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Observations of Blue Corona Discharges in Thunderclouds

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Key Points:

- Characterization of blue corona discharges and their meteorological environment during 3 years of observations
- The optical pulses of the events fall into fast (≤30 μs) and slow (40 μs to 5 ms) rise times, signifying different cloud depths
- The discharges occur when is 38%–70% larger than for lightning cells and are associated with overshooting tops 34%–50% of the time

Supporting Information:

Supporting Information may be found in the online version of this article.

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Abstract

Blue electric streamer discharges in the upper reaches of thunderclouds are observed as flashes of 337.0 nm (blue) with faint or no emissions of 777.4 nm (red). Analyzing 3 years of measurements by the Atmosphere-Space Interactions Monitor on the International Space Station, we find that their distribution in rise time falls into two categories. One with fast rise times of 30 μs or less that are relatively unaffected by cloud scattering and emanate from within ~2 km of the cloud tops, and another with longer rise times from deeper within the clouds. 50% of cells generating shallow events are associated with overshooting tops compared to 34% of cells generating deeper events. The median Convective Available Potential Energy of the cells is ~70% higher for the shallow events and ~38% higher for the deeper events than for lightning cells, suggesting the discharges are favored by strongly convective environments.

Plain Language Summary

Corona discharges can be seen as flashes of blue light with little or no light in a red spectral line normally emitted by lightning. They are so-called streamers and have been observed from space in the upper regions of thunderstorm clouds. In this work we present their characteristics based on 3 years of data from the Atmosphere-Space Interactions Monitor on the International Space Station. We find two categories of discharges, one is located at the very top of the clouds and the other a few kilometers inside the clouds. We find that the discharges on average are favored by stronger convection and higher cloud tops than normal lightning.

1. Introduction

Streamers are a type of electrical discharge characterized by a filament of weakly ionized plasma propagating as an ionisation wave. A multitude of streamers may be launched, for instance, from lightning leader tips, where their optical emissions form a corona. They pre-ionize and condition the atmosphere ahead of a lightning leader, assisting its continued propagation (Ebert et al., 2010; Raizer, 1980). Flashes of light from thunderstorm clouds have been observed in the second positive band of Nitrogen ($N_2$2P) at 337 nm (blue) with no emission in the main lightning leader lines of OI at 777.4 nm (red), suggesting they are made of streamer breakdown. They are observed in the upper regions of clouds, with some at the very top (Chang et al., 2010; Chanrion et al., 2017; Dimitriadou et al., 2022; Kuo et al., 2009; Krehbiel et al., 2008; Lyons et al., 2003; Liu et al., 2015; Soler et al., 2021), and have been shown to be associated with Narrow Bipolar Events (NBEs) observed in VLF/LF radio signals (3–300 kHz) (Li et al., 2021; Liu et al., 2018; Soler et al., 2020). They are related to a wider family of discharges, which includes blue starters and blue jets that propagate from the cloud tops into the stratosphere, or beyond to the ionosphere (Chanrion et al., 2017; Chou et al., 2018; Gordillo-Vázquez et al., 2012; Pasko, 2008; Pasko et al., 2012; Riousset et al., 2010; van der Velde et al., 2007; Wescott et al., 1995).

Just as NBEs often occur at the onset of lightning (Rison et al., 2016), a blue corona discharge has been observed at the onset of a blue jet (Neubert et al., 2021). Consequently, they are a distinct process close to the cloud tops that is difficult to observe from the ground because the clouds interfere with the view, and the atmosphere absorbs and scatter photons. Most observations of blue discharges are from space by the Imager of Sprites and Upper Atmospheric Lightning (ISUAL) instrument (ISUAL) on Formosat-2 (Frey et al., 2016), ASIM on the International Space Station (ISS) (Neubert et al., 2019) and by an astronaut on the ISS (Chanrion et al., 2017). The rise time of the blue flashes range from 10 μs to several ms and has been approximated with an instantaneous point source with extended rise times caused by scattering of photons in cloud particles (Luque et al., 2020;

Soler et al., 2020). Therefore, the optical source is consistent with fast streamer break-down (∼10 μs) over a few kilometers, as assumed for NBEs. A study of these flashes then relates to the general problem of how lightning is triggered in clouds.

