Quantitative Differences between Lightning and Nonlightning Convective Rainfall Events as Observed with Polarimetric Radar and MSG Satellite Data

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ABSTRACT

To increase understanding of the relationships between lightning and nonlightning convective storms, lightning observations from the National Aeronautics and Space Administration (NASA) African Monsoon Multidisciplinary Analyses (NAMMA) campaign were analyzed with Meteosat Second Generation (MSG) geostationary satellite and S-band NASA Polarimetric Doppler Weather Radar (NPOL) data. The study’s goal was to analyze the time evolution of infrared satellite fields and ground-based polarimetric radar during NAMMA to quantify relationships between satellite and radar observations for lightning and nonlightning convective clouds over equatorial Africa. Using NPOL data, very low-frequency arrival time difference lightning data, and MSG Spinning Enhanced Visible and Infrared Imager observations, the physical attributes of growing cumulus clouds, including ice mass production, updraft strength, cloud depth, and cloud-top glaciation were examined. It was found that, on average, the lightning storms had stronger updrafts (seen in the satellite and radar fields), which lead to the formation of deeper clouds (seen in the satellite and radar fields) and subsequently much more ice in the mixed-phase region (as confirmed in radar observations), as well as much more nonprecipitating ice in the top 1 km of the cloud (as quantified in both satellite and radar fields) than the nonlightning storms. Computed radar-derived ice masses in cumulus clouds verifies the traditional MSG indicators of cloud-top glaciation, while NPOL verifies internal structures (i.e., large amounts of graupel) where satellite and radar show strong updrafts.

1. Introduction

The main motivation for this study was to increase understanding of the differences between lightning and nonlightning producing storms when analyzing the time evolution of cloud-top infrared (IR) geostationary satellite, ground-based polarimetric radar, and lightning fields. For this study, observations from the National Aeronautics and Space Administration (NASA) African Monsoon Multidisciplinary Analyses (NAMMA) campaign were used, along with Meteosat Second Generation (MSG) geostationary satellite observations. These fields were analyzed in concert to describe physical attributes of growing cumulus clouds, including ice mass production, updraft strength, cloud depth, and cloud-top glaciation. The goals for the present study are as follows:

1) to develop an understanding of how the radar fields behave relative to MSG observations that describe cloud-top glaciation, cloud growth rate, and cloud depth; and
2) to evaluate how MSG and radar fields behave and evolve together, for lightning and nonlightning storm events. Another unique aspect of the study is that it documents convective weather in equatorial Africa, which is very poorly observed relative to other regions of the earth. To date, numerous studies (as highlighted below) have used radar and lightning observations in an attempt to develop physical understanding between hydrometeor fields and lightning occurrence, behavior, and frequency. In contrast, few studies have attempted to use geostationary satellite observations in concert with radar and lightning to connect cloud-top views of convective clouds with in-cloud processes.

The methodology in this study follows closely that of Matthee and Mecikalski (2013, hereafter MM13) that examined only MSG satellite IR fields with respect to lightning and nonlightning storms. Similarly, 33 lightning and 30 nonlightning storms that occurred during August and September 2006 over Kawsara, Senegal.
(West Africa), as part of the NAMMA campaign, were analyzed as clouds grew from the cumulus to cumulonimbus cloud scale. As an extension to MM13, this study analyzes evolving clouds using various polarimetric fields to characterize hydrometeors, and compare these to what was found in MM13, thereby drawing connections between cloud-top and in-cloud aspects of growing and evolving cumulus clouds, (in contrast to MM13, which focused on cloud-top attributes). The expectation is that the analysis of radar fields will complement the results of MM13.

Developing a clearer understanding of the relationships between satellite, radar, and lightning in convective clouds becomes valuable for follow-on studies that may diagnose storm intensity (e.g., important for aviation), for short-term prediction of rainfall and convective storm attributes (e.g., lightning, hail), and for climate-based studies. Furthermore, forming relationships between satellite-based cloud-top features and precipitation fields as observed with polarimetric data becomes particularly relevant given the 2013–14 upgrade of the U.S. National Weather Service Weather Surveillance Radar-1988 Doppler (WSR-88D) systems that have these added capabilities. Similarly, developing improved uses of multi-spectral IR data is important given the forthcoming Geostationary Operational Environmental Satellite (GOES)-R/S sensors over North America, whereas use of lightning data together with geostationary IR observations helps prepare the community for the Geostationary Lightning Mapper on GOES-R, and the Lightning Imager on the Meteosat Third Generation.

This paper proceeds as follows: section 2 provides background for the research performed and overviews the three datasets used. Section 3 documents the methodology. Section 4 presents a short discussion of the MSG satellite fields analyzed for the lightning and nonlightning storms, while section 5 overviews one characteristic lightning and one nonlightning event. Section 6 discusses the average radar fields for all storm types, along with computed ice masses to corroborate the satellite signatures between the different storm types. Last, section 7 concludes the paper.

2. Background and data

Observations from the S-band NASA Polarimetric Doppler Weather Radar (NPOL), in conjunction with very low frequency (VLF) arrival time difference (ATD) lightning [from the Met Office (UKMO)] and MSG Spinning Enhanced Visible and Infrared Imager (SEVIRI) fields, were analyzed coincidently. These datasets were utilized to evaluate and describe the physical attributes of growing cumulus and cumulonimbus clouds, including precipitation and nonprecipitation ice mass ($M_{np}$) production, updraft strength, cloud depth, and cloud-top glaciation between lightning and nonlightning convective storms.

