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Brief communication: Extreme rainfall–driven flooding associated with the equatorial development of Tropical Cyclone Senyar in Aceh, Indonesia

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Abstract. In late November 2025, Tropical Cyclone (TC) Senyar brought intense flooding to northern Sumatra, Indonesia. The worst effects were experienced by Aceh Province, with the extensive damage and loss of life that cannot be fully quantified. A quick analysis was performed using the GPM IMERG rainfall product, the ERA5 reanalysis, and surface observation data from BMKG. Local daily rainfall >400 mm occurred on 25-26 November, primarily over northern and eastern Aceh. The reduction in surface pressure near the equator was relatively weak. But there was enough residual low-level moisture convergence and deep moisture transport to produce torrential rainfall and widespread flooding.

1 Introduction

Tropical cyclones (TCs) are classified as some of extreme hydrometeorological hazards in the world, due to their ability to trigger severe rainfall and flooding. Those impacts generally extends well beyond the near-core region of the storm itself (Young and Hsiang, 2024; Sparks and Toumi, 2024). A recent study found that human-induced climate change has amplified rainfall from TCs. This intensification is mostly driven by increased water vapor in the atmosphere and precipitation efficiency (Wu et al., 2024). As a consequence, the impacts of precipitation associated with TCs flooding have increased exponentially, even in regions that do not show significant increases in cyclone intensity as measured by maximum surface wind speeds (Chen et al., 2025).

Southeast Asia is one of the region's most vulnerable to TCs–related flooding. This susceptibility is a result of the interplay between warm tropical seas, irregular coastlines, high mountainous terrain, and dense populations (Gnann et al., 2025; Noor and Abdul Maulud, 2022). The interaction of tropical disturbances and mountains, particularly through orographic lifting and organized mesoscale convection, can greatly increase cloudiness. This often results in extreme precipitation total recorded over relative short time intervals (Houze Jr., 2012). However, relatively few studies have examined TC-induced flood hazards in equatorial Southeast Asia. This lack of research is driven by the classical assumption that TC genesis should be inhibited around the equator. This is due to the small Coriolis parameter, which permits only weak angular momentum exchange (Turton, 2025). Furthermore, global models often fail to resolve these subtle circulations, frequently misidentifying them as disorganized rain clusters rather than structured vortices (Chang et al., 2003; Li and Toumi, 2025).

At low latitudes, the weak Coriolis force limits the development of sustained cyclonic rotation, leading to the traditional expectation that cyclonic systems weaken as they approach the equator. However, recent studies have indicated that cyclonic eddies could survive or even reform at the low latitudes when they are forced by favorable thermodynamics and sufficient moisture supply (Li and Toumi, 2025). Although not generally accompanied by strong surface winds, such infrequent equatorial regeneration events can generate some persistent intense precipitation when moisture supply is unending over more than a short period of time (Zhou et al., 2025).

TC Senyar that struck the northern region of Sumatra in late November 2025 is an example of such events. The system was initially stationary over the Bay of Bengal basin jurisdiction of the India Meteorological Department (IMD). However, its physical organization and cyclonic consolidation occurred near the western entrance of the Malacca Strait, within the equatorial North Sumatra – Andaman corridor. Senyar subsequently intensified locally before affecting northern Sumatra, which includes Aceh Province. This event is notable not only for its rare equatorial regeneration but also because its most severe impacts were driven by extreme rainfall rather than surface winds intensification. Reports from Meteorology, Climatology and Geophysical Agency (BMKG) observed that daily rainfall locally over 400 mm/day in November 25–26 in parts of northern and eastern Aceh, while much of the province experienced heavy to very heavy (Kumparan, 2025).

Unlike the major floods associated with monsoon (2000) or the transition period (2020) in Banda Aceh, which were characterized by intensive rainfall but with lower daily maxima than those observed in 2025. The 2025 floods were triggered by the intensification of Tropical Cyclone Senyar in the Strait of Malacca. Although the cyclone's center did not make landfall directly, this phenomenon triggered an extreme weather anomaly with recorded rainfall reaching 411–418 mm/day at several station, it is marking a shift from a seasonal disturbance pattern to a cyclone scale. These results highlight the significance of atmospheric physicochemical processes, that substantially influence the Earth system system-particularly the sustained large-scale moisture transport to the area, low-level wind convergence combined with orographic enhancement along the Bukit Barisan Mountains, in strengthening and prolonging rainfall duration (Lamers et al., 2023).

This brief communication attempts to provide a rapid hydrometeorological investigation of the Senyar–related flooding in Aceh through combining satellite–based rainfall estimates, ground data and ERA5 reanalysis. Analysis is used to document the synoptic evolution of the system, identifying why extreme rainfall near the equator was maintained, and emphasizing the

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Preprint. Discussion started: 23 March 2026

implications for flood risk assessment in equatorial regions where traditional cyclone intensity metrics my underestimate the actual level of hazard. By identifying a rainfall-driven impact pathway, this paper highlights that cyclone risk management approaches in equatorial regions need to be reviewed.

2. Data and Methods

2.1 Atmospheric reanalysis data

We analyzed the atmospheric circulation associated with TC Senyar using the European Centre for Medium-Range Weather Forecasts (ECMWF) operational analysis ERA5 reanalysis data. This information is available through the Copernicus Climate Data Store. ERA5 is available on a 0.25° grid (approximately 31 km) and provides hourly data. The dataset is based on assimilating numerical weather models with global observations to create a coherent approach to the atmospheric condition (Soci et al., 2024).

The main variables include mean sea level pressure (MSLP) to track the evolution of the low-pressure center development, zonal (u) and meridional (v) wind components at 850 hPa to depict the circulation and convergence of low-level flows, and integrated vapor transport (IVT), which is derived from the integrated water vapor fluxes in the east and north directions. The analysis focuses on the maritime Southeast Asia region, with domains covering the South China Sea, the Strait of Malacca, and northern Sumatra, thus allowing tracking of the system's evolution from the pre-regeneration phase to the post-regeneration phase.

