts in monsoonal wind direction.

Additionally, extreme events were evaluated based on days with maximum precipitation at the Sembalun grid point and on the spatial distribution of extreme rainfall frequency (greater than 50 mm/day) along the transects. This approach provided further insights into how topography influences not only mean rainfall accumulation but also the probability of high-impact extreme events.

Results and Discussion

This section presents the spatial characteristics of precipitation across multiple timescales in the Mount Rinjani region, with a focus on the Sembalun Valley. The analysis is based on two main transects, west–east (WE) and north–south (NS), strategically selected to represent slope orientation relative to monsoonal winds. Visualizations, including transect graphs and regression scatter plots, illustrate the spatial relationship between precipitation and topography. The results confirm the central role of orography in shaping rainfall patterns and reveal seasonal dynamics that influence the position of windward and leeward slopes. The following subsections systematically discuss the findings at different temporal scales.

Annual Precipitation Transects

The distribution of annual rainfall highlights the dominant role of Mount Rinjani’s topography in shaping regional precipitation patterns in eastern Lombok (**Figure 4**). Rainfall is unevenly distributed across slopes, controlled mainly by slope orientation to monsoonal winds and local elevation.

Along the WE transect, annual precipitation increases sharply from the western lowlands to the mountain crest, reaching approximately 1,950 mm/year—the western slope serves as the primary zone of moisture accumulation from the Java Sea. Beyond the summit, rainfall decreases dramatically on the eastern side, particularly in the Sembalun Valley, underscoring the strong rain-shadow effect. This creates a distinct ecological contrast between dense forest on the west and dry savanna on the east. In contrast, the NS transect displays a more balanced pattern: rainfall gradually increases from the north toward the summit, then declines slowly southward without a sharp drop. This suggests that the north-westerly monsoon winds are not perpendicular to the NS transect, resulting in a more diffuse orographic influence than in the WE transect.

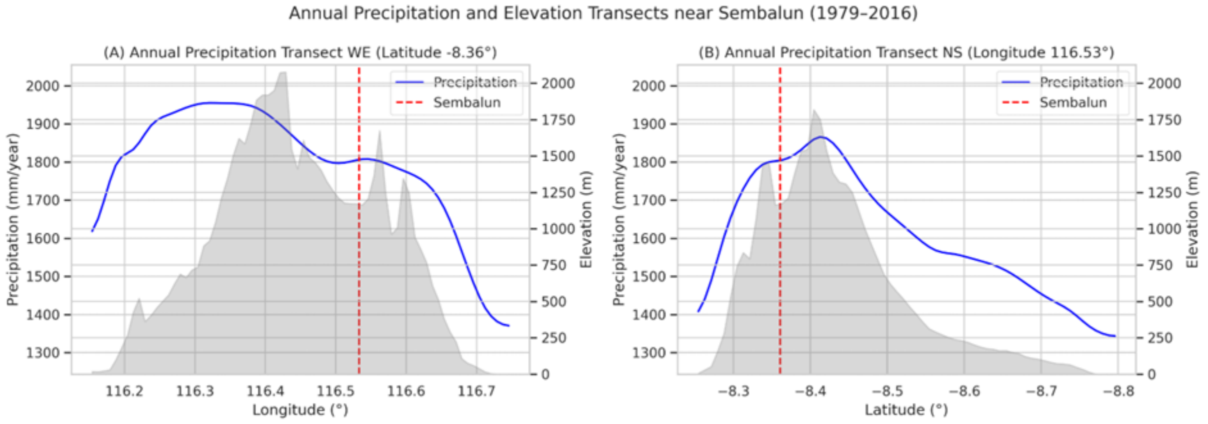

Figure 4. Annual precipitation (blue line) and elevation (gray shading) along (a) the west–east transect at 8.36°S and (b) the north–south transect at 116.53°E for 1979–2016. The red dashed line indicates the location of the Sembalun Valley, used as the central reference point for the transect analysis.

Data source: CHELSA-W5E5 (Karger et al., 2022); figure processed by the authors

Linear regression analysis (**Figure 5**) reveals marked asymmetry. The western (windward) slope shows a precipitation–elevation gradient of 9.0 mm/100 m with $R^2 = 0.42$, reflecting high variability due to a mix of local winds and initial uplift. Conversely, the eastern (leeward) slope is more structured, with a gradient of 22.6 mm/100 m and $R^2 = 0.85$. Although total rainfall is lower, the strong relationship with elevation indicates systematic post-peak drying, consistent with orographic precipitation theory (Roe, 2005).

