Jurnal Penelitian Fisika dan Terapannya (Jupiter), 7 (2), 2026
Available online at: http://jurnal.univpgri-palembang.ac.id/index.php/Jupiter
DOI: 10.31851/jupiter.v7i2. 19665

Topographic Enhancement of Extreme Rainfall in IKN Nusantara Based on Multi-Satellite Observations

David F. Sinaga[1], Fira Humaira[1], Khezia T. J. Sinurat[1], Fataya A. R. Priatnam[1], Jogi Panggabean[1]*
[1]Marine Science Program, Faculty of Fisheries and Marine Sciences, Padjadjaran University, Sumedang 45363, Indonesia
**email: jogi22001@mail.unpad.ac.id*

Received: 18 07 2025. Accepted: 23 01 2026. Published: 02 2026

Abstract

Indonesia's new capital city (IKN Nusantara) in East Kalimantan experienced devastating extreme rainfall on March 15-16, 2022, with mesoscale convective systems causing widespread flooding. This study aims to quantify the contribution of topographic forcing to extreme precipitation enhancement during the March 2022 event in IKN Nusantara. Daily GPM IMERG precipitation data, ERA5 reanalysis, and SRTM digital elevation models were employed to examine rainfall-topography relationships across IKN's complex terrain (elevation 0-812m). Results revealed counter-intuitive findings with a significant negative correlation between elevation and precipitation (r = -0.328, p < 0.01), contrasting classical orographic theory. The optimal precipitation zone occurred at 200-300m ASL (393.4 mm) with a 20% degradation at higher elevations. Forcing decomposition indicated that combined local effects contributed 41.5% of total precipitation, with topography contributing 17.5%. Cross-sectional analysis revealed a complex temporal evolution of orographic mechanisms with extreme spatial variability during the extreme event. These findings challenge the conventional understanding of tropical orographic precipitation and provide critical insights for infrastructure planning in Indonesia's new capital.

***Keywords**: Orographic precipitation, Mesoscale convective systems, Satellite precipitation, IKN Nusantara, Extreme rainfall*

INTRODUCTION

Extreme precipitation events in tropical regions are increasingly recognized as complex phenomena involving interactions between large-scale atmospheric dynamics and local environmental factors (Houze et al. 2015; Roca and Fiolleau 2020). Indonesia's new capital city (IKN Nusantara) in East Kalimantan experienced a devastating extreme rainfall event on March 15-16, 2022, where mesoscale convective systems (MCS) produced intense precipitation leading to widespread flooding and significant economic losses (Hermawan et al. 2025). This event highlighted the critical need to understand precipitation mechanisms in complex terrain environments, particularly for infrastructure planning and disaster risk management in developing regions.

Previous research has shown that MCSs are key drivers of extreme precipitation in tropical regions. Their intensity and duration are influenced by both large-scale atmospheric conditions and local environmental factors. (Nuryanto et al. 2019; Da Silva and Haerter 2023). Hermawan et al., (2025) demonstrated that the March 2022 IKN event was primarily caused by MCS interactions with large-scale atmospheric phenomena, including the Madden-Julian Oscillation (MJO) and equatorial waves, which contributed up to 80% of moisture flux convergence during the growth phase. However, their analysis also identified significant contributions from a "residual term" in the water vapor budget, which could not be fully explained by large-scale forcing alone. The presence of this residual component strongly suggests that local forcing mechanisms, particularly topographic effects, played important but unquantified roles in precipitation enhancement, forming the primary motivation for the present investigation (Panggabean et al., 2025).

Orographic precipitation enhancement is a well-documented phenomenon where terrain features modify precipitation patterns through various physical mechanisms, including forced lifting, flow blocking, and seeder-feeder processes (Kunz and Kottmeier 2006; Roe 2005). Studies in different geographic regions have shown enhancement factors ranging from 2-8 times reference precipitation, depending on terrain characteristics, atmospheric stability, and moisture availability (Adhikari and Behrangi 2022; Colle 2004). However, most of these studies were conducted in high-elevation mountain regions with different characteristics compared to low-elevation tropical hills like those found in IKN.

The Indonesian Maritime Continent, with its complex topography and warm ocean surroundings, poses unique challenges for studying precipitation processes. (Norman and Trilaksono 2019; Sudarman et al. 2024). Recent advances in satellite remote sensing, particularly high-resolution precipitation products from the Global Precipitation Measurement (GPM) mission, provide unprecedented opportunities to study orographic effects in data-sparse tropical regions (Sun and Tang 2020; Tan et al. 2015).

Understanding how topography influences extreme rainfall in Indonesia is crucial for assessing flood risks, developing early warning systems, and planning infrastructure for the country's new capital city. (Panggabean et al., 2025).

This study aims to quantify the impact of topographic features on extreme precipitation during the March 2022 event in IKN Nusantara by: (1) analyzing the spatial relationship between terrain elevation and precipitation patterns, (2) separating total precipitation into large-scale and local forcing components, and (3) identifying optimal elevation zones for orographic enhancement. This research fills important gaps in knowledge by offering the first comprehensive satellite-based analysis of topographic precipitation enhancement mechanisms in Indonesia's new capital region.

