Using Satellite Observations of Lightning and Precipitation to Diagnose the Behavior of Deep Convection in Tropical Cyclones Traversing the Midlatitudes

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Abstract

This study uses a unique combination of geostationary and low-Earth orbiting satellite-based observations of lightning and precipitation, respectively, to examine the evolution of deep convection during the tropical cyclone (TC) lifecycle. The study spans the Atlantic Basin hurricane seasons of 2018-2021 and is unique as it provides the first known analysis of total lightning (intra cloud and cloud to ground) observed in TCs through their extratropical transition and post-tropical cyclone (PTC) phases. We consider the TC lifecycle stage, geographic location (e.g., land, coast, ocean), shear strength, and quadrant relative to the storm motion and environmental shear vectors. Total lightning maxima are found in the forward right quadrant relative to storm motion and downshear of the TC center, consistent with previous studies using mainly cloud-to-ground lightning. Increasing environmental shear focuses the lightning maxima to the downshear right quadrant with respect to the shear vector in tropical storm phases. Vertical profiles of radar reflectivity from the Global Precipitation Measurement mission show that super-electrically active convective precipitation features (>100 flashes) within the PTC phase of TCs have deeper mixed phase depths and higher reflectivity at -10°C than other phases, indicating the presence of more intense convection. Differences in the net convective behavior observed throughout TC evolution manifest in both the TC-scale frequency of lightning-producing cells and the intensity variations amongst individual convective cells. The combination of continuous lightning observations and precipitation snapshots improves our understanding of convective-scale processes in TCs, especially in PTC phases, as they traverse the tropics and mid-latitudes.

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Key Points:
\begin{itemize}
  \item This study provides the first characterization of lightning in tropical cyclones (TCs) that have undergone extratropical transition
  \item Unique composites of collocated satellite-based passive microwave, radar, and lightning observations partition TC precipitation features
  \item Differences in overall lightning frequency between TC phases may be governed more by the frequency of lightning-producing convection
\end{itemize}
Abstract
This study uses a unique combination of geostationary and low-Earth orbiting satellite-based observations of lightning and precipitation, respectively, to examine the evolution of deep convection during the tropical cyclone (TC) lifecycle. The study spans the Atlantic Basin hurricane seasons of 2018-2021 and is unique as it provides the first known analysis of total lightning (intra-cloud and cloud to ground) observed in TCs through their extratropical transition and post-tropical cyclone (PTC) phases. We consider the TC lifecycle stage, geographic location (e.g., land, coast, ocean), shear strength, and quadrant relative to the storm motion and environmental shear vectors. Total lightning maxima are found in the forward right quadrant relative to storm motion and downshear of the TC center, consistent with previous studies using mainly cloud-to-ground lightning. Increasing environmental shear focuses the lightning maxima to the downshear right quadrant with respect to the shear vector in tropical storm phases. Vertical profiles of radar reflectivity from the Global Precipitation Measurement mission show that super-electrically active convective precipitation features (>100 flashes) within the PTC phase of TCs have deeper mixed phase depths and higher reflectivity at -10°C than other phases, indicating the presence of more intense convection. Differences in the net convective behavior observed throughout TC evolution manifest in both the TC-scale frequency of lightning-producing cells and the intensity variations of amongst individual convective cells. The combination of continuous lightning observations and precipitation snapshots improves our understanding of convective-scale processes in TCs, especially in PTC phases, as they traverse the tropics and mid-latitudes.

Plain Language Summary
Tropical cyclones (TCs) are a global weather phenomenon that can cause significant damage, especially to densely populated coastal regions. TCs are characterized by convective elements that produce intense precipitation and sometimes grow strong enough to produce lightning. However, little is known about convective attributes of TCs as they traverse the mid-latitudes and undergo extratropical transition. This study uses new satellite observations of the mid-latitudes to examine how the nature of convection changes throughout the TC lifestyle. Satellite-observed total lightning (cloud-to-ground + intra-cloud) maxima in TS primarily occurs on their right side of the storm motion and downshear of their center. Differences in environmental shear shift the observed lightning maxima during the tropical storm phase and plays a larger role in precipitation distribution than motion. Satellite-based radar observations indicate that electrically active convective precipitation features are deeper, have stronger vertical motions, and more intense rainfall than their non-electrically active counterparts. The results of this study reveal new insights about the distribution and intensity of convective elements within a TC, which could be incorporated into TC assessments and forecasts to ultimately help reduce their impacts on society.

1 Introduction
Tropical cyclones (TCs) form from low-level cyclonic vorticity maxima located in weak wind-shear conditions and are associated with deep convection and heavy precipitation. Latent heat and sensible fluxes from the warm, near-surface layers of the tropical ocean provide energy to the TC. TCs that maintain their organization are often steered poleward where they may
encounter land or cooler ocean temperatures and interact with increasingly baroclinic environments leading to an extratropical transition (ET). During TC phase changes, from initial formation to ET stages (cf. Klein et al., 2000), the temperature and instability structures of the incipient TC are markedly altered, which in turn affect TC thermodynamic, microphysical, and kinematic characteristics (i.e., convective character). Hence, we expect to see changes in precipitation and lightning behavior throughout the TC lifecycle, in particular, the ET stage.

Even though approximately 50% of Atlantic TCs (Hart & Evans, 2001), 30% of western North Pacific TCs (Klein, 1997; Klein et al., 2000), and 10% of Australian TCs (Foley & Hanstrum, 1994) undergo ET and become post-tropical cyclones (PTCs), knowledge gaps concerning PTC storm structure and processes still remain as many TCs that undergo ET are well removed from the coverage of land-based observational networks (C. Evans et al., 2017). These PTCs are still often associated with extreme precipitation, high winds, and can cause loss of life and property around the globe (Blake et al., 2013; Meltzer et al., 2021; Roy et al., 2022; Sainsbury et al., 2020; Stewart, 2018). Therefore, it is important to characterize PTC storm and precipitation structures to acquire a more complete understanding of kinematic and thermodynamic processes occurring throughout the TC lifecycle. In turn, a more complete understanding and characterization of TC lifecycle phases and associated storm structure will lead to improved warning decision support and numerical weather prediction.