Many studies have been performed on convective storms using either radar (Hondl and Eilts 1994; Carey and Rutledge 1996; Vivekanandan et al. 1999; Carey and Rutledge 2000; Carey et al. 2003; Lund et al. 2009) or satellite (Reap 1986; Donovan et al. 2008; Harris et al. 2010; Mecikalski et al. 2010a,b, 2011) and lightning data, yet the combined evaluation of these three datasets, along with the study’s domain being over equatorial Africa, is unique. This research is technically similar to that done with the Tropical Rainfall Measuring Mission (TRMM) sensor suite, however, this study significantly expands on this work by utilizing temporally continuous observations of both ground-based polarimetric radar and geostationary satellite multispectral IR over equatorial Africa. Relevant TRMM-related research has shown that convective systems over tropical continents typically have higher cloud-top reflectivity ($Z$) values, with stronger ice scattering and greater supercooled water contents aloft, and thus more lightning, as compared to convective systems over oceans (Boccippio et al. 2000; Petersen and Rutledge 2001; Toracinta et al. 2002; Cecil et al. 2005; Petersen et al. 2005; Pessi and Businger 2009). Pessi and Businger (2009) found that heights of radar echo tops show strong correlation to lightning rates. These echo tops also relate to cloud-top temperatures ($T_s$): colder $T_s$ (higher echo tops), therefore, correlate to increases in lightning rates (Toracinta et al. 2002). Cecil and Zipser (2002) stated that lightning storms with colder microwave brightness temperatures ($T_B$) tend to have larger reflectivities in the mixed-phase region. In addition, ice scattering from deep convective cloud tops—cloud-top heights located above the homogeneous freezing level (approximately $-40^\circ$C)—will lead to lower $T_B$ values (Vivekanandan et al. 1991). Futyan and Del Genio (2007) quantify aspects of evolving convective systems from a Meteosat-8 and TRMM radar perspective, but do not focus on lightning.

Previous studies have also shown that polarimetric variables provide important information on the size, shape, thermodynamic phase, and the orientation of hydrometeors, to distinguish water drops, graupel, hail, and ice crystals; these variables can be used to locate areas of lightning preceded by some form of active charging (Doviak and Zrnić 1993; Hondl and Eilts 1994; Carey and Rutledge 1996, 2000; Straka et al. 2000; Brindi and Chandrasekar 2001; Cifelli et al. 2002; Carey et al. 2003; Wang and Carey 2005; Lund et al. 2009). Carey and Rutledge (2000) showed that precipitation ice and water in the mixed-phase region are strongly correlated
to lightning, and that ground locations of cloud-to-ground (CG) flashes clustered beneath radar-inferred precipitation ice mass \( M_p \) maxima. Further, increased updraft strength estimated from radar variables directly resulted in more ice mass aloft, and thus more lightning (Carey and Rutledge 1996). These updraft strengths can also be inferred from satellite \( T_{\text{IR}} \) (e.g., Roberts and Rutledge 2003). Thus, polarimetric variables of horizontal \( Z (Z_H) \), differential \( Z (Z_{\text{DR}}) \), and difference \( Z (Z_{\text{DP}}) \) are often used to distinguish and categorize hydrometeor types.

Besides the importance of radar polarimetric variables when delineating various precipitation particles, information from satellites, such as cloud-top \( T_{\text{IR}} \), inferred updraft strength, and cloud-top glaciation, are also important. These can help distinguish deep convective clouds that have large amounts of ice at the top and thus may eventually produce lightning, versus convective clouds that may not produce lightning.

In a closely related study, Mecikalski et al. (2013) have quantified the behavior of WSR-88D and GOES IR fields in the 75-min time frame leading to lightning production in cumulonimbus clouds, helping to understand the sequence of events leading to in-cloud charging. Mecikalski et al. (2013) examined storms in two widely different convective environments of the United States; Florida and Oklahoma, using only \( Z_H \) observations. Hence, this present study extends our knowledge by exploiting polarimetric datasets toward quantifying further in-cloud processes that \( Z_H \) data alone cannot do. Here, lightning and nonlightning convective events are contrasted providing quantification of in-cloud processes related to the main charging zone with respect to polarimetric radar-estimated quantities, in relation to satellite fields.

The main satellite dataset used in this study was calibrated level-1.5 IR channels collected from the SEVIRI instrument on MSG (specifically Meteosat-8) located over the equator at 0° latitude. It has a 15-min repeat cycle, consisting of 12 spectral channels, including 8 IR channels (Schmetz et al. 2002). All IR, water vapor, and near-IR channels have a 3-km sampling distance at nadir, with the main focus here being on the 6.2-, 7.3-, 8.7-, 10.8-, and 12.0-μm channels.

### 3. Methodology

Since many of the data and methods followed here are as in MM13 for the satellite and lightning fields, and as in Doviak and Zrnić (1993), Carey and Rutledge (1996, 2000), and Cifelli et al. (2002) for the radar observations, we refer the reader to those papers. Yet, we will discuss the more important aspects of all three datasets here as pertinent to this analysis.

To compare the lightning producing and nonlightning convective storms, a “t time” had to be obtained for all the convective storms used, from which backward and forward time trends were obtained for all events. For the lightning storms, the t time was defined as the time when the first CG lightning flash occurred; for example, if the first flash occurred at 1435 (1440) UTC, then this flash fell into the closest 15-min radar time; the lightning t time was then 1430 (1445) UTC to correspond to the radar timeframes. Once a t time was established for a given storm, the storm’s evolution was then divided into 15-min intervals, from \( t - 45 \) through \( t + 30 \) for both the lightning and nonlightning storms. The t time for the nonlightning storms was 15 min before the maximum volume of \( Z \) values above 35 dBZ was reached; this was obtained after various studies and tests were analyzed and performed (MM13).