To highlight some synoptic changes, all ERA5 variables were averaged daily and visualized as a series of sequential maps over the pre-Senyar period (23–24 November 2025), the peak regeneration and impact period (25–26 November 2025), and the post-Senyar period (27–28 November 2025). This procedure was utilized to depict the temporal evolution of pressure structures, low-level wind convergence patterns, and water vapor transport pathways, while reducing the influence of sub-daily variability. This approach was used to capture the temporal evolution of pressure structures, low level wind convergence patterns, and water vapor transport pathways, while reducing the influence of sub-daily variability. This daily visualization is particularly relevant for short-lived cyclonic systems and systems interacting strongly with land in low latitudes, where intensification and decay can occur on daily time scales (Chang et al., 2003; Li and Toumi, 2025).

2.2 Rainfall observations and satellite estimates

The characteristics of extreme rainfall during the late November 2025 flood event were analyzed using a combination of surface station observation data and satellite-based precipitation estimates. Daily rainfall data were obtained from the Aceh Climatology Station–BMKG through a network of meteorological, climatology, and rainfall stations in Aceh Province, with a focus on representative stations in the northern and eastern regions of Aceh – the area's most severely impacted by floods and flash floods – as well as several comparison stations in other, relatively less affected areas. We used observation data from 170 station, mainly rain gauges, to document daily intensities, identify maximum rainfall accumulation at a local scale, and assess whether rainfall events exceeded the BMKG's extreme rainfall threshold (>150 mm/day). The spatial distribution of rainfall was described descriptively through interpolation of point rainfall data using the Inverse Distance Weighting (IDW) method.

To address the spatial limitations of in situ observations, we used satellite-based Global Precipitation Measurement (GPM) Integrated Multi-satellite Retrievals for GPM (IMERG) Late Run version 07 data, which have a spatial resolution of 0.1° and a temporal resolution of 30 minutes. This product was selected because it incorporates additional calibration against ground-based observations and applies a backward morphing algorithm, making it well suited for post-event analysis (Uwihirwe et al., 2022; Li et al., 2025). The IMERG rainfall data was accumulated at a daily timescale for 25–26 November 2025, consistent with the BMKG observation time (07:00 WIB), Furthermore, approach in a comparative–descriptive manner to determine the spatial and temporal consistency of extreme rainfall associated with TC Senyar, without undertaking a statistically robust quantitative assessment of satellite product performance.

2.3 Flood mapping using Sentinel-1 SAR

We mapped flood inundation using Sentinel-1 C-band Synthetic Aperture Radar (SAR) data to avoid the limitations of optical sensors, which often fail under dense cloud cover during extreme precipitation. Sentinel-1 offers all-weather day and night coverage at medium spatial resolution- an essential feature for fast flood response monitoring (Roth et al., 2023). We tested the hypothesis above using Interferometric Wide (IW) mode with a VV polarization pair, given its higher sensitivity to transitions from dry to flooded surfaces.

The analytical framework is in coherence with the radar backscatter change detection methodology as suggested by UN-SPIDER. Areas were delineated by comparing pre- and post-event satellite images to identify strong decreases in radar backscatter, a typical feature when specular reflection is no longer topographically normal (Un-Spider, 2014; Twele et al., 2016). This physics-based approach exploits the specular reflection of microwaves from water bodies, resulting in lower backscatter intensity than from non-flooded terrain.

The spatial analysis was focused on the northern and eastern parts of Aceh Province, accounting for the distribution of extreme rainfall and surface geomorphology features of the coastal lowlands. The resulting inundation maps provide the basis for interpreting hydrometeorological conditions, correlating inundation patterns with rainfall distribution, and examining meteorological (synoptic-scale) atmospheric dynamics available from the ERA5 reanalysis.

2.4 Analysis framework

This study provides a rapid hydrometeorological assessment of the massive flooding event associated with the generation of TC Senyar in Aceh. We adopted a multi-level framework to link large-scale atmospheric dynamics with local rainfall. This structure connects large-scale atmospheric circulation patterns, extreme precipitation impacts, and hydrologic responses. We

https://doi.org/10.5194/egusphere-2026-694
Preprint. Discussion started: 23 March 2026

used ERA5 reanalysis data to characterize the synoptic evolution of MSLP, low-level wind convergence, and IVT during the pre-event, peak, and post-event periods.

To overcome the limited number of ground stations, we used GPM IMERG satellite data alongside BMKG records to analyses rainfall distribution patterns and their intensity. These two datasets complemented each other to evaluate peak phase extremes and subsequent rainfall persistence. We used GPM IMERG data to complement spatial gaps in the interpolated BMKG station records. This approach allowed for the capture of localized extreme precipitation that sparse field observations would have otherwise missed.

We reviewed the antecedent wetting conditions by examining daily rainfall maps from November 24-27, 2025. This enabled us to track how the soil became saturated leading up to the flood peak. Operationally, we defined antecedent wetting conditions as the hydrological status after several days and hours of accumulating rainfall. Next, inundation maps derived from Sentinel-1 SAR data were used to assess the spatial extent of flooding and establish its relationship to extreme rainfall, persistent precipitation, and synoptic conditions. This complementary approach provides a short examination of the relationship between atmospheric processes and flooding, in line with the objective of this Brief Communication, namely to document rare extreme events relevant to equatorial hydro-meteorological risk assessment.

Multi-antecedent wetting is operationally defined as the initial hydrological condition resulting from multi-day rainfall accumulation, described from the daily rainfall BMKG maps based on multi-day rainfall accumulation (07:00 to 07:00 WIB). The assessment of the spatial extent of flood mapping, and flooding persistence, extreme rainfall, and synoptic weather, can be done using Sentinel-1 SAR-derived inundation maps. This approach further streamlines the analysis of the relationship between the flooding and atmospheric processes. It aligns with the Brief Communication's objective of documenting rare extreme events. Furthermore, this analysis is highly relevant to equatorial hydrometeorological risk assessments.