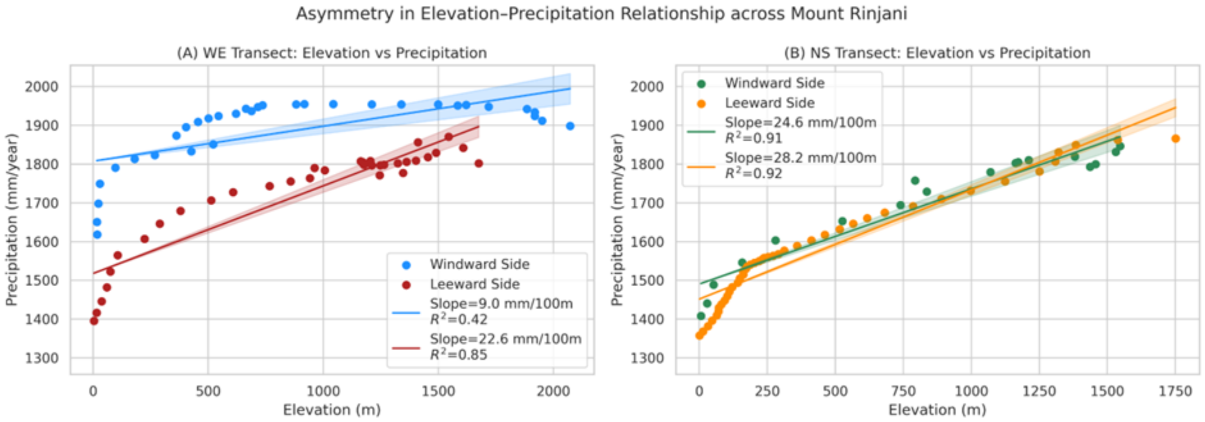

Figure 5. Elevation–precipitation relationships for windward and leeward slopes along (a) the west–east transect and (b) the north–south transect of Mount Rinjani. Regression slopes indicate contrasting precipitation gradients: 9.0 mm 100 m^{-1} ($R^2 = 0.42$) on the windward versus 22.6 mm 100 m^{-1} ($R^2 = 0.85$) on the leeward side of the west–east transect, and 24.6 mm 100 m^{-1} ($R^2 = 0.91$) versus 28.2 mm 100 m^{-1} ($R^2 = 0.92$) for the north–south transect.

Data source: CHELSA-W5E5 (Karger et al., 2022); figure processed by the authors

Along the NS transect, the distribution is more symmetrical. Rainfall increases from the north toward the summit, then decreases gradually to the south without the sharp decline seen along the WE transect. Regression analysis shows gradients of 24.6 mm/100 m ($R^2 = 0.91$) on the northern slope and 28.2 mm/100 m ($R^2 = 0.92$) on the southern slope. The high R^2 values indicate that elevation remains a dominant predictor of rainfall. This symmetry reflects both the oblique orientation of the north-westerly monsoon relative to the NS transect and the broader meridional slope structure.

Overall, the annual analysis reveals a classical orographic pattern: western and northern slopes function as windward zones with high precipitation. In contrast, the eastern (Sembalun) and southern slopes are leeward zones with lower rainfall. The enhancement of rainfall on windward slopes aligns with moist air uplift, whereas rainfall reduction on leeward slopes reflects post-condensation drying (Smith et al., 2009). This pattern not only confirms orographic theory but also explains the long-term ecological contrasts and water availability across the Rinjani region.

Seasonal Precipitation Transects

While annual patterns highlight the dominance of topography, rainfall distribution over Rinjani is also shaped by monsoonal dynamics that vary throughout the year. Seasonal analysis (**Figure 6**) shows that December–February (DJF) is the peak rainfall period along both the west–east (WE) and north–south (NS) transects, coinciding with the arrival of north-westerly monsoon winds from the Java Sea. Maximum rainfall is recorded on the western slopes, followed by a sharp decline beyond the summit, especially in Sembalun, demonstrating a pronounced rain-shadow effect. In contrast, March–May (MAM), June–August (JJA), and September–November (SON) are relatively drier, particularly JJA when southeasterly winds reduce the moisture supply to Lombok.

