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Recommended Citation
Williams, J. E. S., Tournay, R. C., Tseng, H. R., Emmons, D. J., & Nava, O. A. (2021). Impact of Hurricane Michael (2018) on local vertical total electron content. Journal of Atmospheric and Solar-Terrestrial Physics, 219, 105647. https://doi.org/10.1016/j.jastp.2021.105647
Impact of Hurricane Michael (2018) on local vertical total electron content

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ARTICLE INFO

Keywords:
Total electron content
Ionosphere
Tropical cyclone
Lightning
Rainfall rates

ABSTRACT

An analysis of vertical total electron content (TEC) estimates from the MIT Madrigal database is performed for the regions surrounding the eye of Hurricane Michael (2018). Absolute and detrended TEC values show a noticeable increase during the tropical cyclone (TC) relative to fluctuations at the same locations prior to the storm. Direct comparisons of TEC perturbation magnitudes to the number of lightning flashes in $1^\circ \times 1^\circ$ latitude-longitude boxes surrounding the eye of Hurricane Michael for each 5 min period of 10 October 2018 showed no visible trends. A similar comparison of the vertical TEC fluctuations with respect to the rainfall rates showed a positive correlation as the rainfall rate increased from light to moderate. However, a decrease in TEC perturbations were observed for the most intense rainfall rates. Additionally, ionosonde measurements in the Gulf of Mexico Region reveal an increased production of waves with periods less than 90 min after TC formation. These results indicate that the measured TEC fluctuations are most likely caused by atmospheric gravity waves produced by Hurricane Michael, which supports previous research.

1. Introduction

Tropical cyclones (TCs) are large, natural, destructive phenomena causing significant damage to people, property, and resources. For example, Hurricane Michael (2018), is the 8th costliest hurricane in the United States (US) Atlantic basin to date with 25 billion dollars of damages (Beven II et al., 2019). Due to the high damage costs, it is important to prepare for the impacts of TCs through accurate forecasts as they develop and intensify.

It is well known that the structure of the ionosphere is affected by many sources, including solar radiation, geomagnetic activity, composition of the thermosphere, as well as energy transfer and wave activity from tropospheric weather (Sickle, 2018; Yu et al., 2015). Monitoring changes in the total electron content (TEC) of the ionosphere is important to communications, positioning, navigation, broadcast, and financial systems. For example, Global Navigation Satellite System (GNSS) signals are impacted by significant fluctuations in ionospheric plasma densities (and subsequently TEC), which deteriorates the reliability and accuracy of position, navigation, and timing (PNT) for civilian and military applications such as aviation, humanitarian aid, and disaster relief (Groves et al., 1997; Kintner et al., 2007).

Recently, tropospheric weather has been shown to have a significant impact on the ionosphere, primarily through internal atmospheric gravity waves (AGWs) (Vadas and Liu, 2009; Immel et al., 2009). Traveling ionospheric disturbances (TIDs) produced by tropical cyclone induced AGWs, can cause large perturbations to ionospheric plasma densities (Vadas and Crowley, 2010; Polyakova and Perevalova, 2011, 2013; Song et al., 2017). Additionally, the relationship between lightning activity and local TEC perturbations has also been examined, with an unclear physical mechanism (Lay et al., 2013) that may be attributed to AGWs (Ogunsua et al., 2020). Lightning is known to impact the ionosphere through lightning-induced electron precipitation (Inan et al., 1988) and heating from electromagnetic pulses (Inan et al., 1996), but the temporary nature of the effects may not induce noticeable changes to TEC measurements. Additionally, rainfall rates and corresponding atmospheric tides from tropospheric moist convection has been shown to impact the lower thermosphere (Jin et al., 2011) and correlate with AGW activity in the mesosphere-lower thermosphere (Kovalam et al., 2011).

This research attempts to find a direct relationship between local ionospheric perturbations and the TC parameters of lightning and rainfall rates. While the relationship between TEC fluctuations and AGWs is well studied, here we attempt to analyze the direct vertical influence of the TC by focusing on regions surrounding the eye and comparing the activity to the response in the ionosphere directly above. Additionally, the diurnal TEC fluctuations in these regions are investigated before, during, and after the TC providing a measure of the general ionospheric perturbations caused by the storm.

