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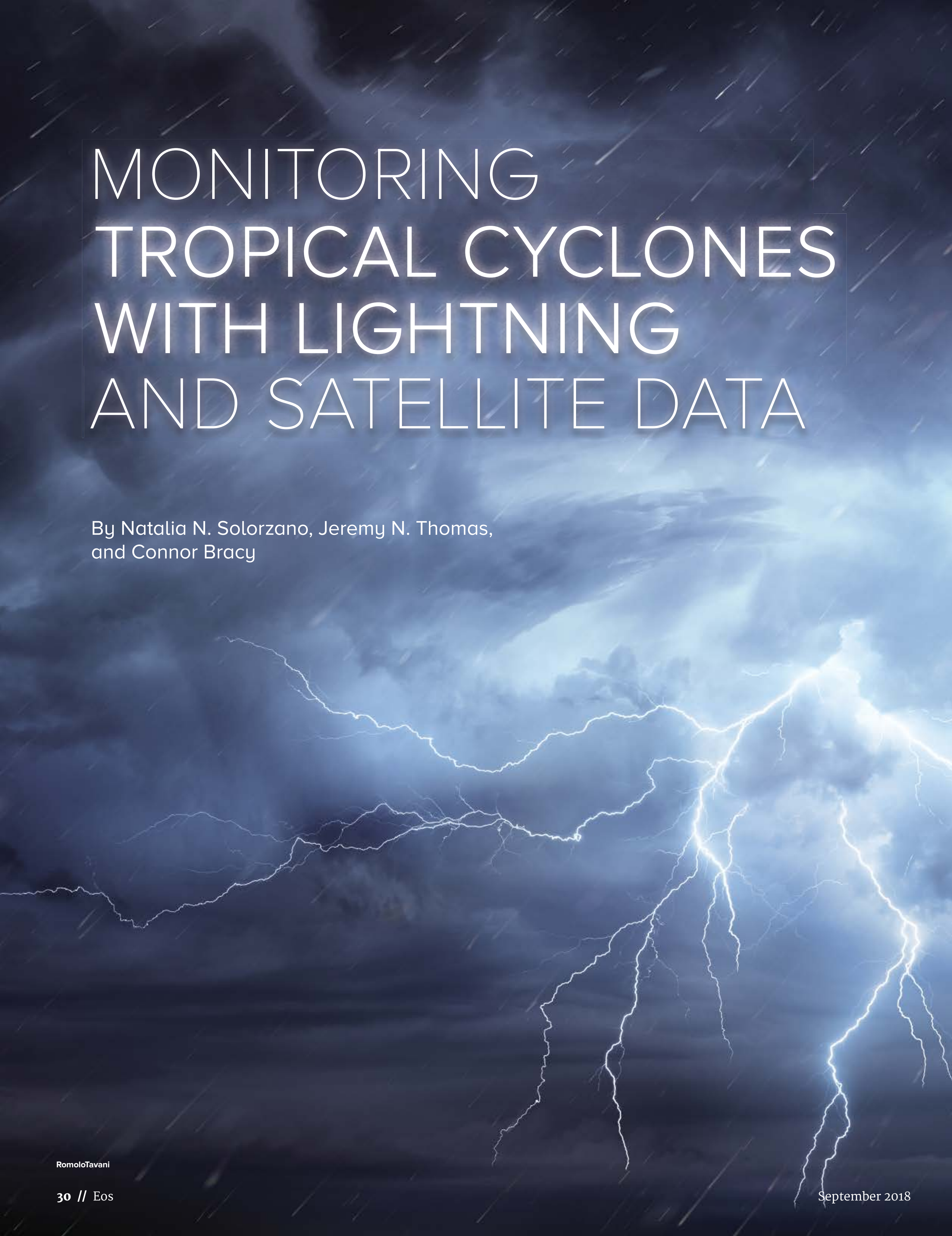

MONITORING TROPICAL CYCLONES WITH LIGHTNING AND SATELLITE DATA

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To better understand tropical cyclones, forecasters and researchers need to monitor these storms continuously. Keeping a real-time eye on lightning associated with tropical cyclones is an important step toward such continuous monitoring. The multiple physical connections between lightning, convection, precipitation, and rapid storm intensity changes make lightning a rich source of information on how these storms evolve.

