IDENTIFYING CRITICAL STRENGTHS AND LIMITATIONS OF CURRENT RADAR SYSTEMS

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ABSTRACT

This study aims to investigate the correlation between lightning activity and intensity changes in Hurricane Milton (2024). Geostationary Lightning Mapper (GLM) data was used to analyze lightning flash event counts and area in relation to the tropical cyclones minimum central pressure and structural evolution. Inner core lightning bursts were analyzed within two to three times the radius of maximum wind (RMW). Various stages of Hurricane Milton's lifetime were analyzed, including before rapid intensification, rapid intensification, the eyewall replacement cycle, re-intensification, and landfall. Resemblance to other major hurricanes studied in similar works was found; inner core lightning bursts were an indication of rapid intensification in Hurricane Milton. There was parallel contraction of lightning and the RMW during peak intensity, and during periods of contraction, when Hurricane Milton was at its strongest, flash size tended to decrease. Additionally, the symmetrical pattern during intensification is an indicator that convective elements wrap around the eyewall in the inner core. Asymmetry indicates a weakening of Hurricane Milton influenced by shear and other factors. During the eye wall replacement cycle the lightning activity patterns of the eye wall replacement cycle is present.

1. INTRODUCTION

Lightning is a weather phenomenon often associated with thunderstorms and severe weather; however, its presence in tropical cyclones can give further insight into hurricane intensity. Lightning in tropical cyclones is found both in the inner core and outer rainbands (Stevenson et al. 2018). The most frequent lightning activity is typically found within the outer rainbands, with less activity occurring in the eyewall and the inner core (Cecil and Zipser 1999). The presence of lightning in a tropical cyclone can serve as an early indicator of a potential shift in its intensity.

The location of lightning within a tropical cyclone is critical to assessing potential changes of intensification (Stevenson et al. 2018; Fierro et al. 2018). The location of lightning within tropical cyclones shows more about different phases of intensification (Fierro et al. 2018). In particular, multiple studies show how the inner core lightning shows an indication of intensity change (Stevenson et al. 2018; Fierro et al. 2018). A key

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location of lightning to observe intensification in the inner core of a hurricane is the radius of maximum wind, the distance from the storm's center to the strongest surface winds (Stevenson et al. 2018). In the Stevenson et al. (2018) study, the inner core is defined as about one and a half to two times the radius of maximum wind. This region is especially significant because this is where inner core lightning bursts most commonly occur. Inner core lightning bursts are brief periods of intense lightning activity within the storm's inner-core region, and are linked to vigorous convection and vertical motion, and are often an indication of deepening of the storm (Stevenson et al. 2018).

Inner core lightning bursts that occur near or just outside the radius of maximum wind are more strongly associated with storm strengthening. In contrast, lightning farther from the core, such as in the outer rainbands, often signals a weakening or reorganization of storm structure (Stevenson et al. 2018). Inner core lightning bursts often precede rapid intensification, with storms typically intensifying within 24 hours of inner core lightning burst onset, when environmental conditions are favorable. Hence, lightning is an indicator of tropical cyclone intensification, particularly inner core lightning bursts as an indication of intensity change in tropical cyclones. Lightning activity can be observed remotely from the Geostationary Lightning Mapper (GLM) to identify and analyze lightning activity patterns through tropical cyclones' lifecycles (Fierro et al. 2018). This study aims to utilize the GLM to identify lightning characteristics within Hurricane Milton.

2. OVERVIEW OF HURRICANE MILTON

Hurricane Milton was the most intense hurricane in 2024 (Henson and Masters 2025), with a minimum central pressure of 895 mb and sustained one-minute maximum winds of 180 mph, with details of its life cycle discussed in Beven et al. (2025). Milton is tied with Hurricane Rita for the 4th most intense Tropical Cyclone in the Northern Atlantic and the most intense hurricane ever in the Gulf of Mexico (Holpuch 2024). On October 5th at approximately 1200 UTC, in the Bay of Campeche, an organized system of convection formed into a tropical depression. The depression shifted northwards through a favorable environment of weak vertical wind shear and warm sea surface temperatures. This permitted intensification, allowing the system to be upgraded to a named tropical storm approximately 6 hours after tropical cyclogenesis at 1800 UTC. Development of a surface low altered Milton's motion eastward. Following this, Milton steadily intensified, progressing to hurricane strength roughly 24 hours after genesis around 1800 UTC on October 6th.