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2. Methodology

There are four data sets used in this study: hurricane position, vertical TEC, lightning, and precipitation. Hurricane data from the National Hurricane Center is used as the reference point for the location of the TC to determine localized effects (Beven II et al., 2019). Vertical TEC data, from MIT Haystack’s Observatory Madrigal database, is used to characterize the state of the ionosphere above the TC (Coster, 2019). The lightning data, from the Geostationary Lightning Mapper (GLM) on-board the Geostationary Operational Environmental Satellite (GOES)-16 satellite, and precipitation data, from the National Center for Environmental Prediction (NCEP), are used as proxies for the electric and dynamic components of a TC (NOAA CLASS, 2019; Lin and Mitchell, 2005).

2.1. Data reformatting

Each type of data varies in temporal resolution and area of coverage. The vertical TEC data has one value for each 1° latitude by 1° longitude box, which sets the spatial resolution for the study. This single vertical TEC value is calculated from the median of each line-of-sight measurement with an ionospheric pierce point (IPP) within the box of interest. An IPP altitude of 450 km is used for the slant to vertical TEC conversions in the Madrigal database (Rideout and Coster, 2006). For regions with a sufficiently dense network of GNSS receivers, such as the Southeastern United States and Gulf of Mexico Region, each box contains a large number of line-of-sight measurements which increases statistical confidence in the median values. An example of the global line-of-sight measurements used for the Madrigal vertical TEC calculations is displayed in Fig. 1, showing dense measurements in the region of interest.

Additionally, the 5 min cadence (288 data points per day) of the TEC data from the Madrigal database is used as the temporal resolution for the comparison. This resolution is able to capture the dominant TEC fluctuations near thunderstorms with periods between 16 and 76 min found by Ogunsua et al. (2020), but will not capture the faster 4 min period oscillations observed by Lay et al. (2013) during increased geomagnetic activity. The hourly precipitation data is properly sampled with the 5 min time resolution, as well as the typical AGWs affecting ionospheric altitudes with periods above ~ 15 min (Hines, 1960).

The five positions for the location of Hurricane Michael’s eye on 10 October 2018 from the NHC best track data are used as reference points for the spatial grid. The Gulf of Mexico and Florida coastal area are the primary regions of interest (green square in Fig. 2) consisting of a 22–34°N latitude range and 78–90°W longitude range. This region is

Fig. 1. Raw line-of-sight measurements converted to vertical TEC for the 5 min interval leading up to 17:00 UTC on 10 Oct 2018 (Coster, 2019). The sufficiently dense measurements for the Gulf of Mexico Region provide confidence in the median values used for each 1° × 1° box.

Fig. 2. NHC best track data for Hurricane Michael (2018). The data points in red show the positions of Hurricane Michael on 10 October 2018. The green square outlines the latitudes and longitudes used in this study.
selected because it encompasses the area of Hurricane Michael on 10 October 2018 while also allowing for investigation of the rainbands extending outward from the eye of the storm.

The lightning and precipitation data is reformatted into arrays matching the spatial and temporal resolution of the daily TEC data files over the Gulf of Mexico. The GLM data is compiled for each 5-min interval to contain fifteen 20-s lightning files, and the number of lightning flashes recorded during each 5-min period for every 1° × 1° box are counted. Precipitation data is projected on the national Hydrologic Rainfall Analysis Projection (HRAP) grid, a polar stereographic grid, and is processed using a kd-tree to align with the TEC data grid (Lin and Mitchell, 2005; Greenspan and Yuric, 2003). Through the kd-tree, the precipitation data is reformatted to a 1° × 1° grid and then isolated to the designated 12° × 12° region of interest. In addition, the precipitation data is hourly, and each hour’s rainfall rate is repeated for the 12 5-min intervals within the hour.

2.2. Data processing

The primary aim of this comparison is to find a correlation between the absolute value of the change in vertical TEC, |ΔTEC|, and the number of lightning flashes or rainfall rates within each 1° × 1° box surrounding the TC eye. This analysis examines: (1) the closest eight 1° × 1° boxes surrounding the eye of the TC (shown as red in Fig. 3) and (2) the 16 boxes 2° out from the TC center (shown as blue in Fig. 3). Each 1° × 1° box is approximately 110 km by 90 km, including both the eye wall and inner rainbands. The boxes 2° away from the TC center cover the majority of the outer rainbands (Moliniari et al., 1994). Comparisons are performed for each box in Fig. 3 for all five TC center points of interest, resulting in 45 boxes for the TC center and 80 boxes for the outer rainbands. The lightning/rainfall to |ΔTEC| comparison is performed for each box separately to examine the direct vertical relationship, and the statistics are combined in the end to provide a measure of correlation. Additionally, the structure of the TC and atmospheric dynamics are different for the center and outer rainbands, which may affect the relationship between the TC parameters and ionospheric density fluctuations. From this, we treat the center and outer rainbands separately to allow for the possibility of distinct correlations.

