Lightning and the Eye of the Storm: Understanding Burst Patterns and Cyclone Intensification

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Background

Tropical cyclones (TCs) are among the most powerful and destructive weather systems on Earth, posing significant threats to life, property, and infrastructure. To mitigate these impacts, researchers monitor various storm characteristics like wind speed, convection, and lightning activity. Lightning, in particular, is a potential indicator of changes in storm dynamics. Previous studies suggest that lightning activity may be closely linked to changes in storm intensity, with inner core and rainband lightning potentially signaling different storm behaviors. Understanding these patterns offers valuable insights into TC intensification patterns and could enhance TC intensification forecasting accuracy.

Project Goals

- ➢ Identify WWLLN lightning bursts for inner core and rainband lightning
- ➢ Investigate the relationship between lightning bursts and tropical cyclone intensification stages

Data Sources

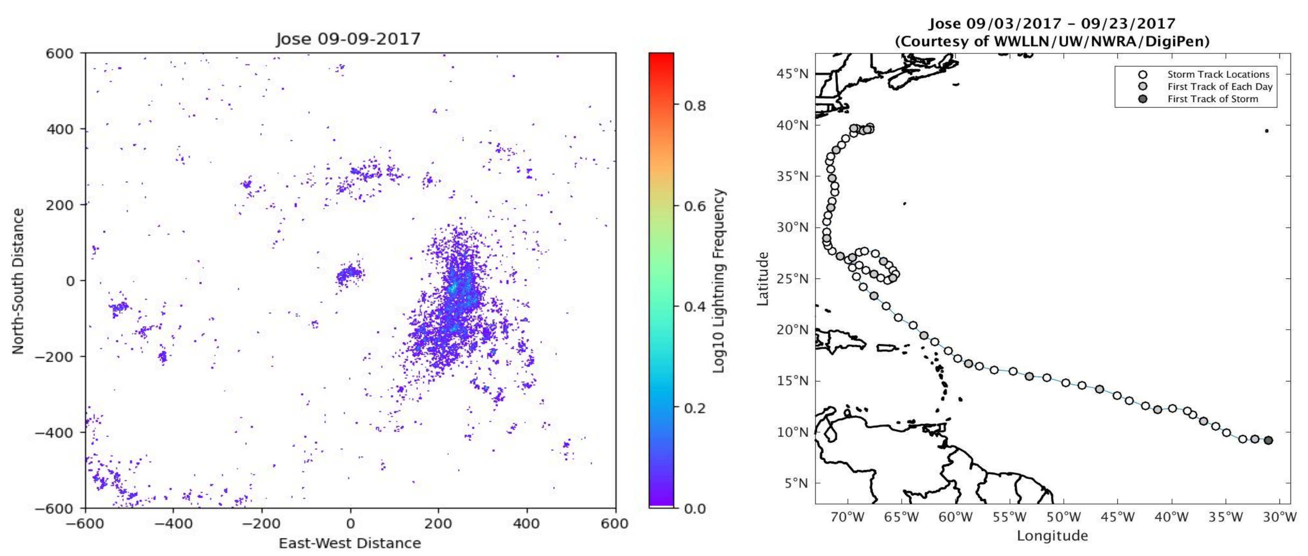


Fig. 1: WWLLN lightning data (left), TC track data (right) provided by NWRA

We use the following datasets for each tropical cyclone (TC):

- **World Wide Lightning Location Network (WWLLN) Data:** (.txt)
  - Lightning strokes with timestamp and distance from storm center
  - Includes 472 Category 1 or higher TCs across 6 basins from 2010 to 2020
- **Storm Track File:** (.txt)
  - Storm center coordinates, wind speed, pressure with timestamps taken at regular intervals throughout the storm
- **Vertical Wind Shear Vector Data:** (.mat)
  - Shear vector angle and magnitude for WWLLN lightning strokes
  - Vector angle determines the shear quadrant, used with rainband lightning due to storm behavior differences depending on quadrant

Vertical wind shear is the change in wind speed or direction with altitude, represented by a vector showing the difference between wind vectors at different heights.