MATERIALS AND METHODS

The study focuses on Indonesia's new capital city (IKN Nusantara) located in East Kalimantan (0.5°S-2.0°S, 116.0°E-118.0°E), encompassing portions of North Penajam Paser Regency and Kutai Kartanegara Regency. The region features complex topography with elevations ranging from sea level to 812 meters ASL, characterized by rolling hills, river valleys, and mountainous terrain in the southwestern portions. The area experiences a tropical climate with annual precipitation exceeding 2500mm, with distinct wet (November-April) and dry (May-October) seasons modulated by monsoon circulation patterns.

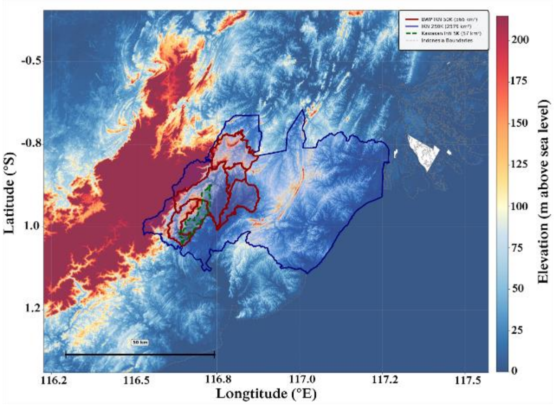

Figure 1. Study area map of IKN Nusantara showing topographic elevation, dministrative boundaries, and location in East Kalimantan, Indonesia.

Daily precipitation data were obtained from the Global Precipitation Measurement (GPM) Integrated Multi-satellite Retrievals for GPM (IMERG) Final Product Version 06 (Huffman et al. 2020). IMERG provides precipitation estimates at 0.1° spatial resolution with daily temporal coverage. Atmospheric fields were obtained from the European Centre for Medium-Range Weather Forecasts (ECMWF) ERA5 reanalysis dataset (Hersbach et al. 2020) at 0.25° spatial resolution. High-resolution terrain information was derived from the Shuttle Radar Topography Mission (SRTM) Digital Elevation Model at 90-meter spatial resolution (Farr et al. 2007). Administrative boundaries were obtained from official IKN shape files including general delineation, development zones, and core areas.

To harmonize the different spatial resolutions of the datasets, the SRTM DEM (90m) was aggregated to match the IMERG grid (0.1° ≈ 11km at equator) using bilinear resampling for elevation values and spatial averaging for slope calculations. ERA5 data (0.25° resolution) were spatially interpolated to the IMERG grid using bilinear interpolation to ensure consistent spatial registration for cross-dataset analysis. All datasets were reprojected to a common geographic coordinate system (WGS84) prior to analysis.

Topographic enhancement factors were calculated using the following equation:

$$(EF) = \frac{Precipitation_{terrain}}{Precipitation_{reference}}$$

where reference precipitation was defined as mean rainfall over flat terrain areas (elevation < 50m).

Subsequently, statistical relationships between elevation and precipitation were examined using correlation analysis and linear regression techniques. Elevation data were binned into categories (0-50m, 50-100m, 100-200m, 200-300m, >300m) to assess precipitation distribution characteristics.

Total precipitation was decomposed into large-scale and local forcing components following Hermawan et al., (2025):

$$P_{total} = P_{large} - \text{scale} + P_{local} + P_{residual}$$

where Ptotal is the total observed precipitation, Plarge-scale represents large-scale atmospheric forcing contributions derived from ERA5 atmospheric fields, Plocal represents local forcing effects estimated as the difference between total observed precipitation and large-scale components, and Presidual represents unresolved processes.

Large-scale forcing contributions were calculated using ERA5 atmospheric fields, while local forcing effects were estimated by subtracting the total observed precipitation from the large-scale components.

West-east cross-sections were extracted through areas with the highest precipitation to analyze orographic lifting patterns and precipitation distribution in relation to terrain features.

Statistical significance was assessed using Student's t-tests and ANOVA, with all tests conducted at a significance level of α = 0.05.

RESULTS AND DISCUSSION

The analysis of temporal precipitation patterns in March 2022 showed significant variability, with intensities ranging from 0 to 147 mm/week and a mean of 71 mm/week (Figure 2). Week 3 (March 15-21, 2022) had the highest intensities, with highly diverse spatial patterns, including the extreme event on March 15-16, 2022. The maximum precipitation zones were concentrated in the eastern and northern regions, with sharp intensity gradients.