The lightning data is binned into 11 categories for lightning flashes 0–9, and one final category for greater than nine lightning flashes. The number of points beyond 10 lightning flashes decreases significantly in comparison to the data for 0–9 lightning flashes. Rainfall rates are separated into 13 bins from zero increasing every 500 mm per hour (mm/hr) to 6000 mm/hr.

A Savitzky-Golay filter using a 6-h window and 3rd order polynomial is employed to calculate vertical TEC perturbations, ΔTEC, by removing the diurnal cycle in the TEC data (Savitzky and Golay, 1964). Information on the Madrigal database TEC processing including conversion of slant to vertical TEC and removal of satellite and receiver biases can be found in Vierinen et al. (2016). The continuously operating reference stations (CORS) GNSS receivers in the Southeastern United States and Gulf of Mexico Region are sufficiently dense (Map, 2019), which reduces data gaps in the vertical TEC maps.

The bootstrap method is used to compute confidence intervals for TEC variability (Efron and Tibshirani, 1986). Bootstrapping involves resampling the original data set with replacement, creating an array of the same size as the original data which can be used to recalculate statistics of interest. This process can be repeated a large number of times, providing a measure of confidence in the statistics. Here, we use 2000 iterations to calculate median values and determine the 90% confidence intervals.

3. Analysis and results

3.1. TEC analysis

The TEC values over the five locations of Hurricane Michael on 10 October 2018 are compared for the 25 days leading up to the TC, through the lifespan of Hurricane Michael, and 6 days following the TC in Fig. 4. Daily diurnal cycles for “normal” undisturbed conditions before the TC are contrasted with the fluctuations during and after the TC.

During the 25 days leading up to Hurricane Michael, there are sporadic peaks in TEC values; however, the maximum values generally remain below 15 TEC units (TECU). In comparison, during Hurricane Michael, the peak values increase to approximately 17 TECU and remain elevated for the days of the TC (7–11 October). The greatest concentration of elevated TEC measurements occurred on 10 October, when the TC rapidly intensified and reached its peak intensity. Additionally, the minimum vertical TEC values show an increase during the TC. Following Hurricane Michael, the maxima return back to pre-TC levels, but the minima remain elevated. Considering that no solar or geomagnetic activity was reported during this time period, these results indicate that Hurricane Michael had a measurable influence on the local ionosphere and caused variations in the vertical TEC surrounding the TC eye. This is consistent with the results of Polyakov and Perevalova (2013); the greatest TEC variations are observed when the TCs are most intense.

Next, the vertical TEC is detrended by removing the diurnal cycle using a Savitzky-Golay filter. After detrending, a standard deviation is calculated for each five-day segment (with a single six-day segment for the days after Hurricane Michael) of the 36-day window to analyze the detrended TEC variance. These seven segments for each TC location are shown as horizontal lines in Fig. 5. For all five best track locations, the standard deviation values increase during Hurricane Michael, then return to pre-TC levels after the storm dissipates. These results indicate that TEC variations faster than the normal diurnal cycle are present during the TC, and we attempt to correlate these fluctuations with lightning and rainfall rates in the following sections.

3.2. Lightning results

In an attempt to find a direct vertical relationship between TC parameters and TEC perturbations, the number of lightning flashes is compared to the TEC perturbations above each 1° × 1° box surrounding the eye of Hurricane Michael. Lightning is an electric component of a TC and is more common in the rainbands in comparison to the eye wall of the storm (Moliniari et al., 1994). Fig. 6 shows a compilation of all the lightning flashes within the Gulf of Mexico and Southeastern US on 10 October 2018. There is a concentration of flashes along Hurricane Michael’s path (marked and labeled in black) and the concentration around
the eye are most likely due to storm movement throughout the day. Furthermore, lightning from the rainbands can be identified stretching out from the center of the storm along Hurricane Michael’s path.