Previous studies have used a variety of both ground- and satellite-based sensors to examine lightning in TCs – the rate of lightning activity being applied herein as a proxy for particularly intense and deep tropical, convective intensity. TC studies utilizing ground-based radio networks composed of very low-frequency (VLF) sensors, such as the National Lightning Detection Network (NLDN; e.g., Lyons & Keen, 1994; Molinari et al., 1994, 1999; Samsbury & Orville, 1994), very-high frequency sensors, such as the Los Alamos National Laboratory’s Sferic Array (Fierro et al., 2011; Shao et al., 2006), or lightning mapping arrays (Griffin et al., 2014; Logan, 2021) are typically confined to a ~500 km (or less) buffer of the U.S coast. Such networks have supplemented other datasets when observing TC lightning (Fierro et al., 2011; Hu et al., 2020; Shao et al., 2005). Meanwhile, other TC studies utilize networks such as the World Wide Lightning Location Network (e.g., Abarca et al., 2011; DeMaria et al., 2012; Pan et al., 2010; Stevenson et al., 2014; Wang et al., 2016, 2018; Zhang et al., 2015) where the VLF sensors are distributed globally. Though these networks do not perform exactly the same, they primarily detect cloud-to-ground (CG) and some higher peak current intra-cloud (IC) lightning, which is an incomplete depiction of the total lightning flash rates (CG + IC) that are needed to provide a better, physically-integrated indicator of convective lifecycle dynamics and vigor (e.g., Carey & Rutledge, 1996; Deierling & Petersen, 2008; Goodman et al., 1988; Schultz et al., 2011). TC lightning is frequent in the inner core/eyewall region and can be even more frequent in the outer rainbands (Abarca et al., 2011; Fierro et al., 2018; Molinari et al., 1999; Stevenson & Corbosiero, 2016; Wang et al., 2018; Xu et al., 2017). Additionally, previous studies utilizing ground-based lightning observations show that there tends to be more lightning detected during weaker TC phases (e.g., tropical storms) than during more intense TC phases (e.g., major hurricanes) (DeMaria et al., 2012; W. Zhang et al., 2015).

Satellite-based optical lightning sensors onboard low-Earth orbiting (LEO) satellites such as the Optical Transient Detector (OTD; Christian et al., 2003) and the Lightning Imaging Sensor (LIS) on the Tropical Rainfall Measuring Mission satellite (TRMM-LIS; Christian et al., 1992)
have provided the opportunity to collect many TC samples within the global tropics, build up TC
climatologies, and perform statistical studies on TC lightning evolution (Cecil et al., 2002; Cecil
& Zipser, 1999, 2002; Jiang et al., 2013; Xu et al., 2017). However, the short duration snapshots
afforded by LEO satellites do not allow a temporally continuous analysis of electrical activity for
an individual TC. More recent satellite-based lightning observations including those from the
Geostationary Lightning Mappers (GLMs; Goodman et al., 2013; Rudlosky et al., 2019;
Rudlosky & Virts, 2021) onboard the GOES-16,-17, and -18 satellites enable us to observe total
lightning trends in TCs as these systems develop, evolve, and undergo ET, primarily ≥ 35° (Hart
& Evans, 2001), a region not well-sampled by TRMM-LIS. Alternatively, while providing
temporally continuous lightning and convective cloud-top observations, geostationary satellites
do not provide specific samples of collocated vertical profiles of convective precipitation
structure. The microwave sensors onboard TRMM have provided insights into TC vertical
precipitation structure (Fritz et al., 2016; Hence & Houze, 2011, 2012) as well as electrical,
kinematic, and microphysical processes during the TC lifecycle equatorward of 35° (Cecil et al.,
Tao & Jiang, 2015). Moreover, as a result of the creation of a TRMM precipitation feature (PF)
database (Liu et al., 2008) and the resultant TRMM PF research methodology (e.g., Jiang et al.,
2011; Liu et al., 2011; Nesbitt et al., 2000), a similar approach has been recently extended into
the Global Precipitation Measurement (GPM) and GLM era and been used to examine the
precipitation and lightning characteristics of mid-latitude systems (Heuscher et al., 2022).

Recent studies have used GLM-proxy data (Stevenson et al., 2018) or GLM data in
comparison to ground-based networks (Fierro et al., 2018; Hu et al., 2020; Ringhausen & Bitzer,
2021) to gain further understanding of TC processes on convective timescales. Similar to other
lightning studies utilizing ground-based lightning networks, these studies are limited due to
network detection efficiency (DE), which drops significantly with distance from the US
mainland. These studies emphasize how the temporally continuous GLM lightning observations
provide the opportunity to further address lingering questions the occurrence and significance of
lightning (and by proxy, convection) in TCs. Including GLM observations in the GPM PF
database enables a new capability to temporally resolve the electrical evolution of individual
TCs, which can be used as a proxy for understanding changes in processes on convective
timescales. Accordingly, this study is the first to combine continuous lightning observations from
GLM with discrete instantaneous precipitation samples (e.g., feature “snapshots”) from GPM to
help elucidate the behavior of convection and lightning through the entire TC lifecycle, including
tropical storm, hurricane, and PTC stages, from the tropics to the mid-latitudes.

2 Data and Methodology

2.1 Lightning data

Lightning data collected from the GOES-16 GLM is used in this study. GLM ground
sample distance varies from ~8 km at nadir to ~14 km at the edges of its field of view (FOV), the
FOV spanning roughly 137°W to 15°W, 57°S to 57° N. The mean daily GLM flash DE has been
shown to be ~75% (D. Zhang & Cummins, 2020), is higher at night, decreases significantly near
the edge of its FOV, and can be reduced for flashes that occur at low altitudes within optically
thick clouds (e.g., Bateman & Mach, 2020; Marchand et al., 2019; Rudlosky & Virts, 2021;
Rutledge et al., 2020). This study utilizes GLM flash data that has been declared both provisional
(Provisional Validation was 19 January 2018) and fully validated (Full Validation was 1 November 2018). To mitigate decreased data quality, only GLM flashes with a quality flag = 0 are used in this study (Carlomusto, 2019; Rudlosky et al., 2019; Rudlosky & Virts, 2021). Due to the DE decrease near the FOV edges, only data occurring between 0° to and 57°N latitude 110°W to 14°W longitudes are used in this study.

2.2 GPM Precipitation Features (PFs)

The GPM mission consists of a constellation of LEO satellites (numbers vary based on those satellites operating at any instant as part of the constellation) that collectively provide global precipitation maps on approximately a 3-hourly temporal scale (Hou et al., 2014). These satellites carry microwave instrumentation at frequencies spanning 10-183 GHz, which are sensitive to different sizes and phases of precipitation particles distributed throughout the atmospheric column. The GPM Core Observatory (GPM-CO) carries the Dual-frequency Precipitation Radar (DPR), effectively two radars operating at the Ku- (13.5-GHz) and Ka- (35.5-GHz) bands (Iguchi et al., 2003), and the multi-channel GPM microwave imager (GMI; Hou et al., 2014).