Solution Pipeline

Combining data files

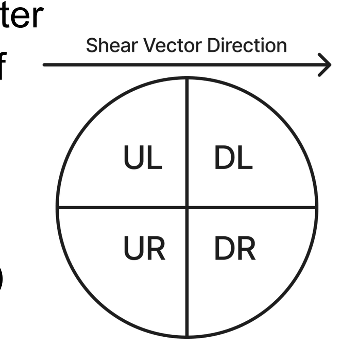
- Combine individual .txt files into one consolidated file
- Join WWLLN lightning strokes to the nearest track file wind speed and pressure observation
- Sum lightning strokes per 30-minute time bin

Defining inner core and rainband lightning

Inner core: Lightning within 100 km of storm center

Rainband: Lightning between 200 and 400 km of storm center

Shear quadrants (for rainband only):
UL (Upshear Left), UR (Upshear Right),
DL (Downshear Left), DR (Downshear Right)



Classifying intensification stages

Calculate intensification stages using forward-looking 24-hour differences in wind speed

Intensification Stage	Change in Winds (Knots) in 24 Hours
Weakening	<-30 to -10
Neutral	-10 to 10
Intensifying	10 to >30

Classify the storm using the Saffir-Simpson scale, where the overall category is based on maximum wind speeds, and the current category reflects wind speeds for the current period.

Category	Sustained Winds (Knots)
1	64-82 kt
2	83-95 kt
3	96-112 kt
4	113-136 kt
5	137 kt or higher

Identifying lightning bursts

- A **lightning burst** is a spike in activity relative to the storm's overall lightning, identified by comparing 30-minute counts to other time bins within the same storm
- Exclude data with wind speeds under 40 knots and periods without lightning activity from calculations
- Apply the following methods to each TC individually to calculate lightning burst thresholds (3 techniques, 2 thresholds each):
  - **Median Absolute Deviation** (MAD)
  - **Interquartile Range** (IQR)
  - **Log-normal Standard Deviations from the Mean** (LOGN)
- Create dashboard showing lightning activity and identified bursts

Lightning burst and intensification analysis

- Investigate the statistical relationship between lightning activity and storm intensification stages for three threshold methods
- Examine overall lightning activity, basin-level trends, and category-specific trends for both inner core and rainband lightning

Lightning Burst Detection

We display sample plots from our lightning burst dashboard below.

Inner Core - Maria

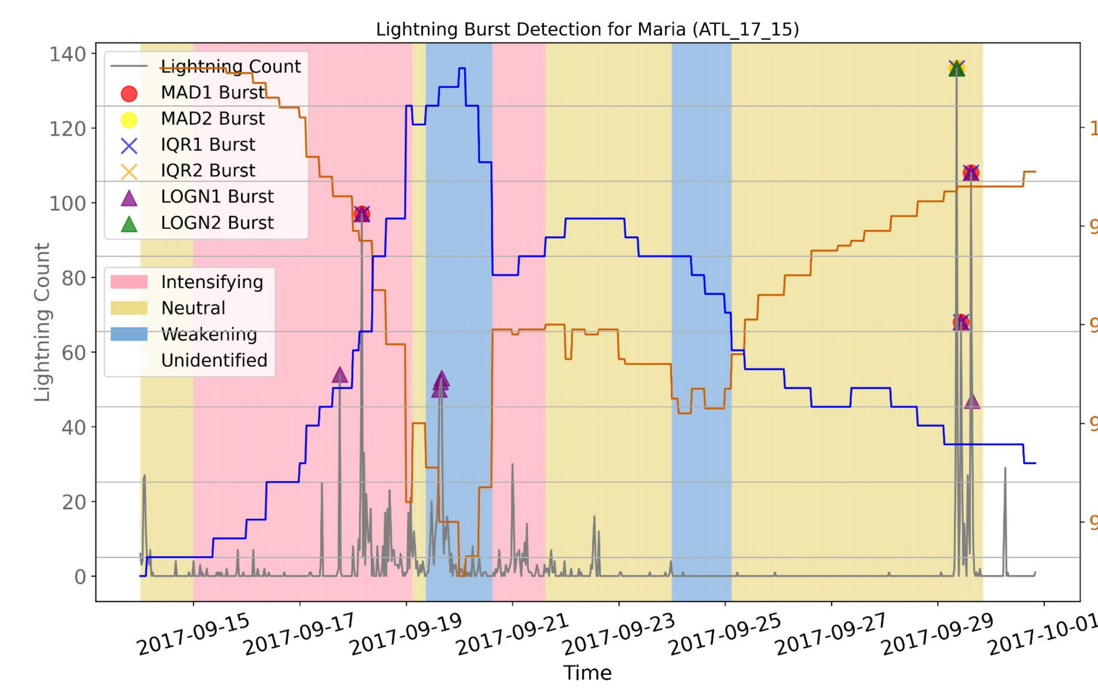


Fig. 2: Inner core lightning bursts for Maria, background colored by intensification category

The plot displays inner core lightning for Maria, a 2017 category 5 hurricane in the ATL basin. The background colors indicate the intensification stages of the storm and the markers indicate identified lightning bursts for each of the 6 methods.

