ABSTRACT: The dependence of lightning frequency on the life cycle of an idealized tropical cyclone (TC) was investigated using a three-dimensional meteorological model coupled with an explicit lightning model. To investigate this dependence, an idealized numerical simulation covering the initial state to the steady state (SS) of an idealized TC was conducted. The simulation was consistent with the temporal evolution of lightning frequency reported by previous observational studies. Our analyses showed that the dependence originates from changes in the types of convective cloud with lightning over the life cycle of the TC. Before rapid intensification (RI) and in the early stage of RI, convective cloud cells that form under high-convective available potential energy (CAPE) conditions are the main contributors to lightning. As the TC reaches the late stage of RI and approaches SS, the secondary circulation becomes prominent and convective clouds in the eyewall region alongside the secondary circulation gradually become the main contributors to the lightning. In the convective cloud cells formed under high-CAPE conditions, upward velocity is strong and large charge density is provided through noninductive charge separation induced by graupel collisions. This large charge density frequently induces lightning in the clouds. On the other hand, the vertical velocity in the eyewall is weak, and it tends to contribute to lightning only when the TC reaches the mature stage. Our analyses imply that the maximum lightning frequency that occurs before the maximum intensity of a TC corresponds to the stage of a TC’s life cycle in which convective cloud cells are generated most frequently and moisten the upper troposphere.

KEYWORDS: Lightning; Tropical cyclones; Cloud microphysics; Clouds; Cloud-resolving models

1. Introduction

Tropical cyclones (TCs) often lead to extensive destruction through strong winds, heavy rain, storm surges, and thunderstorms. Over the past two decades, the scientific community has focused on the lightning that accompanies TCs; observational studies have reported several basic characteristics of this phenomenon. Using data from the National Lightning Detection Network (NDLN) and the World Wide Lightning Location Network (WWLLN), respectively, Molinari et al. (1999) and Abarca et al. (2011) found that lightning is more active in the outer region of TCs than in the inner core region. Cecil and Zipser (2002) and Cecil et al. (2002) also reported a contrast between the outer region and the inner core region by analyzing Tropical Rainfall Measuring Mission Lightning Imaging Sensor data. NDLN data have also been used to investigate the relationships of lightning with motion, vertical wind shear, and convective asymmetries of TCs (Corbosiero and Molinari 2002, 2003).

Recent advances in the accuracy of observations and numerous investigations have gradually elucidated the relationship between lightning frequency and the life cycle of TCs. On the basis of WWLLN data from 56 TCs, Price et al. (2009) found that lightning occurred most frequently 1 day before a TC reached its maximum intensity. They suggested that lightning frequency can be used as a proxy for the intensification and decay of TCs in forecasting applications.

Following Price et al. (2009), several observational studies investigated the timing of high lightning frequency during the life cycle of TCs. DeMaria et al. (2012) observed that lightning frequency in the outer rainband regions (200–300 km) was higher in cyclones with rapid intensification (RI) (Kaplan and DeMaria 2003) in the following 24 h. Stevenson et al. (2016) indicated that lightning frequency was high in the outer region when TCs were intensifying. In addition to the outer region, previous studies also reported a relationship between TC development and lightning frequency in the inner region.
et al. (2016) found that lightning frequency was high in the inner region of a nonintensifying TC. Thomas et al. (2010) reported that lightning frequency in the inner region increased prior to or during periods of TC weakening. DeMaria et al. (2012) reported that high lightning frequency in the inner region sometimes signalled the end of intensification. By contrast, Zhang et al. (2015) showed that lightning frequency in the inner regions of TCs in the northwest Pacific reached a maximum before RI.

These previous studies were based on data obtained for several TCs. The case studies reported different trends in the relationship between lightning frequency and the life cycle of a TC. Zhang et al. (2015) reported that the maximum lightning frequency occurred just before RI in Supertyphoon Rammus (2008). Stevenson et al. (2014) also reported that the lightning in the inner core reached its maximum just prior to RI in Hurricane Earl (2010), which was generated and then intensified over the open ocean. Squires and Businger (2008) reported that the lightning in the eyewall of Hurricane Katrina (2005) and Hurricane Rita (2005) occurred most frequently during the RI phase. They also reported that in Hurricane Rita (2005) the lightning density ratio between the outer rainband and the eyewall was 1.6, which indicates that the lightning was much more frequent in the eyewall than in the outer rainband. Austin and Fuelberg (2010) reported that in Hurricane Wilma (2005) and Hurricane Emily (2005), the maximum lightning frequency in the inner core occurred at around the same time as the maximum intensity. Solorzano et al. (2008) also reported that the maximum intensity occurred at around the time of the maximum lightning frequency in the eyewalls of Typhoon Durian (2006) and Typhoon Chanchu (2006). The relationship between lightning frequency and the life cycle of a TC implied by these observations is inconsistent, although it has the potential to be used for forecasting TC intensification.

In addition to studies that have classified the radial locations of lightning into the inner and outer regions, recent observational studies have indicated that the location of the lightning relative to the radius of maximum wind (RMW) can be a good indicator of the intensification or weakening of a TC (Stevenson et al. 2018). These studies have determined that TCs intensify when lightning occurs inside the RMW and weaken when lightning occurs outside it. It has also been reported that lightning bursts occur mostly at the RMW in TCs at steady state (SS). Results also indicate differences in the locations of convective clouds between intensifying TCs and TCs at SS that have been observed from aircraft (Rogers et al. 2013), based on consideration of the relationship between intensification and convective bursts (e.g., Steranka et al. 1986; Cecil et al. 2002; Houze et al. 2009).

A numerical simulation is a powerful tool that can be used to interpret relationships in detail and investigate reasons for discrepancies among previous studies. Fierro et al. (2015) conducted a real-case simulation using a meteorological model coupled with a three-dimensional explicit lightning model and compared the results with observed lightning frequencies. In addition to the real-case simulation, Fierro and Mansell (2017, 2018) simulated idealized TCs using a meteorological model coupled with a lightning model to elucidate the relationship between the life cycle of a TC and lightning frequency. Fierro and Mansell (2017) reproduced the contrast in lightning frequency between the inner and outer regions reported by Molinari et al. (1999) and Abarca et al. (2011). They suggested that the contrast was because the warm-rain process was more dominant and charge separation was less effective in the inner region. Fierro and Mansell (2017, 2018) also investigated lightning frequency in TC decay and RI periods. However, extensive computational resources are required for the simulations in a lightning model that covers the entire life cycle of a TC. To reduce computational costs, Fierro and Mansell (2017, 2018) first conducted a simulation without a lightning model until a TC-like vortex formed. After generating the TC-like vortex, they then conducted simulations coupled with an explicit lightning model. These simulations provided important knowledge about the relationship between lightning and the life cycle of a TC. To extend this knowledge, numerical simulations covering the whole period from the initiation of a TC to SS are required.