Similar to the approach used for creating the TRMM PF database (Liu et al., 2008), GPM PFs are defined for Ku-band radar-derived near-surface precipitation rates > 0.1 mm hr⁻¹ (rPFs) and contiguous Ku-band radar pixels defined as convective precipitation (cPFs). Since TCs may go unsampled by the GPM DPR for several days due to overpass frequency and a relatively narrow DPR swath, PFs derived from GMI brightness temperatures (Tb) with precipitation rates > 0.1 mm hr⁻¹ are also used herein (hereafter defined as “1CPFs”). Due to similar footprint sizes at 89-GHz, 1CPFs are also derived from the AMSR2 instrument onboard the GCOM-W1 satellite (Kasahara et al., 2012; Oki et al., 2010) to increase TC sample sizes. Although previous studies have studied TCs utilizing multi-platform passive microwave observations (e.g., Alvey et al., 2015; Cecil & Zipser, 1999), this study is the first to do so in the combined GLM and GPM era. Following Heuscher et al (2022), GLM lightning observations within +/- 10 minutes of the GPM-CO or GCOM-W1 overpass are incorporated into the 1CPFs to define those features as electrically active or non-electrically active. The cPFs represent discrete convective regions within larger precipitation systems (e.g., we interchange “cPF” with “cell” – acknowledging that they are not necessarily exactly the same) associated with rPFs, although not all rPFs have convective rain. Additionally, cPFs and rPFs may be associated with 1CPFs in a similar manner due to the different PF definitions.

2.3 TC data and classification

North Atlantic Basin TC best-track observations for the 2018-2021 seasons are obtained from the National Hurricane Center (Landsea & Franklin, 2013) via the International Best Track Archive for Climate Stewardship (IBTrACS; Knapp et al., 2018; Knapp & Kruk, 2010), version 4. Within IBTrACS, 6-hourly position information is temporally interpolated to 3-hourly individual time periods (ITPs) using splines. Parameters not related to position (e.g, maximum sustained wind speed (MSW) and minimum sea level pressure (MSLP)) are interpolated linearly (Knapp, 2019). Position uncertainty included in such datasets generally decreases with increasing intensity (Torn & Snyder, 2012). Information on the radius of tropical storm force winds (TSR) and the radius of maximum winds (RMW) is also available from IBTrACS for each
ITP, and we make extensive use of this information in this study. Eyewall convection is
collocated with the RMW due to radial convergence, an increased tangential wind speed, and a
sudden upward turning of air within the RMW (Houze, 2010). Note that a 5 km buffer is added
to the RMW to account for sloped eyewalls (e.g., Hazeltan & Hart, 2013; Jorgensen, 1984;
Rogers et al., 2012; Shea & Gray, 1973; Stern & Nolan, 2009). The TSR used is the mean of the
34-knot wind within each quadrant. If no RMW (TSR) value is present in IBTrACS, a value of
80 (120) km is used. The 80 km RMW value was chosen as it is roughly the 75th percentile of
Atlantic Basin TC RMWs from 1988-2002 (Kimball & Mulekar, 2004). This 80 km distance
from the TC center is approximately where previous lightning studies have observed a lightning
minima associated with the area between the inner core and outer rainbands (e.g., Cecil et al.,
2002; Corbosiero & Molinari, 2002, 2003; Molinari et al., 1994, 1999; Squires & Businger,
2008). The climatological mean TSR found within the Atlantic Basin from 1988-2004 has been
shown to range from 107 km to 225 km depending on the number of samples used (Kimball &
Mulekar, 2004; Knaff et al., 2007). Herein, a TSR value of 120 km was used to align with Knaff
et al (2007), due to their larger sample size (and possibly more diverse environmental
conditions).

While a few previous studies (Stevenson et al., 2014; Stevenson & Corbosiero, 2016) do
further position interpolations to 1-minute intervals to calculate the lightning azimuth in relation
to storm center, the majority of previous studies use 3-hourly (or greater) ITPs. To enable better
comparisons with previous studies as well as data availability in IBTrACS, this study utilizes the
3-hourly ITPs available in IBTrACS, which occur at either main or intermediate synoptic times.
Because part of the focus of this study is to look at the PTC phase of the TC lifecycle (i.e., after
ET), which may not always be included in the NHC best-track data, the best-track positions are
extended by tracking MSLP minima and vorticity maxima at 850, 700, and 600-hPa (Hodges &
Emerton, 2015; Serra et al., 2010) in the fifth-generation European Centre for Medium-Range
Weather Forecasts (ECMWF) global atmospheric reanalysis (ERA5; Hersbach et al., 2020).
ERA5 has a 0.25° x 0.25° horizontal grid spacing and is available in hourly time steps, although
3-hourly time steps are used to match the IBTrACS temporal resolution. This reanalysis dataset
has been used to track TCs and extratropical cyclones using either vorticity alone (Gramcianinov
et al., 2020) or a combination of vorticity and MSLP (Zhong et al., 2023). Also, ERA5 is able to
depict TC and PTC structure (Bian et al., 2021; Dullaart et al., 2020; Malakar et al., 2020; Sarro
& Evans, 2022).

Based on the 1-minute MSW, ITPs are classified into life-cycle phase. Classifications
include tropical storms (TS; 34 ≤ MSW ≤ 63 kt), category 1 to 2 hurricanes (CAT12; 64 ≤ MSW
< 95 kt), and category 3 to 5 hurricanes (CAT35, MSW ≥ 95 kt) or post-tropical cyclones (PTC;
classified based on an asymmetry factor, B). B measures the symmetry shift in the thickness
field, resulting from low-level frontogenesis and increasing baroclinicity (J. L. Evans & Hart,
2003; Hart, 2003) and is calculated via:

\[
B = \begin{cases} 
\Delta Z_{\text{lower}} : & \frac{Z_{\text{TSR}/3} - Z_{\text{TSR}}}{750} < 0 \\
\Delta Z_{\text{upper}} : & \frac{Z_{\text{TSR}/3} - Z_{\text{TSR}}}{450} < 0 \\
T_{\text{UTC}} > T_{\text{min}(\text{MSLP})} 
\end{cases} 
\]
The geopotential height (ΔZ) horizontal change between the TSR and one-third of the TSR is calculated at both lower (750-hPa) and upper levels (450-hPa). These levels are representative of the lower (upper) atmosphere, without substantial influence from the surface (tropopause). Warm (cold) core designations are assigned if ΔZ at that level is positive (negative). The ET transition is considered complete when both lower and upper levels are designated as cold-core (i.e., negative) and the ITP time is after the minimum MSLP time in IBTrACS. ITPs after ET transition are classified as PTC ITPs. ITPs are classified as oceanic (continental) if less than 40% (more than 60%) of the latitude/longitude pairs within 2*TSR are over land. This classification scheme is used to account for the continental influence on landfalling TC rainbands (e.g., May et al., 2008; Morin & Parker, 2011).

