Investigating the Spatiotemporal Evolution of Pre-Landfall Rainfall in Gulf Coast Tropical Cyclones

Sanaa Burke, Shuai Wang
College of Earth, Ocean, and Environment, Department of Geography and Spatial Sciences

Abstract

Tropical cyclones (TCs) that impact the U.S. Gulf Coast are often associated with notable rainfall prior to the storm's landfall, but the structure and timing of this precipitation remain underexamined. Using the Multi-Source Weighted-Ensemble Precipitation (MSWEP) dataset, we examined the spatiotemporal evolution of daily rainfall in several historical Gulf TC events, including the following: Allen (1980), Alicia (1983), Chris (1982), and Elena (1985).

In each case, we see a tendency for a crescent-shaped band of enhanced precipitation to form ~3 days before landfall, typically around 10° distance from where the TC eventually made landfall. In most instances, the band enhancement peaked on the landfall day and was usually separated from the cyclone by an area of little to no precipitation.

While we are not establishing causation, the consistent co-occurrence of this feature suggests a potential relationship between the TC's approach to land and the surrounding precipitation structure. Better characterization of these features may allow for earlier flood preparedness in advance of landfall, and might help elucidate the large-scale factors that affect the precipitation that occurs prior to the landfall of TCs.

Data and Methodology

1. **Storm Identification:** We used the IBTrACS v04r01 dataset to identify all U.S. landfalling tropical cyclones from 1971–2020. Storms were filtered by selecting records with LANDFALL = 0 and DIST2LAND ≤ 30 km. The first landfall instance per storm was retained using unique storm IDs (SID).

2. **Landfall Timing & Precipitation File Matching:** Each storm's landfall date was converted into YYYYDDD format to match daily files from the MSWEP v2.8 dataset, which provides global gridded precipitation data at 0.1° resolution. Each file contains one day of precipitation totals under the precipitation variable.

3. **Spatial Precipitation Mapping:** For each storm (193 storms total), we generated a sequence of six maps of the Continental United States showing daily precipitation from five days before to the day of landfall. Each plot includes a 10° × 10° red box centered on the storm's landfall coordinates. The percentage above each panel represents the amount of rainfall in the box relative to landfall-day precipitation, providing insight into spatial and temporal precipitation evolution.

4. **Histogram Generation:** We created histograms comparing pre-landfall rainfall to landfall-day rainfall. Each bar shows the percentage of landfall-day rainfall that occurred on a given prior day. This allowed us to evaluate the frequency and magnitude of early precipitation relative to landfall intensity.

5. **Azimuthal Totalling of Landfall-Day Precipitation:** On the landfall day, we computed azimuthal precipitation totals centered on each storm's landfall location. Using the Haversine formula, we calculated distances from the center to each grid cell and totaled precipitation in 10 km radial bins from 0 to 10,000 km, producing radial rainfall profiles.