In Fig. 7, the median values of the TEC perturbation magnitude, $|\Delta \text{TEC}|$, are binned by the number of lightning flashes (Table 1) within each $1^\circ \times 1^\circ$ box. The median TEC perturbations fluctuate with the variation in the number of lightning flashes, but do not show a consistent trend. Likewise, the confidence intervals (error bars) do not show a general increase (or decrease) as a function of lightning flashes. In regards to the elevated median calculated for the inner (red) boxes for seven lightning flashes, the 33 data points incorporated into the bootstrap resampling have a range of 0.2–1.7 TECU with 13 of the values greater than 1.2 TECU, which results in an elevated median. However, this raised median appears to be an outlier with respect to the general trend, and the outer (blue) boxes show a decreased median for this same bin of seven lightning flashes. In comparison, for eight lightning flashes the inner (red) boxes have 41 data points with seven greater than 1.0 TECU, which results in a median inline with the zero lightning flashes bin. Overall, there does not appear to be a difference in the medians calculated for the inner and outer regions, and a direct relationship between overhead TEC fluctuations and the number of lightning flashes is not clear. This result agrees with previous comparisons of lightning
activity and TEC fluctuations (Lay et al., 2013; Ogunsua et al., 2020), indicating that the observed TEC fluctuations in Figs. 4 and 5 are not caused by lightning.

3.3. Precipitation results

In addition to the direct comparison with lightning, TEC fluctuations are also compared with precipitation in the form of rainfall rates for each 1° × 1° box surrounding the TC center. Precipitation is a dynamic component of a TC and is used here as a proxy for convective activity. In a TC, heavier precipitation is expected in the eye wall and in the front or front-right quadrant of the storm relative to the direction of travel. Fig. 8 shows a plan view of the rainfall rate at 18:00 UTC on 10 October just following land fall, with the concentration of heaviest precipitation being consistent with the expected locations.

Fig. 9 shows the median TEC perturbation magnitudes, |ΔTEC|, binned by rainfall rates (Table 2) for each 1° × 1° box. A general increase in |ΔTEC| is observed for rainfall rates increasing from light (2000 mm/h or less) to moderate (2000–5000 mm/h). The greatest increase for both the median values and the confidence intervals is highlighted by the gray arrow from 1500 to 3000 mm/h. A continuation of the increase is observed for the inner (red) regions up through 5000 mm/h. Besides the >6000 mm/h bin and the 5000–5499 mm/h outer (blue) regions bin, the TEC perturbation magnitudes remain elevated at these moderate to heavy rainfall rates. Similar to the comparison with lightning, both the inner and outer regions appear to follow the same trend with respect to rainfall rate, indicating that the relationship does not depend on position within the TC center.

The increased perturbation magnitudes with respect to increasing rainfall rates are most likely due to increased convection and stronger

![Figure 6](image)

Fig. 6. A plan view of the Gulf of Mexico and Southeastern US with Hurricane Michael’s path on 10 October 2018 shown in black and all the lightning flashes measured by GOES/GLM from that day shown in red.

Table 1

| Lightning Flashes | Inner (Red) Region | Outer (Blue) Region |
|-------------------|-------------------|--------------------|
| 0                 | 10,409            | 19,622             |
| 1                 | 592               | 739                |
| 2                 | 203               | 329                |
| 3                 | 213               | 202                |
| 4                 | 119               | 123                |
| 5                 | 127               | 94                 |
| 6                 | 77                | 69                 |
| 7                 | 33                | 33                 |
| 8                 | 41                | 24                 |
| 9                 | 23                | 19                 |
| >9                | 141               | 110                |
| Total             | 12,078            | 21,364             |

![Figure 7](image)

Fig. 7. The |ΔTEC| for each 1° × 1° box binned by the number of lightning flashes within the box, separated for the inner (red) and outer (blue) regions with respect to the TC center. Black dots and stars are the median values for each of the lightning bins, with the stars indicating median values larger than the median for zero lightning flashes (horizontal red and blue lines). The error bars correspond to the 90% confidence intervals calculated by the bootstrap method.
updrafts that ultimately impact thermosphere/ionosphere altitudes. However, the largest rainfall rates (>6000 mm/h) correspond to a decreased $|\Delta TEC|$ which suggests that convective activity above a certain threshold may alter the thermospheric response. Perhaps the AGWs produced by these moist convection modes (Jin et al., 2011) are weakly coupled to the lower thermosphere directly overhead.