Lightning flashes and PFs are collocated with storm ITPs if they are within the three hours following the ITP start time and are within 2*TSR. To ensure high quality data, ITPs are not used if the storm center for a particular ITP is outside the GLM FOV. Resulting ITP counts are listed in Table 1, with TS and PTC ITPs each having more than 1,500 samples and CAT12 (CAT35) hurricanes having approximately 400 (200) samples. For results broken down by TC phase, the two ITPs immediately following when a TC transitions phase are removed to ensure that the results fully represent that phase (i.e., if a TC transitions from a TS to a CAT12, the 6 hours immediately following the transition at the CAT12 phase are removed). A conservative approach to considering PFs for use in this study was taken, i.e., PFs are constrained to having all of their constituent pixels reside entirely within the GLM FOV. Similar to the conservative approach of Heuscher et al (2022), features were also removed if they were not fully within the DPR (GMI/GCOM-W1) scan for cPFs and rPFs (1CPFs).

<table>
<thead>
<tr>
<th>Year</th>
<th>TS (34 ≤ MSW ≤ 63 kt)</th>
<th>CAT12 (64 ≤ MSW &lt; 95 kt)</th>
<th>CAT35 (MSW ≥ 95 kt)</th>
<th>PTC (Asymmetry factor)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2018</td>
<td>411 (365)</td>
<td>143 (117)</td>
<td>34 (28)</td>
<td>478 (450)</td>
</tr>
<tr>
<td>2019</td>
<td>347 (304)</td>
<td>62 (48)</td>
<td>59 (53)</td>
<td>349 (315)</td>
</tr>
<tr>
<td>2020</td>
<td>594 (518)</td>
<td>152 (115)</td>
<td>53 (38)</td>
<td>715 (656)</td>
</tr>
<tr>
<td>2021</td>
<td>308 (256)</td>
<td>58 (42)</td>
<td>42 (34)</td>
<td>592 (552)</td>
</tr>
<tr>
<td>Total</td>
<td>1,660 (1,443)</td>
<td>415 (322)</td>
<td>188 (153)</td>
<td>2,434 (1,973)</td>
</tr>
</tbody>
</table>
Figure 1. TC tracks from the 2018-2021 Atlantic Basin hurricane seasons within the GLM FOV (a) and associated GPM mission overpasses used in this study (b). Counts on panel b indicate the number of GPM overpasses for each phase.
Following Corbosiero and Molinari (2002, 2003; hereafter CM02, CM03) and Matyas (2010), TCs are partitioned into motion-relative and shear-relative quadrants with the motion and shear vectors aligned to a northward-directed reference frame. This results both in forward motion and downshear quadrants being located to the north of the storm center (cf. Matays 2010 Figure 2). Angles relative to the shear and motion vectors are calculated for lightning and PF locations as well as an RMW-scaled distance, r*, from the TC center via:

\[ r^* = \frac{r}{RMW} \]

with r being the distance from the TC center [km]. This RMW-normalized compositing scheme is used to dynamically account for the different TC sizes. Due to differing RMWs for TC phases, r* for different strengths are not necessarily equal (i.e., TS^r_\ast \neq CAT12^r_\ast). For reference, in hurricanes, 1-2 r* roughly corresponds to the primary eyewall location, whereas 2-3 r* corresponds to rainbands and secondary eyewalls (DeHart et al., 2014; Rogers et al., 2012). Following Zhang et al. (2015) and Yang et al. (2020), the environmental vertical wind shear for each ITP is calculated by averaging the ERA5 850-hPa and 200-hPa 3-hourly horizontal wind vectors over a 200-800 km radius from the TC center in order to remove the TC circulation center.

3 Results

3.1 GLM observations

A total of 3,793,854 lightning flashes were detected by GLM in the 88 TCs and associated phases observed during the 2018-2021 Atlantic hurricane seasons (Table 2). A total of 82 TCs (93%) completed ET, a larger sample fraction than previously reported (Hart & Evans, 2001). It should be noted that lightning is constrained by 2*TSR, which may vary by TC phase. The results suggest more lightning flashes occur in PTCs than in tropical phases. This may be influenced by larger areas during the PTC phase, the higher probability of PTC ITPs being over land where lightning activity is generally more frequent than over ocean (Boccippio et al., 2000; Williams & Stanfill, 2002), or increased ice-phase processes in baroclinic environments. We also find that CAT35 major hurricanes phases typically contain less lightning than other TC phases, consistent with previous studies (e.g., Cecil & Zipser, 1999; DeMaria et al., 2012; W. Zhang et al., 2015). A few reasons for this lightning frequency difference are fewer CAT35 samples (Table 1), these samples are over the open ocean (Figure 1a) where less lightning occurs when compared to continents, and that while lightning has been associated with hurricane intensification (Fierro et al., 2011; Molinari et al., 1994, 1999; Squires & Businger, 2008; Stevenson & Corbosiero, 2016), major hurricanes have a lower chance of increasing intensity on the Saffir-Simpson classification scale.

TC phase flash rates were also examined as this is a common storm intensity metric. TS and PTC phases have larger mean and 95th percentile flash rates than hurricane phases within TCs. Although TCs spend most of their lifecycle as TS or PTCs (Table 1), which contain larger areas than hurricanes (not shown), more lightning flashes in the TS/PTC phases combined with similar mean flash rates to hurricane phases but higher extreme flash rates suggests that convection within TCs is driven by a balance of storm-scale convective frequency (as inferred by
the number of lightning flashes) and convective intensity (e.g., flash rate). This balance between lightning frequency and convective intensity has been previously seen when looking at lightning land/ocean contrasts as well as the diurnal timescale (Boccippio et al., 2000; Williams et al., 2000).

As observed in Figure 2, TS and PTC phases, as well as all lightning flashes, exhibit a single peak in their distribution whereas a bimodal distribution is observed for hurricane phases, with large inter-storm variability. The radial distributions of lightning partitioned by TC phase add more insight into the source of bimodal radial lightning distributions reported in previous TC studies that included multiple TC phases in a single distribution (Abarca et al., 2011; Cecil et al., 2002; Molinari et al., 1999; Stevenson & Corbosiero, 2016; Xu et al., 2017). A bimodal lightning distribution in hurricane phases might be expected due to updraft strength differences between the eyewall (i.e., 1-2 r*) and rainband regions (2-3 r*). Stronger updrafts, which are observed in eyewalls when compared to rainbands (Black et al., 1996; Jorgensen et al., 1985), can lead to more turbulence as well as loft more hydrometeors into the mixed phase region, supporting more frequent flashes (Bruning & MacGorman, 2013; Carey et al., 2019; Deierling & Petersen, 2008). These strong eyewall updrafts, while extending through the troposphere (Black et al., 1996), maximize around 8-km altitude (Lord et al., 1984; Marks & Houze, 1987), well within the mixed phase zone for this study. One might also see a greater influence on TC convection in the rainband regions due to environmental inhomogeneities (e.g., sea surface temperature gradients, conditional instability/aerosol gradients, underlying surface inhomogeneities, fronts/jets, etc.), whereas TC inner-core convection is more strongly driven by TC dynamics that interact with relatively small perturbations in mixed layer thermodynamic properties. The unimodal peak for TS and PTC phases also differs in lightning peak location as a function of RMW. The TS phase (1.5-2 r*) peak may show the principal convective band location, whereas the PTC peak, at 1r*, may be located at strongest residual circulation left for a surface low. The lack of a bimodal distribution in total flashes may be due to our compositing of storms, the inclusion of ITPs

Table 2: Lightning statistical measures by TC phase.