Event studies of single storms suggest that corona discharges are generated in cloud cells with strong convection (Dimitriadou et al., 2022). In order to gain a global view of their relation to storm properties, we present a statistical study of observations over 3 years by ASIM. We identify the Cloud Top Temperature (CTT) and CAPE at the time and location of each event and compare the average values of these meteorological parameters to those of a subset of normal lightning detected by ASIM.

2. The Observations

ASIM includes three photometers and two cameras. The photometers measure the second positive line of N_2 at 337 nm with a bandwidth of 5 nm (blue), part of the N_2 Lyman-Birge-Hopfield (LBH) band at 180–235 nm (UV), and a line of atomic oxygen OI at 777.4 nm with 3 nm bandwidth (red). The red line is strong in lightning leader emissions and the blue line is emitted both by leaders and streamers (Arcanjo et al., 2021). The cameras measure in the blue and red bands with a spatial resolution of ∼400 m at sea level toward nadir. The instruments measure continuously during the night, but in the normal trigger mode, data is only saved when a flash is detected. In this mode, the sample rate of the photometers is 100 kHz and the frame rate of the cameras is 12 frames per second. Up to 8 frames and the corresponding photometer data are saved for each ASIM observation, with one frame before the trigger to identify the background levels. The images are cropped to the region of activity before they are queued for downlink (Chanrion et al., 2019).

Examples of the two characteristic types of blue discharges are shown in Figures 1 and 2 with exact definitions of rise time and duration found in text S1 in Supporting Information S1. Both occur near the coldest part of their respective cloud cell but one has a rise time of 30 μs and a duration of 1.16 ms while the other has a longer rise time of 250 μs and a duration of 2.02 ms, indicating that the fast event occurs at the cloud top while the other occurs a few kilometers below the cloud top.

The blue discharges are identified from the photometer signals. We first select the blue photometer data that contain peaks where the flux increases more than 2.5 μWm^{-2} in 5 samples (50 μs). If more than one peak is present within ±250 samples, only the largest peak is kept. Next, we reject narrow peaks caused by energetic particle radiation, for instance, in the South Atlantic Anomaly (SAA). They are identified from the ratio of the sum of the illuminance of 100 samples before and 100 samples (1 ms) after a peak which is the typical time constant of blue discharges. If the ratio is less than 2, the peak is narrow and likely from energetic particles and therefore rejected. A real event will always have a tail while an energetic particle will not as seen in Figures S1 and S2 in Supporting Information S1. For the condition of faint red emissions, we require that the ratio of the sum of 50 samples of the red and blue peaks must be less than 0.1. To be sure to reject all energetic particle events, we finally reject any remaining pulses that last less than 150 μs *and* have rise times less than 40 μs. The thresholds for the algorithms were determined empirically by testing the algorithm during times when ASIM was active in the SAA known for its high number of cosmic rays.

The events are geolocated from the measurements of the blue camera. The pixel that correspond to the maximal intensity is projected to 16 km altitude, considered an average altitude of the events. The location is cross-checked with data from the Global Lightning Detection network (GLD360) that identifies the location of electrical activity. The accuracy of projection is estimated to be better than 10 km (Neubert et al., 2021). To ensure that the cell is electrically active, GLD360 database is checked for lightning strokes ±2 min within the detection of the blue discharge and within the accuracy of the projection. If no strokes are detected, the event is discarded. It is not guaranteed that the on-board software can crop and download image data (Chanrion et al., 2019). However, all trigger events have camera meta-data containing the sums of the rows and columns from which the events can be geolocated. If the peak identified in the meta-data sums is less than 500 raw pixel digital unit counts, corresponding to approximately 4 standard deviations, the observation is discarded. If the camera image is saturated, the projection may be off by a few pixels but will remain within the 10 km uncertainty.