Rainband - Maria

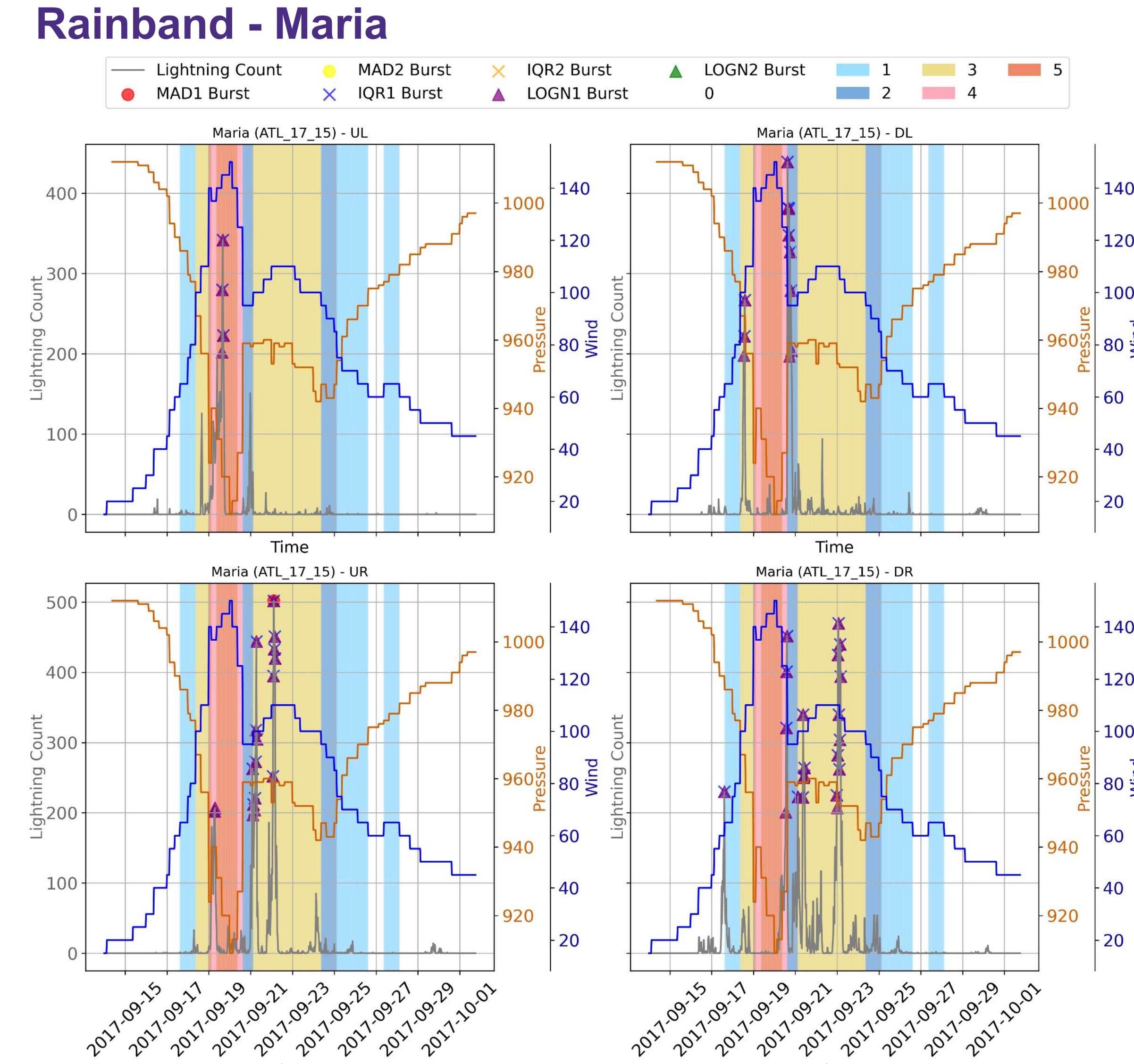


Fig. 3: Rainband lightning bursts for Maria, split by shear quadrants and background colored by current category

The plot shows rainband lightning activity for Maria split into the four shear quadrants. The background colors indicate the current category of the storm based off wind speeds for that time bin.