3 Results

3.1 Evolution and regeneration of TC Senyar

ERA5 reanalysis (Fig. 1) shows an unusual synoptic evolution of Tropical Cyclone Senyar during 23–28 November 2025. According to official bulletins from the India Meteorological Department (IMD, 2025), the storm was categorized as disturbance 95B within the Bay of Bengal-Andaman Sea Sector. However, the initial closed circulation was first observed in the western Malacca Strait south of northern Sumatra (approximately 4–5°N) and later traveled northeast into the South China Sea. This implies that, although they are administratively classified under the Bay of Bengal jurisdiction, the physical genesis and early organization of Senyar occurred in a narrow corridor between Sumatra and Peninsular Malaysia.

During the pre-Senyar phase (23–24 November; Fig. 1a–b), the MSLP field shows an extensive and shallow low-pressure system over the Malacca Strait. Low-level winds at 850 hPa exhibit weak but persistent convergence along the eastern coast of Aceh. At this stage, no well-defined closed vortex is evident; instead, the system is characterized by a disorganized convective structure within a moist equatorial environment.

https://doi.org/10.5194/egusphere-2026-694
Preprint. Discussion started: 23 March 2026

During 25 - 26 November (Fig. 1c-d), the system locally organized and was regionally operationally assessed as a Cyclonic Storm (C) (Imd, 2025). Purely circulatory features of the system were neither fully symmetric nor compact, and the inner core of the system was absent. A weak surface pressure gradient and lack of significant central pressure deepening were observed over the land. The Aceh region, however, shows the IVT fields consistently and has well-established a moisture corridor. This moisture flux motion was primarily sustained by low-level flow from the South China Sea into the Malacca Strait, and interacting with the surrounding landmasses. The intensification of Senyar appears to be controlled mainly by low-level moisture convergence. Taken together, these factors indicate that Senyar's intensification was more the result of low-level moisture convergence as opposed to the classical dynamic strengthening that would be expected at lower latitude tropical cyclones (Chang et al., 2003; Ramos et al., 2016).

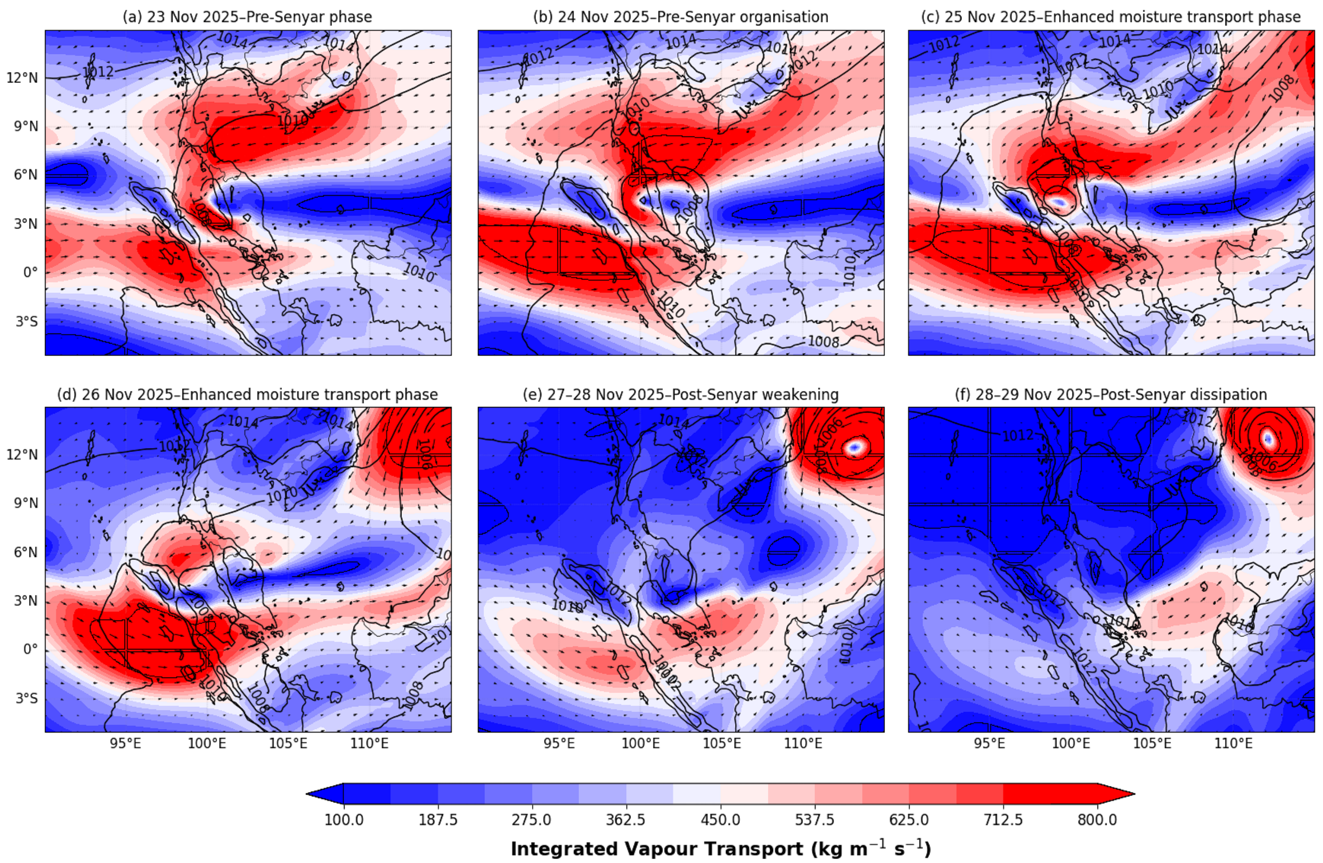

Figure 1. ERA5 reanalysis for 23-28 November 2025 of TC Senyar in synoptic scale. Panels (a–b) represent the pre-Senyar period, associated with weak low-level convergence over the Malacca Strait and a shallow low-pressure area. Panels (c–d) show the period of increased moisture transport (25–26 November), when Senyar was in cyclonic storm (C) intensity but still strongly asymmetric, with increased low-level wind convergence and high integrated water vapor extending to north Sumatra. Panels (e–f) represent the post-Senyar weakening period (27, 28-29 November), with a decayed circulation and less moisture supply. Contours are mean sea level pressure (MSLP; hPa), vectors 850-hPa winds, and shaded color IVT magnitude (kg m^{-1} s^{-1}). The system intensity class (D =

https://doi.org/10.5194/egusphere-2026-694
Preprint. Discussion started: 23 March 2026

depression, DD = deep depression, C = cyclonic storm) is according to operationally assessed by the regional cyclone warning center for maximum sustained surface wind and should not be derived directly from ERA5 reanalysis data (Imd, 2025).