The CTT is from measurements by imagers on meteorological satellites, usually the channel at 10.8 μm, and accessed via the University of Wisconsin-Madison Space Science and Engineering Center (SSEC) using their

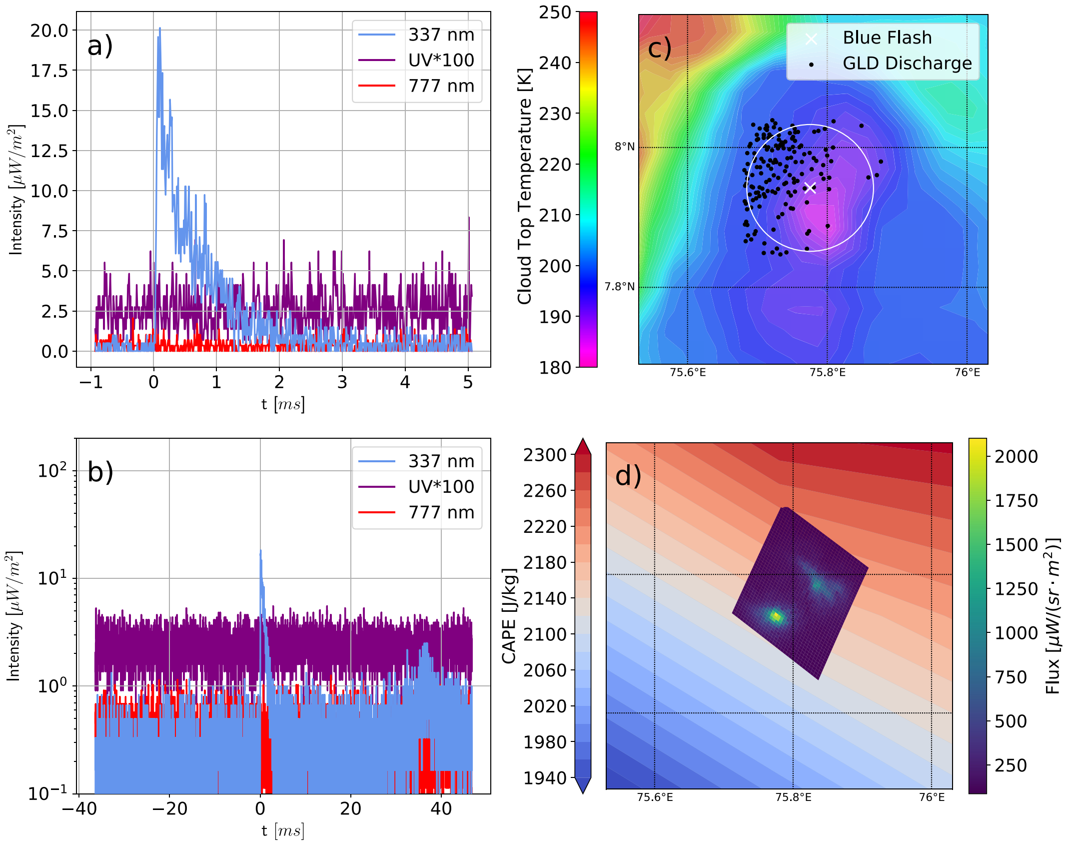

Figure 1. Fast blue discharge observed by ASIM. No present signature in the red or UV photometer. (a) The photometer data for the event showing the rise time of 30 μs and a duration of 1.2 ms (b) The photometer data in log scale showing the photometer data for the full camera frame (83 ms). (c) Satelite data for the cloud top temperature and the event location showing that it occurs close to the coldest part of the cloud cell. The white cross determines the location of the event while the circle is the location uncertainty, black points are GLD360 flashes close in time to the event (±2 min). (d) The 337 nm camera image for the event with the CAPE of the event.