The NPOL S-band polarimetric radar located in Kawsara, Senegal, West Africa (14.65654°N, 17.09803°W), operated nearly continuously from 19 August to 30 September 2006. Full volume scans were produced every 15 min, and either 270- or 150-km long-range scans were available. Every 15 min, a 1-tilt (0.8°) surveillance scan (270-km range) and one 19-tilt volume scan (150-km range) were collected. Both scanning strategies comprised of an azimuthal resolution of 1.4°, a pulse width of 0.8, and horizontal and vertical polarization. The maximum range of the radar was 150 km, and the unambiguous range before folding occurs was 157.8 km. The NPOL data were used to track storms and to collocate the MSG data with the lightning data to analyze the lightning and nonlightning events.

Prior to NPOL analysis, quality control procedures were implemented as part of NAMMA’s postprocessing, with various filters being incorporated in the process [refer to Kucera (2006) for these filters]. Raw data were subsequently converted to universal format (UF) and then to Doppler Radar Data Exchange (DORADE) format sweep files for processing in the National Center for Atmospheric Research’s Solo-II software (Lee et al. 1994). Using Solo-II, clear-air radar echoes from dust, insects, and other particles, and backlobe echoes were manually removed at each elevation for all times. No additional corrections (i.e., to compensate for biases/system errors) were made, so caution should be taken when comparing the results found here to other polarimetric radar studies. The data were gridded using REORDER (Oye et al. 1995) to a common Cartesian grid of 100 km × 100 km × 15 km applying the Cressman weighting inverse distance scheme. The horizontal resolution was 1 km and the vertical resolution was 0.5 km. Even after NAMMA’s postprocessing filters, NPOL data were biased by −0.04 for the correlation coefficient.
(ρHV). For other S-band radars, median ρHV values are ≃0.99 in drizzle, while for NPOL it was 0.95 (Carey 2007). This low bias in ρHV was due to engineering artifacts associated with NPOL’s antenna design at the time and will lead to an increase in uncertainty/random errors in other radar variables (Bringi and Chandrasekar 2001). Additionally, the random measurement error in the ZDR field was 3 times higher (0.3 dB) for NPOL (cf. typical S-band radars of 0.1 dB) that is due to the low bias in ρHV associated with the antenna (Bringi and Chandrasekar 2001; Carey 2007). However, only data where ZH ≥ 35 dBZ and where ZH > vertical Z (ZV) were used in our Mnp calculations, thereby mitigating the possibility of using very negative ZDR values (at warmer T) that were caused by artifacts. Furthermore, and particularly relevant, the NPOL radar experienced problems with attenuation when the antenna became wet; ZH values were found to be −9 dB lower than the WSR-88D during heavy rain periods over the United States (Carey 2007). This problem was avoided by taking care not to analyze any storms that developed or moved close to the radar within ~1 h after a previous storm moved directly over NPOL (so to avoid a wet antenna).

As the clouds evolved, ZH and ZDR were analyzed to help understand the changing microphysical structure within the clouds. A storm was seen as either a single-cell isolated cumulonimbus cloud, or a multicell convective event (that went through mergers and divisions). Using the same methods as presented in Doviak and Zrnić (1993), Carey and Rutledge (1996, 2000), and Cifelli et al. (2002), polarimetric variables were used to accurately obtain hail and graupel in the mixed-phase region of the clouds, and Z values above certain Z and T thresholds. These included obtaining rain lines, liquid water, and ice fractions, and finally Mnp values from ZH, ZV, ZDR, and ZDP, as in Carey and Rutledge (1996, 2000), for each of the 33 lightning and 30 nonlightning convective storms.

In addition to the mixed-phase Mp, small, non-precipitating ice mass (Mnp) in the top 1 km of the cloud was calculated to compare to the MSG glaciation fields. As stated in Straka et al. (2000), hail has ZH > 45 dBZ below 0°C, while graupel–small hail has ZH > 20 dBZ between 0° and −15°C. Raindrops from 1 to 3 mm in diameter have ZH between 28 and 60 dBZ at T > −5°C, while rain–hail mixtures have ZH between 45 and 80 dBZ (for rain–giant wet hail combinations) at T > −10°C. However, snow crystals and dry crystals (e.g., plates, columns, and needles) have ZH < 35 dBZ below 0°C (Straka et al. 2000). Apart from Straka et al.’s (2000) findings, Deierling et al. (2008) found a relationship between lightning activity and ice fluxes by developing two methods that incorporated different ZH and T levels for Mnp calculations: 1) ZH < 20 dBZ at T < −50°C and 2) ZH < 20 dBZ at T < −5°C. They found that using a T level of <−5°C instead of <−50°C is more accurate for obtaining the Mnp values and that if T < −40°C (homogeneous freezing point) are used, the Mnp will be underestimated. In addition, Heymsfield et al. (2003) used ZHV values between −5 and 25 dBZ between 0° and −50°C when investigating the relationship between cloud optical depth and ice water path in cirrus and deep stratiform ice cloud layers. Therefore, in order not to underestimate Mnp while excluding larger, precipitation-sized ice, it is best to use ZH < 20 dBZ at −20° < T < −40°C and ZHV > 0 dBZ at T < −40°C.