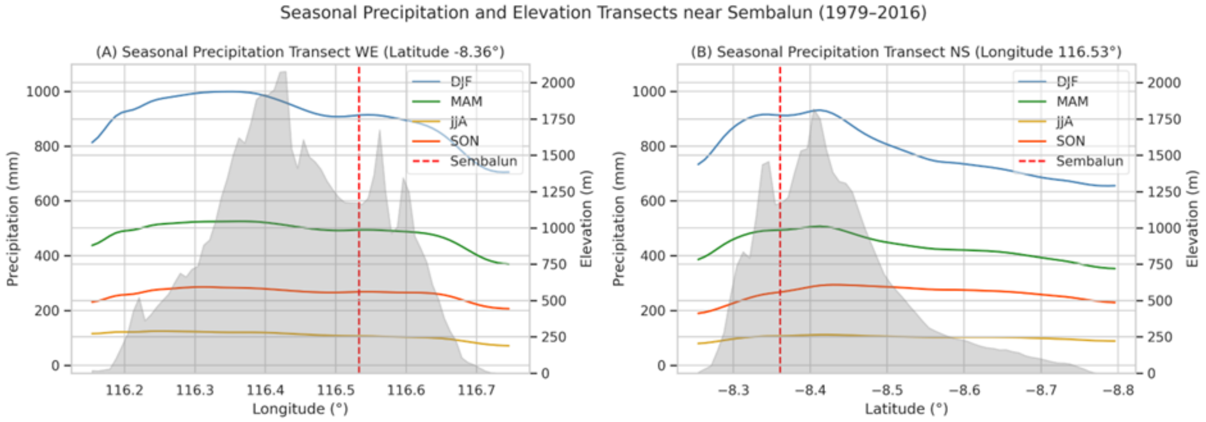

Figure 6. Seasonal precipitation (lines) and elevation (gray shading) along (a) the west–east transect at 8.36°S and (b) the north–south transect at 116.53°E near Sembalun, Mount Rinjani, for 1979–2016. Precipitation is shown for December–February (DJF, blue), March–May (MAM, green), June–August (JJA, yellow), and September–November (SON, red). The red dashed line marks the location of Sembalun.
Data source: CHELSA-W5E5 (Karger et al., 2022); figure processed by the authors

On the WE transect, DJF shows a sharp rainfall increase on the western slopes, reaching maximum values at the summit, then declining steeply eastward, especially across Sembalun. This pattern reflects the rain-shadow phenomenon, where air that has lost its moisture at the summit descends dry on the leeward side. During MAM, JJA, and SON, rainfall is more evenly distributed at lower magnitudes, with JJA representing the driest season. The NS transect, however, exhibits a more symmetrical gradient from north to south. During DJF and MAM, the northern slope is wetter, consistent with north-westerly monsoon inflow. In SON and JJA, southeasterly winds enhance rainfall on the southern slope, reversing windward and leeward conditions.