The World Wide Lightning Location Network (WWLLN) team, a group coordinated by the University of Washington in Seattle, operates a network of lightning location sensors that produces regular maps of lightning activity all over the world. To tackle the demand for continuous tropical cyclone monitoring, the WWLLN team has developed a unique storm-following tool and a public website known as WWLLN Tropical Cyclones (WWLLN-TC; https://wwlln.net/storms/). The website visualizes lightning data in near-real time for all tropical cyclones across the globe. An archive of all of the

A nighttime astronaut's-eye view from the International Space Station of inner core lightning in Tropical Cyclone Bansi as it travels over the Indian Ocean in 2015. Credit: ISS Crew Earth Observations Facility and the Earth Science and Remote Sensing Unit, NASA Johnson Space Center

Together, lightning and microwave data can track a range of parameters in tropical cyclones; storm intensity changes are related to the density of lightning strokes.

more than 700 tropical cyclones that have occurred since November 2009 is also available to those who visit the site.

WWLLN-TC also integrates these data with microwave satellite data from the Naval Research Laboratory (NRL). Adding in the lightning data can help fill gaps in and between satellite microwave images.

Together, the lightning and microwave data can track a range of parameters, including intensity changes in tropical cyclones; past research has shown that intensity changes are related to the density of lightning strokes [e.g., *Solorzano et al.*, 2008; *DeMaria et al.*, 2012]. Thus, WWLLN-TC offers the potential to improve forecasts of tropical cyclone intensification and associated rainfall forecasts.

Monitoring Lightning and Tracking Cyclones

WWLLN provides real-time lightning locations globally by measuring electromagnetic pulses generated by lightning strokes (Figure 1). The network is a collection of more than 70 receiver stations around the world. At present, WWLLN data are being combined with lightning data collected by Earth Networks (https://www.earthnetworks.com), which greatly increases the overall lightning detection efficiency of the existing WWLLN.

WWLLN-TC users can access four categories of images to follow the lightning activity and satellite observations of tropical cyclones:

- The website provides a storm track map generated from data provided by NRL (Figure 2a).
- Lightning time series graphs include histograms of strokes per hour within 100 and 1,000 kilometers of the storm center, along with maximum wind speed and minimum pressure data from NRL (Figures 2b and 3) and a