software MCFetch. Depending on the location of the discharges, one of the following satellites is used, with its longitudinal interval specified: FY2G (90°–160°), GOES15 (160°–180° and −180° to −120°), GOES16 (−120° to −30°), MET11 (−30°–0°) or MET8 (0°–90°). We determine the CAPE at the location of the discharges using ERA5 reanalysis data, which provides hourly estimates of various atmospheric variables in a 30 km grid. This reanalysis data is the best available estimate of the CAPE at the time of the event (Hersbach et al., 2018). Correcting the satellite images for parallax (See text S2 in Supporting Information S1), we record the lowest temperature within 10 km of the event, the geolocation accuracy. The CAPE value and the tropopause temperature is taken at the nearest grid point from the discharge in the ERA5 data set corresponding to within 15 km.

To understand if thunderstorms that generate blue discharges differ from those that only generate normal lightning, we have also created a lightning reference data set that consists of 20 randomly chosen MMIA lightning observations per day during the 3-year period. The procedure for geolocation and identification of the CTT and the CAPE is identical to the corona data set.

A total of 57,636 blue discharge candidates were detected, consistent with numbers quoted in (Soler et al., 2021). However, because our analysis require availability of ERA5, GLD360, satellite data and that the event able to be geolocated, only 11,625 events are included in our blue discharge data set. The reference lightning data set contains 9565 lightning flashes.