During 27–28 November (Fig. 1e–f), the system's classification was downgraded from Deep Depression (DD) to Depression (D). With this, the levels of low-level convergence decreased, and there was a substantial reduction in the IVT flow towards Aceh. he interaction with the Sumatran landmass, the Bukit Barisan Mountain range, and the topography of Peninsular Malaysia appears to have restricted the potential for closed symmetric circulation. In addition, the weak Coriolis force near the equator made it difficult for the system to consolidate into a tight vortex (Chang et al., 2003; Wang et al., 2020). Therefore, the energy of the system was released mainly as sustained, torrential rain potential, instead of as strong winds, which is why flooding occurred in Aceh despite the absence of damaging wind speeds (Zhong et al., 2026).

Overall, the synoptic patterns in Figure 1 reveal a critical convergence of moist airflow over Aceh rather than intense cyclonic deepening. This process was sustained by persistent supply of water vapor which established highly conducive conditions for extreme precipitation in Aceh (Fan et al., 2025). Additionally, Sections 3.2 and 3.3 examine the effects of extended precipitation coupled with antecedent wetting on the distribution of the flooding and flash flooding events spatially, as outlined in Section 3.4.

3.2 Extremely heavy rainfall and Senyar regeneration of TC Senyar

Figure 2 depicts the rainfall distribution of BMKG stations and GPM IMERG satellites estimates. During the Senyar regeneration phase, rainfall was noted as widespread heavy to extreme throughout the Aceh Province which was the peak intensity for the 25-26 November 2025 period. Rainfall extreme (>150 mm day^{-1}) was recorded in the northern and eastern coast regions, especially in Bireuen, Pidie Jaya, Aceh Tamiang, Langsa, and South Aceh, while the rest recorded some regions of Aceh Province to very heavy rainfall (50-150 mm day^{-1}) (BMKG, 2025).

The spatial pattern closely resembles the moisture corridor from the IVT analysis (see Section 3.1). It suggests that persistent low-level moisture convergence coupled with a low translating speed of the system was critical in sustaining rainfall accumulation over several days. Moreover, Orographic lifting along the Bukit Barisan Mountains is likely to have further increased precipitation efficiency, particularly in areas where the moist inflow, even with greater moisture, crossed the coast and the elevated terrain. Comparison of station records with satellite estimates show overall consistency for spatial distributions of rainfall. However, IMERG tends to locally overestimates peak values. The coincident time span with strengthened IVT and peak rainfall suggests that the primary driver for the hydrological impacts was moisture rather than dynamically through strong wind intensification.

https://doi.org/10.5194/egusphere-2026-694
Preprint. Discussion started: 23 March 2026