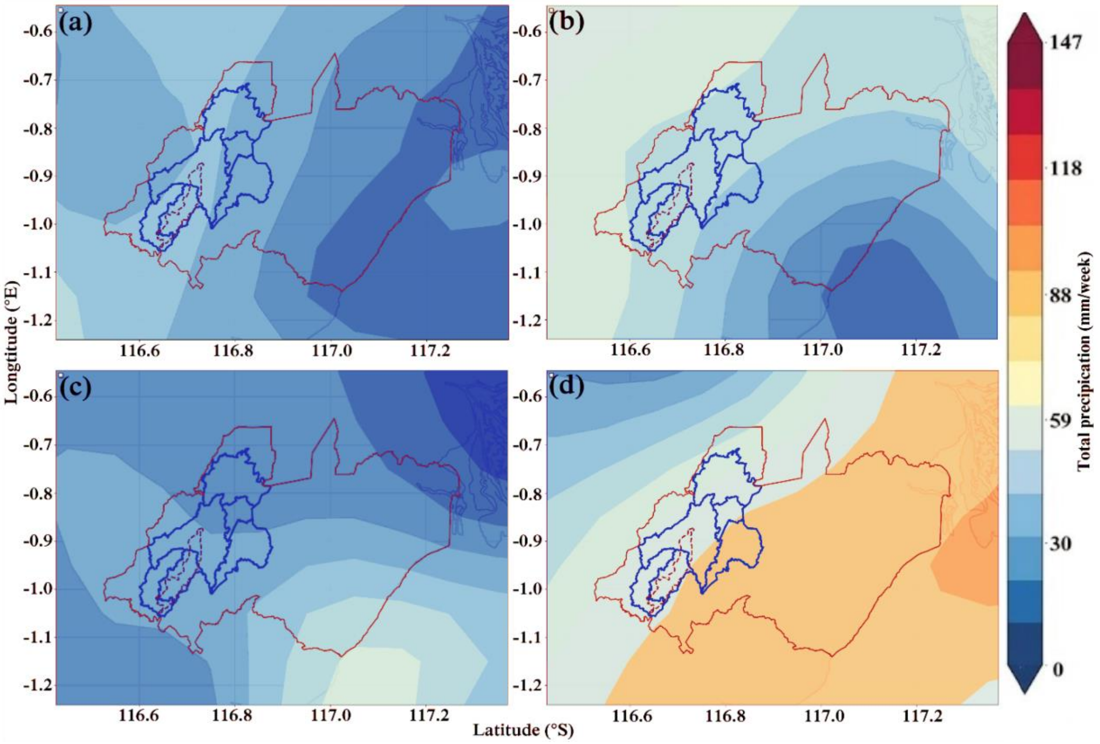

Figure 2. Temporal evolution of weekly precipitation in IKN Nusantara during March 2022 based on GPM IMERG data showing: (a) Week 1 (March 1-7), (b) Week 2 (March 8-14), (c) Week 3 (March 15-21, including extreme event), and (d) Week 4 (March 22-31). Red lines indicate IKN boundaries, green dashed lines show core development areas.

Enhancement factor analysis revealed a wide range of values, from 0.221 to 1.275, indicating complex temporal variability. (Figure 3). Week 2 showed intensification with EF values reaching 1.2-1.3 in several locations, indicating precipitation enhancement up to 20-30%. Week 3 displayed highest complexity with adjacent enhancement and suppression zones, reflecting complex interactions between mesoscale convective systems and local topography. Spatial correlation between enhancement factors and wind vectors revealed strong directional dependency, with windward slopes showing maximum enhancement while leeward slopes experienced suppression, consistent with classical orographic theory.