<table>
<thead>
<tr>
<th></th>
<th>TS</th>
<th>CAT12</th>
<th>CAT35</th>
<th>PTC</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Flash Count</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total Land</td>
<td>1,247,813</td>
<td>192,831</td>
<td>129,137</td>
<td>1,360,113</td>
</tr>
<tr>
<td>Total Ocean</td>
<td>42,280</td>
<td>348</td>
<td>21</td>
<td>418,144</td>
</tr>
<tr>
<td>Total</td>
<td>1,181,884</td>
<td>170,549</td>
<td>118,122</td>
<td>863,034</td>
</tr>
<tr>
<td><strong>Percentage of Total Flashes</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Land</td>
<td>3.4%</td>
<td>0.2%</td>
<td>0.02%</td>
<td>30.7%</td>
</tr>
<tr>
<td>Ocean</td>
<td>94.7%</td>
<td>88.4%</td>
<td>91.5%</td>
<td>63.5%</td>
</tr>
<tr>
<td><strong>Flashes/ITP [fl 3 hr⁻¹]</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total Land</td>
<td>864.7</td>
<td>598.9</td>
<td>844.0</td>
<td>689.3</td>
</tr>
<tr>
<td>Total Ocean</td>
<td>983.3</td>
<td>174.0</td>
<td>21.0</td>
<td>1,548.7</td>
</tr>
<tr>
<td>Total</td>
<td>981.6</td>
<td>613.5</td>
<td>820.3</td>
<td>802.1</td>
</tr>
<tr>
<td><strong>Mean (95th percentile) Flash Rate [fl min⁻¹]</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Land</td>
<td>5.5 (25.7)</td>
<td>3.6 (16.3)</td>
<td>4.6 (14.5)</td>
<td>5.4 (25.5)</td>
</tr>
<tr>
<td>Ocean</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

As observed in Figure 2, TS and PTC phases, as well as all lightning flashes, exhibit a single peak in their distribution whereas a bimodal distribution is observed for hurricane phases, with large inter-storm variability. The radial distributions of lightning partitioned by TC phase add more insight into the source of bimodal radial lightning distributions reported in previous TC studies that included multiple TC phases in a single distribution (Abarca et al., 2011; Cecil et al., 2002; Molinari et al., 1999; Stevenson & Corbosiero, 2016; Xu et al., 2017). A bimodal lightning distribution in hurricane phases might be expected due to updraft strength differences between the eyewall (i.e., 1-2 r*) and rainband regions (2-3 r*). Stronger updrafts, which are observed in eyewalls when compared to rainbands (Black et al., 1996; Jorgensen et al., 1985), can lead to more turbulence as well as loft more hydrometeors into the mixed phase region, supporting more frequent flashes (Bruning & MacGorman, 2013; Carey et al., 2019; Deierling & Petersen, 2008). These strong eyewall updrafts, while extending through the troposphere (Black et al., 1996), maximize around 8-km altitude (Lord et al., 1984; Marks & Houze, 1987), well within the mixed phase zone for this study. One might also see a greater influence on TC convection in the rainband regions due to environmental inhomogeneities (e.g., sea surface temperature gradients, conditional instability/aerosol gradients, underlying surface inhomogeneities, fronts/jets, etc.), whereas TC inner-core convection is more strongly driven by TC dynamics that interact with relatively small perturbations in mixed layer thermodynamic properties. The unimodal peak for TS and PTC phases also differs in lightning peak location as a function of RMW. The TS phase (1.5-2 r*) peak may show the principal convective band location, whereas the PTC peak, at 1r*, may be located at strongest residual circulation left for a surface low. The lack of a bimodal distribution in total flashes may be due to our compositing of storms, the inclusion of ITPs
during and after ET, and the observation of temporally continuous IC and CG lightning from GLM.

Figure 2. Radial distributions of the normalized (panel a) and actual (panel b) distance from the TC center for all lightning flashes, as well as by TC phase.

Figure 3 shows the motion and shear relative lightning within analyzed ITPs. The GLM data indicate that TC lightning flashes tend to mostly occur on the forward right flank as well as downshear of the TC center (Figure 3a, 3b). Motion and shear relative lightning distributions correspond to the unimodal radial distribution for all flashes observed in Figure 2a, with the peak 1-2 $r^*$ from the TC center. To remove TC duration bias from this lightning analysis, Figures 3c and 3d show the flash count per ITP, which can be interpreted similar to a three-hour average flash rate. The flash rates show lightning maxima in the back left quadrant (with respect to TC motion), approximately 1-2 $r^*$ from the center, where a lightning maximum occurs (Figures 3a, 3c). The lightning maxima in the forward quadrants and the back left quadrant are similar (Figure 3a), but flash rates are lower in forward quadrants (Figure 3c) due to more ITPs contributing to the overall flash count in those quadrants. More frequent flashes are in the downshear right quadrant approximately 1-2 $r^*$ from the TC center, which is similarly collocated with flash count maxima (Figure 3b, 3d) and the unimodal radial distribution (Figure 2a). The region between 1-2$r^*$ from the TC center aligns with the strongest updrafts (e.g., Black et al.,
1996; Jorgensen et al., 1985). Additionally, lightning could be more widely distributed within this region due to tilted eyewall convection with cloud tops where lightning is located being radially removed from the RMW, which occurs at low altitudes. Pockets of higher flash rates occur downshear, approximately 4-5 r* from the TC center, which may be indicative of convection occurring in the TC outer rainbands.
Figure 3. Motion relative (panels a, c) and shear relative (panels b, d) locations for GLM flash counts (0.25 r°, 10° bins; panels a, b) and flash rate (0.25 r°, 10° bins; panels c, d). Arrows indicate motion/shear vector direction.