The Heymsfield and Palmer’s (1986) Z–M relationship was used for computing Mnp: Mnp = 0.089 76ZHV0.529 (with Mnp in g m−3 and ZHV in mm6 m−3; Deierling et al. 2008). The dielectric factor of 5.28 has been incorporated to adjust for differences in ice mass between ZHV and effective Z. When the cloud top is from 8 to 11 km (−20° to −40°C, respectively, with T obtained from sounding data), then all values of ZH < 20 dBZ were used to calculate Mnp from cloud top to 1 km downward (i.e., ZH < 20 dBZ at −20° to −40°C; Fig. 1a). When the cloud top is >11 km (colder than −40°C), then all values of ZH > 0 dBZ were used to compute Mnp from cloud top to 1 km downward (Fig. 1b). For example, if the cloud top is 10 km, all values of ZH < 20 dBZ were used to calculate Mnp for the layer 9–10 km (Fig. 1a), and if the cloud top is 14 km all values of ZH > 0 dBZ were used to calculate Mnp for the 13–14-km layer (Fig. 1b). If however, the cloud top is 11.5 km, then the top 0.5 km is calculated using ZHV > 0 dBZ and the bottom 0.5 km is calculated using ZHV < 20 dBZ. We include T and ZHV thresholds in order to account for the small, nonprecipitating ice that occurs in these layers, as opposed to the larger, precipitating ice mass in the mixed-phase layer computed earlier using the rain line equations. Although homogeneous freezing depends on drop size, we need to ensure that only ice particles are used, and thus all hydrometeors will be considered frozen when T < −40°C. Between 0° and −40°C a mixture of water and ice hydrometeors can exist (Straka et al. 2000), and therefore only ZH < 20 dBZ are used to calculate Mnp for the nonprecipitating ice in the top half of the mixed-phase region. For storms with tops lower than 8 km (warmer than −20°C), no small ice was calculated.

The Mnp was converted to kilograms per cubic kilometer and compared to MSG glaciation fields. Although this method is not exactly a direct comparison, the purpose was to compute roughly how much non-precipitating ice must be present in the top 1 km of the
ZH field before the IR satellite fields indicate cloud-top glaciation (i.e., switch signs; see Strabala et al. 1994; Baum et al. 2000; MM13). The method described above ensures that most of the small, nonprecipitating ice is captured, whereas using only $Z_{H}$ at $T = -40^\circ$C will underestimate the small, nonprecipitating ice at echo top (Deierling et al. 2008).

The MSG satellite data were collocated with the NPOL radar and lightning data. These data have a temporal resolution of 15 min, thus the storms were tracked from 45 min before $t$ time (i.e., $t - 45$) to 30 min after $t$ ($t + 30$) for every storm, at a spatial sampling distance of 3 km $\times$ 3 km per pixel at nadir. The MSG processing procedure is fully outlined in MM13, but the pertinent aspects are that the 10.8-$\mu$m channel was used to track the main cumulus updraft locations (in a 3 $\times$ 3 IR pixel region covering clouds) over 15-min intervals, and the three coldest 10.8-$\mu$m pixels (focused then on the main updraft region) were used to compute the other four IR channels. All 10 MSG fields (Table 1) were then computed by differencing the various channels and to obtain the 15-min time trends.

Last, UKMO VLF ATD network (hereafter called ATDNET, as is currently used) lightning data were utilized for delineating lightning from nonlightning events. The ATDNET is a ground-based detection system that observes the vertical component of the electromagnetic field generated by lightning discharges at a

![Diagram](a) ZH Vertical cross on 20060914 at t=30 ![Diagram](b) ZH Vertical cross on 20060914 at t=15

**Fig. 1.** Explanation of how nonprecipitation ice is calculated depending on where the cloud top is located. (a) Cloud top is located between $-20^\circ$ (at 8 km) and $-40^\circ$C and (b) when the cloud top is colder than $-40^\circ$C.

**Table 1.** MSG interest fields used here that indicate updraft strength, glaciation, and cloud depth, as well as the critical values that indicate the occurrence of ice clouds (adapted from Strabala et al. 1994; Ackerman 1996; Baum et al. 2000; Mecikalski et al. 2010a).

<table>
<thead>
<tr>
<th>Channel differencing and time trends</th>
<th>Category</th>
<th>Critical value</th>
</tr>
</thead>
<tbody>
<tr>
<td>15 min $6.2 - 7.3\mu$m</td>
<td>Updraft strength</td>
<td>Positive trends</td>
</tr>
<tr>
<td>30 min $6.2 - 7.3\mu$m</td>
<td>Updraft strength</td>
<td>Positive trends</td>
</tr>
<tr>
<td>15 min $10.8\mu$m</td>
<td>Updraft strength</td>
<td>$&lt;-4^\circ$C</td>
</tr>
<tr>
<td>30 min $10.8\mu$m</td>
<td>Updraft strength</td>
<td>$&lt;-5\text{ min} 10.8\mu$m</td>
</tr>
<tr>
<td>$6.2 - 7.3\mu$m</td>
<td>Cloud depth</td>
<td>Differences toward $0^\circ$C</td>
</tr>
<tr>
<td>$6.2 - 10.8\mu$m</td>
<td>Cloud depth</td>
<td>From $-30^\circ$ to $-10^\circ$C</td>
</tr>
<tr>
<td>$8.7 - 10.8\mu$m</td>
<td>Cloud-top glaciation</td>
<td>$&gt;0^\circ$C</td>
</tr>
<tr>
<td>15 min $8.7 - 10.8\mu$m</td>
<td>Cloud-top glaciation</td>
<td>Becoming $&gt;0^\circ$C</td>
</tr>
<tr>
<td>$(8.7 - 10.8\mu m) - (10.8 - 12.0\mu m)$</td>
<td>Cloud-top glaciation</td>
<td>Positive trends</td>
</tr>
<tr>
<td>15 min $(8.7 - 10.8\mu m) - (10.8 - 12.0\mu m)$</td>
<td>Cloud-top glaciation</td>
<td>Positive trends</td>
</tr>
</tbody>
</table>
frequency near 10 kHz (Keogh et al. 2006; De Leonibus et al. 2007; Gaffard et al. 2008). The network consists of seven remote stations, with one central control station in the United Kingdom and records mostly high peak current CG lightning. MM13 provides a more in-depth discussion on how ATDNET works and how the data was analyzed.