Over this period, Hurricane Milton began rapid intensification while a distinct small inner core developed. Aircraft reconnaissance dropsonde data revealed that at 325 UTC on October 7th, Milton held a central pressure of 977 mb. By 2000 UTC, Milton achieved a record-breaking central minimum central pressure in the Gulf of Mexico at 895 mb, becoming a major hurricane. This pressure dropped 82 millibars in 17 hours at a rate of approximately 4.8 millibars per hour, making this the third fastest rapid intensification of a tropical cyclone in the Northern Atlantic and the fastest in the Gulf of Mexico in recorded history.

Hereafter, Milton underwent an eyewall replacement cycle and weakened for the next 12 hours, approximately as the center shifted eastward off the Yucatan Peninsula. Milton never impacted the peninsula directly, as hurricane-force winds and the inner core remained in the Gulf of Mexico, and the size of the storm remained undersized early in its life cycle compared to other Atlantic cyclones.

On October 8th, a low-to-mid-level ridge formed between the Caribbean and the Florida Peninsula after the low-pressure system ahead of Milton passed through Florida. This transition allowed for the track to be redirected towards the northeast. At 1200 UTC, once the eyewall replacement cycle was complete, a period of re-intensification occurred where the central pressure dropped to 900 mb at about 2200 UTC.

Additionally, intensity oscillations transpired on the turn of October 9th due to a potential second eyewall replacement cycle. Milton proceeded to enter a deep-layered southwestern flow associated with increasing wind shear, which caused the track to head northeastward towards colder sea surface temperatures. Hurricane Milton remained a major Hurricane until landfall at around 0000 UTC on October 10th, causing a significant tornado outbreak in Central Florida, before dissipation in the Atlantic Ocean.

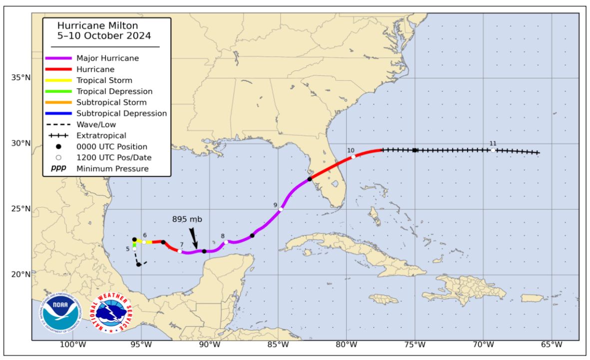

Figure 1. A depiction of Hurricane Milton's strength and track path throughout its lifetime (After Beven et al. 2024).

3. DATA & METHODS

To analyze lightning in Hurricane Milton, the GLM was chosen to be able to detect lightning flashes over the Gulf of Mexico. The GLM provides coverage from space, whereas ground-based lightning detection networks have difficulty receiving full coverage of oceanic regions. The GLM is mounted on the GOES-16 East satellite in geostationary orbit, enabling continuous monitoring over the eastern portion of the Western Hemisphere. Brief optical pulses of lightning are detected at 777 nm, a wavelength emitted during lightning discharges. These pulses are known as flash events and are recorded constantly every 2 ms. To categorize these flash events, the Lightning Flash Clustering Algorithm groups them by time and location into larger-scale flashes (Rudlosky et al. 2018).

GLM flash data was grouped in 30-minute intervals throughout Hurricane Milton's lifetime (from Tropical Depression formation to Landfall). Flashes were spatially filtered utilizing buffer zones of two and three times the radius of maximum wind (RMW), as well as 500 km from the center of the storm.

Track and intensity information were obtained by combining National Hurricane Center HURDAT2 best track (Landsea and Franklin 2013) with aircraft reconnaissance data (Sheets 1982). While HURDAT2 provides a best estimate of the hurricane position, it is limited to position information every six hours. In between these times, aircraft data were used to provide a better estimate of location than a simple interpretation between the HURDAT2 locations. The HURDAT2 data were the sole source of intensity, wind, and size information. These values were evenly interpolated between HURDAT2 values.