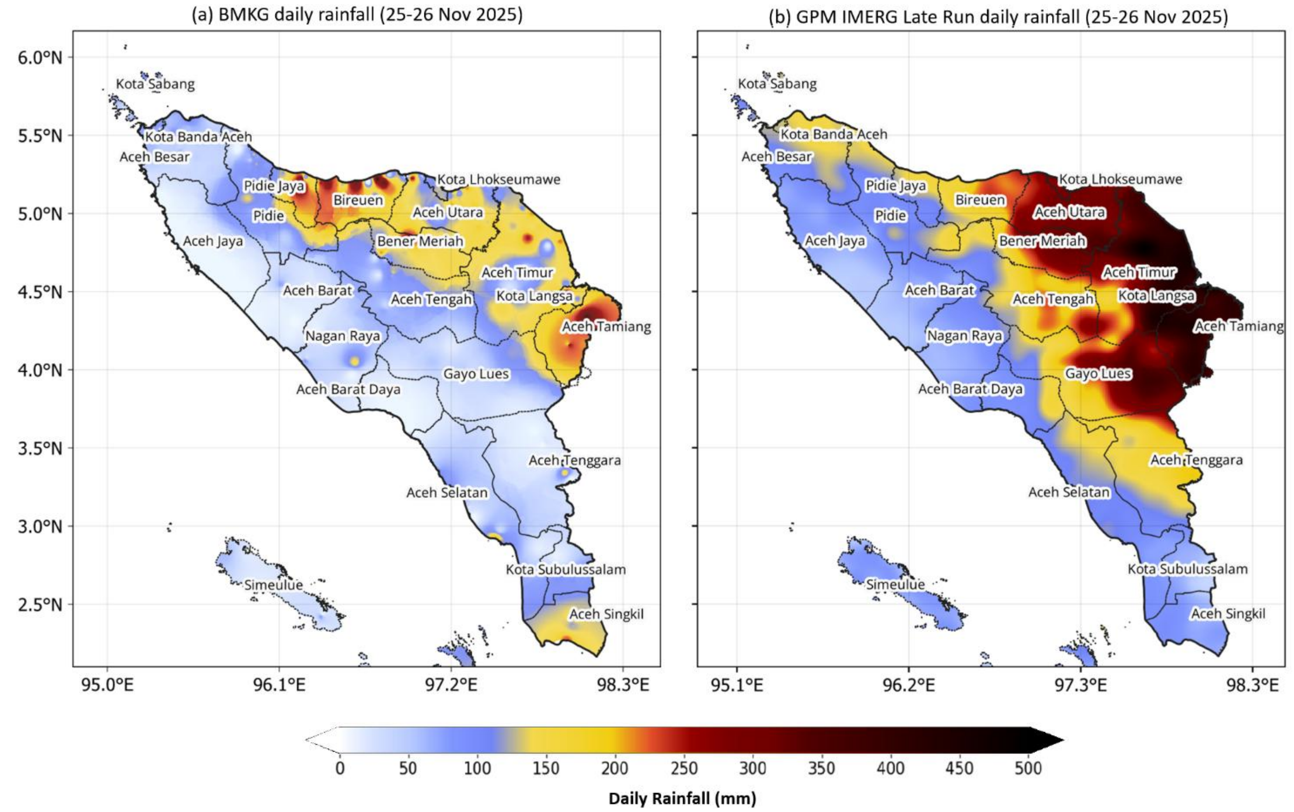

Figure 2. Spatial distribution of daily rainfall during the peak Senyar regeneration phase (25–26 November 2025) derived from (a) BMKG rain gauge observations and (b) GPM IMERG satellite estimates. In both datasets, the strongest rainfall is clearly concentrated in the north and east of Aceh, with local daily accumulations exceeding 300–400 mm, whereas lower intensities are found along portions of the western coast of Aceh.

Several meteorological stations observed daily rainfall totals of around 400 mm or even exceeding this amount. an extremely rare 24-hour accumulation for Aceh. Northern and eastern regions received the highest amounts of rainfall consistent with low-level moisture convergence and IVT pathways directing moisture towards northern Sumatra. Orographic lifting from the Bukit Barisan Mountains may have also contributed to this (Marra et al., 2022 (Marra et al., 2022). The most significant TC Senyar hazard was not the destructive cyclonic winds, but rather the rainfall which was widespread and persistent. The rainfall which continued after the peak of November 25-26, contributed to the saturation of the soil and the antecedent wetting, which was preconditioning the catchments for rapid runoff. As discussed in section 3.3.

Several meteorological stations observed daily rainfall totals of around 400 mm, or in some cases even exceeding this amount. Such total rainfall amounts observed within a 24-hour period is extremely rare in the Aceh region. Such extreme rainfall amounts in this case would be concentrated in the northern and eastern sectors and in line with the convergence zone and Integrated Vapor Transport (IVT) that directs moisture towards the northern region of Sumatra. The Bukit Barisan mountain range likely played a critical role in enhancing orographic precipitation by forcing moist air upward. The most

https://doi.org/10.5194/egusphere-2026-694
Preprint. Discussion started: 23 March 2026

significant TC Senyar hazard was not the destructive cyclonic winds, but rather the rainfall which was widespread and persistent. The rainfall which continued after the peak of November 25-26, contributed to the saturation of the soil and the antecedent wetting, which was preconditioning the catchments for rapid runoff. As discussed in section 3.3, the primary cause of flooding and flash flooding was the prevailing hydraulic conditions.

3.3 Persistent daily rainfall and antecedent wetting

The daily rainfall maps provided by BMKG, which are based on a standard 24-hour rainfall accumulation from 07:00 to 07:00 WIB, show that moderate to heavy rainfall covered nearly all areas of Aceh from 25 to 28 November 2025 (Figure 3). Despite daily totals on November 25 and 26 being the highest, on November 26 27 and 28, rainfall remained extensive and influenced many of the major river basin areas which indicates a long-sustained supply of moisture to the atmosphere which was present after the peak rainfall phase.

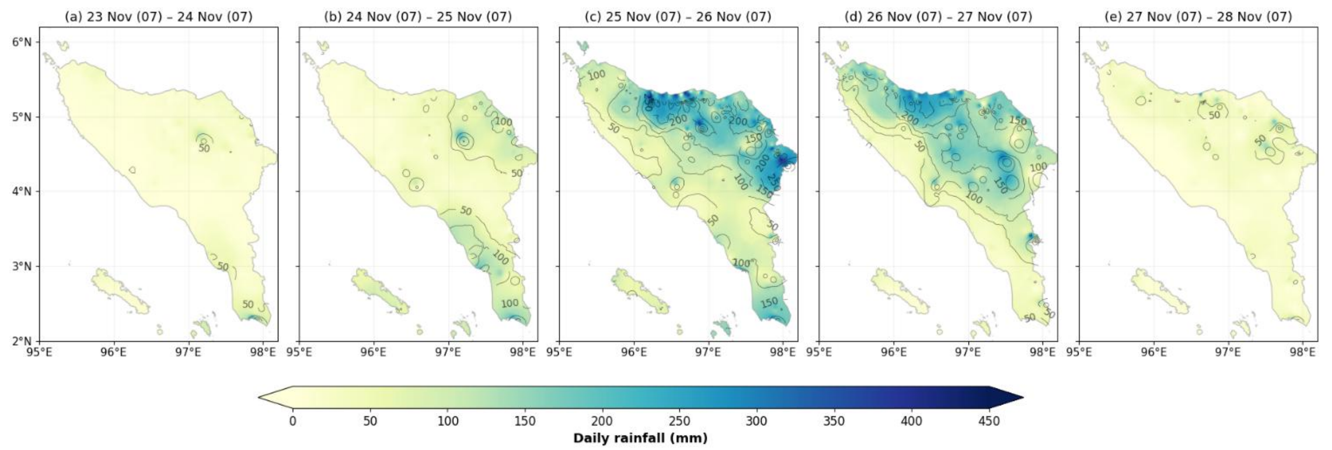

Figure 3. The daily rainfall distribution according to BMKG observations (24-h accumulation, 07:00–07:00 WIB) for consecutive episodes on 23–24 November, 24–25 November, 25–26 November, 26–27 November, and 27–28 November is shown in Fig. The time series makes apparent the sustained nature of the rainfall before, during, and after the extreme peak on 25–26 November, including the development of multi-day antecedent wetting conditions and indicative thresholds for primary river discharge in Aceh.