On the basis of the background mentioned above, we conducted an idealized numerical simulation of a TC from the initial state to SS using a meteorological model coupled with a lightning model in an attempt to examine the relationship between lightning frequency and the life cycle of a TC.

2. Model description and experimental setup

The meteorological model used in this study was the Scalable Computing for Advanced Library and Environment (SCALE), version 5.0.0 (Nishizawa et al. 2015; Sato et al. 2015), combined with a bulk lightning model (hereinafter referred to as the lightning model) developed and implemented into SCALE by Sato et al. (2019). In the lightning model, the charges of cloud hydrometeors \( r_{xx} \) were prognostic variables, as was the case in the lightning models used by several previous studies (e.g., Mansell et al. 2005; Fierro et al. 2013; Barthe et al. 2012; Courtier et al. 2019), where the subscript \( xx \) indicates the category of the hydrometeor (e.g., cloud, rain, ice, snow, graupel, and so on). Noninductive charge separation through collisions between graupel and ice/snow was considered the process of charge separation. The numbers of collisions during each time step were calculated by the microphysical model included in SCALE, and the magnitude of the charge separation was calculated based on Takahashi’s (1978) lookup table, which gives the magnitude of charge separation by one collision of graupel. SCALE has three types of microphysical models that consider the ice microphysics: a one-moment bulk scheme (Tomita 2008), a two-moment bulk scheme (Seiki and Nakajima 2014), and a one-moment spectral bin scheme (Suzuki et al. 2010). In this study, Seiki and Nakajima’s (2014) two-moment bulk scheme was used. The two-moment bulk scheme calculates the number of cloud condensation nuclei (CCN; \( N_{ccn} \)) as

\[
N_{ccn} = N_{0} s^{k}, \tag{1}
\]

where \( s \) is the supersaturation and \( k (=0.462) \) is a constant. The number concentration of CCN at 1% supersaturation \( N_{0} \) was set as 100 cm\(^{-3}\), a typical value over the ocean as based on Pruppacher and Klett (1997).

The electric field \( \mathbf{E} \) was calculated by solving the Poisson equation:
\[ E = -\nabla \phi \quad \text{and} \]
\[ \nabla^2 \phi = -\frac{\rho_i}{\varepsilon_i}. \]

where \( \phi \) is the electrical potential, \( \rho_i \) is the sum of \( \rho_{e,xx} \) at each grid point, and \( \varepsilon \) is the permittivity. Equation (3) was solved using the biconjugate gradient stabilized method (BiCGSTAB; van der Vorst 1992). The lightning model has two types of neutralization schemes, based on the works of MacGorman et al. (2001) and Fierro et al. (2013). The former predicts the lightning path and the neutralization that occurs along this path, and the latter scheme describes the neutralization that occurs over a cylindrical volume of radius \( r_{\text{cylinder}} \), in which the center of the cylinder is determined as grid points whose electrical field exceeds \( E_{\text{int}} \). The lette scheme is computationally efficient because the computational cost of calculating the lightning path is not required. In this study, the latter neutralization scheme (Fierro et al. 2013), with \( E_{\text{int}} = 110 \text{kV m}^{-1} \) and \( r_{\text{cylinder}} = 15 \text{ km} \), was used to reduce computational cost. The flash frequency calculated by the neutralization scheme is largely dependent on \( r_{\text{cylinder}} \) and \( E_{\text{int}} \). In addition, the lightning simulated by the models is not always equivalent to observed lightning. Thus, it is difficult to discuss the absolute value of flash frequency using the results of the scheme. To overcome the difficulty of discussion based on absolute values of flash frequency, we discuss only the relative frequency of lightning throughout the life cycle of an idealized TC. In this study, the relative lightning frequency is defined as the number of times the neutralization scheme was called, and we refer to the relative lightning frequency as the model lightning frequency or simply frequency hereinafter.

The initial vertical profiles of thermodynamics quantities were obtained from tropical mean sounding (Jordan 1958) with no wind (Fig. 1). The surface pressure was set at 1000 hPa at the initial time. An axisymmetric vortex based on Rotunno and Emanuel (1987) was inserted at the center of the domain at the initiation of the calculation. The maximum wind speed of the vortex was 20 m s\(^{-1}\), with a radius of 120 km. The outermost radius of the vortex was 750 km. The Coriolis force was added as the \( f \)-plane assumption with \( f = 5 \times 10^{-5} \text{s}^{-1} \), which corresponded to the Coriolis force at 20\(^\circ\) north. The surface sensible and latent heat fluxes were calculated based on a bulk scheme (Uno et al. 1995), assuming a constant sea surface temperature of 300 K. The calculation was conducted for 180 h. The simulated values were output every 30 min. In our previous study,
we conducted simulations by coupling with the lightning model for the last 36 h of the simulation, with a horizontal grid spacing of 5 km (Sato et al. 2019). In the current study, the lightning model was coupled from the initial state of the TC to the end of the simulation. This enables us to discuss the lightning frequency throughout the period from the initial state to the SS of the TC.