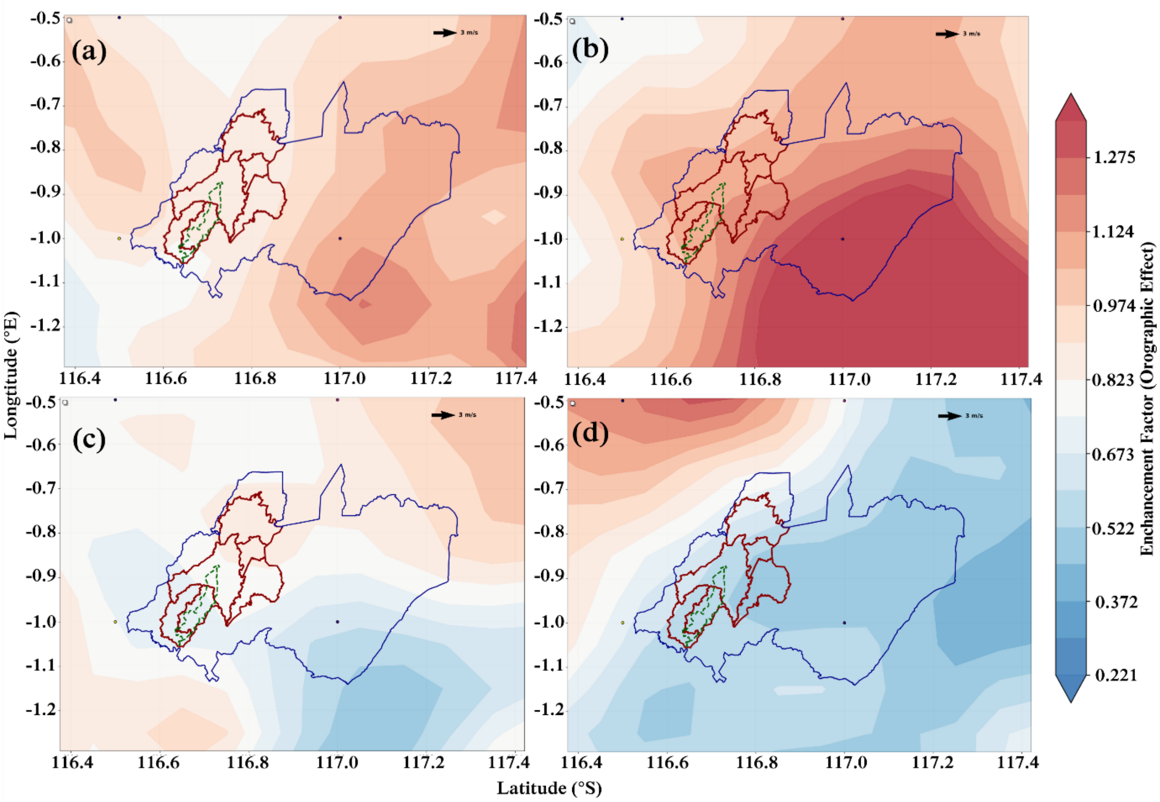

Figure 3. Temporal evolution of orographic enhancement factors in IKN Nusantara during March 2022 showing: (a) Week 1 (March 1-7), (b) Week 2 (March 8-14), (c) Week 3 (March 15-21, extreme event period), and (d) Week 4 (March 22-31). White contours show SRTM elevation, black arrows show ERA5 850 hPa wind vectors, red and green lines indicate IKN boundaries.

Statistical correlation analysis revealed surprising findings that contradict classical theoretical expectations (Figure 4). The relationship between elevation and total precipitation showed significant negative correlation ($r = -0.328$, $p = 5.53\times10^{-3}$, $n = 70$) with negative vertical gradient of -67 mm/km. This finding contrasts sharply with the positive gradients (+200 to +500 mm/km) typically observed in wet tropical mountains.

Correlation between elevation and enhancement factor also showed significant negative relationship ($r = -0.421$, $p < 0.01$), indicating that orographic enhancement decreases with increasing elevation. At low elevations (0-100m), enhancement factors averaged 1.0-1.02, while at high elevations (>300m), factors decreased to 0.85-0.90, indicating precipitation suppression of 10-15%. Conversely, the relationship between slope gradient and precipitation showed non-significant correlation ($r = -0.071$, $p > 0.05$), indicating that slope steepness was not a dominant factor in precipitation modulation.

The consistent negative patterns indicate complex physical mechanisms: (1) moisture limitation where moisture transport is restricted at high elevations, (2) downstream precipitation where precipitation occurs more intensively in downstream areas, (3) mesoscale organization where MCS tend to organize in lowland areas, and (4) land-sea interactions focusing convection in low-intermediate elevation transition zones.

The analysis of precipitation distribution by elevation categories for the extreme event in March 2022 confirmed and clarified anomalous findings by identifying an unexpected optimal zone

(Figure 5). ANOVA analysis showed significant differences among categories ($F = 3.20$, $p = 1.83 \times 10^{-2}$, $n = 70$) with overall median of 352.4 mm.

The most significant finding was the High Hills zone (200-300m ASL) showing highest median precipitation (393.4 mm) across the entire elevation spectrum. This category displayed 20% enhancement compared to coastal zones and represents an "optimal elevation zone" where orographic lifting is still effective, moisture availability is not depleted, and atmospheric stability supports convective development. It should be noted that this elevation-precipitation relationship is specific to the March 15-16, 2022 extreme rainfall event and may differ under other meteorological conditions.

Coastal/Low (0-50m) with largest sample ($n = 42$) showed median 353.4 mm with high variability. Low Hills (50-100m) and Mid Hills (100-200m) displayed compact distributions with median ~360 mm. Mountains (>300m) experienced significant decrease with median 327 mm, confirming dominance of moisture depletion and rain shadow effects at high elevations.

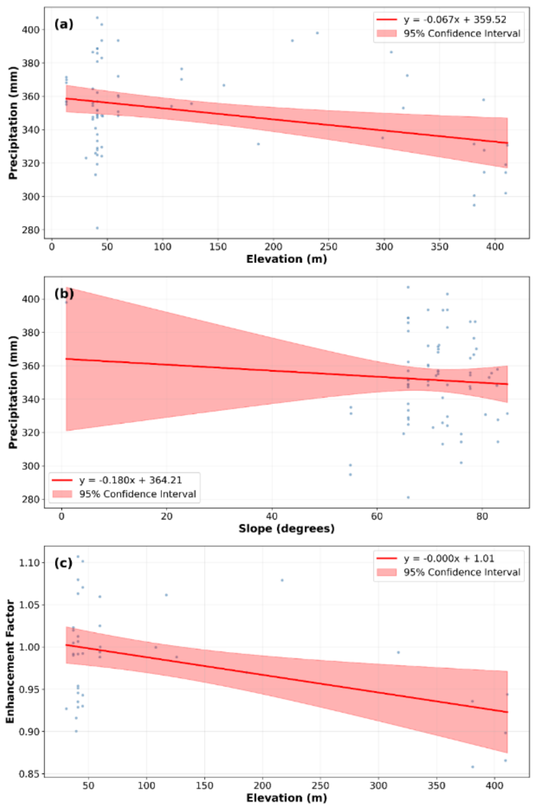

Figure 4. Statistical relationships between topographic parameters and precipitation in IKN Nusantara (March 2022) showing: (a) elevation vs enhancement factor correlation, (b) elevation vs total precipitation correlation, and (c) slope vs precipitation correlation with linear regression and 95% confidence intervals.