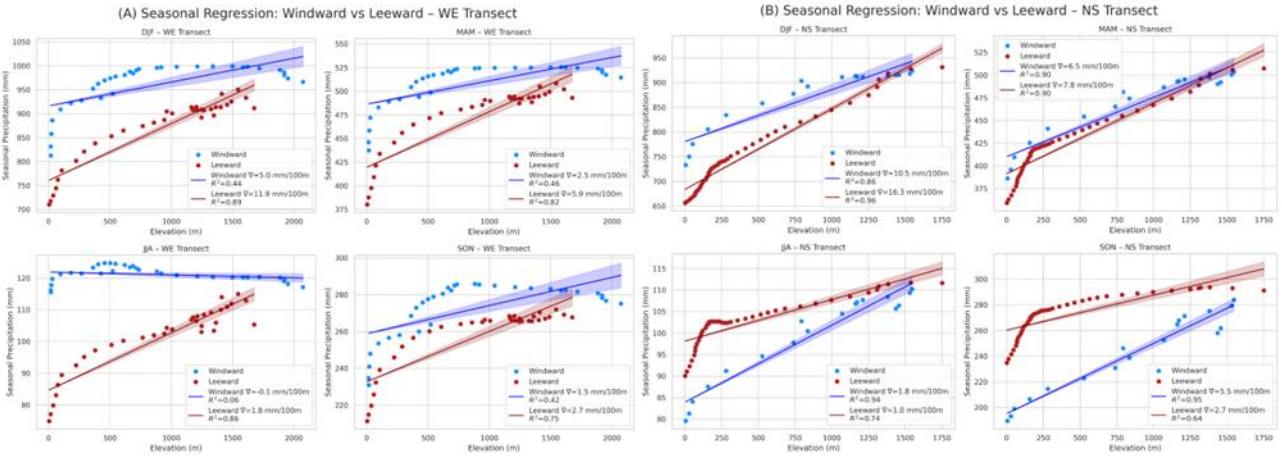

Figure 7. Seasonal elevation–precipitation regressions for windward and leeward slopes along (a) the west–east transect and (b) the north–south transect of Mount Rinjani for 1979–2016. Each panel shows linear regressions for December–February (DJF), March–May (MAM), June–August (JJA), and September–November (SON), highlighting seasonal shifts in orographic gradients and asymmetry between windward and leeward slopes. Data source: CHELSA-W5E5 (Karger et al., 2022); figure processed by the authors

To evaluate the elevation–precipitation relationship across seasons, separate linear regressions were conducted for windward and leeward slopes (**Figure 7**). Results show that precipitation gradients vary by season and slope. On the WE transect, the western slope is consistently wetter than the east. During DJF, the windward gradient was 5.0 mm/100 m ($R^2 = 0.44$), while the leeward slope showed a steeper gradient of 11.9 mm/100 m ($R^2 = 0.89$). The higher R^2 values on the leeward side indicate a more structured vertical distribution despite lower rainfall volumes. Similar trends were observed in other seasons, though with weaker magnitudes during the dry months.

The NS transect shows more pronounced seasonal shifts. In DJF and MAM, the northern slope acts as the windward side, with higher rainfall accumulation and relatively gentle gradients (e.g., DJF: 10.5 mm/100 m, $R^2 = 0.86$ vs. 16.3 mm/100 m, $R^2 = 0.96$). This pattern reverses during SON and JJA, when southeasterly winds enhance precipitation on the southern slope (e.g., SON: 5.5 mm/100 m, $R^2 = 0.95$ vs. 2.7 mm/100 m, $R^2 = 0.64$). This shift indicates a seasonal reversal of windward–leeward conditions driven by monsoonal rotation.

Overall, the seasonal regressions maintain positive precipitation–elevation gradients, but slope orientation strongly influences sensitivity. The WE transect, aligned with the north-westerly monsoon, displays a more stable pattern year-round, whereas the NS transect is more responsive to seasonal wind shifts.

Daily Precipitation Transects and Extreme Rainfall Conditions

Seasonal analysis does not fully capture intraseasonal variability and extreme events. Therefore, this section highlights average daily rainfall patterns and extreme rainfall in the Rinjani region, with emphasis on Sembalun's position in the leeward zone. The average daily rainfall distribution (**Figure 8**) is consistent with the annual pattern: rainfall increases across the western and northern slopes toward the summit, then declines sharply eastward and southward. On the windward side, daily averages exceed 5.0 mm/day, while the leeward side records lower values but still exhibits a clear spatial structure.