In the following three sections, the two storm types will be analyzed in light of the main study goals, and hence physical relationships between datasets will be developed. Emphasis will be placed on describing how the SEVIRI fields behave relative to the NPOL radar fields of precipitation as well as nonprecipitation ice (for the top 1 km of clouds), for lightning and nonlightning storms. The focus will first be on the analysis of one characteristic storm of each type, and then on the average behavior of all 33 lightning and 30 nonlightning storms.

4. MSG satellite fields

The MM13 results are summarized to bring to the forefront the key physical processes of growing convective clouds as deduced from MSG observations, which will be a focus of the radar analysis to follow:

1) Eight of 10 IR fields that describe updraft strength, cloud depth, and glaciation (or ice at cloud top) are significantly different for the nonlightning and lightning producing convective clouds. The lack of notch overlap in “box and whiskers” plots indicates a 95th confidence level that the two datasets are different [with the exception of both 15 min (8.7 – 10.8 μm) – (10.8 – 12.0 μm), so-called “trispectral,” and 8.7 – 10.8-μm trends]. Nonlightning clouds are found to be far less vertically developed, and possess at least >50% weaker updrafts than clouds that produce lightning. Note that the updrafts estimated from geostationary satellite IR fields will be biased low (for both lightning and nonlightning storms) by up to a factor of ~10 because the main updrafts do not fill an entire 3-4-km resolution pixel (Adler and Fenn 1981).

2) Little to no evidence exists of glaciation at cloud top for nonlightning storms, denoted by a lack of a sign change in the trispectral or 8.7 – 10.8-μm fields. IR observations pertain to the top ~100 m of clouds within the structure of the weighting function of a given IR channel, as the signal from beneath these levels is mostly obscured in the IR measurements (Nakajima and King 1990; Plantnick 2000). Hence, the change in sign of the 8.7 – 10.8-μm channel difference or trispectral field implies significant ice volumes across a 3 km × 3 km region within the MSG pixel analyzed. Furthermore, a cloud-top “ice” or glaciation signature is different than an in-cloud ice volume in relation to electrical charging processes. MSG satellite data, therefore, provide proxies for where active charging is likely to be occurring, which are where strong updrafts are present at significant altitudes above the freezing level (enough to loft and suspend larger ice particles like hail and especially graupel), so to create a mixed-phase region of a cloud.

In light of these results, as storms evolve over a 45-min period before time t, NPOL data are interpreted with an emphasis toward supporting or contradicting the satellite signatures. In the process, a view of physical processes in lightning and nonlightning convective storms will emerge in both radar and satellite observations.

5. Single storm radar and satellite analysis

The $M_p$ fields in the mixed-phase region, and the $M_{np}$ fields for the top 1 km of the cloud, will be compared and contrasted to the eight significant MSG fields of one lightning (L2) and one nonlightning (N2) convective storm to validate the points developed in MM13. L2 had a radar cloud-top height of 14.5 km at time t, while N2 only had a cloud-top height of ~6 km. In addition, L2 had an area of ~600 km$^2$ (30 km × 20 km), while N2 was much smaller with an area of ~150 km$^2$ (15 km × 10 km). It was found that 72% of the lightning storms had similar vertical extent (i.e., cloud tops are within ±1 km lower or higher), and 44% similar horizontal extent (i.e., ±200 km$^2$ smaller or larger horizontally) as L2; the rest of the storms were smaller both vertically and horizontally. For the nonlightning storms, 67% of the storms have similar vertical and horizontal extent as N2 (i.e., cloud tops are within ±1 km lower or higher but the horizontal extent was only ±50 km$^2$ smaller or larger), with 33% being larger vertically and horizontally. Hence, both L2 and N2 are considered representative events for both storm types. For reference, L2 had its t time at 1415 UTC 13 September and N2 at 1115 UTC 3 September.

The $M_p$ (kg; from the mixed-phase region) is compared to the satellite glaciation signature obtained for L2 and N2 from t – 45 to t + 30 (Figs. 2a,b). Figure 2a compares $M_p$ with the 8.7 – 10.8-μm glaciation field, while the trispectral glaciation field is in Fig. 2b. The $M_p$ values in the mixed-phase region were obtained using the rain line calculations as in Doviak and Zrnić (1993), Carey and Rutledge (1996, 2000), and Cifelli et al. (2002) for all $Z_H > 35$ dBZ. This method makes it possible to distinguish ice from water particles in the mixed-phase region to calculate their respective masses. The amount of ice at cloud top ($M_{np}$) was calculated as
described above. As seen, storm L2 started developing pronounced amounts of precipitation ice from \( t - 30 \) (\( 2.16 \times 10^6 \) kg) to \( t \) (\( 1.18 \times 10^7 \) kg) and onward. N2, in contrast, did not have much precipitation ice; \(<1.0 \times 10^6 \) kg of ice was recorded at all times, except at \( t + 15 \). The 8.7 – 10.8-μm field (Fig. 2a) shows that as \( M_p \) for L2 increases between \( t - 30 \) and time \( t \), the glaciation field becomes positive (crosses the 0-K line) before time of first flash. For N2, the 8.7 – 10.8-μm only becomes positive at \( t + 30 \). The trispectral field [(8.7 – 10.8 μm) – (10.8 – 12.0 μm), Fig. 2b] shows the same trends, becoming positive at \( t - 15 \) for L2 while it stays negative for N2, indicating that cloud-top glaciation is not occurring in N2 (as expected as no CG lightning was produced). It is interesting (yet not surprising), that the peak increase in both the glaciation signatures (between \( t - 15 \) and \( t \)) lag the peak increase in \( M_p \) (between \( t - 30 \) and \( t - 15 \)) by \( \sim 15 \) min.