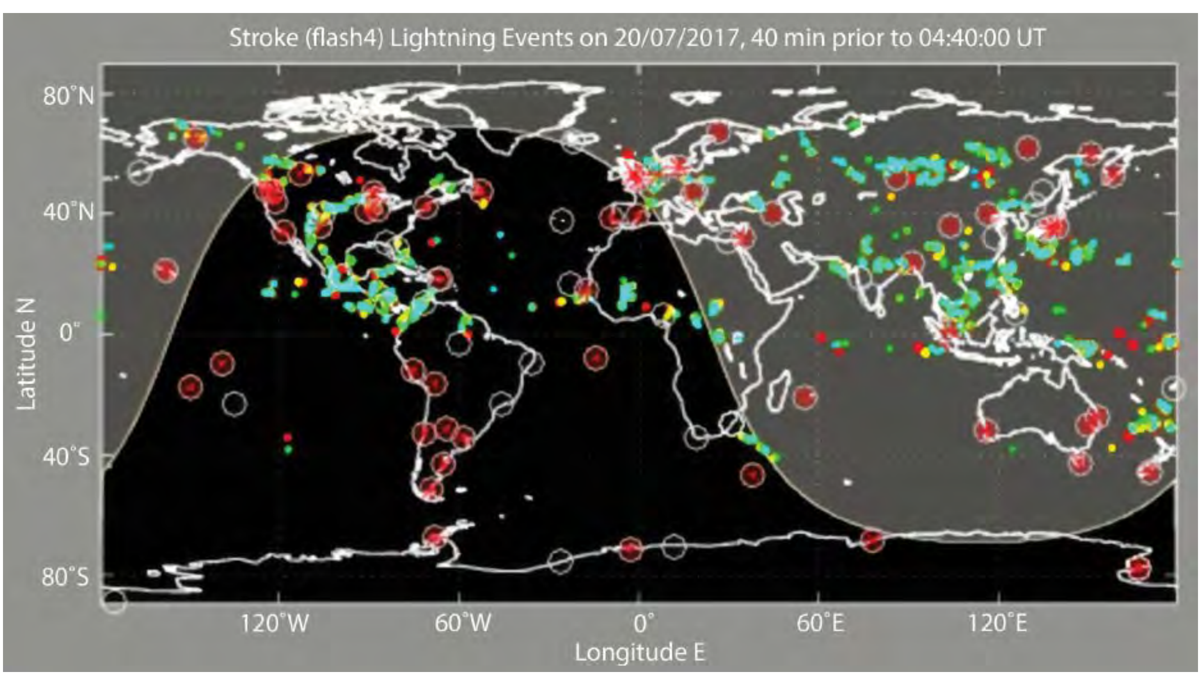

Fig. 1. WWLLN lightning strokes are shown as colored dots for 20 July 2017. Blue represents the most recent strokes (during the 10 minutes before the plot was made), followed by green and yellow and then red for the oldest (30–40 minutes earlier). Red asterisks inside white circles indicate active WWLLN lightning sensor locations. The terminator (the day–night boundary) is shown, with the daylit section of the globe in gray. Credit: WWLLN