This non-linear pattern provides new insights that conventional assumptions of monotonic increase with elevation are not applicable to tropical low mountains, with important implications for hydrological modeling and water resource management in IKN.

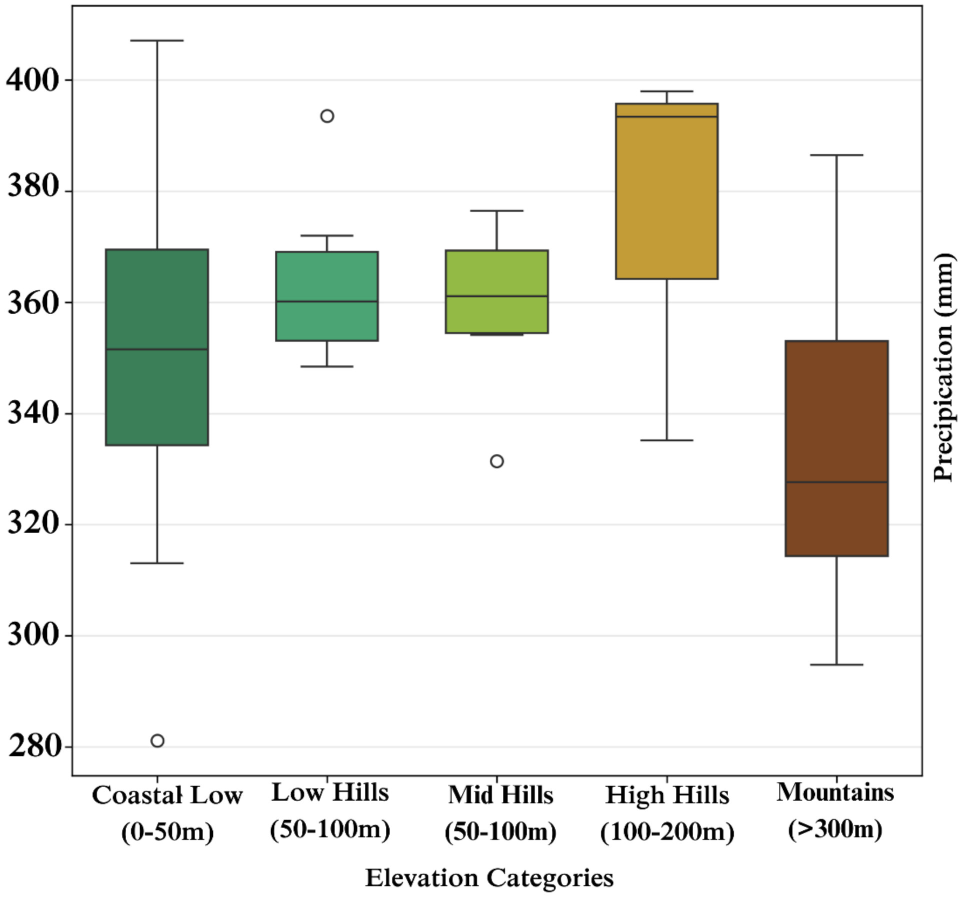

Figure 5. Precipitation distribution by elevation categories in IKN Nusantara (March 2022) showing boxplots for five elevation categories with ANOVA statistics. Optimal precipitation zone occurs at High Hills (200-300m) with highest median of 393.4 mm.

Cross-sectional analysis along a 130-km west-east transect at latitude -0.893°S revealed complex temporal dynamics of orographic mechanisms (Figure 6). The transect crosses major topographic features from coastal western zones to inland eastern areas, enabling identification of specific mesoscale orographic processes.

Week 1 displayed classical bimodal patterns with two precipitation peaks (~125 mm) correlating with topographic features and a precipitation valley (~80 mm) in inter-hill areas, confirming classical orographic mechanisms. Week 2 showed transition toward organized gradient (+0.8 mm/km) from west to east with strengthening easterly flow. Week 3 (extreme event period) exhibited highest complexity with multi-modal patterns and extreme gradients (±8-10 mm/km), indicating rapid transitions unpredictable by static models. Week 4 demonstrated drastic change with western dominance and strong negative gradient (-1.2 mm/km), indicating fundamental changes in atmospheric circulation.