To prevent prolific lightning-producing TCs from dominating the flash count distribution (Figure 3a, 3b), the preferred lightning quadrant (i.e., the quadrant with a lightning maxima) for each ITP is calculated. Similar to CM02/CM03, the preferred lightning quadrant for each 3-hour ITP is defined as the quadrant with the most flashes during that 3-hour ITP. Figure 4 shows the GLM-observed lightning maxima is located on forward right side (Figure 4a) and downshear (Figure 4b), consistent with previous studies (cf. CM03’s Figure 1). As the downshear right quadrant count in this study exceeds the downshear left quadrant by two ITPs, the marker for all ITPs (blue star in Figure 4b) is placed on the shear vector and the maxima is described as being “downshear” as opposed to either right or left of the shear vector. Similar results are obtained when TC phase is separated, if the ITP time is centered (i.e., lightning flashes from 1030 UTC to 1330 UTC are associated with an ITP time of 1200 UTC), and for ITPs constrained to GPM overpass occurrences (i.e., there are PFs associated with the TC during that ITP).

Several key differences between this and previous studies in Figure 4 should be noted. First, previous studies included in Figure 4 use either ground-based lightning detection networks (Abarca et al., 2011; CM02, CM03) or ground-based radar reflectivity (Matyas, 2010), which do not necessarily capture the vertical distribution of precipitation and the total lightning flash count. Fierro et al (2018) uses GLM lightning data, but only a single 72 hour period during Hurricane Maria (2017). Previous studies also look at the lightning max in the inner core/outter rainband regions, whereas this study does not differentiate these spatial regions. The shear relative plot shows that most other studies find one maximum to the left and another maximum to the right of the shear vector (e.g., CM02/03 for the inner core and outer rainband maxima respectively). If both maxima for CM02/03 are combined, a downshear right maximum is observed, consistent with this study. It should be noted that for CM02/03 does not separate out PTC phases, but uses tropical depression, TS, and hurricane phases. Furthermore, although CM02/03 separate out pre- and post-landfall observations into separate ITPs, post-landfall ITPs, which could be a proxy for PTC phases, are not analyzed separately.

The results from this study support previously developed conceptual models of TC structure (Hence & Houze, 2012). In these models, convection initiates downshear right and intensifies as it rotates counterclockwise to the downshear left quadrant. Figures 3b and 3d show that the downshear right quadrant has the most lightning flashes and highest flash rates respectively, followed by the downshear left quadrant. This is consistent with convective cell initiation (growth and intensification) in the downshear right (left) quadrant. Figure 4b shows that these quadrants are the preferred GLM lightning quadrant for all ITPs, as well as PTC ITPs. Figures 3b and 4b also support previous modeling studies (e.g., Frank & Ritchie, 2001), where the preferred region for low-level convergence (and hence positive vertical velocities) due to differential vorticity advection with height is downshear of the TC center. These positive vertical velocities help support convective initiation and growth, which can be inferred through lightning observations, in the downshear quadrants.
Figure 4. Lightning maxima locations in a motion-relative (a) and shear relative (b) sense for this study compared to previous literature. For previous studies, markers inside the inner circle represent lightning maxima within the TC inner core, while markers within the outer circle represents lightning maxima in the TC outer bands. As TCs in this study were not grouped into inner core/outer rainband designations, markers are placed on the circle representing the inner core. See legend for symbol definitions and references for their datasets/methodologies. Arrows indicate the motion/shear vector direction.

The vertical wind shear influence on TC lightning is further analyzed by breaking TCs into ITPs characterized by weak (< 5 m s\(^{-1}\)), moderate (5-10 m s\(^{-1}\)), and strong shear (> 10 m s\(^{-1}\)) (CM02, CM03; Matyas, 2010; Wang et al., 2018). Figure 5 shows a clear shift in lightning maxima between weak and strong shear cases for TS and PTC ITPs. Weakly sheared ITPs produce more total lightning than strongly sheared ITPs (Figure 5a, 5c), with a clear shift in lightning location as shear increases. More lightning production in weakly sheared systems is consistent with less ice particle advection out of supercooled water regions, resulting in either or both more efficient charge production and/or maintenance and spatial coherence of charged regions, higher flash rates, and more total lightning flashes. Strong shear may also introduce more dry air and subsequent evaporation via entrainment into the system, thereby reducing lightning production. Even though weak shear is consistent with increased lightning production, we note that other dynamical effects (e.g., differences in CAPE, land surface, surface temperature gradients) especially in the rainband regions and during PTC phases may play a role in microphysical charging and lightning production as convection in these regions/ITPs is less controlled by TC dynamics. Weakly sheared TS ITPs (Figure 5a) exhibit a broad radial distribution, with a lightning maximum roughly 2-3\text{r}^* from the TC center and decreasing beyond 3\text{r}*. In contrast, TS ITPs characterized by strong shear (Figure 5c) exhibit a distinct lightning maximum in the downshear right quadrant extending from the RMW (1\text{r}*) to the rainband region (2-3\text{r}*) and a secondary region of enhanced lightning activity on the upshear right quadrant beyond 3\text{r}*, indicative of deeper convection within some TS rainbands. PTC ITPs characterized by weak environmental shear (Figure 5b) reveal a lightning maximum downshear, roughly 1-2\text{r}^* from the center. Beyond this normalized radius, there are banded features that may be indicative of convective pockets on the downshear side of the system (as PTCs do not exhibit symmetrical
rainbands). Strongly-sheared PTC ITPs have overall less lightning within 5r* of the TC center, and their lightning tends to occur upshear of the TC center, roughly 3-4r* from the center. Due to the smaller number of hurricane phase samples (Tables 1 and 2), CAT12 and CAT35 ITPs do not show a clear shift in lightning activity. Weakly sheared CAT12 ITPs are characterized by lightning maxima in the downshear left quadrant 4-5r* from the TC center, whereas weakly sheared CAT35 ITPs are characterized by a radial lightning maxima 1-2 r* from the center (i.e., around the RMW).
**Figure 5.** Shear-relative locations for GLM flash counts (panels a-d) for weakly sheared (< 5 m s\(^{-1}\); panels a, b) and strongly sheared (> 10 m s\(^{-1}\), panels c, d) TS (panels a, c) and PTC (panels b, d) ITPs. Shear-relative locations for flash rate (flashes/ITP; panels e-h) for the same ITPs as...
panels a-d. Bins are the same as in Figure 3a-d. ITP counts for each panel are indicated to the bottom left of each panel. Arrows indicate shear vector direction.