3. Results

a. Dependence of lightning frequency on the life cycle of an idealized TC

Figure 2a shows the temporal evolution of the model lightning frequency (solid line) and maximum wind speed at $z = 1$ km (dotted line), which is often used as an index of TC strength. In this study, we defined the period of RI based on Kaplan and DeMaria (2003). They defined the RI period to be when a wind velocity growth rate of $> 15.4 \text{ m s}^{-1}$ occurs over 24 h; this rate is denoted by the dashed line in Fig. 2a. Comparison between the dashed and dotted lines enabled us to determine whether the TC was in RI. We should also note again that the model lightning frequency was defined as the number of times the neutralization scheme was called in the model during the output interval (i.e., 30 min in this study) and does not correspond to the lightning frequency recorded from observations [e.g., WWLLN, NDLN, and Geostationary Lightning Mapper (GLM)]. In addition, the flash rates of GLM and WWLLN are not directly comparable with each other. Thus, the magnitude of the lightning frequency simulated by the model cannot be compared directly with observations. However, the trend in the model lightning frequency is sufficient for a discussion of the relationship between lightning frequency and the idealized life cycle of a TC. Henceforth, we refer to the model lightning frequency as the lightning frequency.

The wind speed was approximately $25 \text{ m s}^{-1}$ until $t \sim 60$ h. After $t \sim 60$ h, the wind speed increased rapidly, and the growth rate was larger than the RI threshold until $t = 135$ h; this period was regarded as the RI phase. After the RI phase, the wind speed did not change until the end of the simulation; this period corresponded to the SS. These trends in maximum wind speed are similar to those in previous studies that conducted idealized simulations with weak background shear (e.g., Miyamoto and Takemi 2013); thus, the life cycle of a TC was reasonably well simulated from initiation to SS. In addition, it should be noted that the simulated TC became an annular structure (e.g., Knaff et al. 2003) with time (Figs. 3a–d) as was also reported by Miyamoto and Takemi (2013). Such annular TCs are not observed frequently (Knaff et al. 2003), but have certainly been observed.

Successful simulation of the life cycle of a TC facilitated study of the relationship between the life cycle of the TC and lightning frequency. We defined the inner region and the outer region as the regions where the distance $R$ from the center of the TC was smaller and larger than 100 km, respectively. We separated the life cycle of the TC into four phases on the basis of the change in the maximum wind velocity. Phase I was defined as $t = 40–60$ h, which was before RI. Phase II was defined as $t = 60–90$ h, which was the early RI, when lightning occurred mainly in the outer region (Fig. 2b). Phase III was defined as $t = 90–135$ h, which was the late RI, when lightning occurred mainly in the inner region (Fig. 2b). Phase IV was defined as $t > 135$ h, which was the SS. The boundary of each phase is shown as the gray or white solid lines in Figs. 2a–c.

In the simulation, lightning frequency increased gradually with time. The frequency reached a maximum at $t \sim 50$ h, 10 h before the end of phase I. After starting RI at $t \sim 60$ h, the lightning frequency exhibited two small peaks, at $t \sim 70$ h and $t \sim 85$ h, of about half the maximum frequency of that during phase I. During phase III, the lightning frequency was maintained at about half that of the two small peaks during intensification ($t < 135$ h). When the TC reached SS at $t = 135$ h, that is, phase IV, the lightning frequency was maintained for several
tens of hours \((t < 160 \text{ h})\), and then decreased until the end of the simulation.

The temporal evolution of the lightning frequency in the inner and outer regions (Fig. 2b), and the Hovmöller diagram of vertically integrated hydrometeors (i.e., the sum of the liquid water path (LWP) and the ice water path (IWP)) with lightning frequency (Fig. 2c) helped us to understand the position of the lightning. From the initial time until \(t \approx 60 \text{ h}\), including phase I when lightning frequency reached a maximum for the entire simulation, lightning occurred in both the inner and outer regions. The occurrence of lightning over a wide range of \(R\) resulted in high lightning frequency during phase I. During phase II, lightning occurred mainly over the outer region, and this contributed to the two small peaks at \(t \approx 70\) and 85 h. In phase III, the area with the most frequent lightning gradually changed from the outer region to the inner region, and lightning frequency in the inner region was high during \(t = 120\text{–}135 \text{ h}\), when the TC reached SS. After the TC reached SS in phase IV, the lightning occurred mostly in the inner region.

The results described above support the temporal evolution of lightning frequency through the life cycle of a TC reported in a previous observational study by Price et al. (2009). The maximum lightning frequency \((t \approx 50 \text{ h} \text{ in this study})\) occurred before the TC reached maximum strength. The time lag between the maximum wind velocity and maximum lightning frequency was about 90 h. The time lag in this study was longer than that reported by Price et al. (2009), who indicated that the maximum lightning frequency occurred about 1 day before the maximum TC intensity. However, they also reported that the maximum lightning frequency in several TCs occurred 3–4 days before the maximum TC intensity (see Fig. 3 of Price et al. 2009). Therefore, the results of this study do not contradict the results of Price et al. (2009), in that the lightning frequency reached a maximum before the TC reached maximum strength.

The high lightning frequency in the outer region contributed to the two small peaks seen during the early period of intensification (phase II). This result agrees with those of DeMaria et al. (2012) and Stevenson et al. (2016), who reported that frequent lightning in the outer region was an indication of intensification during the next 24 h. A high lightning frequency over the inner region shortly before or when the TC reached SS was also reported in previous studies, indicating that high lightning frequency in the inner region is indicative of a nonintensifying TC (DeMaria et al. 2012; Stevenson et al. 2016). These results indicate that our simulation reasonably reproduced the contrast in lightning frequency between the outer and inner regions, and the relationship between lightning frequency and the life cycle of a TC observed in some previous studies. On the other hand, the relationship between the location of lightning and the RMW reported by Stevenson et al. (2018) was not well reproduced by our simulation. Their results indicated that lightning occurred inside the RMW in intensifying TCs and outside the RMW in weakening TCs, whereas the lightning in our model was always located outside the RMW (Fig. 2c). This discrepancy between the previous observational study and our simulation is addressed in the final part of this paper (i.e., the discussion section).

Although there were some differences between the model and observations, the model successfully simulated the maximum lightning frequency prior to maximum TC intensity, and the contrast between the outer and inner regions. We then investigated the reasons for these phenomena by analyzing the results of the simulation.
Table 1. Mean cloud size, cloud number, and number of flashes per unit cloudy area in convective cloud cells and eyewall clouds averaged over $t = 40$–$180$ h (i.e., from phase I to phase IV).