The \( M_{np} \) for the top 1 km of the cloud is compared to the 8.7 – 10.8 μm (Fig. 3a) and trispectral fields (Fig. 3b) for L2 only (as explained earlier, \( M_{np} \) was only calculated for the lightning storms, as the radar cloud-top

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**Fig. 2.** Line plots of the (a) radar precipitation ice compared to the 8.7 – 10.8-μm \( T_B \) glaciation interest field, and (b) radar precipitation ice compared to the (8.7 – 10.8μm) – (10.8 – 12.0 μm) \( T_B \) trispectral glaciation interest field from \( t - 45 \) to \( t + 30 \). The lightning storm (L2) is seen in black and the nonlightning storm (N2) is seen in gray. For both images, the radar precipitation field is a solid line and the satellite interest field is a dashed line.

**Fig. 3.** Line plots of nonprecipitating ice mass for the top 1 km of the cloud (black solid line) for the lightning storm L2 compared to (a) the 8.7 – 10.8-μm glaciation field and (b) the satellite trispectral glaciation field, both in black, dashed lines.
height for the nonlightning storms was rarely colder than \(-20^\circ C\). The ice masses are presented in kilograms per cubic kilometers in order to more easily compare it to MSG cloud-top data over a 3 km \(\times\) 3 km pixel. At the time of the reversal in sign of the cloud-top glaciation fields, L2 had large amounts of non-precipitating ice, with \(2.5 \times 10^7\) kg km\(^{-3}\) of ice mass that relates to \(-6.66 \times 10^5\) kg km\(^{-3}\) in the top \(-100\) m of the cloud. These features are not seen for N2 in either the radar or satellite fields. In addition, if one compares the \(M_{np}\) (Figs. 3a,b) to the \(M_p\) (Figs. 2a,b) for L2, the largest increase in \(M_{np}\) occurs between \(t\) and \(t + 15\), while the largest increase in \(M_p\) occurs from \(t - 30\) to \(t - 15\) (a 30-min lag). In contrast, for both the 8.7 - 10.8-\(\mu\)m and trispectral fields, the largest increase occurs between \(t - 15\) and \(t\) (excluding times after \(t + 15\), when the anvil is present and thus the cloud-top no longer cools).

Figures 4a-d show the \(T_B\) trend fields used to estimate updraft strengths of the clouds. These fields are as follows: 15-min 10.8-\(\mu\)m (Fig. 4a), 30-min 10.8-\(\mu\)m (Fig. 4b), 15-min 6.2 - 7.3-\(\mu\)m (Fig. 4c), and 30-min 6.2 - 7.3-\(\mu\)m (Fig. 4d) between lightning and nonlightning storms from \(t - 45\) to \(t + 30\). For Figs. 4a,b, a negative trend shows an increase in updraft strength, whereas for Figs. 4c,d, a positive trend indicates an increase in updraft strength. In addition to these updraft signatures, the height of the storm echo top (in km) as seen from radar is shown for L2 and N2. L2 showed a sharp increase in height from \(-9.5\) to \(-14\) km between \(t - 30\) and \(t - 15\), relating to a 5 m s\(^{-1}\) vertical growth during this time. In contrast, the fastest growth for N2 occurred between \(t\) and \(t + 15\), but this only related to 3.9 m s\(^{-1}\) vertical growth, and as N2 produced no CG lightning at this time, it seems that an increase of \(>4\) m s\(^{-1}\) might be necessary to lead to the production of CG lightning. Recall from above, these MSG-estimated updraft strengths are at least 50% underestimated, for reasons related to the cloud not filling an entire 3 km \(\times\) 3 km pixel, and averaging that occurs within a pixel.
All the satellite updraft fields (Figs. 4a–d) show that the strongest updraft for L2 occurred between $t - 15$ and $t$, while N2 shows little change throughout the time period. The most significant increase in N2 updraft strength only occurs after $t + 15$, however, no CG lightning was ever observed. The positive (Figs. 4a,b) and negative (Figs. 4c,d) trends after time $t$ for L2 are indicative of the anvil forming and a top that no longer cools or grows with time. These satellite trends again correlate well with the storm echo-top height as seen from radar, as well as the $M_p$ and $M_{np}$ results as seen in Figs. 2a,b and 3a,b. Here the peak in updraft speed for both fields correlate well with the peak in the radar echo top height, occurring at $t$ for L2 and at $t + 15$ for N2.

The 6.2 – 7.3- and the 6.2 – 10.8-μm cloud depth fields are compared to the storm echo-top height (in km) as seen from radar in Figs. 5a,b. The more negative the difference for the 6.2 – 7.3-μm field, the shallower the cloud, and thus for deep clouds, the difference will approach zero. The 6.2 – 10.8-μm field behaves similarly with near zero values denoting increasingly taller clouds. Both fields show that strong positive trends occur during the entire period for L2, while positive trends only occur after $t + 15$ for N2. These trends again compare well with what is seen by radar in terms of the height of the radar echo top.