A distance threshold of three times the RMW was used to distinguish outer rain bands and the inner core of Hurricane Milton. This was chosen as there was a clear gap between lightning in the inner core and outer rain bands at this distance. Total flash count was measured within each buffer (2 and 3 times the RMW) and plotted alongside the minimum central pressure over the hurricane's track. Flash area was also plotted over the inner core to determine further parallelism between lightning flashes and tropical cyclone intensification.

Additionally, key phases of the hurricane were isolated to closely observe lightning characteristics during those times. Events to be examined further include before intensification, rapid intensification, the eyewall replacement cycle, re-intensification, and landfall. These events were isolated to examine changes in lightning activity as potential indicators of intensity and structural evolution. Flash size can also be determined through flash area and is examined over key periods of intensity change. This can be achieved by pairing flash count trends with pressure changes over time. This approach allows for the identification of lightning characteristics that may precede or coincide with rapid changes in tropical cyclone intensity.

4. RESULTS

To investigate the relationship between lightning activity and storm intensity in Hurricane Milton, minimum central pressure and flash count are shown in Figure 2. This allows for tracking the evolution of lightning activity over Milton's path and its correspondence to tropical cyclone intensity changes. Through utilizing the buffer of two and three times the radius of maximum wind to define the inner core. A clear representation of the relationship between flash count and central minimum pressure throughout Hurricane Milton's lifetime can be established. Visualizing both parameters over time provides an initial context for Milton's large-scale lightning behavior, which helps to establish whether a notable relationship exists between flash count fluctuations and intensity changes. Notably, the majority of the rapid intensification occurred on October 7th. Before this pressure drop, an increase in flash count was observed before and during Hurricane Milton, reaching a minimum central pressure of 895 mb. Following this, an eyewall replacement cycle occurred for the next 12 hours, causing a decrease in the flash rate. Preceded by an increase in flash count as Milton re-intensified into a Category 5 storm on October 8th. Followed by another decrease in flash activity on October 9th in the inner core, while Milton made landfall.

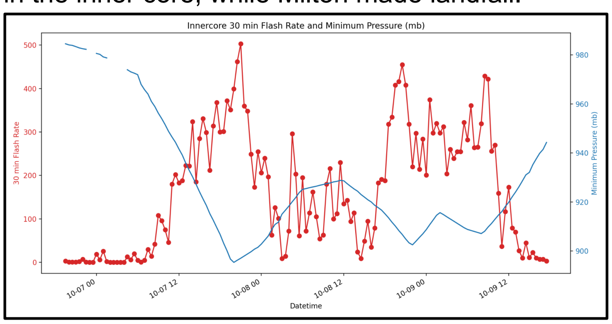

Figure 2. A time series of Hurricane Milton's intensity as denoted by minimum pressure (mb) and 30-minute flash rates in the inner core.

In Figure 3, we can get a better insight into the lighting characteristics during key intensity changes in Milton's lifetime, being able to more accurately define these behaviors. In addition to examining flash count, flash area/size is taken into consideration to be able to gain insight into lightning characteristics during intensity change. Two and three times the radius of maximum wind is defined on the plot to better define the inner core. Before the moment of rapid intensification, there are a few flash events within the radius of maximum wind. But during the rapid intensification noted in Fig. 4b, we can see that there is significant contraction compared to before the period of rapid intensification. Additionally, the radius of maximum wind and the lightning within the storm simultaneously contract. Notably, the inner core is saturated with small flash events. During the eyewall replacement cycle, flash sizes increase during this process while the radius of maximum wind expands as the intensity lowers. Also, a ring from the old eye wall expanding away from the new eyewall is identified. While Milton re-intensified into a category 5 hurricane, the RMW and lightning again contracted in parallel. The inner core becomes symmetrical and saturated with flashes once again. As the hurricane weakened before landfall, the lightning became asymmetric, which is reflective of stronger synoptic-scale vertical wind shear during the landfall, in association with a large number of supercells forming and moving eastward over Florida.