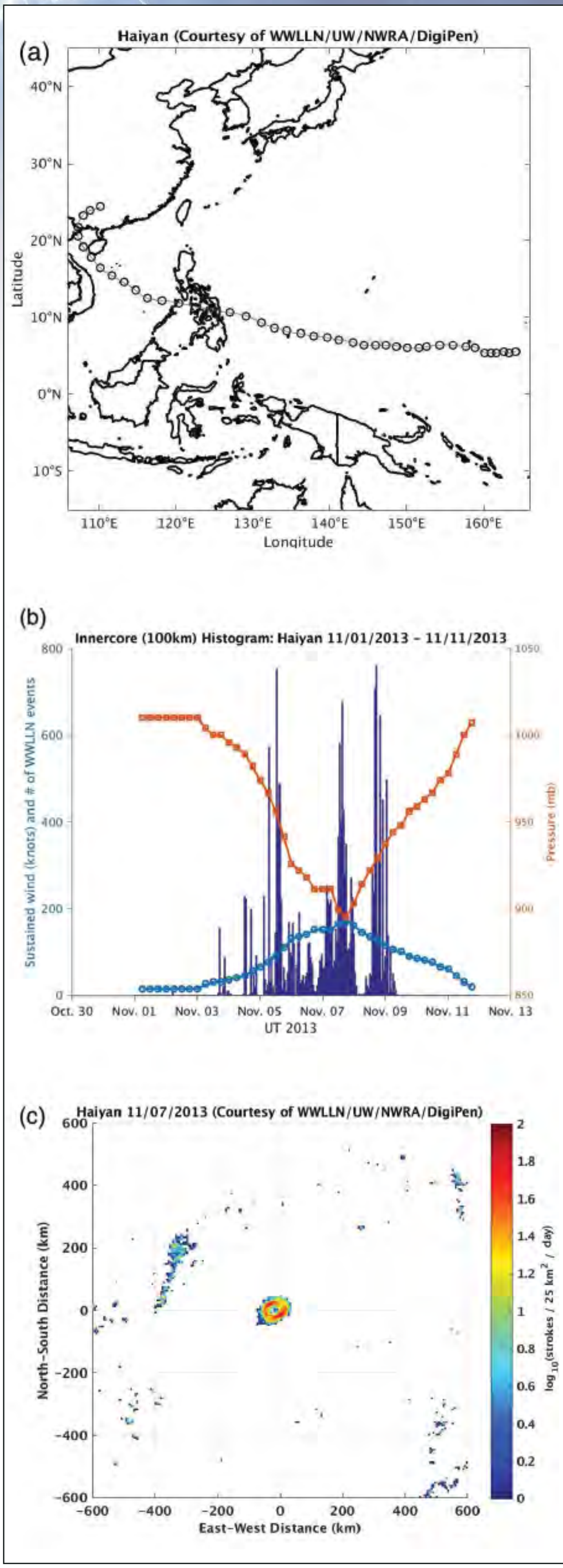

Fig. 2. (a) Storm track for Typhoon Haiyan in 2013. (b) Lightning and intensity histogram, with purple bars representing the number of lightning events, wind speeds depicted in blue, and atmospheric pressure depicted in orange. (c) Lightning density. Credit: WWLLN-TC

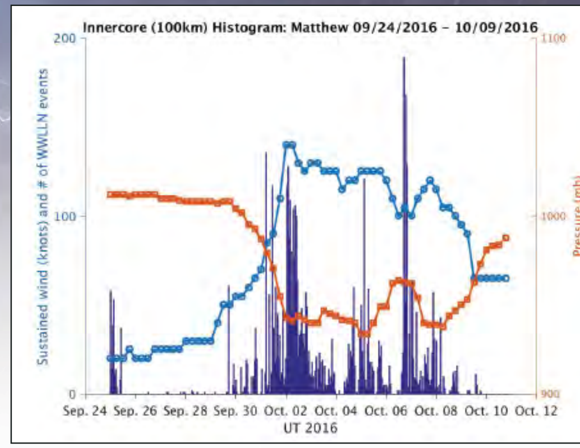

Fig. 3. Histogram of hourly WWLLN lightning, along with wind (purple) and pressure (orange) data, for Hurricane Matthew in 2016. A peak in lightning rate on 6 October precedes rapid weakening of the storm. Credit: WWLLN-TC

lightning density spectrogram binned by the distance from the storm center.

- Daily lightning density data relative to the center of the storm (Figure 2c) are available as static images; this information is also combined into animated GIFs.
- Satellite images from NRL are overlaid with lightning strokes occurring during a time window spanning 15 minutes before to 15 minutes after each satellite pass (Figures 4 and 5). Microwave data are from such satellites as NASA's Tropical Rainfall Measuring Mission (TRMM) and Global Precipitation Measurement (GPM), as well as from the National Oceanic and Atmospheric Administration's (NOAA) Defense Meteorological Satellite Program (DMSP). Infrared data are from geostationary satellites, including NOAA's Geostationary Operational Environmental Satellite (GOES).

Hurricane Matthew Provides a Test Case

Figure 4, an example of data visualization provided by WWLLN-TC, displays Hurricane Matthew at peak intensity (3 October 2016) on its path from the Caribbean to the United States. This figure is an overlay of a lightning stroke map from WWLLN (black circles) and 91-gigahertz brightness temperatures provided by the Special Sensor Microwave Imager/Sounder (SSMIS) radiometer on the low-orbit satellite DMSP F-18. Brightness temperatures, a measure of microwave energy coming out of Earth's atmosphere, are useful in estimating the intensity of convection in tropical cyclones.