The consecutive day analysis shows that after the 26 November peak rainfall, there was a decreasing trend in rainfall intensity, but there was still a large spatial coverage of the rainfall. This rainfall, that was sustained over multiple days, produced a significant antecedent wetting, which in turn increased soil saturation and reduced the infiltration capacity throughout the entire catchment areas (Tramblay et al., 2012). Under these conditions, relatively small amounts of rainfall can produce large amounts of surface runoff and increased the river discharge in a significant way. The rainfall maps in this section were created to show the evolving hydrological preconditioning rather than the direct spatial extent of the flooding. The analysis of the spatial relationship of the persistent rainfall to the areas where flooding and flash flooding was observed is further analyzed in the flood analysis of Sentinel-1 in Section 3.4.

https://doi.org/10.5194/egusphere-2026-694
Preprint. Discussion started: 23 March 2026

3.4 Spatial Distribution of Floods and Flash Flooding.

Figure 4 illustrates the Sentinel-1 SAR flooding maps from the Senyar event. Inundation from the flooding event was most prevalent in the coastal lowlands and large river systems in the northern and eastern regions of Aceh Province. Large flood-impacted areas were also noted in the regions of East Aceh, Aceh Tamiang, Pidie Jaya, Bireuen, Lhokseumawe, and North Aceh, where alluvial plains are less elevated, and drainage systems are more developed. Areas with severe flooding in the province involved East Aceh, Aceh Tamiang, Pidie Jaya, Bireuen, Lhokseumawe, and North Aceh. These areas are known for their poor drainage but dense networks; in addition, the alluvial plains are located strategically and circumstantially low.

The pattern for the flooded regions spatially corresponded with the pattern for extreme rain events, showing parallelism for the events spanning November 25-26, and the continued rainfall events after November 28. This correlation provides evidence that the magnitude of flooding is a result of combining the peak rainfall and the antecedent conditions of peak flooding. Continued rainfall events would have increased surface runoff, through the increased runoff due to soil saturation. In contrast, the central highlands did not have the same hydrological response. Unlike the coastal regions which experienced flooding quickly, the highlands had runoff flooding surface inundation, which is detected through imaging. This suggests that flooding predominantly stemmed from surface runoff through the river valleys and plains to the coast. The floodwaters then spread into the western river systems which showed more runoff than the central highlands.

Overall, flood mapping analysis shows the Senyar event generated hydrological impacts, not as a result of extreme wind damage, but due to sustained and extreme rainfall, with topographic and pre-soil moisture preconditioning. These results reinforce the conclusions drawn from the rainfall analysis discussed in Sections 3.2 and 3.3 and further confirm that in the Aceh floods, moisture convergence and rainfall persistence were the most significant factors.

https://doi.org/10.5194/egusphere-2026-694
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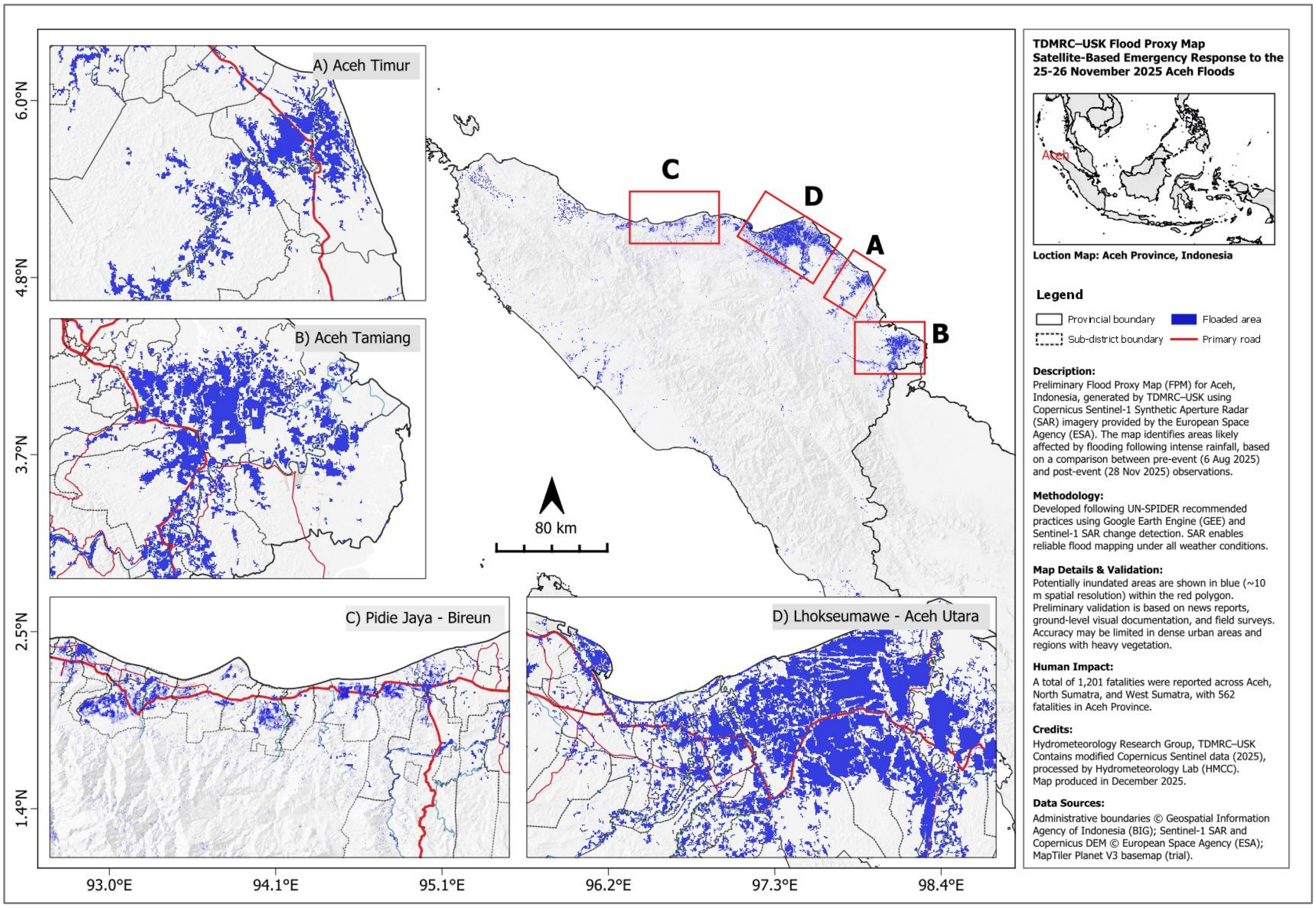

Figure 4 Flood Proxy Map shows the flood inundation of Sentinel-1 SAR of the Aceh flood event on the 25 -26 November. The blue areas in the images show the flooded areas as detected by the SAR backscatter. The Insets highlight the main affected regions: (A) Aceh Timur, (B) Aceh Tamiang, (C) Pidie Jaya–Bireuen, and (D) Lhokseumawe-Aceh Utara. The map shows that the inundation was concentrated in the low coastal plain areas and the river systems of northeastern part of Aceh.