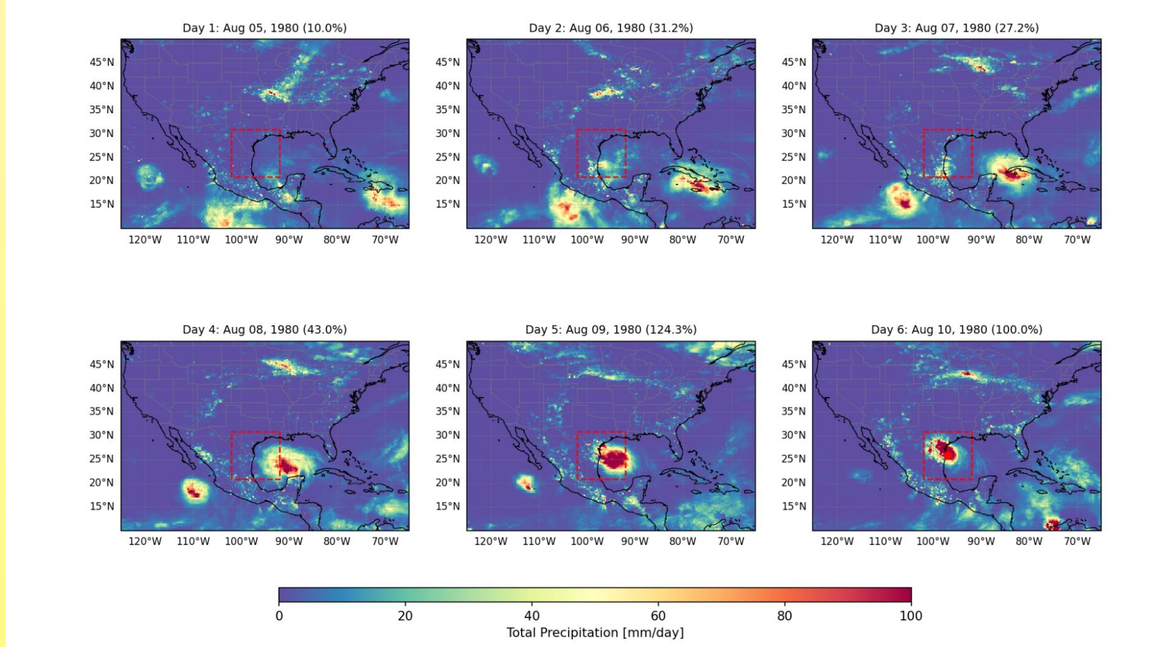


Figure 1: Daily precipitation [mm/day] associated with Hurricane Allen (1980), derived from the MSWEP v2.8 dataset. Each panel shows total precipitation for one day, from five days prior (top left) to the landfall day (bottom right). The red dashed box highlights the CONUS-centered landfall region. Percentages indicate the fraction of landfall-day rainfall within the landfall region.

Results

1. **Precipitation Timing and Location Vary Across Storms:** Although most storms produced peak rainfall on the day of landfall, many exhibited substantial precipitation 1–2 days prior, with some pre-landfall totals exceeding 50% of landfall-day rainfall, as seen in Figure 2. The extent and intensity of early rainfall within the 10° × 10° box surrounding each landfall location varied widely, indicating that some storms begin impacting coastal regions well before official landfall.

2. **Ring-Shaped Precipitation Structures Are Common:** Spatial plots often reveal a ring of enhanced rainfall approximately 100–200 km from the storm center, separated from the core by a relative minimum or "moat" in precipitation, as seen in Figure 1. This recurring structure likely corresponds to outer rainbands commonly seen in landfalling tropical cyclones.

3. **Evidence of Potential Predecessor Rain Events (PREs):** A subset of storms showed organized, long-range precipitation occurring far ahead of the storm center, indicative of possible PRE-like behavior. These patterns suggest interactions between tropical moisture and mid-latitude dynamics, though further study is needed to confirm causal links.