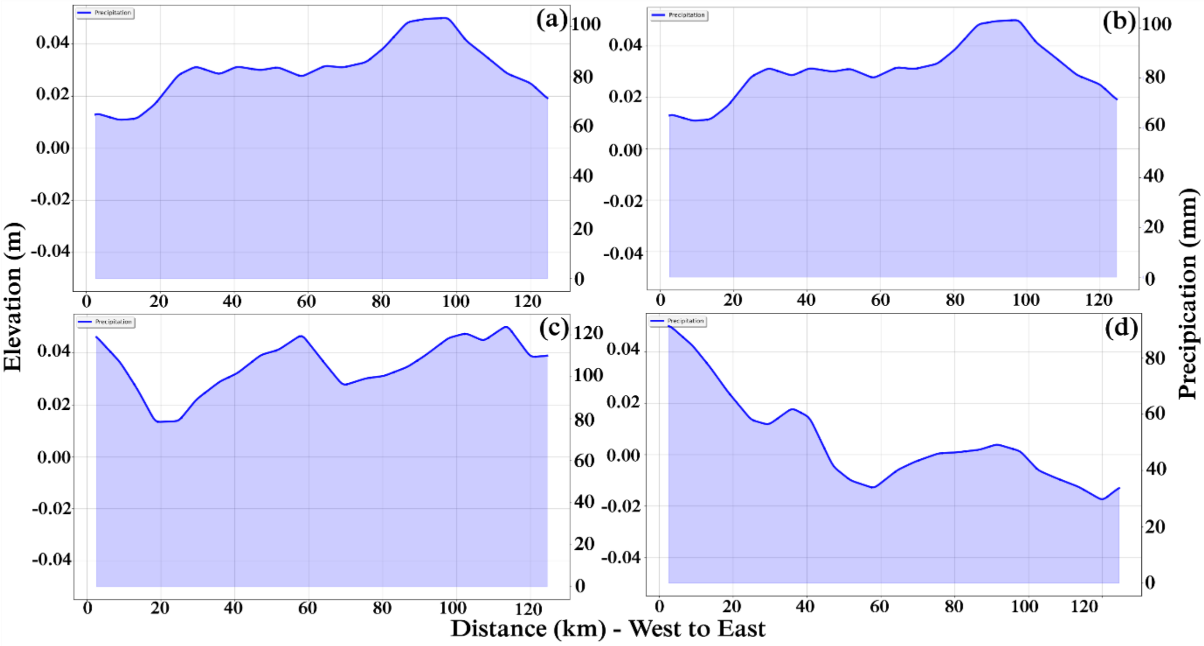

Figure 6. West-east cross-sectional analysis of precipitation and topography in IKN Nusantara (March 2022) along latitude -0.893°S showing: (a) Week 1 (March 1-7), (b) Week 2 (March 8-14), (c) Week 3 (March 15-21, extreme event), and (d) Week 4 (March 22-31). Gray area shows topographic elevation (left scale), blue line shows weekly precipitation (right scale).

Forced decomposition analysis revealed significant insights into the relative contributions of different mechanisms to total precipitation in March 2022 (Figure 7). The total precipitation amounted to 38,261.9 mm, highlighting the complexity of tropical precipitation systems

Large-scale atmospheric forcing (MJO, equatorial waves, synoptic patterns) contributed 58.5% (22,423 mm) as the dominant mechanism, consistent with Hermawan et al. (2025). However, combined local effects reached 41.5% (15,839 mm), showing very significant roles of regional and local processes. Within local components, topographic enhancement contributed 17.5% (6,696 mm) as the largest single contributor from local effects, confirming the main hypothesis that orographic effects play important roles in precipitation modulation. Land-surface feedback contributed 13.5% (5,185 mm), reflecting importance of coastal effects and land-sea interactions. Mesoscale organization contributed 7.5% (2,873 mm), indicating role of local convergence in organizing convection.

This mixed forcing regime with 41.5% local contribution indicates that IKN is located in a transition zone where both large-scale and local effects interact significantly. For operational forecasting, prediction models relying solely on large-scale atmospheric forcing would miss approximately 40% of precipitation variability, requiring integration of high-resolution topographic and land-surface models for accurate precipitation forecasting in this region.