<table>
<thead>
<tr>
<th>Cloud type</th>
<th>Mean size of each cloud (km²)</th>
<th>Mean cloud No.</th>
<th>Flash No. per unit cloudy area (m⁻²)²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Convective cloud cell</td>
<td>35.6</td>
<td>34.1</td>
<td>$1.09 \times 10^2$</td>
</tr>
<tr>
<td>Eyewall cloud</td>
<td>780.0</td>
<td>6.5</td>
<td>$0.52 \times 10^2$</td>
</tr>
</tbody>
</table>

* Cloudy area was determined as the sum of the cloudy areas in the cloudy grid, and the cloudy grid was defined as the grid column in which LWP + 1WP exceeded 10 kg m⁻².

b Convective cloud cells were defined as clouds in the whole calculation during phase I and those in the outer region ($R > 100$ km) during phases II, III, and IV.

c Eyewall clouds were defined as clouds in the inner region ($R < 100$ km) during phases II, III, and IV.

The geographical distribution of lightning and cloud shown in Fig. 3 was considered in this investigation. In addition to the figure, an animation of the geographical distribution also helped us to interpret the results (see Movie S1 in the online supplemental material). During phase I, when the lightning frequency was at its maximum, the eyewall cloud was not defined clearly (Fig. 3a). Instead, convective clouds, whose horizontal scale was smaller than that of eyewall cloud, generated over convective cells over a wide range of $R$, and lightning occurred frequently in the convective clouds (Fig. 3a). Hereinafter, we refer to these convective clouds over small-scale convective cells as convective cloud cells. In phase II, convective cloud cells consisted of the rainbands in the outer region, and frequent lightning occurred over the outer region (Fig. 3b). In addition, eyewall cloud started to develop in the inner region, but lightning rarely occurred there (Figs. 2c and 3b). These lightning characteristics were similar to those reported in a previous modeling study (see Figs. 4a and 4d of Fierro and Mansell 2017) and an observational study (Abarca et al. 2011). During phase III, the number of convective cloud cells with frequent lightning over the outer region gradually decreased (Figs. 2c and 3c). In contrast, the eyewall cloud became better defined than in phase II and lightning occurred in the eyewall cloud (Figs. 2c and 3c). After the TC reached SS, that is, phase IV, the eyewall cloud was dominant and lightning occurred mostly in the eyewall (Figs. 2c and 3d).

The results described above indicate that the convective clouds that primarily contributed to lightning could be roughly separated into two cloud types: convective cloud cells (including convective clouds comprising the outer rainbands), and the clouds in the eyewall region. The former contributed to the maximum value and the two small peaks in lightning frequency in phases I and II, respectively, while the latter contributed to the lightning during phases III and IV. Throughout the life cycle of the TC, the cloud type primarily contributing to lightning gradually changed from the former to the latter.

In addition, the number of lightning flashes per unit of cloudy area was also considered. In Figs. 3a and 3b, the orange cross symbols are densely distributed over each convective cloud cell, whereas they are sparsely distributed over the eyewall cloud (Figs. 3c,d). These results show that lightning was more frequent in cloudy units of area of convective cloud cells than in eyewall cloud. This trend is also evident in the data for the numbers of lightning flashes in cloudy units of area (Table 1). The results indicate that lightning occurred more frequently in the convective cloud cells than in the clouds in the eyewall region, even though lightning occurred in both.

In addition to the high frequency of lightning generated in each convective cloud cell, the lifetime of the convective cloud cells was about 3–6 h, and they were generated repeatedly as seen in Movie S1 in the online supplemental material. The frequent generation of lightning in each convective cloud cell, and the short lifetime of lightning and its repeated generation, resulted in high lightning frequency when the convective cloud cells were the main contributors to the lightning (i.e., during phase I and in the outer region during phase II).

In contrast, the eyewall cloud contributed to the lightning after the eyewall cloud became well defined and the TC reached a more mature stage (i.e., phases III and IV). Even if the frequency was relatively low, lightning still occurred in the eyewall cloud in phases III and IV, which did not contradict the observational studies. It could be concluded that the dependence of lightning frequency on the life cycle of the TC was due to the following factors. First, there was a gradual change in the main contributor to the lightning, from convective cloud cells to the clouds in the eyewall. Second, there was a difference between the lightning frequency in each convective cloud cell and that in each cloud in the eyewall region.

In the following sections, we consider the reason for the high lightning frequency in each convective cloud cell through an analysis of the mechanisms that produce these two types of clouds, and the vertical structure of cloud hydrometeors, charge density, and other related factors. Through the analyses of each phase, we examined the basis of the relationship between lightning frequency and the life cycle of a TC.

b. Phase I (before RI: 40 < $t < 60$h: convective cloud cells were the main contributor to lightning)

During phase I, when lightning frequency reached a maximum, convective cloud cells were the main contributors to high lightning frequency. The convective cloud cells were initially triggered by local convergence in the boundary layer generated along the vortex at the initial time. Once the convergence triggered convection, the convection strengthened through consuming the convective available potential energy (CAPE) under the environmental conditions with weak stability (i.e., high CAPE condition) used in this study (Jordan 1958), and resulted in convective clouds with lightning, i.e., the convective cloud cells.

The horizontal distribution of CAPE shows that it decreased as the convective cloud cells were generated (Movie S1 in the
online supplemental material) and was lower around these convective cloud cells than in the surrounding area (Fig. 3e). The probability density function (PDF) of the lightning frequency with respect to the difference in CAPE from azimuthally averaged values supports these results (Fig. 4). During phase I, the center of the PDF was at $-300 \text{ J kg}^{-1}$, corresponding to the area with a lower CAPE than the surrounding area. These results indicate that CAPE was consumed to strengthen the convection and resulted in the convective cloud cells. In this study, we did not consider vertical wind shear, large-scale forcing, or movement of the TC. Therefore, convective instability was the most likely reason for the strengthening of convection in the cloud cells.