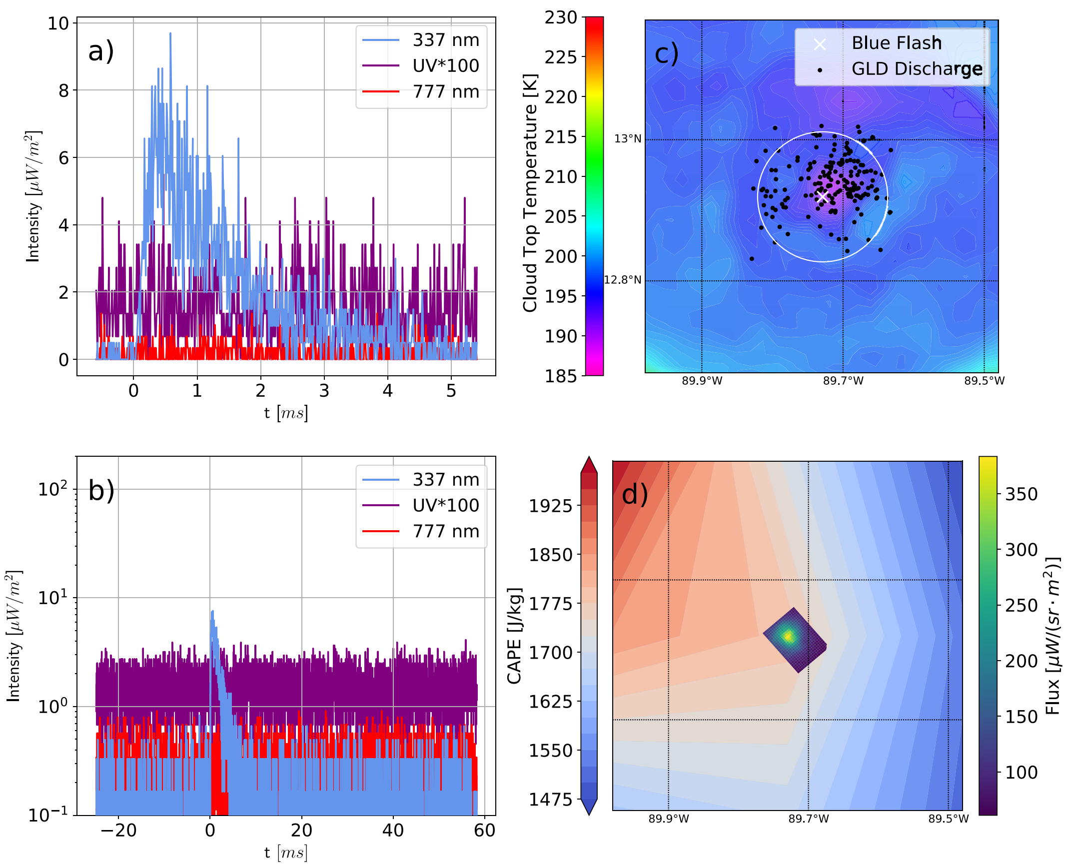

Figure 2. A slow blue discharge with a rise time of 250 μs and a duration of 2.02 ms. The cloud top temperature shows the event originating from the coldest part of the cloud and the rise time suggests an event deeper within the cloud. Panels and legend as Figure 1.

3. Results

The 11,625 blue discharges ASIM were detected from the first of July 2018 to the first of July 2021. Their geographical distribution is shown in Figure 3 where it has been smoothed by a $4 \times 4°$ boxcar convolution. The discharges are found in the three main regions of high activity of normal lightning (Kaplan & Lau, 2021), Central America, Central Africa and South East Asia which is consistent with (Soler et al., 2021). The panels of selected regions show that the occurrences tend to be near the edge of mountains or near the coasts, particularly noticeable along the Andes mountain range. The influence of coastline and mountain topography on convection in systems that generate blue discharges will be further discussed in Section 4.

The distribution of the pulse rise times is shown in Figure 4a with the irradiance and intensity of the events shown in Figure S3 in Supporting Information S1. There appears to be two populations, one is fast pulses with rise times less than 40 μs and one is slower with longer rise times. Of the 11,625 discharges, the fast population has 715 events (6.2%). The distributions of the discharge duration of the two populations are shown in Figure 4b. We see that the fast discharges extend to about 1 millisecond and the slower discharges to 2–3 milliseconds.

As mentioned earlier, the rise times of the optical pulses reflect how deep the discharges are in the cloud. We estimate the cloud depth L from the formula of Soler et al. (2020) as a starting point. Since peak attenuation in 337 nm is ~0.01% for expected values of N_{ice} (See Figure S4 in Supporting Information S1 and Luque et al. (2020)), we neglect absorption and have

$$I(t) = \frac{I_m}{\left(\frac{3}{2}\frac{t}{\tau}\right)^{\frac{3}{2}}} \exp\left(\frac{3}{2} - \frac{\tau}{t}\right) \tag{1}$$