The radar echo-top height, sounding height, and satellite 10.8-μm $T_B$ updraft field for the lightning storm L2 and nonlightning storm N2 are shown in Fig. 6. We wanted to compare these fields simultaneously to see whether the satellite 10.8-μm $T_B$ updraft indicator field and corresponding sounding height corroborates what is seen in radar data. The sounding heights were obtained using the 10.8-μm $T_B$ and matching this $T$ to the height from the sounding data. As seen for L2, the sounding height follows the same trend as the radar echo top height, but is ~3 km lower than the radar height, until a height of >12 km is reached. This could indicate that
the satellite senses deeper into the cloud than just \(\sim 100 \text{ m}\) due to cloud tops being relatively diffuse, but could also be due to the cloud itself not occurring directly over and at exactly the same time as when the radiosonde was launched, and/or because not all \(3 \text{ km} \times 3 \text{ km}\) IR pixels are filled with a cumulus cloud updraft, or could be due to the weighting function behavior of the IR fields at cloud top (assuming optically thick clouds; as explained in MM13). Not surprisingly, the time of greatest increase in the sounding height compares well to the time of greatest updraft increase from the 10.8-\(\mu\)m \(T_B\) field, between \(t - 15\) and \(t\) but lags the radar echo top by 15 min. However, the 10.8-\(\mu\)m \(T_B\) trend field already shows a negative slope from \(t - 45\), indicating that this cloud is already going through stronger updraft periods and growing vertically at this time (as confirmed by the radar and sounding height increase). N2, on the other hand, only shows a slightly negative trend in the 10.8-\(\mu\)m \(T_B\) trend field after \(t + 15\), while maximum vertical growth, according to the radar, occurred between \(t\) and \(t + 15\).

The satellite fields (increased updraft strength, cloud-top glaciation occurrence, and increased cloud depth) compare well to radar in terms of cloud-top height, \(M_p\), and \(M_{np}\). For L2, as the updrafts increased (satellite), so did the cloud depth (satellite), cloud-top height (radar), the amounts of \(M_p\) and \(M_{np}\) (radar), as well as the glaciation fields (satellite). It is noteworthy that the satellite fields can sometimes lag the radar \(M_p\) field by \(\sim 15\) min, but lead the radar \(M_{np}\) field by \(\sim 15\) min. In contrast, the lack of vertical cloud growth of N2 is confirmed by the MSG fields, which show that N2 had very weak updrafts, and thus comprised shallower clouds with no cloud-top glaciation.

6. Results after storm averaging

The average NPOL results obtained from the 33 lightning and 30 nonlightning events are presented, again in light of the MSG satellite results of section 4 and MM13. Each storm was initially analyzed separately, followed by per time and per altitude averaging in order to obtain a single result for each variable.

The average satellite field results for the lightning and nonlightning storms are discussed in detail in MM13. The main results relating the radar to the satellite fields are in Figs. 7a,b showing the averaged radar \(M_p\) compared to the 8.7 – 10.8-\(\mu\)m field (Fig. 7a), and radar \(M_p\) compared to the trispectral field (Fig. 7b) from \(t - 45\) to \(t + 30\). In both cases, the lightning storms had a sharp increase in \(M_p\) at the same time that the glaciation fields showed a sharp positive trend (between \(t - 15\) and \(t\)), with peaks coinciding at time \(t\); this was also the case for the single storm results in section 5a. In contrast, the nonlightning storms produced much less \(M_p\) than the lightning storms, and thus neither glaciation fields switched signs.

The \(M_{np}\) in the top 1 km of the cloud for the lightning storms is compared to the 8.7 – 10.8-\(\mu\)m and trispectral fields (Figs. 8a,b). Here, both satellite fields correlate well with the increase in the amount of cloud-top \(M_{np}\) (at \(t\), \(M_{np}\) was \(1.15 \times 10^6\text{ kg km}^{-3}\) in the top 1 km; this relates to \(2.88 \times 10^6\text{ kg km}^{-3}\) in the top \(\sim 100\text{ m}\) of the cloud). Through time \(t\), the strongest positive trends in the satellite glaciation fields occurred in conjunction with the largest increase in the \(M_{np}\). Figure 8 therefore quantifies the ice volumes in relation to what MSG views radiometrically across a \(3 \text{ km} \times 3 \text{ km}\) pixel with respect to these two channel differences. Specifically, we find
~6.6 × 10^7 (L2, Figs. 5a,b) to 2.88 × 10^6 kg km^{-3} (average of all lightning storms) of ice in the cloud’s top ~100 m at time t. The minimum $M_{np}$ in the top 100 m (for all the lightning storms) at time t was 2.7 × 10^5 kg km^{-3}. Although this method is not an exact comparison, the goal was to quantify roughly how much ice is required in the top 1 km of the $Z_H$ field before the satellite glaciation fields switch signs to indicate that the cloud’s top is glaciated.

Figures 9a–d show the radar cloud-top height (in km) compared to the following updraft indicator fields (in K): 15-min 10.8-$\mu$m trend (Fig. 9a), 30-min 10.8-$\mu$m trend (Fig. 9b), 15-min 6.2 – 7.3-$\mu$m trend (Fig. 9c), and 30-min 6.2 – 7.3-$\mu$m $T_B$ trend (Fig. 9d), from t – 45 to t + 30. All four of the satellite updraft fields show an increase in updraft strength as the radar echo top increases. For the 15- and 30-min 10.8-$\mu$m fields, the strongest increase lags the radar echo-top height’s strongest increase by 15 min, while the 15- and 30-min 6.2 – 7.3-$\mu$m trends have their strongest increases coinciding with the radar echo-top height’s strongest increase, especially for the lightning storms. Note, again, that the decrease in updraft strength after t for all the fields is due to anvil formation. Therefore, these updraft indicators correlate well with the storm echo-top height as seen from radar, as well as to the $M_p$ and $M_{np}$ results as seen in Figs. 7a,b and 8a,b.

The radar cloud-top heights are next compared to cloud depth indicator fields 6.2 – 7.3-$\mu$m difference (Fig. 10a), and 6.2 – 10.8-$\mu$m difference (Fig. 10b), from t – 45 to t + 30 (Figs. 10a,b). Once again, as the radar echo-top height increases, the cloud depth field shows an increase, while the strongest increase in both cloud depth coincides with the time of greatest increase in radar echo-top height, as was seen in the previous cases with respect to the MSG updraft indicators.