We then examined why convective clouds cells generated lightning more frequently than the convective clouds in the eyewall region, by focusing on electrification and cloud properties. Vertical cross sections of the hydrometeor mixing ratio $q_{\text{hyd}}$, vertical velocity $w$, $\rho_e$, charge separation rate, and $|E|$ were used to examine the associations among electrification, lightning, and cloud properties. Figure 5 shows the $x$–$z$ cross section over some convective cloud cells, indicated by a red dotted line in Fig. 5f. High $w$ values exceeding 20 m s$^{-1}$ were generated over the convective cloud cells (Fig. 5b). This carried supercooled water upward in each convective cloud cell, generating large amounts of graupel (shown as the black contour lines in Fig. 5a). The large amounts of graupel induced charge separation via collisions between the graupel and ice/snow (Fig. 5d) over the convective cloud cells in the range $z = 6$–10 km. The charge separation produced the large-magnitude charge density around the high $w$ area (Fig. 5c). As a result of this large-magnitude charge density, $|E|$ became large (Fig. 5e) and lightning occurred over the convective cloud cells. These features of the convective cloud cells were largely identical among almost all convective cloud cells generated during phase I (figure not shown). Thus, the vertical distributions of $q_{\text{hyd}}$, $w$, $\rho_e$, and the charge separation rate averaged during phase I (Fig. 6) over a cloudy grid (defined as a grid with LWP + IWP exceeding 10 kg m$^{-2}$), displayed a similar trend to that of the snapshot shown in Fig. 5. In the averaged distribution in Fig. 6, $q_{\text{hyd}}$ is distributed over a wide area over the $R$–$z$ plane (Fig. 6a), which corresponds to the signal of the convective cloud cells. The strong convection is clearly shown by the high $w$ values over a wide area on the $R$–$z$ plane (Fig. 6b). The strong $w$ carried hydrometeors upward in each convective cloud cell. In this case, high charge separation rates (Fig. 6c) and large $|E|$ (Fig. 6d) were also seen. The distribution of the charge separation rates and the charge densities averaged for each polarity are shown in Fig. S1 in the online supplemental material, which also indicates that charge separation actively occurred in convective cloud cells and $|E|$ was large in the cloudy grid in phase I. Furthermore, the repeated generation of convective cloud cells over a wide range of $R$ resulted in a large number of lightning flashes during this phase.

**c. Phase II (early RI: $60 < t < 90$ h: lightning occurred over convective cloud cells in the outer region)**

In phase II, lightning was generated mostly in the outer region (Fig. 2c). Convective cloud cells continued to form in the outer region ($R > 100$ km) and composed the rainband in the outer region (Fig. 3b and online supplemental Movie S1). The vertical cross section of $q_{\text{hyd}}$, $w$, $\rho_e$, the charge separation rate, and $|E|$ over some convective cloud cells in the outer region at $t = 86.5$ h are shown in Fig. 7, and all were similar to those over the convective cloud cells in phase I (Fig. 5). Thus, the vertical distribution of hydrometeors, $w$, charge separation, and $\rho_e$ over the $R > 120$ km averaged during phase II, as shown in Fig. 8, were also similar to those in phase I (Fig. 6). Lightning was generated frequently in the convective cloud cells in the outer region, which created the two small peaks seen during phase II.

In contrast, eyewall cloud, which was accompanied by the secondary circulation of the TC (Houze 2010), was generated in the inner region ($R < 100$ km) (Fig. 3b and online supplemental Movie S1). However, the secondary circulation was not strong. In addition, CAPE was smaller in the inner region than over the eyewall in the outer region, which is similar to the report of Molinari et al. (2012). These are reflected in the weak $w$ (Fig. 9b) and small $q_{\text{hyd}}$ (Fig. 9a) over the cross section of the eyewall cloud at $t = 86.5$ h in phase II. Because $w$ was weak, solid hydrometeors, including graupel, were not generated frequently in the eyewall, and charge separation did not occur frequently (Fig. 9d). The small amount of charge separation resulted in a small-magnitude charge density (Fig. 9c), small $|E|$ (Fig. 9e), and low lightning frequency in the eyewall region. These characteristics were also seen in the averaged profiles as a weak $w$ (Fig. 8b), small $q_{\text{hyd}}$ (Fig. 8a), small magnitude of charge density (Fig. 8d), and small charge separation rate (Fig. 8c) over $R < 100$ km.

From the above discussion, the contrast in lightning frequency between the outer and inner regions originated from
the difference in the strength of the convection in the convective cloud cells and that accompanying the secondary circulation during phase II. The $w$ values in the eyewall were not as high as those in convective cloud cells (e.g., Marks and Houze 1987), especially during the early stage of TC intensification. Thus, it is speculated that the high lightning frequency over the outer region of intensifying TCs reported by observations (DeMaria et al. 2012) may be explained by the contrast between the strength of the convection of convective cloud cells over the outer region and that of the convection that accompanies the secondary circulation in the inner region.

d. Phase III (late RI: 90 $t$ $135$ h: Lightning generated mainly over the eyewall cloud)

During phase III, the number of convective cloud cells in the outer region gradually decreased over time (Figs. 3c and online supplemental Movie S1), and the eyewall cloud gradually became defined. In parallel with this change, the lightning frequency over the outer region also decreased (Fig. 2c) and the eyewall cloud became the main contributor of lightning. Figure 10 shows the $y$–$z$ cross section of $q_{\text{hyd}}$, $w$, $\rho_e$, the charge separation rate, and $|E|$ over the eyewall cloud at $t = 110$ h in phase III. In phase III, $w$ values along with the secondary circulation (Fig. 10b) became higher than in phase II (Fig. 9b), although they were less than in convective cloud cells in the outer region (Figs. 5b and 7b). As a result of the higher $w$ values in the eyewall cloud than in phase II, a large amount of $q_{\text{hyd}}$ corresponding to well-defined eyewall cloud was generated. Large amounts of graupel were also generated, as shown by the black contour lines in Fig. 10a. The large amounts of graupel induced charge separation via collisions between the graupel and ice/snow (Fig. 10d). The large charge separation produced the large-magnitude charge density around the strong $w$ area (Fig. 10c). As a result of the large-magnitude charge density, $|E|$ became large (Fig. 10e) and lightning occurred over the eyewall cloud.

Figure 11 shows the vertical distribution of $q_{\text{hyd}}$, charge density, and other key parameters averaged over a cloudy grid during phase III. It can be seen that the vertical distribution of $q_{\text{hyd}}$, $w$, the charge separation rate, and $\rho_e$ over the outer region were similar to values in the outer region in phase II. However, these vertical distributions were created using the average over cloudy grids (defined as grid columns where LWP $>$ 10 kg m$^{-2}$). The numbers of convective cloud cells over the outer region gradually became smaller than during phases I and II, so there was little lightning in this area during phase III (Fig. 2b).