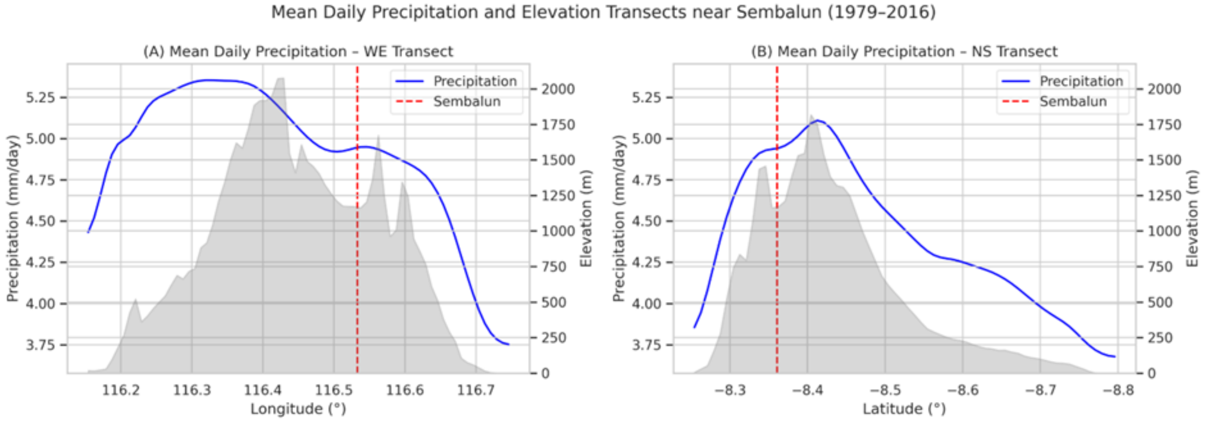

Figure 8. Mean daily precipitation (blue line) and elevation (gray shading) along (a) the west–east transect at 8.36°S and (b) the north–south transect at 116.53°E near Sembalun, Mount Rinjani, for 1979–2016. The red dashed line indicates the location of the Sembalun Valley, which serves as the central reference point for analysis.

Data source: CHELSA-W5E5 (Karger et al., 2022); figure processed by the authors

The maximum rainfall day was recorded on 7 January 2013, when Sembalun registered 83.3 mm/day (**Figure 9**). The distribution during this event shows a surge of precipitation on the western and northern slopes, followed by a steep decline toward the east and south, reflecting intensified orographic uplift under an active north-westerly monsoon. This event highlights the vulnerability of Rinjani's windward slopes to heavy rainfall. At the same time, the leeward effect in Sembalun reduced total rain, although the area was still affected by the extreme event.

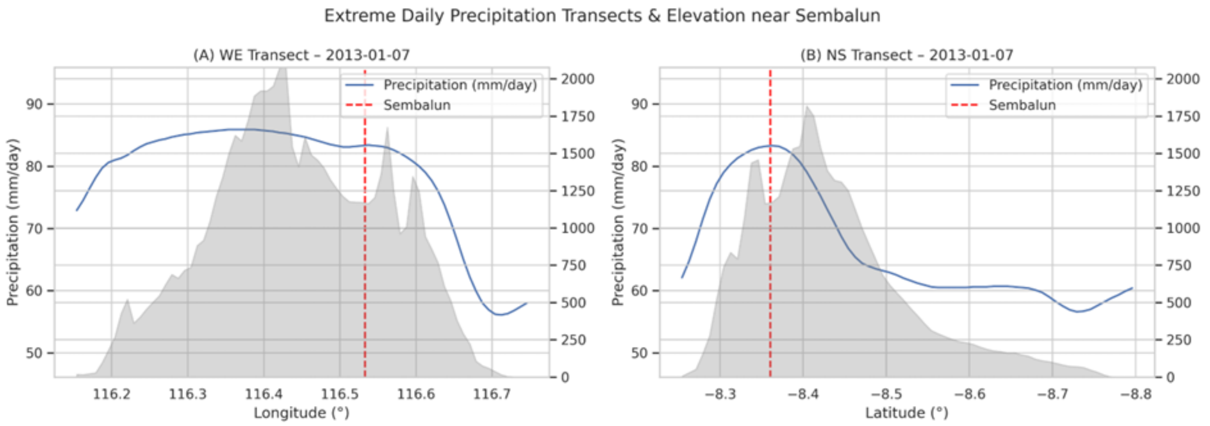

Figure 9. Extreme daily precipitation (blue line) and elevation (gray shading) along (a) the west–east transect at 8.36°S and (b) the north–south transect at 116.53°E near Sembalun, Mount Rinjani, during the 7 January 2013 event. The red dashed line indicates the position of the Sembalun Valley.

Data source: CHELSA-W5E5 (Karger et al., 2022); figure processed by the authors

The distribution of extreme rainfall frequency >50 mm/day (**Figure 10**) further demonstrates the role of topography in regulating heavy rainfall over Rinjani. Along the WE transect, more than 25 events were recorded over 38 years on the western slope (116.25°–116.45°), whereas the eastern side recorded fewer than 10. Along the NS transect, the pattern is more gradual: peak frequency occurs on the northern slope near the summit (~−8.44°) and decreases progressively southward. Although more balanced than the WE transect, the rain-shadow effect is still evident, particularly during the dry season, as indicated by seasonal analysis.