Conclusion: We can see that most of the lightning bursts are located in UR and DR for category 3, UL for category 4 and 5, and DL and DR for category 1 and 2.

Lightning Burst Analysis

Chi-squared tests ($p<0.05$) reveal a significant relationship between lightning bursts and tropical cyclone intensity for both inner core and rainband regions.

Basin-level analysis suggests a consistent relationship between lightning bursts and intensification across most basins for both inner core and rainband.

Current category analysis shows varying burst distributions, with categories 1 and 2 yielding less significant results in the inner core lightning.

Grouping categories 0–2 and 3–5 highlights the strongest differences for both inner core and rainband:

- Categories 0–2: More bursts occur during the intensifying stage.
- Categories 3–5: More bursts occur during the weakening stage.

Conclusion: For both inner core and rainband, lower-category storms exhibit the highest lightning burst activity during intensification, while higher-category storms show increased bursts during weakening.The log-normal 2 sigma method demonstrates exceptional sensitivity in comparison with others.

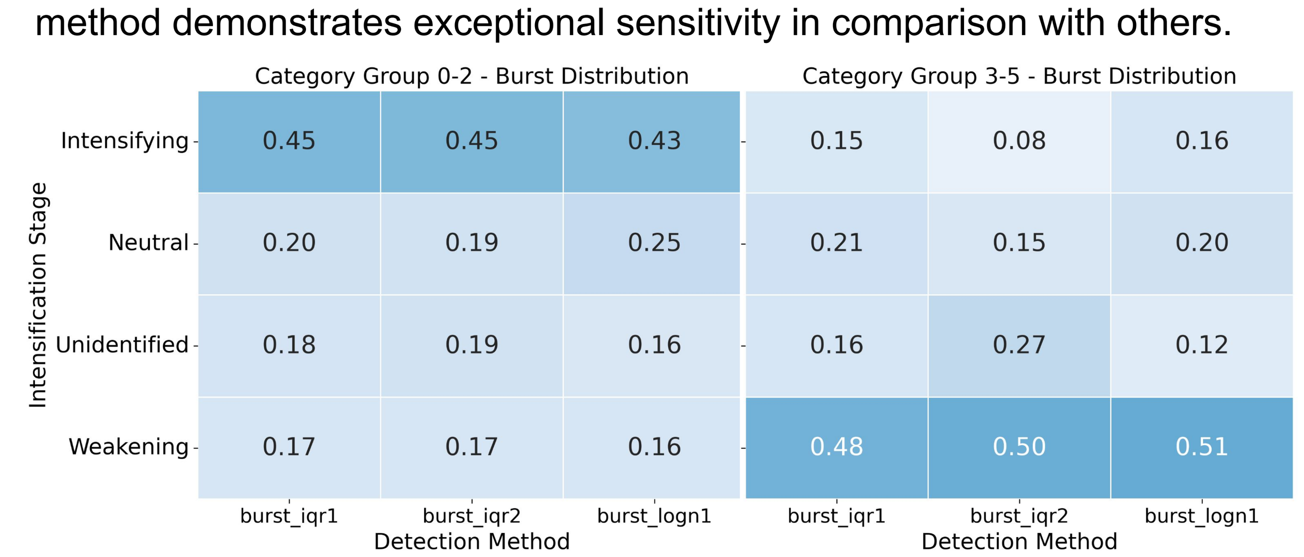


Fig. 4: Heat map for inner core lightning distribution in grouped categories

Limitations

- Joining the six-hour interval track file data to higher-resolution WWLLN measurements (≤1 hour) results in room for error
- Burst identification may be less effective for unpredictable, extreme, or small storms, as well as storms with landfall
- Inherent error associated with the WWLLN lightning dataset due to data collection methods

Future Work

- Improve lightning burst identification by excluding landfall data - landfall is often associated with increased lightning activity in TCs
- Perform the same analysis using Geostationary Lightning Mapper (GLM) image data for deeper insights
- Utilize machine learning methods to detect lightning bursts systematically for use in future predictive models

References

WWLLN Data Acknowledgment - The authors are using data from the World Wide Lightning Location Network, a collaborative consortium of over 70 worldwide collaborators, managed at the University of Washington.

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