The hurricane's eye wall is distinct in the image, and lightning in this case is present in both the eye wall and the rainbands. Lightning is often detected in the rainbands, and it occurs episodically in the inner core of tropical cyclones (within 100 kilometers of center). In storms, ice and liquid water not only are key ingredients for separating the positive and negative electrical charges that initiate a lightning strike; they also are the main features detected by microwave sensors on satellites. In general, clouds with more ice, and thus lower brightness tempera-

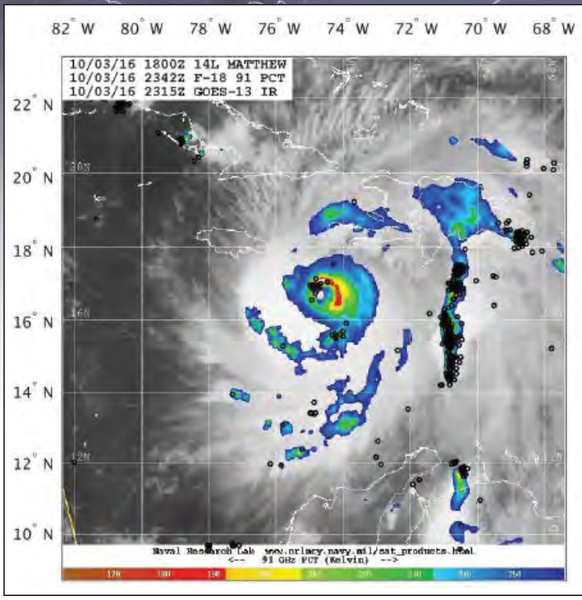

Fig. 4. Results from the WWLLN-TC data product, showing lightning (black circles) and SSMIS 91-gigahertz polarization-corrected temperature (PCT) brightness temperatures (color contours) for Hurricane Matthew in 2016, pinpointing regions of intense convection. Credit: WWLLN-TC

tures, are more likely to produce lightning and to have moderate to strong updrafts and precipitation.

Lightning is therefore an indicator of significant convection, although not all intense convective systems have lightning. This is important because deeper, organized convection tends to be more persistent, unless it is regulated by such external factors as vertical wind shear or insufficient moisture.

Hurricane Matthew exemplifies a storm with lightning and long-lasting convection. In Figure 4, lightning accompanies some areas of deep convection, indicating that the storm might persist. We can see that the environmental conditions were favorable for Matthew as it continued as a category 4 (and occasionally 5) hurricane until 6 October (Figure 3), with inner core lightning activity indicating that persistent convection was indeed present.

Lightning Surge Signals a Change in Storm Intensity

Atlantic hurricanes often have a significant peak in inner core lightning preceding rapid weakening [e.g., *Solorzano et al.*, 2008; *DeMaria et al.*, 2012]. Inner core discharges are typically episodic, and a peak in lightning occurrence can be straightforward to visualize by using the histograms and spectrograms available from WWLLN-TC. For