3.4. Ionosonde analysis

In a preliminary attempt to show the larger TEC perturbations are likely due to AGWs rather than direct lightning and precipitation rates, ionosonde estimates of the Maximum Useable Frequency (MUF) for a 3000 km circuit are analyzed before and during the TC in a search for TIDs, the ionospheric manifestation of AGWs (Hooke, 1968). This MUF (3000) parameter can be used for HF interferometry to track and

Table 2

| Rainfall Rate (mm/hr) | Inner (Red) Region | Outer (Blue) Region |
|-----------------------|--------------------|--------------------|
| 0–499                 | 6655               | 15,279             |
| 500–999               | 1615               | 2408               |
| 1000–1499             | 1252               | 1665               |
| 1500–1999             | 972                | 768                |
| 2000–2499             | 447                | 357                |
| 2500–2999             | 429                | 287                |
| 3000–3499             | 108                | 96                 |
| 3500–3999             | 192                | 144                |
| 4000–4499             | 96                 | 132                |
| 4500–4999             | 48                 | 48                 |
| 5000–5499             | 84                 | 60                 |
| 5500–5999             | 72                 | 48                 |
| ≥6000                 | 108                | 72                 |
| Total                 | 12,078             | 21,364             |

Fig. 8. Hurricane Michael’s rainfall rates at 18:00 UTC on 10 October with dark red regions corresponding to rates greater than or equal to 5700 mm/h. The heaviest precipitation is found over the TC center and the front/front-right quadrant, as expected. The TC path on 10 October in also shown in black.

Fig. 9. The $|\Delta TEC|$ within each $1^\circ \times 1^\circ$ box binned by the rainfall rate within the box, separated for the inner (red) and outer (blue) regions with respect to the TC center. Bin sizes of 500 mm/h are used, and the black stars indicate median values larger than the median for the 0–499 mm/h bin (horizontal red and blue lines). The greatest increase in $|\Delta TEC|$ is highlighted by the gray arrow from 1500–3000 mm/h, and the error bars correspond to the 90% confidence intervals calculated by the bootstrap method.
identify TIDs using measurements from multiple ionosonde sites (Altdill et al., 2020). TID characteristics can be calculated from the MUF(3000) phase differences (time delays) between the different ionosonde locations. A similar technique using real height estimates from a network of ionosondes is outlined in Emmons et al. (2020). For both techniques, wave-like oscillations of the ionosonde derived parameters are required to calculate TID phase velocities.

While estimating TID/AGW parameters from ionosonde measurements can be quite involved, a preliminary analysis of the MUF(3000) spectra provides insight into the existence of TIDs/AGWs. TIDDBIT ionospheric sounder measurements at Wallops Island, VA during Tropical Storm (TS) Noel determined that TIDs produced by the TS had periods between 15 and 90 min (Vadas and Crowley, 2010). The TIDs generated by TS Noel consisted of both direct waves produced by deep convection (periods greater than \( \sim 45 \) min) and secondary waves produced by thermospheric body forces (periods of \( \sim 15-20 \) min). Interestingly, these TID periods agreed with the dominant TEC fluctuation periods observed near thunderstorms (Ogunsua et al., 2020).

Analyzing the MUF(3000) spectra for three separate ionosonde stations near the Gulf of Mexico Region (Eglin FL, Wallops Island VA, and Austin TX) before and during Hurricane Michael shows increased production of waves with periods less than 90 min after TC formation. Fig. 10 displays the MUF(3000) estimates from the Global Ionosphere Radio Observatory (http://giro.uml.edu/didbase/scaled.php) and corresponding wavelet spectrograms for the three Digisonde sites over the period of 1–12 Oct 2018. The wavelet analysis is performed using a one-dimensional continuous wavelet transform with complex Morlet wavelets implemented through PyWavelets (Lee et al., 2019). To remove the diurnal MUF(3000) variation, a Savitzky-Golay filter using a 6-h window and 3rd order polynomial is applied before performing the continuous wavelet transform.

The MUF(3000) estimates in Fig. 10 show larger fluctuations after TC formation on 7 Oct. These larger fluctuations correspond to an increase in the short period (below 90 min) spectral energy, as displayed in the power spectral density (PSD) estimates. While the secondary AGW waves with periods near 20 min measured by Vadas and Crowley (2010) are not captured with the standard 15 min Digisonde measurement cadence, there is a noticeable increase in the PSD for shorter periods after TC formation. As a whole, the PSD shows a shift towards the shorter periods during the TC, which agrees with the AGW/TID theory and measurements of Vadas and Crowley (2010), indicating that the fluctuations most likely correspond to AGWs/TIDs produced by Hurricane Michael.