In the inner region, the vertical distributions of $q_{\text{hyd}}$, $w$, $\rho_e$, and the charge separation rates, were similar to those obtained by the snapshot (Fig. 10). The vertical distribution of $q_{\text{hyd}}$ over the inner region in phase III (Fig. 11a) indicates that $q_{\text{hyd}}$ was larger than during phase II (Fig. 8a), corresponding to the well-defined eyewall cloud. The secondary circulation was stronger in phase III (Fig. 11b) than in phase II (Fig. 8b) because $w$ values were high over the eyewall region. Because of the high $w$ values, graupel was generated frequently and charge separation occurred, which is reflected in the high charge separation rates in the inner region (Fig. 11c). As a result of the large

![Image](64x464 to 499x677)
charge separation, the magnitude of the charge density in the inner region was larger in phase III (Fig. 11d) than in phase II (Fig. 8d), which resulted in lightning over the eyewall cloud (Figs. 2c and 3c).

Comparison between phases II and III with respect to the inner region indicates that lightning occurred over the eyewall clouds only when the secondary circulation was strong enough to carry hydrometeors above the height at which the temperature was 0°C. Therefore, the high lightning frequency in the inner region of a nonintensifying TC that has been reported in observational studies (Stevenson et al. 2016) could be interpreted as a signal of strong secondary circulation at the mature stage.

Although the values of $w$ alongside the secondary circulation were large enough to generate large charge densities and lightning in the inner region in phase III, the values of $w$ in the inner region were weak compared with the corresponding values in the outer region and those in phase I. The weaker $w$ in the cellular updraft over the secondary circulation than in the convective cloud cells in the outer region may explain the lower lightning frequency in the inner region in phase III when compared with that in the outer region in phases I and II. In addition, the number of cloud cells was lower in the inner region, including the eyewall cloud, than in the outer region (Table 1). The smaller numbers of convective clouds in the inner region in phase III compared to the numbers of convective cloud cells in phases I and II may also explain the low lightning frequency in the inner region in phase III compared with that in the outer region in phases I and II.

e. Phase IV (SS: $t > 135$ h): Most of the lightning occurred in the inner region

During phase IV, the convective clouds in the eyewall region were the main contributor to lightning, with the contribution of the convective cloud cells in the outer region being further reduced. The numbers of convective cloud cells were small when $R > 180$ km. The reason for the small numbers of convective cloud cells is not obvious, but we speculate that this was...
associated with the higher stability (i.e., lower-CAPE conditions) in the latter period of the simulation compared to that in the early period of the simulation. This is seen as the gradual decrease in CAPE with time (Figs. 3e–h). Due to the higher stability in the latter period of the simulation, the numbers of convective cloud cells in the outer region were small in phase IV. The basic characteristics of the vertical distribution of $q_{\text{hyd}}$, the $w$, charge separation, and $r_e$ in the inner region (Fig. 12) were similar to those of phase III (Fig. 11). However, there were some differences between phases III and IV. In phase IV, the secondary circulation became stronger than in phase III, and the $w$ values of the secondary circulation were high (Fig. 12b). The strong secondary circulation resulted in the eyewall cloud becoming better defined (Fig. 12a), and $q_{\text{hyd}}$ over the eyewall in phase IV was larger than before phase III (Fig. 11a). Because of the higher $w$ values (Fig. 12b) and large $q_{\text{hyd}}$, large numbers of hydrometeors were carried upward. In this case, graupel was generated more frequently and charge separation occurred more frequently (Fig. 12c). The large charge separation resulted in large-magnitude charge densities (Fig. 12d) and lightning occurred over the eyewall region. This was similar to the results of the observational studies of Stevenson et al. (2016), who reported high lightning frequency in the inner region of a nonintensifying (including SS) TC.

However, the lightning frequency was lower in the inner region at the end of phase IV than at the early stage of phase IV. A mechanism that could explain the low lightning frequency was the dominance of the warm-rain process, which was similar to the results of the simulation of Fierro and Mansell (2017). The temporal evolution of $q_{\text{hyd}}$, $r_e$, and the charge separation rates over the eyewall region helped us to determine whether the warm-rain process was dominant (Fig. 13). Figure 13a indicates that $|r_e|$ above $z = 8 \text{ km}$ gradually increased during phase III. The increase in $|r_e|$ originated from the large amounts of graupel (Fig. 13b) that were generated by the strong $w$ alongside the strong secondary circulation. The large amounts of graupel resulted in high charge separation rates at around $z = 10 \text{ km}$ as a result of the collision of graupel with ice/snow (Fig. 13c), which in turn resulted in lightning in the inner region.

In contrast, during phase IV, the magnitude of the charge density gradually reduced (Fig. 13a), due to a decrease in charge separation rates at around $z = 10 \text{ km}$ (Fig. 13c). The decrease in charge separation rates was due to the dominance of the warm-rain process in the eyewall region. The warm-rain process gradually became active, as reflected in the large $q_{\text{hyd}}$ below the melting layer ($z \sim 5 \text{ km}$), which is shown as the gray contour line in Fig. 13b. As the warm-rain process became active, the number of hydrometers carried up to the melting layer decreased. The amounts of graupel also decreased, which is reflected in the reduction in the dot–dashed black contour line above the melting layer in Fig. 13b. Because of the reduced amounts of graupel, the charge separation rates in the upper layer ($z \sim 10 \text{ km}$) decreased. As a result, the magnitude of the charge density gradually decreased during phase IV, particularly above a height of 8 km. The active warm-rain process, small magnitude of the charge density, and small charge separation ratio compared to phase III can also be seen in the cross section of the eyewall cloud (Fig. 14). Figures 11 and 12 were created by averaging throughout phases III and IV, respectively; therefore, the magnitudes of the averaged $r_e$ charge separation rates in phases III and IV were similar.

Although the number of lightning flashes in the inner core was relatively small in phase IV when compared with phase III,
the lightning was confined to the inner region after phase IV (Fig. 2). This result is supported by previous observations of lightning frequency in the eyewall of strong TCs (Squires and Businger 2008). The reason for the low frequency of lightning in the inner region later in phase IV is examined further in the next section.