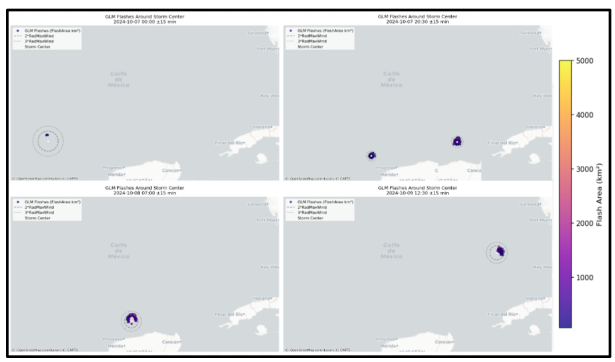

Figure 3. A panel of flash count in the inner core, encompassed by a ring denoted 2 and 3 times the radius of maximum wind. the color bar denoting the flash area. Before rapid intensification (top left), rapid intensification (left top right) and re-intensification (right top right), the eyewall replacement cycle (bottom left), and landfall (bootom right).

Proceeding to the prior time series, a new attribute, flash area, with a standard deviation of one, is applied to the inner core as seen in Figure 4. While the minimum pressure drops in correlation to the increase in flash counts, the flash size notably decreases. The flash size then increases during the eye wall replacement cycle as the decrease in flash rate becomes parallel with the increase in flash area. During the storm, the flash count increases and the flash size decreases, having parallel results to the rapid intensification, before Milton made landfall, where flash size increases and flash counts drop to zero.

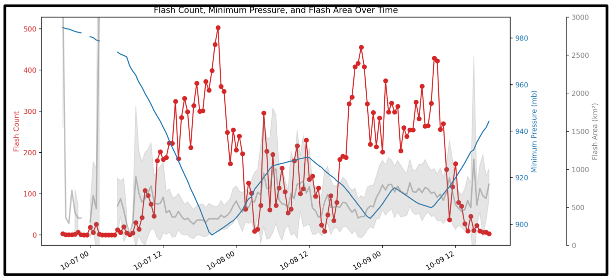

Figure 4. A time series of Hurricane Milton's intensity as denoted by minimum pressure (mb), 30-minute flash rates, and flash area (+- 1σ) in the inner core.

5. DISCUSSION & CONCLUSIONS

When compared to these results of lightning flash behavior to other storms studied in the past, such as Stevenson et al. 2018. We can see that the contraction of the radius of maximum wind was associated with the intensification of the tropical cyclone. With the cyclone weakening, we found that the radius of maximum wind expands as the minimum pressure increases, which was not investigated during this study. Notably, in both this study and Stevenson et al. (2018), we can determine that inner core lighting bursts, within the radius of maximum winds, were an indication of rapid intensification, as noted by the study. While comparing results to the Fierro et al. (2018) study, which utilizes flash rates during Hurricane Maria (2017). Hourly rates were examined instead of 30 minutes, but we are still able to see that before the pressure drops, we can see a notable increase in inner core flash counts. As the flash count increases, the pressure decreases; this occurs as the storm goes through multiple intensification cycles.

In conclusion, from this study, we can determine that the inner core lightning bursts were an indication of intensification and rapid intensification in Hurricane Milton. ICLBs in Milton were packed with small flashes during intensification. The RMW and lightning paralleled each other during periods of intensity change, where flashes within two and three times the RMW decreased during the rapid intensification and minimum central pressure and re-intensification periods. The arrangement of the lightning was noted to have some variation through intensification phases. Symmetrical patterns were an indication of convective elements being advected around Milton's eye in the inner core. Asymmetry patterns were transparent as Milton made landfall in Central Florida, as it moved into a more baroclinic environment. This portion is where the greatest number of flashes occur, happening in the outer rain band associated with a tornadic supercell outbreak. According to the GLM, we are able to see that the inner core was saturated with small flashes. This happened for a period of more than 12 hours as the storm strengthened to Category 5 for the first time. Following the weakening phase during the eye wall replacement cycle, another ICLB took place. During the re-intensification period to a Category TC, which lasted for 18 hours, there were dense rates of flash events occurring.

Additional work that can be done to further this study is to look at the fluctuation of the diurnal cycle artifacts within GLM data, as the GLM has detection differences between day and night. The flash counts can be broken up into the key phases of intensification changes to gain further insight into the lighting activity that occurs. This will allow us to gain further insight into the behaviour of these intensity changes and can potentially give us further insight into the intensification/weakening phases, the eye wall replacement cycle, and the tornadic supercells at landfall.

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