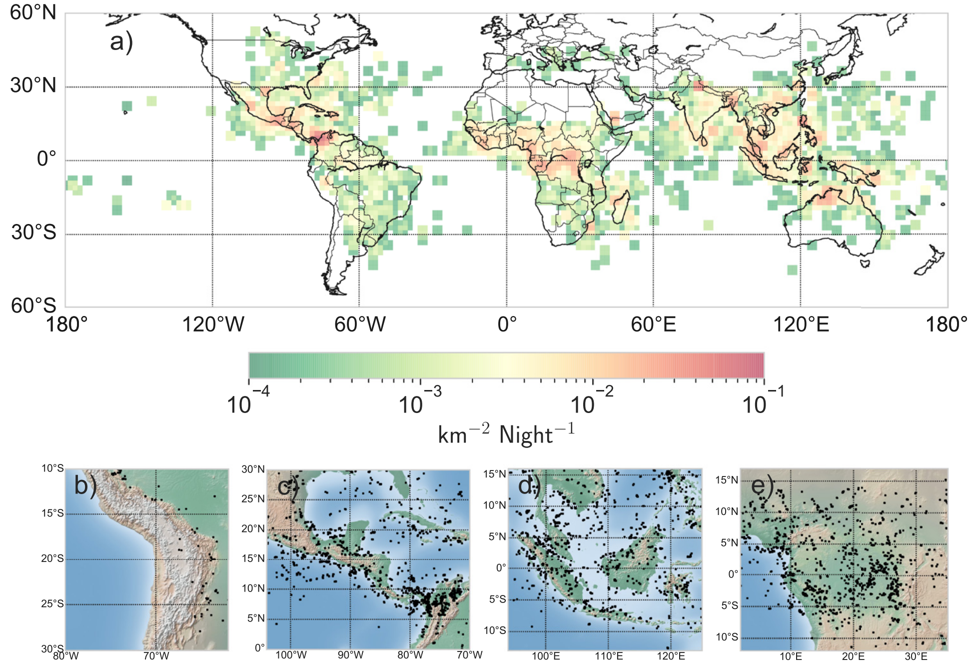

Figure 3. The global distribution of blue discharges detected by ASIM normalized by observation time with smoothing, see Figure S5 in Supporting Information S1 for unsmoothed distribution. (a) The global distribution in 2° × 2° bins in the region covered by the ISS. (b–e) Zoom to selected regions showing events with black markers.

where I_m is the maximum photon intensity, D is the diffusion coefficient for photon scattering and $\tau = \frac{L^2}{4D}$ (See Text S3 in Supporting Information S1 for the derivation). From this we can see the maximum is reached when $\frac{\tau}{t} = \frac{3}{2}$. Using the exponential of this function the 10%–90% rise time may be approximated as $T_r \approx 0.297\tau \approx 0.0742\frac{L^2}{D}$. The cloud depth is then

$$L = \sqrt{\frac{DT_r}{0.0742}} \quad (2)$$

With $D = 7.5 \times 10^9 \mathrm{m}^2\mathrm{s}^{-1}$ (Soler et al., 2020). The distribution of the cloud depths estimated from the rise times is shown in Figure 4c. The fast events have an estimated cloud depth of 1–2 km while the slower events are at 2–5 km though with significant uncertainties. As we discuss in Section 4, this is consistent with altitudes of negative NBEs at the cloud tops and positive NBEs primarily at some kilometers inside the clouds (Liu et al., 2018; Lyu et al., 2015).

The above method is dependant on a diffusion coefficient assumed to be constant for all discharge configurations. To eliminate the variability on this parameter, which indeed depends on the ice crystal density and size distribution (Luque et al., 2020), we suggest an alternate method for calculating the cloud depth of the events when possible. Starting from equation 30 in Luque et al. (2020) the flux of photons without absorption is:

$$\Phi(x, y) = \frac{L}{2\pi(L^2 + x^2 + y^2)^{\frac{3}{2}}} \quad (3)$$

corresponding to how a pulse will look like in the ASIM camera image. Integrating this along one direction in space yields $\bar{\Phi}(x) = \frac{L}{\pi(L^2+x^2)}$. This function has a Full Width Half Maximum (FWHM) of $2L$ and allows to calculate the cloud depth of an event using the MMIA meta-data which contains the sum of pixel values along the rows and columns of the MMIA camera. This method has several advantages over the previous method, in particular it is independent on the assumption on the cloud composition and its resolution is 200 m ($\frac{1}{2}$ MMIA pixels on ground). Unfortunately it requires that there is only one peak in the MMIA blue camera and one peak in the MMIA blue photometer. Therefore it can only be applied to about 13% of the blue discharges (1511 events