**f. Timing of SS**

Another point of interest is the timing of SS, which corresponds to the boundary between phase III and phase IV (i.e., \( t = 135 \) h) (Fig. 13). In this study, we defined the timing of SS based on the maximum wind velocity (Fig. 2a) in accordance with previous modeling studies (e.g., Miyamoto and Takemi 2013) and an observational study (Price et al. 2009), which motivated this study. However, the timing of SS is not necessarily reasonable based on the profiles of \( q_{\text{hyd}} \) and graupel (Fig. 13b).

During phase III, the height reached by graupel gradually increased with time, and consequently \( q_{\text{hyd}} \) in the upper layer also increased with time (Fig. 13b). After reaching a maximum height of about 13 km at \( t \sim 120 \) h, the elevation attained remained unchanged until \( t \sim 156 \) h, and during this period the TC reached SS. The height reached by graupel then gradually decreased. The warm-rain process was one of the mechanisms involved in this decrease in height, as discussed above.

The temporal evolution of the minimum pressure in the lowest layer of the model (Fig. 15a) continued to decrease after the TC reached SS (\( t = 135 \) h) until about \( t \sim 156 \) h. The temporal evolution of the graupel and minimum pressure profiles indicates that the characteristics of the eyewall clouds changed at around \( t = 156 \) h, even though the TC had already reached SS. To examine the change in the eyewall structure at \( t \sim 156 \) h, we divided phase IV into phases IV-1 and IV-2, which were defined as \( 135 < t < 156 \) h and \( 156 < t < 180 \) h, respectively. In addition, we divided phase III into phase III-1 (\( 90 < t < 120 \) h) and phase III-2 (\( 120 < t < 135 \) h).

Throughout phase III and phase IV, the temperature in the upper layer (i.e., above 11 km) gradually increased (Fig. 13c). Thus, the vertical temperature profile highlights the difference between phase IV-1 and phase IV-2. The temperature and relative humidity profiles averaged over phases III-2, IV-1, and
IV-2 are shown in Fig. 16. Note that Fig. 16 was created by averaging the entire calculation domain during each phase. In contrast, Figs. 6, 8, 11 and 12 were created by averaging over wholly cloudy grids.

Figure 16b indicates that the warm core over the upper layer, which was not evident before phase III-2 (Fig. 16a), was generated during phase IV-1 (Fig. 16b), and a double warm core structure (Kieu et al. 2016) was defined in phase IV-1. The warm core in the upper layer and the double warm-core became clearer in phase IV-2 than in phase IV-1; a warm-core would reduce the relative humidity in the upper layer (Fig. 16c).

Due to the generation of a warm and dry core in the upper layer,

Fig. 9. As in Fig. 5, but for \( x = 1500 \) km, \( 1400 < y < 1600 \) km at \( t = 86.5 \) h, which corresponds to the red dotted line in (f) including the inner region. (f) Identical to Fig. 3b.

FIG. 10. As in Fig. 5, but for \( x = 1500 \) km, \( 1300 < y < 1700 \) km at \( t = 110 \) h, which corresponds to the red dotted line in (f). (f) Identical to Fig. 3c.
the inner core regions became stable. Under such stable conditions, the convection in the inner core region became relatively weak in phase IV-2 compared with that in phase IV-1. The weaker convection in phase IV-2 than in phase IV-1 resulted in weaker updraft, decreasing the height reached by graupel (Fig. 13b); consequently, at around $z = 10$ km, the charge separation, charge density, and lightning frequency all decreased. This mechanism, in combination with the warm-rain process, also explains the reduced lightning frequency at the end of the simulation. Based on this discussion, the reduced lightning frequency around the TC after SS could be regarded as indicating the generation of a warm and dry core in the upper layer of the eye.

The results shown above imply that phase change can occur even when a TC is thought to have attained SS. Thus, there is room for further discussion of the definition of SS. However, the purpose of this study was to interpret the observed relationship between a TC’s life cycle and lightning frequency. As the intensity of a TC is defined by the maximum observed wind velocity (Price et al. 2009), it is reasonable that the definition of SS in this study was based on maximum wind velocity. However, the definition of SS merits further discussion, and additional studies are required.

g. The reason for the maximum lightning frequency before RI and the high frequency in the outer region of intensifying TCs

In this section, we discuss why the maximum lightning frequency occurs before the maximum TC intensity (Price et al. 2009). Because the initial sounding of Jordan (1958) was used, CAPE was high in the initial stage of the simulation. In addition, thermodynamic energy continued to be supplied from the sea surface and CAPE increased with time. Under such high-CAPE conditions, local convergence triggered updraft, which strengthened convection and created large numbers of convective cloud cells that transported moisture to the upper layer before RI. Moistening of the upper troposphere is important for TC intensification (Nolan 2007). The time with the maximum lightning frequency ($t \sim 50$ h) corresponded to the moistening of the upper troposphere, and the maximum
lightning frequency of a TC is considered a signal of moistening of the upper troposphere by convective cloud cells before intensification.

However, differences in the time lag between the maximum lightning frequency and the maximum intensity (SS) must be discussed. The time lag was 90 h in this study, similar to that in some of the TCs examined by Price et al. (2009). However, the time lags of other TCs have been reported to be small (~1 day). In addition, several case studies (e.g., Solorzano et al. 2008; Squires and Businger 2008; Austin and Fuelberg 2010; Stevenson et al. 2014) have reported differences in the timing of maximum lightning frequency. More studies are required to explain differences in time lags among TCs.

4. Conclusions and discussion

In this study, the relationship between lightning frequency and the life cycle of a TC was investigated using a meteorological model coupled with a lightning model. The numerical simulation of an idealized TC covered the period from the initial state to SS. In the simulation, the relationship between the TC life cycle and lightning frequency reported by some previous observational studies was successfully reproduced.

The results of the simulation indicate that lightning frequency reaches a maximum value before the TC reaches maximum intensity, which is similar to the results of a previous observational study (Price et al. 2009). The lightning frequency in the outer region was high when the TC was intensifying, which was also similar to the results of a previous observational study (Stevenson et al. 2016). Furthermore, our results also indicate that the lightning frequency in the inner region was high when the TC reached SS, i.e., when TC intensification stopped, as reported by previous observational studies (DeMaria et al. 2012; Stevenson et al. 2016).