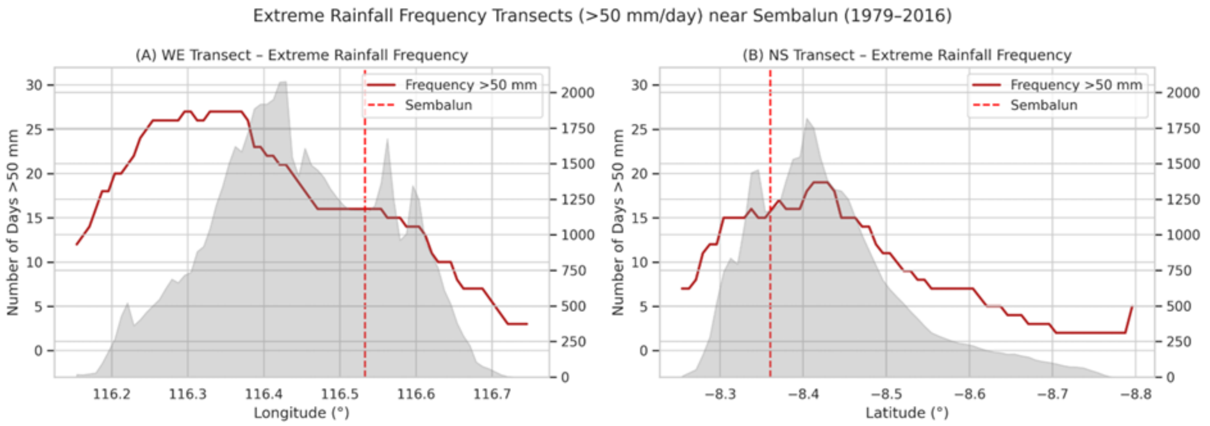

Figure 10. Frequency of extreme rainfall events exceeding 50 mm day^{-1} (red line) and elevation (gray shading) along (a) the west–east transect at 8.36°S and (b) the north–south transect at 116.53°E near Sembalun, Mount Rinjani, for 1979–2016. The red dashed line marks the location of the Sembalun Valley.

Data source: CHELSA-W5E5 (Karger et al., 2022); figure processed by the authors

Overall, Rinjani's topography not only enhances total annual and daily precipitation but also increases the probability of extreme rainfall on high-elevation windward slopes. Consequently, the western and northern slopes are more vulnerable to hydrometeorological hazards than the leeward areas such as Sembalun.

Discussion

The precipitation transects over Mount Rinjani confirm that topography not only governs rainfall gradients but also dictates the spatial distribution of water resources and disaster risks. The western and northern windward slopes receive substantially higher rainfall and more frequent extreme events, which heighten their susceptibility to flash floods and landslides, particularly during the December to January monsoon peak. Comparable orographic intensification has been observed globally. In the Caribbean Island of Dominica, Smith et al. (2009) reported enhancement factors of 2 to 8 under persistent trade winds, while Viale and Garreaud (2015) documented nearly doubled precipitation from the Pacific coast to the windward slopes of the Andes. The substantial windward enhancement on Rinjani thus parallels established global patterns, though the seasonal modulation by monsoonal reversals distinguishes the Indonesian setting.

By contrast, the Sembalun Valley on the eastern leeward side experiences lower rainfall totals and exhibits a more structured elevation–precipitation relationship. This is consistent with the sharp rain shadows documented in Dominica (Smith et al., 2009) and the European Alps, where Foresti & Pozdnoukhov (2011) showed that persistent upwind precipitation cells leave leeward slopes substantially drier. Rinjani’s pronounced leeward gradient (22.6 mm per 100 m) reflects the same processes, yet its tropical island context creates unique vulnerabilities to seasonal drought and irrigation stress. These findings underscore the importance of water conservation strategies for sustaining horticultural production, including highland vegetables and strawberries, which depend on a reliable water supply.