3.2 Precipitation structure of PFs.

Coincident observations and collocation of lightning to GPM-derived PFs and coincident vertical profile and column integrated measurements of precipitation therein may provide insights into the relative intensity versus the number of convective cells (as inferred by PFs) occurring within TCs. Only 3.5% of all PFs analyzed in this study are electrically active (EA), although this varies by PF type. Roughly 5% of 1CPF, 1.5% of rPF, and 4% of cPF are EA (Table 3). The EA percentage differences may arise because of the precipitation type and different derivation techniques for the PF populations (i.e., rPF/cPFs being derived from DPR data and 1CPF being derived from passive microwave data) results in different statistics. For example, due to swath width differences between the GMI/AMSR2 and DPR, 1CPFs have larger areas than DPR-derived PFs. The rPF population has the lowest EA percentage since stratiform systems are included in these PFs, while 1CPFs may be sampling more convection that is occurring either outside the DPR swath or observed by AMSR2. Less than 10% of EA features are classified to be super-electrically active (sEA), defined as consisting of more than 100 flashes. Although partially due to ITP sampling (cf., Table 1), a larger fraction of the sample population is found during TS and PTC phases (Table 3) indicating that the EA cPF frequency observed in each phase makes a contribution to convective characteristics during different TC lifecycle phases.

Table 3: PF counts by TC phase and presence of lightning.

<table>
<thead>
<tr>
<th></th>
<th>TS</th>
<th>CAT12</th>
<th>CAT35</th>
<th>PTC</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Total Count</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1CPF</td>
<td>2,406</td>
<td>654</td>
<td>323</td>
<td>4,718</td>
</tr>
<tr>
<td>rPF</td>
<td>1,744</td>
<td>634</td>
<td>327</td>
<td>2,501</td>
</tr>
<tr>
<td>cPF</td>
<td>2,356</td>
<td>822</td>
<td>572</td>
<td>2,720</td>
</tr>
<tr>
<td><strong>EA Count</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1CPF</td>
<td>149</td>
<td>39</td>
<td>29</td>
<td>182</td>
</tr>
<tr>
<td>rPF</td>
<td>12</td>
<td>8</td>
<td>2</td>
<td>26</td>
</tr>
<tr>
<td>cPF</td>
<td>114</td>
<td>28</td>
<td>16</td>
<td>97</td>
</tr>
<tr>
<td><strong>sEA Count</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1CPF</td>
<td>24</td>
<td>5</td>
<td>2</td>
<td>22</td>
</tr>
<tr>
<td>rPF</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>cPF</td>
<td>4</td>
<td>1</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td><strong>Mean Area [km²]</strong></td>
<td>6,467.5</td>
<td>6,659.7</td>
<td>10,021.3</td>
<td>4,008.9</td>
</tr>
<tr>
<td>1CPF</td>
<td>378.7</td>
<td>398.6</td>
<td>378.0</td>
<td>400.9</td>
</tr>
<tr>
<td>rPF</td>
<td>339.8</td>
<td>317.4</td>
<td>355.4</td>
<td>333.8</td>
</tr>
</tbody>
</table>

To provide a better understanding of the vertical ice mass distribution, contoured frequency by altitude diagrams (CFADs; Yuter & Houze, 1995) are created for TC EA and sEA pre-ET and post-ET cPFs. CFADs (Figure 6) are composed of all Ku-band radar pixels (corrected reflectivity from 2ADPR) within TC-associated cPFs that fall fully within the DPR.
scan; CFAD distributions are normalized by the absolute maximum sample frequency, similar to Houze et al (2007), in order to facilitate comparison among the different populations. The mean 0°C, -10°C, and -40°C heights derived from vertical temperature profiles stored in the GPM datasets are also plotted. Both pre-ET and post-ET EA cPFs exhibit multiple convective modes (Figures 6a, 6b), which have been well documented within the tropics (e.g., Carey & Rutledge, 2000; Liu et al., 2008; Liu & Zipser, 2015; Nesbitt et al., 2006; Petersen et al., 1996). The EA cPFs containing less than 25% small and/or shallow convectively-determined pixels (shallow pixels defined as having a storm top height less than 1 km below the freezing level; Iguchi et al., 2020) constitute the primary mode near 35 dBz reaching the freezing level. The remaining EA cPFs constitute the secondary modal reflectivity near 20 dBz.

Post-ET profiles (Figure 6b, 6d) tend to be shorter than pre-ET profiles for both EA and sEA cPFs. Additionally, post-ET EA cPFs have a larger frequency of profiles containing reflectivities below the freezing level, even though the pre-ET profiles have higher maximum surface reflectivities. Although tendencies are hard to compare due to sample size differences, sEA profiles (Figure 6c, 6d) exhibit a reduced vertical reflectivity gradient relative to EA profiles (i.e., the mode is more vertical, especially in the lower half of the mixed phase zone). Furthermore, the majority of EA profiles (both pre- and post-ET) contain 30 dBz echoes well into the upper mixed phase region. Numerous studies have demonstrated that reflectivity thresholds such as 30-40 dBz at -10°C indicate the presence of ice microphysics conducive to the production of robust storm electrification and associated lightning (e.g., Carey & Rutledge, 2000; Dye et al., 1988; Petersen et al., 1996; Zipser & Lutz, 1994). We clearly see these trends in Figure 6, where 10-15% of the EA cPFs have 40 dBz reflectivity at -10°C and roughly 50% of the sEA cPFs attain this critical threshold. With more of these “intense” features occurring during the PTC phase (Table 3), it can be implied that the overall convective nature is more intense after a TC undergoes extratropical transition. This more intense convective nature suggests that conditions are more conducive to lightning production after ET completes.
Figure 6. CFADs of GPM Ku-band reflectivity [dBz] for pixels within EA pre-ET (panel a), EA post-ET (panel b), sEA pre-ET (panel c), and sEA post-ET (panel d) TC cPFs. The mean freezing height, -10°C, and -40°C heights for each population are displayed.

Although radar observations provide a great deal of information for the ensemble of given precipitation profiles and PFs, DPR-derived PFs represent only a small fraction of the PFs
sampled due to the narrow DPR swath width (245 km; Hou et al., 2014) as compared to that of the GMI on board the GPM-CO (885 km; Hou et al., 2014) as well as microwave imagers onboard other satellites within the GPM constellation (e.g., AMSR2 onboard GCOM-W1 with a swath width of 1,445 km (NASA, 2023)). Thus, we also consider PFs defined from the passive microwave observations, which provide more coverage of TCs during overpass events. Using PCT\textsubscript{37-GHz}, horizontally-polarized 37-GHz (37\textsubscript{H}) and vertically-polarized 37-GHz (37\textsubscript{V}), Jiang et al (2018; hereafter J18) and Lee et al (2002) identified seven different precipitation regions subsequently classified as precipitation-free, shallow convection, stratiform precipitation, and deep convection (cf. Table 2 in J18). As numerous 37-GHz pixels may comprise a single PF, we apply the J18 approach to create precipitation region scatterplots partitioned by TC phase for nEA, EA, and sEA cPFs (Figure 7a, 7b, and 7c respectively), with each PF being plotted at the 37\textsubscript{H} and 37\textsubscript{V} representing the minimum PCT\textsubscript{37-GHz}.