Last, the average results of the radar echo-top height, sounding height, and the 10.8-$\mu$m $T_B$ updraft indicator field are compared (Fig. 11). As was the case for the single storm results (Fig. 6), the sounding-derived height follows the same trend as the radar echo-top height, but is ~3 km lower until a height of >12 km is reached. For the lightning storms, the time of greatest increase in the sounding estimated height compares well to the time of greatest updraft increase from the 10.8-$\mu$m trend field; between t – 15 and t, while both fields lag the radar echo-top height by 15 min. For the nonlightning storms, all the fields coincide, and show maximum increase between t – 15 and t, although these increases are not enough to produce CG flashes.

7. Discussion and conclusions

To increase understanding on the relationship between lightning and nonlightning convective storms, radar and lightning observations from the National Aeronautics and Space Administration (NASA) African Monsoon Multidisciplinary Analyses (NAMMA) campaign were analyzed in concert with satellite data. The goals were 1) to develop an understanding of how the radar fields behave relative to Meteosat Second Generation (MSG) fields that describe cloud-top glaciation, cloud growth rate, and cloud depth; and 2) to evaluate how MSG and radar fields behave and evolve together for lightning and nonlightning storm events. These goals were reached by analyzing the time evolution of 33 lightning and 30 nonlightning convective storms during August and September 2006. Using S-band
NASA Polarimetric Doppler Weather Radar (NPOL) radar, very low frequency (VLF) Arrival Time Difference Network (ATDNET) lightning and MSG Spinning Enhanced Visible and Infrared Imager (SEVIRI) data, the physical attributes of growing cumulus clouds, including water and ice mass production, updraft strength, cloud depth, and cloud-top glaciation were illustrated and explained. In addition to documenting storms in a remote region of the earth, a main outcome of this study is quantifying combined radar–satellite field patterns for lightning and nonlightning convective storms, as an extension to MM13.

From Figs. 2–6 and 7–11, several key features are seen to extend MSG field results found in MM13. The lightning storms had stronger updrafts (shown in both the satellite and radar datasets), which lead to the formation of deeper clouds (both satellite and radar datasets) and subsequently much more precipitation ice mass ($M_p$) in the mixed-phase region (confirmed by radar observations) of the clouds, as compared to the nonlightning storms. In addition, the lightning storms showed an increase in $M_p$ 30 min before any cloud-to-ground (CG) lightning flashes. The lightning storms contained $> 2.7 \times 10^5$ kg km$^{-3}$ nonprecipitation ice mass ($M_{np}$) in the clouds’ top 100 m (averaged over a 3 km $\times$ 3 km IR pixel), which was large enough to cause a reversal in the sign of both cloud-top satellite-based glaciation indicators. As the nonlightning storms had much weaker updrafts and thus were much shallower, these storms did not produce nearly the amount of ice as compared to lightning storms, and hence no glaciation field sign reversals were observed. The main differences between the storm types occurred at and after $t = 30$ for both the radar and satellite fields. In areas that do not have good radar networks, such as in Africa, it would be possible then to use the reversal in satellite glaciation fields to signify that there are large amounts of ice in the convective storm; therefore, these storms might produce lightning in the near future.

There are several sources of error in this analysis: 1) the possibility that some of the nonlightning storms in fact produced lightning, 2) incorrect tracking of storms.

![Fig. 9. As in Fig. 4, but for the average lightning (L; black) and average nonlightning storms (N; gray).](image-url)
in the 75-min timeframe over which each storm was analyzed, and 3) incorporation of poor/low data quality NPOL data (as caused by the “wet antenna” problem described above). For the first issue, MM13 provided statistical differences between IR fields that strongly show that lightning producing convective storms were tall (≥13 km) and possessed strong updrafts, both of which support active charging processes. In contrast, convective clouds without lightning were less tall, possessed weaker updrafts, and although ice existed at cloud top, active charging was not prevalent within these storms. Together with the strict requirements for VLF ATDNET-observed CG lightning to occur immediately above a given storm, we feel confident that our dataset delineates lightning from nonlightning events very well.

For the second item, the use of a human expert for tracking storms, together with three-IR pixel averaging, helped assure accurate tracking. Also, storms in the NAMMA region were found to propagate steadily and slowly, which was not challenging for tracking. Last, none of the storms used were obtained when the antenna was wet, thereby avoiding the systematic lowered Z_H (horizontal reflectivity) values that occurred during the wet antenna problem.

This study, therefore, helps fill an important gap in our knowledge, and in our understanding of how geostationary satellite and ground-based polarimetric observations may be used together to quantify growing convective clouds (both with and without lightning). Given that these results provide increased understanding on the relationships between satellite and radar fields, developers of forecast systems could incorporate satellite fields into their prediction systems. In addition, the results of this study can then be used to enhance the prediction or nowcasting (0–1-h forecasting) of extreme and hazardous weather events as radar and satellite observations are analyzed together within algorithms that assess storm intensity (e.g., the Rapidly Developing Thunderstorm; Autones 2012). The results of this study are also important as an improved understanding of what satellite observations describe for growing convection can be gained, especially in remote and oceanic locations devoid of ground-based radar observations. Last, in advance of meteorological satellites possessing increased spectral and spatial resolutions, and lightning mappers in geostationary orbit (e.g., Meteosat Third

![Fig. 10](image-url) As in Fig. 5, but for the average lightning (L; black) and average nonlightning storms (N; gray).

![Fig. 11](image-url) As in Fig. 6, but for the average lightning (L; black) and average nonlightning storms (N; gray).
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