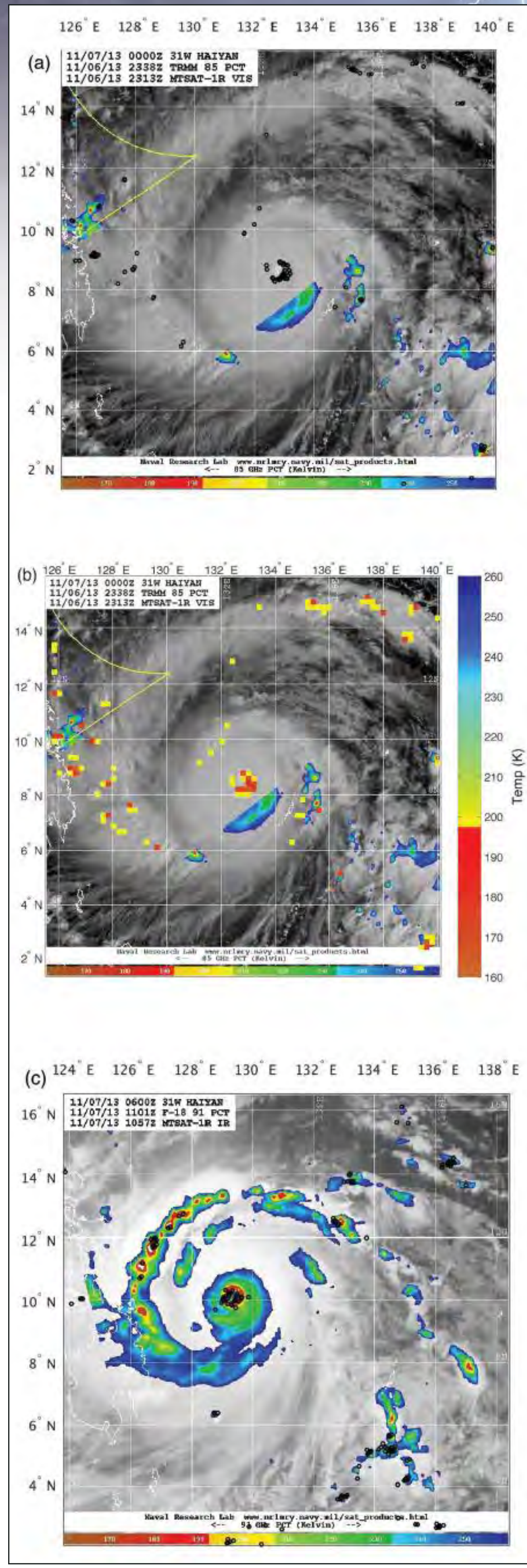

Fig. 5. Reconstruction of satellite data using lightning for Typhoon Haiyan in 2013 at its peak intensity. (a) WWLLN lightning (black circles) and TRMM TMI 85-gigahertz PCT brightness temperatures for a partial pass. (b) WWLLN lightning reconstruction of brightness temperatures for the partial pass. (c) DMSP SSMIS F-18 91-gigahertz PCT brightness temperatures and WWLLN lightning (black circles) 12 hours after the data in Figures 5a and 5b. Images in Figures 5a and 5c are from the WWLLN-TC product.