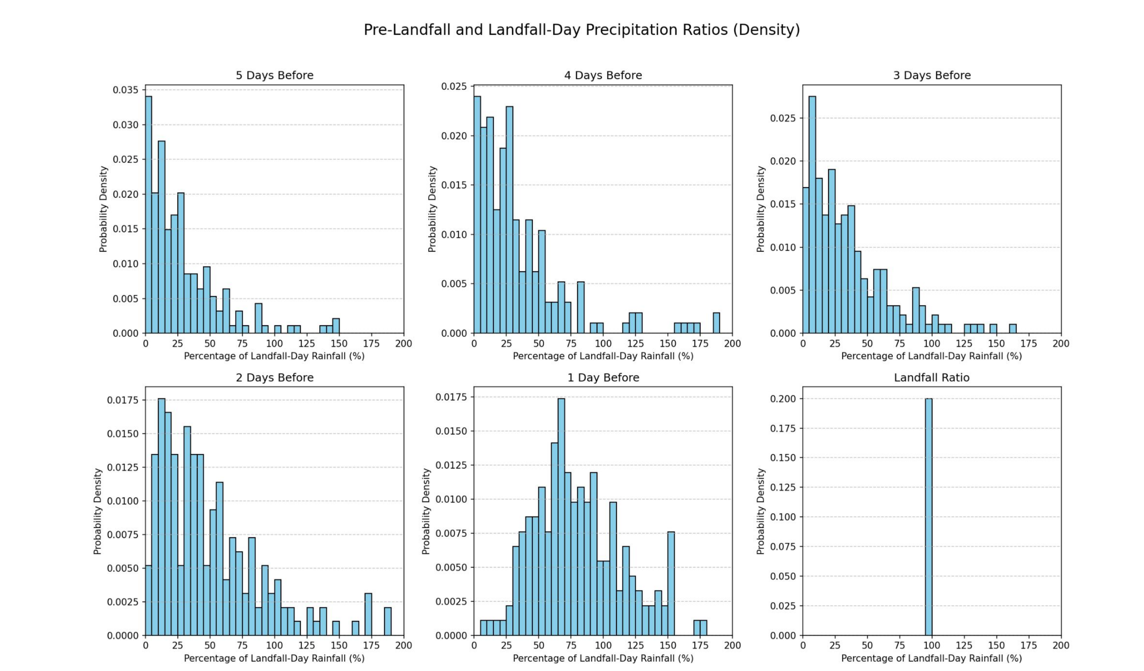


Figure 2: Probability density histograms showing the distribution of precipitation ratios for the five days preceding landfall, compared to the landfall day. Each panel illustrates the proportion of rainfall on a given day relative to the total on landfall day, normalized across all storms. The sharp peak at 100% on landfall day reflects the normalization method.

Discussion

Landfalling tropical cyclones often begin delivering impactful rainfall well before landfall, and their spatial structure plays a critical role in how precipitation is distributed. Figure 2 shows that while the day of landfall typically contains the highest rainfall totals, many storms deliver a substantial portion of their precipitation (sometimes over 50%) in the days prior. This early rainfall varies considerably across storms, both in timing and magnitude, underscoring the need for better characterization of pre-landfall impacts.

Spatial patterns in Figures 1 and 4 reveal the frequent development of crescent- or ring-shaped precipitation structures around the storm, often peaking at distances of 100–200 km from the center. These rings are separated by precipitation minima or "moats" and may correspond to outer rainbands or mesoscale convective features not always captured in operational forecasts.

Figure 3 provides further evidence of this ring-like behavior via azimuthal profiles of landfall-day precipitation. The peaks in total rainfall at intermediate distances support the visual findings and confirm that intense rainfall is often concentrated away from the storm center. Additionally, in Figure 5, a conceptual schematic of a Predecessor Rain Event (PRE) highlights one possible mechanism for early inland rainfall delivery, showing how tropical moisture can interact with mid-latitude systems to produce heavy rain well in advance of landfall.