A more detailed analysis of the TIDs/AGWs is required to quantify the wave parameters during Hurricane Michael, but the effect of the TC on the ionosonde derived MUF(3000) spectra is obvious. The production of the short period waves during the TC supports the hypothesis that the larger TEC fluctuations are caused primarily by AGWs instead of direct lightning and precipitation effects and motivates the need for further investigation to gain insight into the periods, wavelengths, speeds, and origination points.

4. Conclusions

Absolute and detrended vertical TEC estimates for the five positions of Hurricane Michael on 10 Oct 2018 were analyzed to determine the impact on the ionosphere above the TC center. A noticeable increase in the absolute TEC maxima and minima was observed during the TC relative to the period before the storm. Additionally, the detrended TEC showed a larger variation during the TC, indicating a measurable thermospheric/ionospheric response caused by the hurricane. Understanding the physical mechanism responsible for the perturbations would allow for possible characterization of the TC through indirect ionospheric measurements. However, this first requires a detailed

Fig. 10. a) MUF(3000) estimates from Digisondes in Eglin FL, Austin TX, and Wallops Island VA during 1–12 Oct 2018. Wavelet spectrograms (PSD over time) for the b) Eglin FL, c) Austin TX, and d) Wallops Island VA MUF(3000) estimates over the same time period.
understanding of the many possible mechanisms responsible for interactions between terrestrial weather and the thermosphere/ionosphere.

To investigate the cause of the ionospheric plasma density perturbations caused by Hurricane Michael, a spatial and temporal comparison of the TEC fluctuations with rainfall and lightning rates was performed. The comparison was separated into two different regions to allow for the possibility of separate behavior in the center and outer rainbands. A direct relationship between the TEC parameters of lightning and rainfall rate to TEC perturbation magnitudes could not be established. Comparing TEC perturbations to the number of lightning flashes directly below proved unfruitful with no obvious trend present. While the TEC perturbations showed a general increase in magnitude for rainfall rates increasing from light to moderate, a decrease in ΔTEC was observed for the most intense rainfall rates. Neither comparison showed a large difference between the inner and outer regions surrounding the TC eye.

The lack of a direct relationship between overhead TEC fluctuations and lightning/rainfall rates suggests that AGWs are most likely responsible for the large TEC perturbations. This result is supported by previous investigations near thunderstorms (Lay et al., 2013; Ogunsua et al., 2020) and ionosonde observations in the Gulf of Mexico Region that revealed an increased production of waves with periods less than 90 min after TC formation. The ionosonde wave measurements agree with the AGW/TID theory and measurements by Vadas and Crowley (2010) during TS Noel, indicating that the larger TEC perturbations are likely due to AGWs produced by Hurricane Michael. Further investigation is required to gain insight into the specific wave parameters of these AGWs/TIDs.

For future work, if it is possible to remove the larger TEC fluctuations caused by AGWs, a detailed comparison to local lightning and rainfall rates could show a direct relationship with a decreased magnitude in the TEC perturbations. To improve the comparison between lightning and rainfall rates with TEC fluctuations, other datasets, measurements techniques, and models should be employed. There are many other methods for used for lightning detection outside of the satellite based approach used in this analysis. For example, the Earth Networks Global Lightning Network (ENGLN) and Vaisala Global Lightning Dataset use ground based measurements for lightning detection which provide alternate estimates of the lightning rates. Using different lightning datasets in the future may allow for a comparison to confirm or counter the results that lightning, as an electric component of a TC, is not a primary cause of TEC variations. The precipitation data is used as a proxy for convective activity and stronger updrafts within a TC; therefore, investigating other variables for vertical motion and convective activity would be beneficial. To explore this, model simulations may be a viable supplement to the observed data, especially since the observations themselves are limited. Finally, the slant to vertical TEC conversion and mapping provide another source of uncertainty; analyzing other ionospheric parameters in addition to TEC could provide more detail on the relationship between tropical cyclones and the local ionosphere.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The views, opinions, and/or findings expressed are those of the author and should not be interpreted as representing the official views or policies of the Department of Defense or the U.S. Government.

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