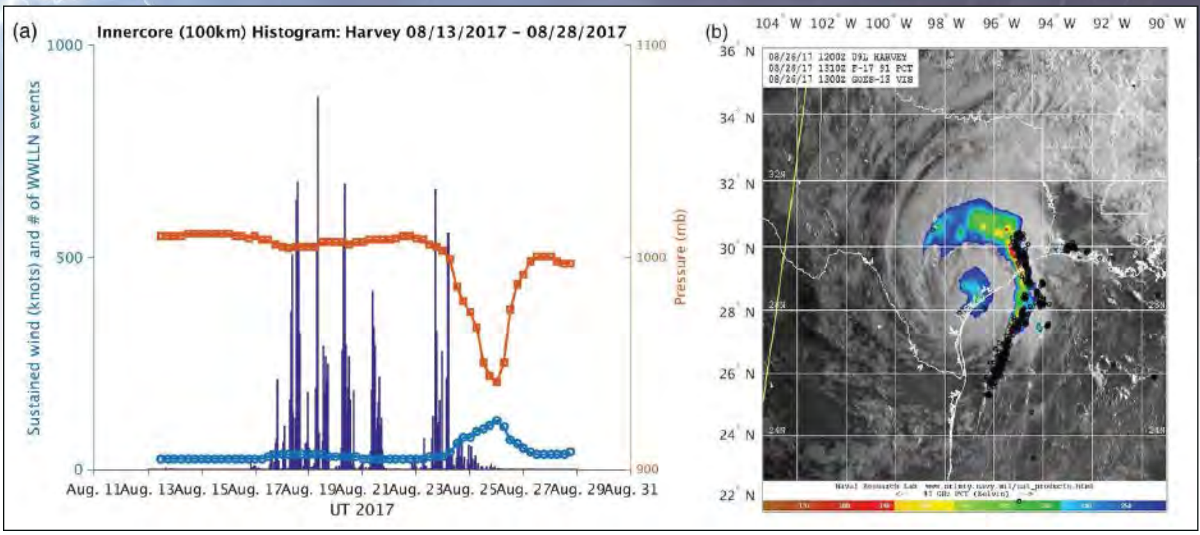

Fig. 6. Hurricane Harvey in 2017. (a) Lightning and intensity histogram and (b) WWLLN lightning (black circles) and SSMIS 91-gigahertz PCT brightness temperatures just after Harvey made landfall on 26 August as a category 4 storm. Credit: WWLLN-TC

example, a pronounced peak in stroke rate was present in the inner core of Hurricane Matthew minutes to hours before it weakened on 6 October, as shown in Figure 3. This peak was a revealing feature of Matthew's final stages.

However, relevant questions linking tropical cyclones and lightning in the inner core remain: Considering the limitations of lightning data, the importance of environmental factors, and the changing climate, how significant is the information provided by episodic discharges in the inner core for forecasting the intensity change? We hope to address these challenges with WWLLN-TC.

Atlantic hurricanes often have a significant peak in inner core lightning preceding rapid weakening.

Microwaves and Lightning

Microwave radiometers are a passive measurement technique; that is, they monitor Earth's own heat energy emissions in the 1- to 200-gigahertz frequency range. Radiometry is a technique complementary to radar, in which the instrument emits a signal and then detects that signal after it bounces off a surface. Microwave radiometry data are used to construct brightness temperatures: an indication of the intensity of electromagnetic energy at a particular wavelength that filters up through the atmosphere and reaches the satellite's sensor.

Mathematical relationships between lightning incidence and microwave-derived brightness temperatures can be used to reconstruct microwave radiometer data where these data are not available. This process can help scientists fill in (to a limited extent) satellite data gaps in areas where WWLLN finds lightning [*Solorzano et al.,* 2016], as shown in Figure 5 for Typhoon Haiyan in the western North Pacific in 2013.

The TRMM satellite provided an incomplete pass of Typhoon Haiyan on 6 November 2017. Lightning data enabled reconstruction of the TRMM Microwave Imager (TMI) sensor brightness temperatures at the peak intensity of the storm. With the reconstruction, we can now identify regions in the inner core and rainbands that have large amounts of cloud ice, including a ring pattern at the inner core.

For forecasters, it is important to fill in those gaps because brightness temperatures are often used to estimate precipitation in tropical cyclones, along with rapid intensification or weakening. For example, a recent study has shown that ring patterns of microwave brightness temperature depressions in the inner core, like we see in Typhoon Haiyan in Figures 5 and 2c, are associated with intensity change [*Harnos and Nesbitt,* 2016].

WWLLN-TC has many other potential uses, most of them focusing on the observation and reconstruction of cloud data.

The 2017 Atlantic Hurricane Season

The hurricane season of 2017 was one of the worst on record, as one hurricane after another made its way across the Caribbean islands and drenched the U.S. Gulf Coast. WWLLN-TC was on the job: The network provided real-time monitoring of Hurricane Harvey as it made landfall in southern Texas as a category 4 storm, the strongest tropical cyclone to hit the United States in 12 years. Figure 6 shows a WWLLN-TC lightning and intensity time series and an overlay of microwave and lightning data for Harvey at landfall on 26 August.