4 Discussion

The TC Senyar event occurring in late November 2025 illustrates that the extreme hydrometeorological effects in the equatorial zone do not require a significant cyclonic intensification. First synoptic assessments of ERA5 data indicate that the system developed and organized in the Malacca Strait where the low-pressure gradient, as well as asymmetric low level wind circulations, which corresponds to the low Coriolis force in the vicinity of the equator (Chang et al., 2003; Li and Toumi, 2025). Although it was operationally classified as a cyclonic storm, Senyar was a weak storm that did not show significant pressure deepening over Aceh nor did it create the widespread destructive surface wind that is characteristic of more developed tropical cyclones at higher latitudes (Emanuel, 2003).

https://doi.org/10.5194/egusphere-2026-694
Preprint. Discussion started: 23 March 2026

The effects were primarily due to the convergence of low-level moisture and sustained integrated vapor transport to northern Sumatra. When this moisture encountered the Bukit Barisan mountains, it caused sustained orographic lifting which resulted in significant extreme multi-day rainfall events, typical of tropical mountain rainfall. Thus, moisture convergence and terrain-induced uplift were the dominant mechanisms, contrasting with the classical view that emphasizes the vortex as the primary driver of rainfall (Houze Jr, 2012). Flooding was more strongly linked to cumulative rainfall than to wind damage. The strong spatial correlation of flood events, the extreme rainfall on 25-26 November, continued rainfall over already wet antecedent conditions, and inundation patterns observed from Sentinel-1 satellite data all indicate that rainfall accumulation was the primary cause of flooding. Other studies have noted the importance of long duration, high intensity, and repeated rainfall as a primary cause of tropical flooding, with continuous high intensity rainfall as the most important factor (Sharma et al., 2018).

In addition to the effects of the atmosphere, the conditions of the surface of the land likely acted to amplify the hydrological response. The conversion of upstream forests to monoculture plantation forests reduces the capacity of the land surface to absorb water, increases the amount of surface water runoff, and floods the land downstream (Asmara and Randhir, 2024). This study was qualitative in nature and the landscape vulnerability was not quantified and may explain the extreme flooding that resulted from the Senyar event. As a result of the Senyar event it was demonstrated that in the equatorial environment, systems with weak cyclonic organization can still produce catastrophic flooding when sustained moisture coupled with the complex topography and catchment areas that have been preconditioned to flooding.

5 Conclusions

This study shows that even for a relatively weak tropical cyclone with an equatorial genesis, significant flooding can occur if extreme peak rainfall develops with multiple days of pre-flood precipitation and antecedent soil moisture saturation. For TC Senyar, impacts on hydrometeorology in Aceh were due more to sustained low-level moisture convergence and enhanced transport as opposed to some strong or deep barreling with destructive surface wind. This research indicates that a tropical flood early warning system for regions with complex terrain like Aceh should not be reliant on cyclone strikes or even coupled cyclone-modulated flooding, but rather consider more of the moisture tracks of the atmosphere, rainfall persistence, and the preconditioning of the catchment.

Data availability

BMKG station rainfall data are available upon request via BMKG (https://www.bmkg.go.id). NASA GPM IMERG precipitation products are freely accessible from the NASA Earth data portal (https://disc.gsfc.nasa.gov). ERA5 reanalysis data can be downloaded from the Copernicus Climate Data Store (https://cds.climate.copernicus.eu). All Python scripts for data

https://doi.org/10.5194/egusphere-2026-694
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processing, rainfall accumulation, and figure generation, along with sample data subsets, are deposited in Zenodo and openly available at: https://doi.org/10.5281/zenodo.12345678.

Supplement link

The link to the supplement will be included by Copernicus, if applicable.

Author contributions

S.S. conceived the study and led the analysis. S.S. and M.S. processed and analyzed the ERA5 reanalysis and satellite rainfall data. A.F. contributed to data interpretation and figure preparation. HBQ and E.C. provided meteorological insights and in situ observational data. All authors discussed the results and contributed to the final manuscript.

Competing interests

The authors declare that they have no competing interests.

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The review statement will be added by Copernicus Publications listing the handling editor as well as all contributing referees according to their status anonymous or identified.

References

Chang, C. P., Liu, C. H., and Kuo, H. C.: Typhoon Vamei: An equatorial tropical cyclone formation, Geophysical Research Letters, 30, https://doi.org/10.1029/2002GL016365Digital, 2003.

Chen, Y., Zhang, S., Wang, H., Chen, D., and Liu, J.: Human-induced climate change intensifies extreme precipitation events in central China's urban areas, Geophysical Research Letters, 52, e2024GL111818, https://doi.org/10.1029/2024GL111818, 2025.

Emanuel, K.: Tropical cyclones, Annual review of earth planetary sciences, 31, 75-104, https://doi.org/10.1146/annurev.earth.31.100901.141259, 2003.

Fan, X., Zhao, D., Li, Y., Zhang, X., Xie, Y., and Chen, L.: Exploring synoptic patterns contributing to extreme rainfall from landfalling tropical cyclones in China, Weather and Climate Extremes, 48, 100768, https://doi.org/10.1016/j.wace.2025.100768, 2025.

Gnann, S., Baldwin, J. W., Cuthbert, M. O., Gleeson, T., Schwanghart, W., and Wagener, T.: The influence of topography on the global terrestrial water cycle, Reviews of Geophysics, 63, e2023RG000810, https://doi.org/10.1029/2023RG000810, 2025.