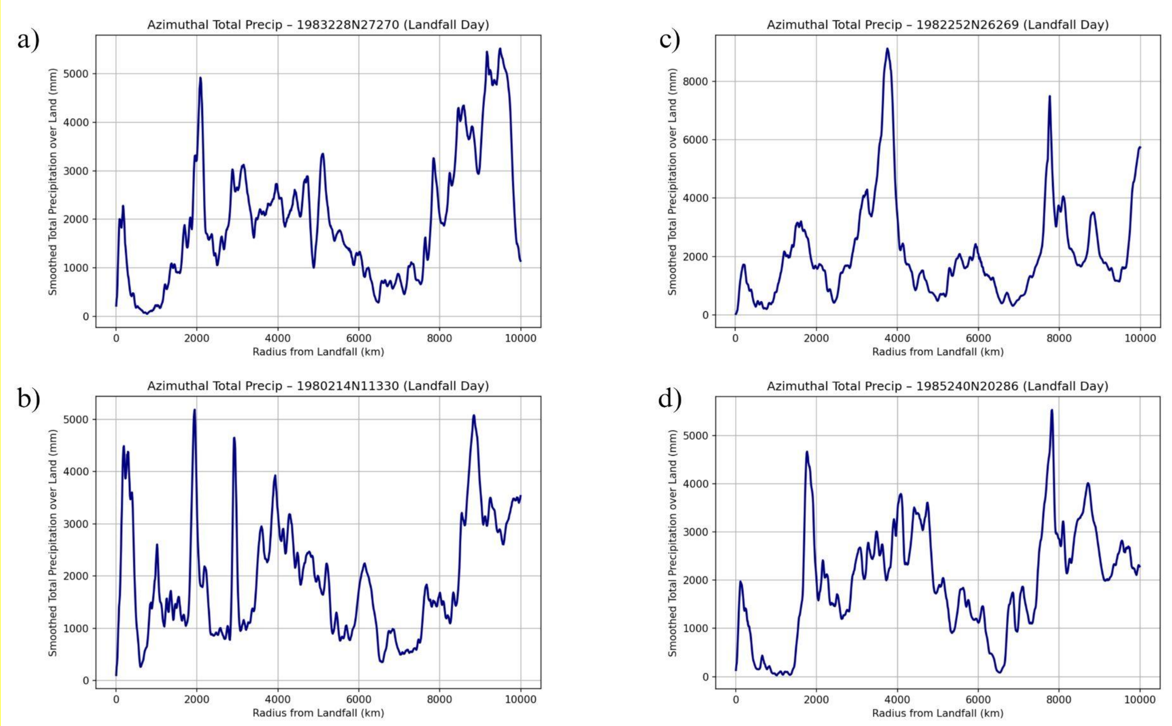


Figure 3: Azimuthal rainfall profiles showing total precipitation (mm) as a function of distance from the landfall point (0–10,000 km) for four storms: **a)** Alicia (1983), **b)** Allen (1980), **c)** Chris (1982), and **d)** Elena (1985). Each plot reflects precipitation structure on the day of landfall.

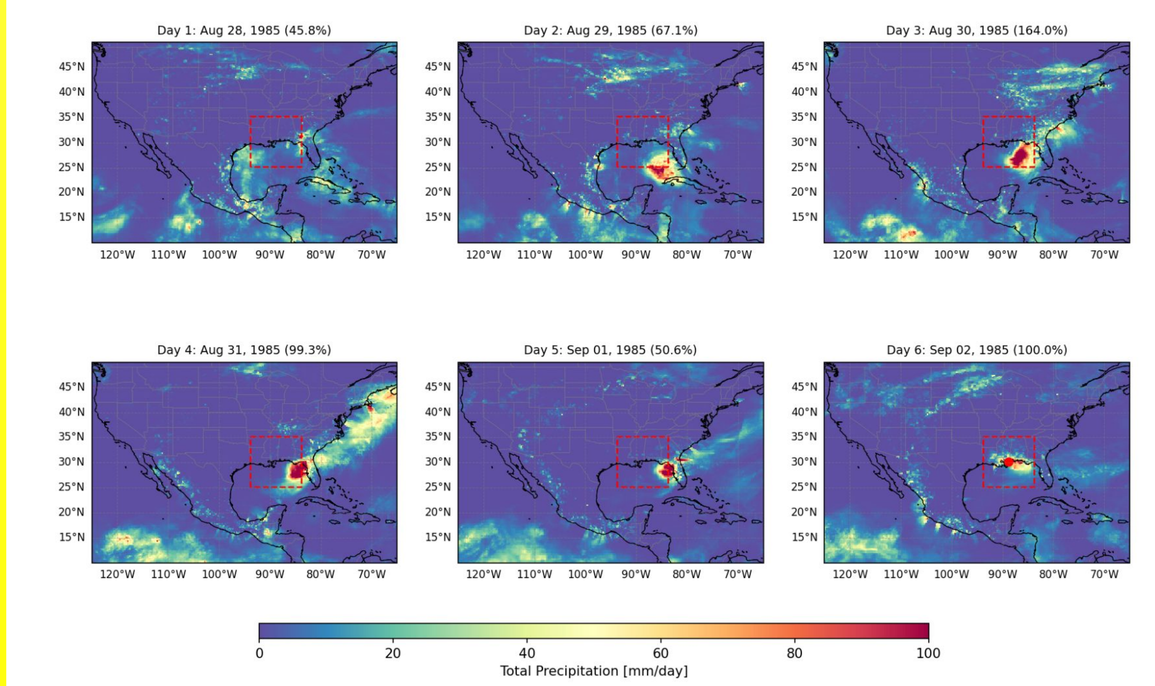


Figure 4: Daily precipitation [mm/day] associated with Hurricane Elena (1985), derived from the MSWEP v2.8 dataset. Note the crescent-shaped "wall" of precipitation that begins to form ahead of the tropical cyclone as it makes landfall near the Gulf.