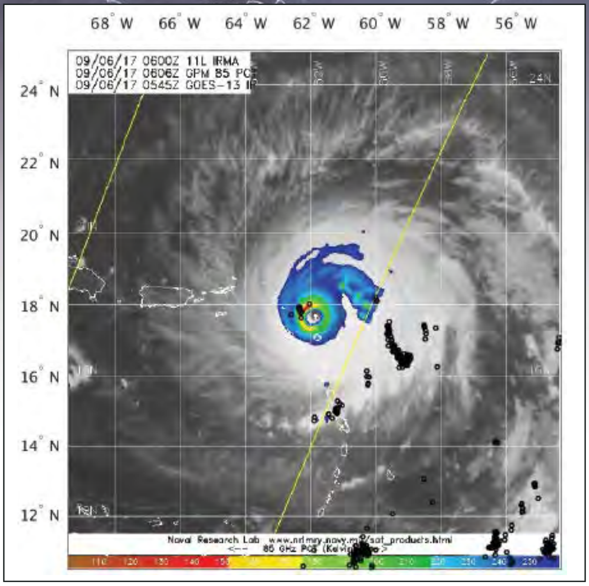

Fig. 7. Hurricane Irma passed over Barbuda on 6 September 2017. Shown here are WWLLN lightning (black circles) and GPM 85-gigahertz PCT brightness temperatures during Irma's maximum intensity as a category 5 storm. Credit: WWLLN-TC

Later, on 6 September, another hurricane, Irma, the first category 5 hurricane on record to strike the Leeward Islands, was near maximum intensity when it crossed Barbuda. Figure 7 shows an overlay of lightning and GPM microwave data as the storm's eye passed over Barbuda. Lightning in the eye wall preceded storm weakening and corresponds to cold brightness temperatures sensed by GPM, whereas lightning in the rainbands indicates regions of strong convection that the satellite missed.

Finally, on 20 September, Hurricane Maria made landfall in Puerto Rico, and its category 4 strength winds caused the National Weather Service radar to stop functioning. WWLLN-TC provided a way to monitor the storm's intensity and precipitation continuously while it crossed the island, as shown in the time series in Figure 8. As Maria was pummeling Puerto Rico, NASA researchers expressed to the WWLLN team the usefulness of WWLLN-TC data for tracking convection in the storm.

In the Future

WWLLN-TC, an automated storm-following product for lightning and satellite data, fills crucial data gaps related to tropical cyclones. It also enables a better understanding of precipitation and intensity changes of these storms.

Nonetheless, it is important that we recognize the limitations concerning these data sets and reconstructions. For example, some storms have insignificant lightning counts, which means that reconstructions are not possible.

We plan to progressively incorporate other sources of data, especially unprocessed satellite data, in addition to the satellite images: This feature is currently prototyped. We also plan to provide users with data organized in standard formats (.txt, .mat, netCDF, HDF, etc.) in addition to the image files currently available.

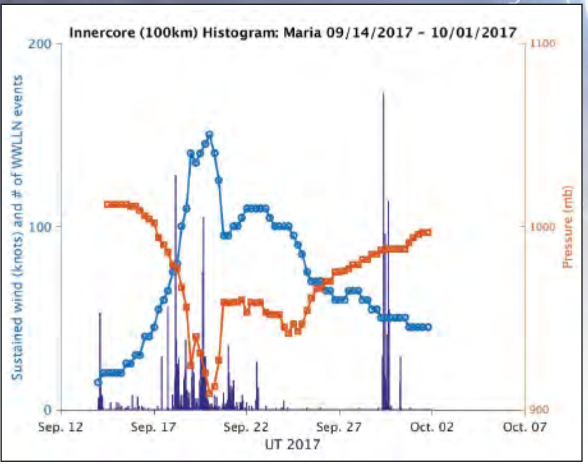

Fig. 8. Lightning and intensity histogram for Hurricane Maria, the most intense tropical cyclone of 2017 and the worst natural disaster on record for Puerto Rico. Credit: WWLLN-TC

One of our main goals is to obtain input from forecasters and assist them in their preeminent role of predicting tropical cyclone intensity changes. We seek feedback from forecasters, researchers, and other potential users to help improve the visualizations and forecasts. Please contact us with your input and needs.

Acknowledgments

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