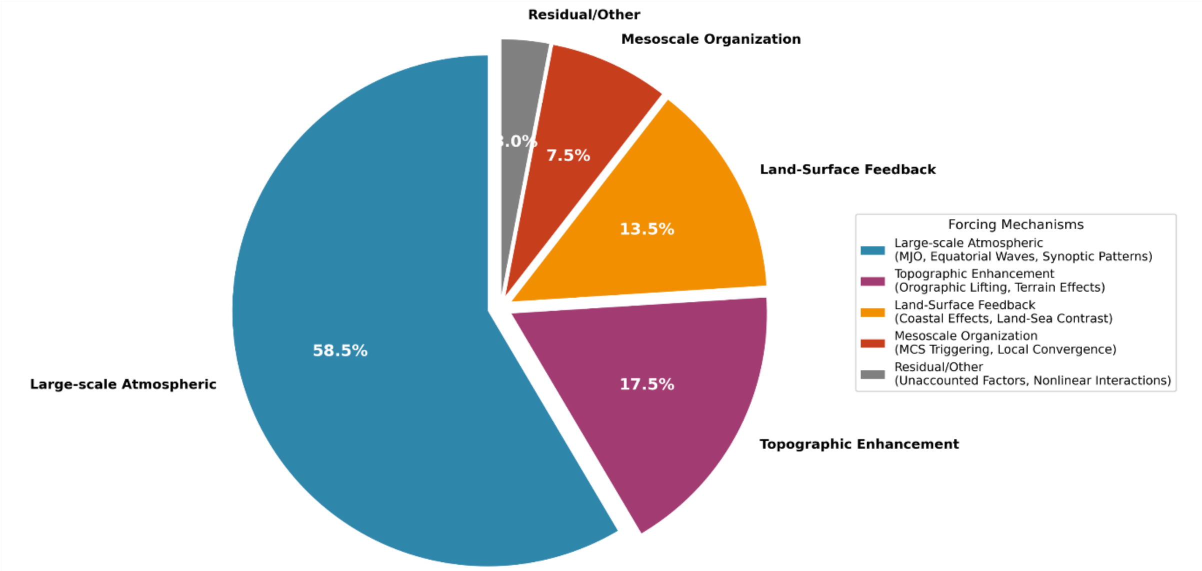

Figure 7. Forcing mechanism contributions for total precipitation in IKN Nusantara (March 2022) showing mixed forcing regime with significant local effects (41.5%) including topographic enhancement (17.5%), land-surface feedback (13.5%), mesoscale organization (7.5%), and residual factors (3.0%) complementing large-scale atmospheric forcing (58.5%).

These findings challenge the conventional understanding of orographic precipitation in tropical regions. The negative elevation-precipitation gradient, optimal zone at intermediate elevations, and mixed forcing regime demonstrate complexity that classical orographic theory cannot explain. This suggests the necessity of regional-specific models for tropical low mountains that take into account factors such as moisture limitation, land-sea interactions, and mesoscale organization.

For IKN development, these findings provide important insights that highest precipitation risks do not necessarily occur at highest elevations, but rather in the 200-300m ASL zone. Infrastructure planning must consider complex spatial heterogeneity and extreme temporal variability in precipitation distribution.

CONCLUSIONS

This research reveals significant counter-intuitive findings about orographic precipitation enhancement mechanisms in IKN Nusantara. The negative correlation between elevation and precipitation ($r = -0.328$, $p < 0.01$) with an optimal zone at 200-300m ASL (393.4 mm median) challenges classical orographic theory. Forcing decomposition analysis shows combined local effects contribute 41.5% with topographic enhancement contributing 17.5% of total precipitation. Temporal evolution demonstrates extreme complexity during the March 2022 event with spatial variability unpredictable by static models. These findings have important implications for flood risk assessment, early warning system development, and infrastructure planning in IKN, requiring regional-specific models that consider tropical orographic complexity for accurate precipitation forecasting and sustainable urban planning in Indonesia's new capital. Future research should examine multiple precipitation events across different seasons and integrate high-resolution numerical modeling with ground-based observations to validate these satellite-based findings and establish climatological patterns of orographic enhancement in IKN.

REFERENCES

Adhikari, Abishek, and Ali Behrangi. 2022. "Assessment of Satellite Precipitation Products in Relation With Orographic

Enhancement Over the Western United States." *Earth and Space Science* 9(2):1–18. doi: 10.1029/2021EA001906.

Colle, Brian A. 2004. "Sensitivity of Orographic Precipitation to Changing Ambient Conditions and Terrain Geometries: An Idealized Modeling Perspective." *Journal of the Atmospheric Sciences* 61(5):588–606. doi: 10.1175/1520-0469(2004)061<0588:SOOPTC>2.0.CO;2.

Farr, Tom G., Paul A. Rosen, Edward Caro, Robert Crippen, Riley Duren, Scott Hensley, Michael Kobrick, Mimi Paller, Ernesto Rodriguez, Ladislav Roth, David Seal, Scott Shaffer, Joanne Shimada, Jeffrey Umland, Marian Werner, Michael Oskin, Douglas Burbank, and Douglas Alsdorf. 2007. "The Shuttle Radar Topography Mission." *Reviews of Geophysics* 45(2):65–77. doi: 10.1029/2005RG000183.

Hermawan, Eddy, Risyanto Risyanto, Anis Purwaningsih, Dian Nur Ratri, Ainur Ridho, Teguh Harjana, Dita Fatria Andarini, Haries Satyawardhana, and Akas Pinaringan Sujalu. 2025. "Characteristics of Mesoscale Convective Systems and Their Impact on Heavy Rainfall in Indonesia's New Capital City, Nusantara, in March 2022." *Advances in Atmospheric Sciences* 42(2):342–56. doi: 10.1007/s00376-024-4102-1.