Conclusion

Landfalling tropical cyclones often begin delivering impactful rainfall well before landfall, and their spatial structure plays a critical role in how precipitation is distributed. Recognizing features like ring-shaped rainfall and early inland moisture delivery is essential for improving flood forecasts and advancing storm-centered rainfall modeling. Incorporating storm structure into rainfall forecasting could lead to earlier warnings and more accurate risk assessments.

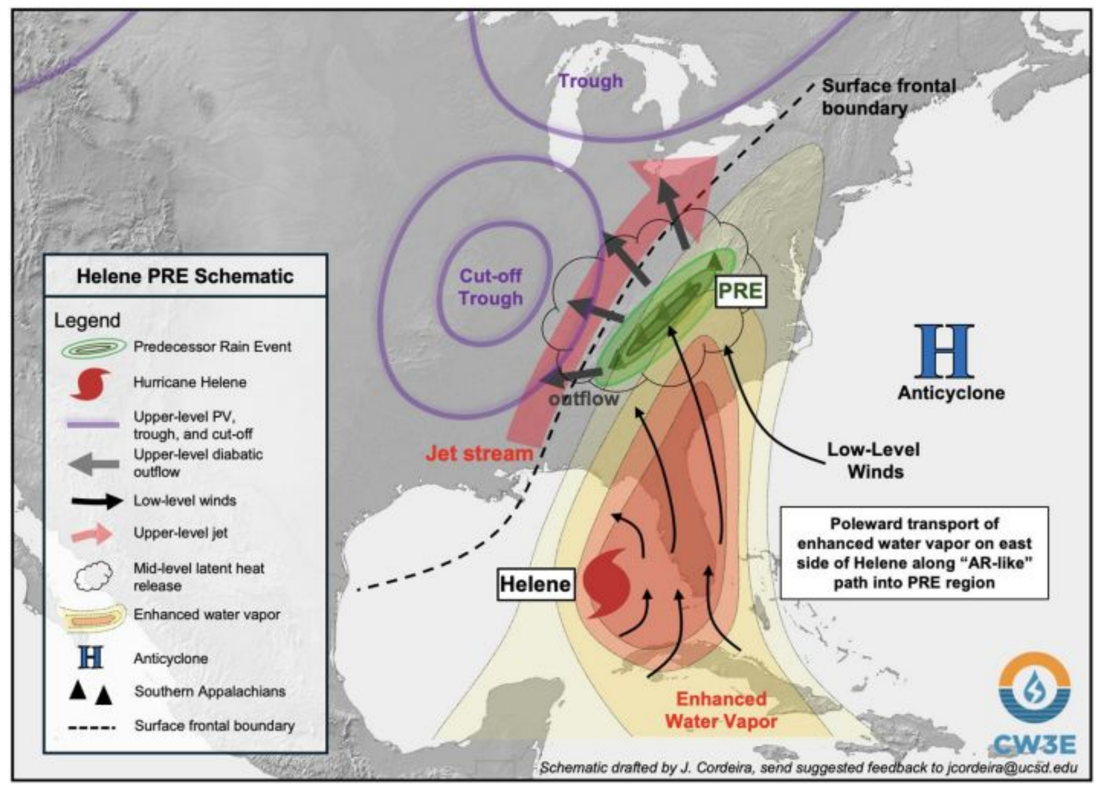
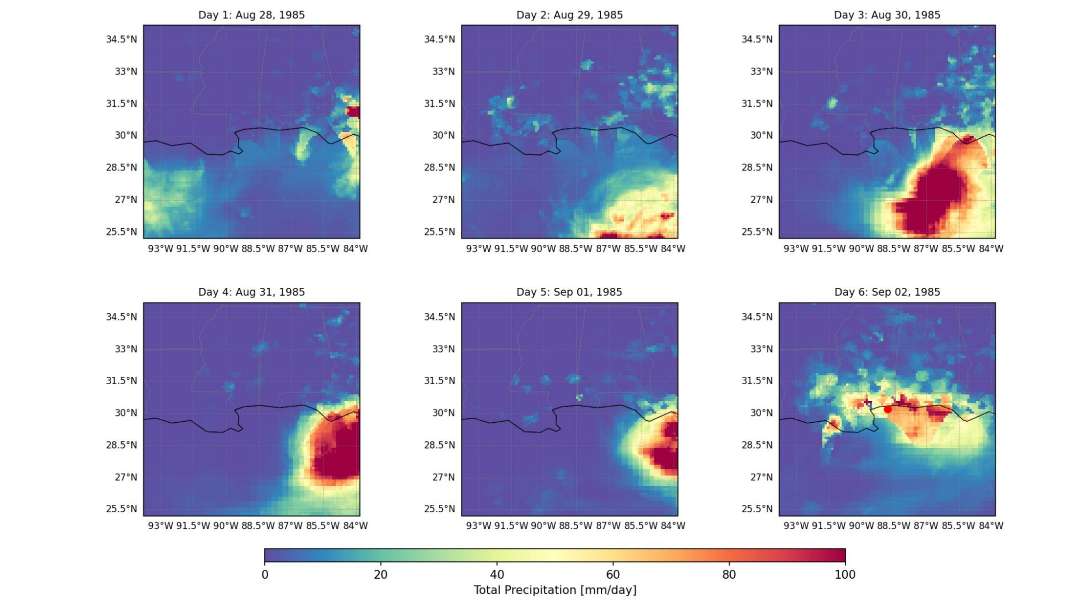