Daily variability and extreme precipitation events also carry significant implications for Rinjani’s trekking tourism. Trails on the western and northern flanks, where rainfall is concentrated, require proactive management strategies to mitigate landslide and flash-flood risks. This mirrors global observations, in which orographic extremes drive acute hazard exposure: in the Andes, frontal systems enhanced by orographic uplift have been shown to increase upstream ice and precipitation loading, amplifying hydrological risks (Viale & Garreaud, 2015). Mapping the distribution of extreme rainfall over Rinjani similarly provides a scientific basis for defining safe trekking seasons, optimizing route planning, and strengthening evacuation preparedness.

Beyond immediate hazard and resource implications, the broader significance of these findings lies in their contribution to understanding climate–topography interactions. Roe (2005) emphasized that orographic precipitation is among the most robust climate gradients globally, yet it varies with circulation and terrain. Roe et al. (2003) further demonstrated that such precipitation patterns interact with erosion to shape mountain morphology, linking climatological processes with long-term geomorphic evolution. The strong leeward drying and seasonal reversals observed over Rinjani extend these theoretical insights into a tropical island context, where orographic controls influence both hazard distribution and landscape evolution.

Finally, the methodological application of CHELSA-W5E5 highlights the value and challenges of using high-resolution gridded climate datasets in mountainous regions. Although the dataset improves upon coarse-resolution reanalyses, its accuracy is constrained by sparse station coverage, gauge bias, and simplified orographic downscaling (Karger et al., 2017, 2021, 2023). Mean precipitation is well represented, but extreme daily events tend to be underestimated, and temporal coverage ends in 2016, omitting more recent anomalies. These limitations should be considered when applying the results for operational planning. Future research should combine CHELSA products with local rain-gauge networks, remote sensing retrievals, and high-resolution convection-permitting models to improve the representation of extremes and capture climate variability. Such efforts would strengthen the reliability of precipitation–elevation analyses and enhance their utility for disaster risk reduction and climate adaptation in tropical mountain regions.

Taken together, the findings situate Rinjani within a global framework of orographic precipitation research while simultaneously highlighting region-specific dynamics driven by monsoonal winds. This dual perspective provides both practical insights for water management, agriculture, and tourism safety, and a scientific contribution by extending high-resolution transect analysis to a tropical island mountain system.

Conclusion

This study demonstrates that the topography of Mount Rinjani consistently shapes rainfall distribution through orographic uplift, confirming the theoretical framework of windward enhancement and leeward rain shadow effects. The western and northern slopes receive substantially higher rainfall, while the Sembalun Valley on the eastern side lies under a pronounced rain shadow. This asymmetry is evident in the steep, structured precipitation–elevation gradient on the leeward slope, compared with the gentler, more variable gradient on the windward slope. Monsoonal dynamics further modulate these patterns by shifting windward and leeward positions seasonally. At the same time, extreme rainfall analyses reveal that heavy events occur more frequently on the windward side than in Sembalun.

The findings highlight topography as a key factor in climate adaptation, water resource management, and disaster risk mitigation in mountainous regions. Windward slopes are more prone to flash floods and landslides, while leeward zones face seasonal drought and irrigation limitations. The practical implications are highly relevant for Sembalun's economy, which depends on highland horticulture (vegetables and strawberries) and nature-based tourism. Knowledge of rainfall gradients and extreme event risks can support irrigation strategies, adaptive planting schedules, and safer management of trekking routes and seasons.

By providing one of the first high-resolution transect-based analyses of orographic precipitation in Indonesia, this study addresses a critical research gap in understanding localized mountain climates. Future work should integrate rain-gauge networks and satellite observations to validate and refine rainfall event representations. Such efforts would enhance the reliability of rainfall estimates and strengthen their application for water management, land-use planning, and climate resilience in tropical mountain systems.

References

Alfiandy, S., Hutauruk, R., & Permana, D. (2020). Peran dinamika laut dan topografi terhadap pola hujan tipe lokal di wilayah Kota Palu. *Depik, 9*(2), 173–183. https://doi.org/10.13170/depik.9.2.16106

Astawa, B. (2002). Finding common ground in Rinjani, Lombok, Indonesia: Towards improved governance, conflict resolution, and institutional reform. *IASCP Panel Paper*, Field Team Coordinator for the Rinjani Participatory Action Research Program.