Figures 7a and 7b are representative of observed behavior in the CFADs for nEA and EA cPFs (Figure 6). The nEA PFs are classified as all 7 types of precipitation, overlapping with EA PFs. The majority of these PFs are classified as precipitation-free, shallow convection, or stratiform precipitation. Contrasting Figures 7a-b, the nEA PFs classified as deep convection in Figure 7a are likely PFs either just below the threshold of becoming electrically active, or with flashes not detected by the GLM. EA PFs are primarily classified as deep convection (Figure 7b), but all precipitation types are found within EA PFs. This is not unexpected as shallow (or early stage) convection and stratiform precipitation are sometimes known to be electrically-active (Carey et al., 2005; Dye & Bansemer, 2019; Lang et al., 2004; Rutledge & Petersen, 1994; Schuur & Rutledge, 2000; Stolzenburg et al., 1994) and also corroborates the two precipitation modes observed in Figure 6b. Another reason that all precipitation types being found within EA PFs is noise and imperfection within the data and algorithms. Reasons for nEA and EA PF overlap (Figure 7a, 7b), as well as the shallow convection classification, may be due to an incorrect assumption that lightning and minimum PCT\textsubscript{37} are collocated or surface contamination via non uniform beam filling influencing the observed T\textsubscript{B} (Kummerow, 1998) with the large 37-GHz surface footprint (~ 125 km\textsuperscript{2}; Hou et al., 2014). Figure 7c shows that sEA PFs are almost exclusively deep convection, consistent with CFADs from pixels within these PFs (Figure 6c). Figure 7c is also consistent with behavior of the deepest DPR cPF profiles with the higher frequencies of 20 dBz reaching above the mean -40°C level, indicating more integrated ice mass.
**Figure 7.** Scatter plots of TC cPFs in the NRL 37 color product as defined by J18 and Lee et al (2002) as a function of $37_H$ and $37_V$. Points are plotted at the $37_H$ and $37_V$ comprising the minimum PCT$_{37\text{-GHz}}$ for a) nEA PFs, b) EA PFs, c) sEA PFs. Panel d) shows the precipitation type associated with each region (Table 2 in J18).

### 4 Summary and Conclusions

New datasets have been created containing merged coincident and spatially-matched satellite observations of convective precipitation features (cPFs) defined from the precipitation profile and column-integrated observations observed by the LEO GPM constellation and temporally continuous geostationary lightning observations from the GOES GLM. These data have been collected over data-sparse, remote locations covering both the tropics and the mid-
latitudes (oceanic and continental), and were used herein for the study of different TC lifecycle phases. The ability to observe and study TCs with continuous observations over tropical and subtropical oceans is critical as this is where these systems spend most of their lifetime. Moreover, TCs typically initiate and develop too far from ground-based detection networks to accurately depict their electrical and microphysical evolution. Hence, geostationary satellite-based lightning measurements combined with frequent active/passive microwave observations from LEO satellites offer a unique observational perspective from which to advance our understanding of TCs. Armed with this new merged dataset, this study uses observations of four Atlantic Basin hurricane seasons, totaling 88 TCs, to examine coevolving convective structure and lightning behavior in different TC phases. This study is unique in that we also specifically characterize lightning observations in TCs that have undergone extratropical transition (ET) and have become post-tropical cyclones (PTCs) - a challenging TC phase that has been previously under-sampled and not well studied in the context of precipitation structure and lightning.

The main findings of this study are as follows:

1) The lightning activity radial distribution within TCs is unimodal when all phases are integrated into a single sample. The radial distribution of lightning activity is also unimodal for TS and PTC phases (Figure 2), two TC phases that dominate the TC phase sample space. However, hurricane phases (CAT12 and CAT35) are characterized by bimodal radial distributions of lightning activity consisting of eyewall and outer rainband peaks.

2) When examined in a TC motion-relative (shear-relative) reference frame, lightning flash counts maximize in the forward motion (downshear) direction/quadrants (Figure 3). When looking at preferred lightning quadrants for every 3-hour ITP, a forward right (downshear) quadrant is found, regardless of TC phase, for motion-relative (shear-relative) analysis (Figure 4). Physically this can be explained by convection preferentially occurring within the downshear right quadrant of the TC and intensifying as it rotates counter-clockwise within the TC.

3) Convective differences between TC phases relative to the lightning activity spatial distribution are driven by a balance between the frequency of occurrence of lightning producing cells and intensity differences among them. Tropical storm (TS) and PTC phases exhibit relatively more lightning flashes, higher extreme flash rates, as well as more electrically active (EA) and super EA (sEA) cPFs than hurricane phases (Tables 2 and 3). Additionally, vertical profiles of reflectivity from sEA cPFs during the PTC phase appear to have greater reflectivity at altitudes above the -10°C level than tropical phases, indicating stronger updrafts in cold regions of the convection during this phase. While relatively more intense, the infrequent occurrence of sEA features results in minimal influence over the EA sample statistics in this study.

4) The addition of passive microwave precipitation classification at 37-GHz (Figure 7) — a means to partition column integrated frozen precipitation behavior weighted more strongly to larger ice hydrometeors — can also help reveal relative presence of electrical activity (EA or sEA) in TCs, but not necessarily TC phase.
Future research will focus on the addition of more seasons from the Atlantic Basin and expansion to the Pacific Basin, which help will increase sample numbers for each TC phase, increase the breadth of convective intensities sampled, and further improve the means to characterize physically meaningful differences in lightning and convective structure as a function of ambient environments (e.g., Table 1). Consideration of different ocean basin environments is important because previous research (DeMaria et al., 2012; Stevenson & Corbosiero, 2016) has indicated that different physical processes may influence TC development in the Atlantic and Pacific Basins. Thus, future research should also focus on TCs in the Pacific Basin using data from the GLMs onboard GOES-17/18, with subsequent comparison to results from the Atlantic Basin to help further isolate the relative occurrence of different physical processes. Analysis of other lightning characteristics observed by the GLM instruments (e.g., area, duration, energy) may provide further insight into the inner workings of deep convection associated with TCs and should also be examined. This study also suggests the importance of continued, targeted future in-situ microphysical, electrical, and environmental TC observations that encircle the hurricane eye at varying radii to resolve discrepancies in the interpretation of radial distributions of lightning and TC intensification.

Acknowledgments

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Open Research

All GPM precipitation feature data is available at http://atmos.tamu.edu/trmm/data/gpm/. The GLM data are available via the National Oceanic and Atmospheric Administration (NOAA) Comprehensive Large Array-data Stewardship System (CLASS) at https://www.avl.class.noaa.gov/saa/products/welcome. The IBTrACS Tropical Cyclone data is available via https://www.ncei.noaa.gov/products/international-best-track-archive. ERA5 reanalysis data is available from the Copernicus Climate Data store at https://cds.climate.copernicus.eu/#!/home.
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