Houze Jr, R. A.: Orographic effects on precipitating clouds, Reviews of Geophysics, 50, https://doi.org/10.1029/2011RG000365, 2012.

IMD: Tropical Cyclone Advisory No. 15: Cyclonic Storm "Senyar" over the Strait of Malacca and North Sumatra based on 1800 UTC of 27.11.2025, Regional Specialized Meteorological Centre (RSMC) - Tropical Cyclones New Delhi, New Delhi, 2025.

Kumparan: Penyebab Banjir di Aceh, Sumut, dan Sumbar, Ada Siklon Tropis Senyar, 2025.

Lamers, A., Devi. S, S., Sharma, M., Berg, R., Gálvez, J. M., Yu, Z., Kriat, T., Cardos, S., Grant, D., and Moron, L. A.: Forecasting tropical cyclone rainfall and flooding hazards and impacts, Tropical Cyclone Research and Review, 12, 100-112, https://doi.org/10.1016/j.tcrr.2023.06.005, 2023.

Li, M. and Toumi, R.: Can tropical cyclones exist near the Equator?, Quarterly Journal of the Royal Meteorological Society, e70014, https://doi.org/10.1002/qj.70014, 2025.

Li, X., Liu, J., Cui, W., Wang, H., Liao, A., Wang, Y., and Gao, W.: Comparative evaluation of GPM IMERG V07 early, late and final run products compared to IMERG V06 in Sichuan Province, China, Theoretical and Applied Climatology, 156, 354, https://doi.org/10.1007/s00704-025-05569-x, 2025.

Marra, F., Armon, M., and Morin, E.: Coastal and orographic effects on extreme precipitation revealed by weather radar observations, Hydrol. Earth Syst. Sci., 26, 1439-1458, https://doi.org/10.5194/hess-26-1439-2022, 2022.

Noor, N. M. and Abdul Maulud, K. N.: Coastal vulnerability: a brief review on integrated assessment in Southeast Asia, Marine Science Engineering, 10, 595, https://doi.org/10.3390/jmse10050595, 2022.

Ramos, A. M., Nieto, R., Tomé, R., Gimeno, L., Trigo, R. M., Liberato, M. L. R., and Lavers, D. A.: Atmospheric rivers moisture sources from a Lagrangian perspective, Earth Syst. Dynam., 7, 371-384, https://doi.org/10.5194/esd-7-371-2016, 2016.

Roth, F., Bauer-Marschallinger, B., Tupas, M. E., Reimer, C., Salamon, P., and Wagner, W.: Sentinel-1-based analysis of the severe flood over Pakistan 2022, Nat. Hazards Earth Syst. Sci., 23, 3305-3317, https://doi.org/10.5194/nhess-23-3305-2023, 2023.

Sharma, A., Wasko, C., and Lettenmaier, D. P.: If precipitation extremes are increasing, why aren't floods?, Water resources research, 54, 8545-8551, https://doi.org/10.1029/2018WR023749, 2018.

Soci, C., Hersbach, H., Simmons, A., Poli, P., Bell, B., Berrisford, P., Horányi, A., Muñoz-Sabater, J., Nicolas, J., and Radu, R.: The ERA5 global reanalysis from 1940 to 2022, 150, 4014-4048, https://doi.org/10.1002/qj.4803, 2024.

Sparks, N. and Toumi, R.: The Imperial college storm model (IRIS) dataset, Scientific data, 11, 424, https://doi.org/10.1038/s41597-024-03250-y, 2024.

Tramblay, Y., Bouaicha, R., Brocca, L., Dorigo, W., Bouvier, C., Camici, S., and Servat, E.: Estimation of antecedent wetness conditions for flood modelling in northern Morocco, Hydrol. Earth Syst. Sci., 16, 4375-4386, https://doi.org/10.5194/hess-16-4375-2012, 2012.

Turton, S.: Death and devastation: why a rare equatorial cyclone and other storms have hit southern Asia so hard, 10.3316/informit.T2025120200001700083774545, 2025.

Twele, A., Cao, W., Plank, S., and Martinis, S.: Sentinel-1-based flood mapping: a fully automated processing chain, International Journal of Remote Sensing, 37, 2990-3004, https://doi.org/10.1080/01431161.2016.1192304, 2016.

UN-SPIDER: Flood Hazard Mapping and Risk Assessment, United Nations Office for Outer Space Affairs (UNOOSA), 2014.

Uwihirwe, J., Riveros, A., Wanjala, H., Schellekens, J., Sperna Weiland, F., Hrachowitz, M., and Bogaard, T. A.: Potential of satellite-derived hydro-meteorological information for landslide initiation thresholds in Rwanda, Nat. Hazards Earth Syst. Sci., 22, 3641-3661, https://doi.org/10.5194/nhess-22-3641-2022, 2022.

Wang, C.-C., Ma, S.-K., and Johnson, R. H.: A numerical study on the influences of Sumatra topography and synoptic features on tropical cyclone formation over the Indian Ocean, Monthly Weather Review, 148, 2777-2799, https://doi.org/10.1175/MWR-D-19-0259.1, 2020.

Wu, J., Kawamura, R., Mochizuki, T., Kawano, T. J. W., and Extremes, C.: Increasing WNP tropical cyclone-related extreme precipitation over East Asia during boreal summer associated with PDO shift, 45, 100714, https://doi.org/10.1016/j.wace.2024.100714, 2024.

Young, R. and Hsiang, S.: Mortality caused by tropical cyclones in the United States, Nature, 635, 121-128, https://doi.org/10.1038/s41586-024-07945-5, 2024.

Zhong, Q., Gan, J., Tu, S., Toumi, R., and Chan, J. C. L.: Global increase in rain rate of tropical cyclones prior to landfall, Nature Communications, 17, 114, https://doi.org/10.1038/s41467-025-68070-z, 2026.

Zhou, Y., Matyas, C., Liu, P., and Li, H.: Identification of tropical cyclone–related flash floods from hazard narratives using a large language model–based approach, Nature, 2, 104, https://doi.org/10.25921/82ty-9e16, 2025.