Foresti, L., & Pozdnoukhov, A. (2011). Exploration of alpine orographic precipitation patterns with radar image processing and clustering techniques. *Meteorological Applications, 19*(4), 407–419. https://doi.org/10.1002/met.272

Hadi, Y., Daraba, D., Ilham, M., & Achmad, M. (2025). Government strategy for Sembalun tourism destination in East Lombok Regency to support Mandalika as a super priority tourism destination. *Journal of Humanities and Social Sciences Studies, 7*(6), 47–73. https://doi.org/10.32996/jhsss.2025.7.6.7

Harbowo, D. G., & Siringoringo, L. P. (2025). Locating geodiversity hotspots through grid-based spatial indexing: Lombok Island, Indonesia. *Journal of Geoscience, Engineering, Environment, and Technology, 10*(2), 215–223. https://doi.org/10.25299/jgeet.2025.10.02.18898

Karger, D. N., Conrad, O., Böhner, J., Kawohl, T., Kreft, H., Soria-Auza, R. W., … Zimmermann, N. E. (2017). Climatologies at high resolution for the Earth's land surface areas. *Scientific Data, 4*, 170122. https://doi.org/10.1038/sdata.2017.122

Karger, D. N., Lange, S., Hari, C., Reyer, C. P. O., & Zimmermann, N. E. (2022). *CHELSA-W5E5 v1.0: W5E5 v1.0 downscaled with CHELSA v2.0* [Data set]. ISIMIP Repository. https://doi.org/10.48364/ISIMIP.836809.1

Karger, D. N., Lange, S., Hari, C., Reyer, C. P. O., & Zimmermann, N. E. (2023). CHELSA-W5E5 v1.0: W5E5 v1.0 downscaled with CHELSA v2.0. *Earth System Science Data, 15*(6), 2445–2464. https://doi.org/10.5194/essd-15-2445-2023

Karger, D. N., Wilson, A. M., Mahony, C. R., Zimmermann, N. E., & Jetz, W. (2021). Global daily 1 km land surface precipitation based on cloud cover frequency downscaling. *Scientific Data, 8*, 307. https://doi.org/10.1038/s41597-021-01084-6

Mahrup, & Idris, M. H. (2018). Asal awan konvektif pembawa hujan lokal di Pulau Lombok. *Prosiding Konferensi Nasional Pengabdian Kepada Masyarakat dan Corporate Social Responsibility (PKM-CSR), 1*, 325–339.

Mahrup, M., Ma'shum, M., Idris, M. H., & Fahrudin, F. (2021). The future of Wallace region in Lombok: The pristine natural resource under climatic and anthropogenic threat. *IOP Conference Series: Earth and Environmental Science, 913*(1), 012049. https://doi.org/10.1088/1755-1315/913/1/012049

Mamenun, Pawitan, H., & Sopaheluwakan, A. (2014). Validasi dan koreksi data satelit TRMM pada tiga pola hujan di Indonesia. *Jurnal Meteorologi dan Geofisika, 15*(1). https://doi.org/10.31172/jmg.v15i1.169

Roe, G. H. (2005). Orographic precipitation. *Annual Review of Earth and Planetary Sciences, 33*, 645–671. https://doi.org/10.1146/annurev.earth.33.092203.122541

Roe, G. H., Montgomery, D. R., & Hallet, B. (2003). Orographic precipitation and the relief of mountain ranges. *Journal of Geophysical Research: Atmospheres, 108*(B6). https://doi.org/10.1029/2001JB001521

Smith, R. B., Schäfer, P., Kirshbaum, D., & Regina, E. (2009). Orographic precipitation in the tropics: Experiments in Dominica. *Journal of the Atmospheric Sciences, 66*(6), 1698–1716. https://doi.org/10.1175/2008JAS2920.1

Suripto, & Maulidan, Y. (2021). Orchid identification and collection techniques in the Kembang Kuning Resort Area, Rinjani Mount National Park (RMNP). *Jurnal Pengabdian Magister Pendidikan IPA, 4*(4), 474–480. https://doi.org/10.29303/jpmpi.v4i4.1246

Viale, M., & Garreaud, R. (2015). Orographic effects of the subtropical and extratropical Andes on upwind precipitating clouds. *Journal of Geophysical Research: Atmospheres, 120*(10), 4962–4974. https://doi.org/10.1002/2014JD023014