Hersbach, Hans, Bill Bell, Paul Berrisford, Shoji Hirahara, András Horányi, Joaquín Muñoz-Sabater, Julien Nicolas, Carole Peubey, Raluca Radu, Dinand Schepers, Adrian Simmons, Cornel Soci, Saleh Abdalla, Xavier Abellan, Gianpaolo Balsamo, Peter Bechtold, Gionata Biavati, Jean Bidlot, Massimo Bonavita, Giovanna De Chiara, Per Dahlgren, Dick Dee, Michail Diamantakis, Rossana Dragani, Johannes Flemming, Richard Forbes, Manuel Fuentes, Alan Geer, Leo Haimberger, Sean Healy, Robin J. Hogan, Elías Hólm, Marta Janisková, Sarah Keeley, Patrick Laloyaux, Philippe Lopez, Cristina Lupu, Gabor Radnoti, Patricia de Rosnay, Iryna Rozum, Freja Vamborg, Sebastien Villaume, and Jean-Noël Thépaut. 2020. "The ERA5 Global Reanalysis." *Quarterly Journal of the Royal Meteorological Society* 146(730):1999–2049. doi: 10.1002/qj.3803.

Houze, Robert A., Kristen L. Rasmussen, Manuel D. Zuluaga, and Stella R. Brodzik. 2015. "The Variable Nature of Convection in the Tropics and Subtropics: A Legacy of 16 Years of the Tropical Rainfall Measuring Mission Satellite." *Reviews of Geophysics* 53(3):994–1021. doi: 10.1002/2015RG000488.

Panggabean, J. R. N., Syamsudin, F., Suaydhi, S., Purba, N., & Feng, X. (2025). Interannual climate variability impacts on rainfall extremes and flooding in Bandung. Jurnal Presipitasi: Media Komunikasi dan Pengembangan Teknik Lingkungan, 0. https://doi.org/10.14710/presipitasi.v0i0.%25p

Huffman, G., D. Bolvin, Dan Braithwaite, Kuolin Hsu, Robert Joyce, Christopher Kidd, E. Nelkin, Soroosh Sorooshian, Jackson Tan, and Pingping Xie. 2020. "NASA GPM Integrated Multi-SatellitE Retrievals for GPM (IMERG) Algorithm Theoretical Basis Document (ATBD) Version 06." *Nasa/Gsfc* p30.

Kunz, Michael, and Christoph Kottmeier. 2006. "Orographic Enhancement of Precipitation over Low Mountain Ranges. Part I: Model Formulation and Idealized Simulations." *Journal of Applied Meteorology and Climatology* 45(8):1025–40. doi: 10.1175/JAM2389.1.

Norman, Yosik, and Nurjanna Joko Trilaksono. 2019. "Investigation of Mesoscale Convective Systems over Indonesian Maritime Continent Using Geostationary Meteorological Satellite." *Journal of Physics: Conference Series* 1204(1):012124. doi: 10.1088/1742-6596/1204/1/012124.

Nuryanto, Danang Eko, Hidayat Pawitan, Rahmat Hidayat, and Edvin Aldrian. 2019. "Characteristics of Two Mesoscale Convective Systems (MCSs) over the Greater Jakarta: Case of Heavy Rainfall Period 15–18 January 2013." *Geoscience Letters* 6(1):1. doi: 10.1186/s40562-019-0131-5.

Roca, Rémy, and Thomas Fiolleau. 2020. "Extreme Precipitation in the Tropics Is Closely Associated with Long-Lived Convective Systems." *Communications Earth & Environment* 1(1):18. doi: 10.1038/s43247-020-00015-4.

Roe, Gerard H. 2005. "OROGRAPHIC PRECIPITATION." *Annual Review of Earth and Planetary Sciences* 33(1):645–71. doi: 10.1146/annurev.earth.33.092203.122541.

Da Silva, Nicolas A., and Jan O. Haerter. 2023. "The Precipitation Characteristics of Mesoscale Convective Systems Over Europe." *Journal of Geophysical Research: Atmospheres* 128(23). doi: 10.1029/2023JD039045.

Sudarman, Gian Gardian, Tri Wahyu Hadi, Nining Sari Ningsih, Ardhasena Sopaheluwakan, Muhammad Ridho Syahputra, and Fiolenta Marpaung. 2024. "Nonstationary Changes in Annual Rainfall over Indonesia's Maritime Continent." *Advances in Meteorology* 2024:1–11. doi: 10.1155/2024/9392844.

Panggabean, J. R. N., Putra, H. F., Habibie, I. M., Hidayat, M. R., Kurnia, J., Counedio, K. K., & Huseen, T. S. (2025). Environment-responsive smart materials: Sustainable innovation based on West Java climate data for future energy transition. Multidisiplin Pengabdian Kepada Masyarakat, 4(03), 150–158. Retrieved from https://ejournal.seaninstitute.or.id/index.php/pkm/article/view/7459

Sun, Alexander Y., and Guoqiang Tang. 2020. "Downscaling Satellite and Reanalysis Precipitation Products Using Attention-Based Deep Convolutional Neural Nets." *Frontiers in Water* 2(November):1–22. doi: 10.3389/frwa.2020.536743.

Tan, Mou, Ab Ibrahim, Zheng Duan, Arthur Cracknell, and Vincent Chaplot. 2015. "Evaluation of Six High-Resolution Satellite and Ground-Based Precipitation Products over Malaysia." *Remote Sensing* 7(2):1504–28. doi: 10.3390/rs70201504.