Our analyses revealed that lightning is associated with two characteristic types of convective clouds: the convective cloud cells formed under high-CAPE conditions, and the clouds in the eyewall region that accompany the secondary circulation. Lightning was more frequent in the convective cloud cells than in the clouds in the eyewall region. The convective cloud cells

![Figure 12](https://example.com/figure12.png)

FIG. 12. As in Fig. 6, but during phase IV (t = 135–180 h). The vertical distributions of the charge separation rate and charge density averaged for each polarity are shown in Fig. S4 in the online supplemental material.
were repeatedly generated over a wide area. The repeated generation of the convective cloud cells and higher lightning frequency therein resulted in high lightning frequency before, and in the early stage of, RI. The eyewall clouds also generated lightning in the late stage of RI and at SS, but the frequency of lightning in the clouds in the eyewall region was lower than that of the convective cloud cells. The dependence of lightning frequency on the life cycle of a TC would be explained by the change in the dominant clouds contributing to lightning during its life cycle, from convective cloud cells that form under high-CAPE condition to convective clouds in the eyewall region that accompany secondary circulation.

On the basis of the discussions above, we speculate that the dependence of lightning frequency on the life cycle of a TC could be explained as follows:

1) The maximum lightning frequency before the maximum intensity reported by an observational study (Price et al. 2009) could be explained by the maximum number of convective cloud cells moistening the upper troposphere before intensification. Therefore, the maximum lightning frequency would indicate moistening of the upper troposphere.

2) The contrast in lightning frequency between the outer and inner regions reported by observational studies (Molinari et al. 1999;...
Abarca et al. (2011) might originate from differences in the strength of the vertical velocity between that of convective cloud cells and that of secondary circulation.

3) The lightning in the inner region of a nonintensifying TC (DeMaria et al. 2012; Stevenson et al. 2016) could be considered a signal of the strong secondary circulation that occurs when eyewall clouds are mature (e.g., phases III and IV in this study).

4) The high lightning frequency in the outer region of an intensifying TC (Stevenson et al. 2016) might be attributed to the large number of convective cloud cells in the outer region, whereas the secondary circulation is not strong enough to generate lightning (e.g., phase II in this study).

These conclusions have also been reached in observational studies, but we confirmed them through our numerical simulation that explicitly simulated lightning using the famous and simple idealized experimental setup of Rotunno and Emanuel (1987), which has been used to elucidate TCs. Several previous modeling studies used the same experimental setup, but most did not consider lightning explicitly.

The conclusions of this study provide a simple interpretation of the observed relationship between lightning frequency and a TC’s life cycles, which can be used as a proxy for prediction of a TC’s life cycle (Price et al. 2009). However, such simple interpretation cannot be applied to all observed TCs, because the simple experimental setup used in this study did not consider the multiple physical mechanisms involved in an actual TC. Thus, it is necessary to discuss the differences between the results of this study and those of other previous observational studies.

Stevenson et al. (2018) reported that intensification of a TC was associated with lightning being generated inside the RMW and weakening of a TC was associated with lightning being generated outside it, as based on the theory of a convective burst (Rogers et al. 2013). On the other hand, the lightning always occurred outside of the RMW in our simulation.

**FIG. 15.** Temporal evolution of (a) minimum pressure in the lowest layer of the model (solid line) and maximum wind velocity at \( z = 1 \) km (dotted line). Vertical red solid and dotted lines indicate the boundaries of phase III and phase IV, and of phase IV-1 and phase IV-2, respectively. (b) As in Fig. 13b, but showing the ranges of phases III-1, III-2, IV-1, and IV-2.

**FIG. 16.** Vertical distributions of relative humidity (shaded) and temperature (dashed lines; °C) averaged over the whole calculation domain during (a) phase III-2 (\( t = 120-135 \) h), (b) phase IV-1 (\( t = 135-156 \) h), and (c) phase IV-2 (\( t = 156-180 \) h). The values are azimuthally averaged.
(Fig. 2c). We interpreted this as indicating that the contradictions originated from the small slant of the eyewall cloud in our results. In our model, lightning was initiated at the point where \(|E|\) was larger than \(E_{\text{init}}\). After lightning started to occur in the eyewall cloud (i.e., phases III and IV), the initiation points of the lightning were distributed mainly around the height of \(z \sim 11-12\) km, based on the distribution of the charge density (Figs. 11c and 12e). Because of the gently slant ed structure of the eyewall, the initiation points at \(z \sim 12\) km were outside the RMW. The results of Stevenson et al. (2018) included data from 51 TCs, and the slant of these TCs would not always have been small as in the TC simulated in this study. In addition, the observed lighting by WWLLN is mainly cloud-to-ground lightning, which is initiated at lower altitude and, therefore, is less affected by eyewall slant. Such differences may explain contradictions with regard to the relationship between RMW and a TC’s life cycle.

In addition, several previous studies mentioned in the introduction to this study reported timing and areas of maximum lightning frequency that differed from those in our simulation (Stevenson et al. 2014; Squires and Businger 2008; Austin and Fuelberg 2010; Solorzano et al. 2008). Our single simulation using a simple experiment setup cannot explain these contradictions, and it is therefore necessary to discuss the representativeness of this study.

The initial profile was one typical of the West Indies. If the initial profile used had been of another area (e.g., the East Pacific or west Pacific Ocean), the basic characteristics of the simulated TC (e.g., the timing of RI, maximum intensity at SS, and extent of the slant of the eyewall) would have differed. The sensitivity of the results to the initial profile should be investigated in future studies. Such sensitivity experiments might also explain the contradictions between the results of this study and those of previous observational studies, such as with regard to the locations of lightning and the RMW. Further numerical simulations are required to fully understand the dependency of the effects of the initial profile on the degree of slant, wind shear, large-scale forcing, and other factors.

As well as the contradictions, there are several issues with regard to the lightning frequency and life cycle of a TC. The first issue is the decay phase of a TC, as reported by Fierro and Mansell (2017). Another concern is the effect of the diurnal cycle, as discussed in Ditchev et al. (2019). These issues cannot be evaluated from the results of this study. Additional numerical simulations and analyses using a meteorological model coupled with a lightning model are expected to provide further insights.

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