Figure 5: A schematic illustrating the atmospheric setup that led to a Predecessor Rain Event (PRE) north of Hurricane Helene. Enhanced water vapor on the storm's eastern flank was transported poleward along an atmospheric river-like pathway by low-level winds and upper-level outflow. This moisture interacted with a surface frontal boundary, a jet streak, and upper-level trough dynamics, producing heavy rainfall well in advance of Helene's core.
Source: CW3E Event Summary – Hurricane Helene PRE (2024)

Figure 6: Daily precipitation (mm/day) from the MSWEP v2.8 dataset for Hurricane Elena (1985), shown within a 10° × 10° box centered on the landfall point. This is a zoomed-in view of the red box highlighted in Figure 4, providing greater spatial detail of rainfall evolution around landfall.



References

Beck, Hylke E., et al. "MSWEP v2 Global 3-Hourly 0.1° Precipitation: Methodology and Quantitative Assessment." AMETSOC, American Meteorological Society, 1 Mar. 2019, journals.ametsoc.org/view/journals/bams/100/3/bams-d-17-0138.1.xml.

Ecmwf. ERA5 Hourly Data on Single Levels from 1940 to Present, 1 May 2025, doi.org/10.24381/cds.adbb2d47.

"MSWEP." GloH2O, 15 Nov. 2024, www.gloh2o.org/mswep/.

Summary of the Predecessor Rain Event Prior to Hurricane ..., cw3e.ucsd.edu/wp-content/uploads/2024/09/30Sep2024_HelenePRE_EventSummary/HelenePRE_EventSummary.pdf. Accessed 1 May 2025.

Tropical Cyclone Introduction | National Oceanic and Atmospheric Administration, www.noaa.gov/jetstream/tropical/tropical-cyclone-introduction. Accessed 1 May 2025.

"What Is a Predecessor Rain Event (Pre)?" Climate and Agriculture in the Southeast, site.extension.uga.edu/climate/2020/10/what-is-a-predecessor-rain-event-pre/. Accessed 1 May 2025.