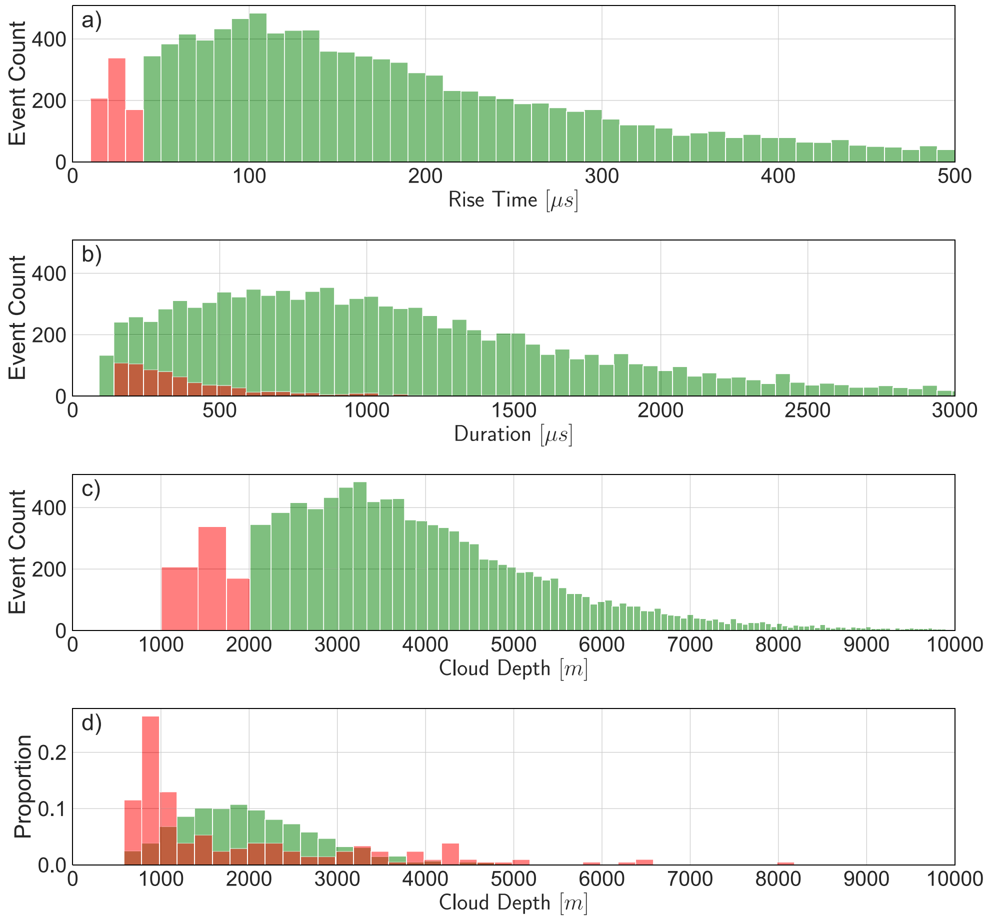

Figure 4. Rise time and duration of all blue discharge observed in the 3 years (1 July 2018–1 July 2021) interval with binsizes of 10 and 50 μs, respectively. Red colored bins indicate a fast blue discharge with rise time less than 40 μs and green a rise time greater than 40 μs. (a) The rise times for the blue discharges, with medians for the two distributions at 20 and 170 μs. (b) Distribution of the duration of blue discharges, resulting in a median of 1 ms. (c) The calculated cloud depth of the event sources given the detected rise times, the medians of the two distributions have cloud depth of 1.4 and 3.2 km respectively. (d) The cloud depth calculated from the camera image using a subset of the available events showing a peak for the fast events at 0.8 km, binsize is 200 m. The two peaks indicate two separate types of events, one at cloud tops close to the tropopause with a fast rise time and another originating deeper into the cloud system with a correspondingly lower rise time.

with 208 fast and 1303 slow). Doing this, we see that the fast blue discharges come from about 0.8 km into the cloud while the slower discharges come from about 2 km into the cloud. Recall that the previous method used a diffusion coefficient of $7.5 \times 10^9 \mathrm{m}^2\mathrm{s}^{-1}$ which is based on the assumptions on the ice particle density and radius from (Soler et al., 2020). Comparing Figures 4c and 4d we see that the diffusion coefficient might be too high and that using a value of $2.5 \times 10^9 \mathrm{m}^2\mathrm{s}^{-1}$ gives a better correlation between the two methods as presented in Figure S6 in Supporting Information S1.

To determine if a relation exists between the fast blue pulses and CTT, the blue discharges have been clustered into cloud cells via density clustering. Each cluster, or cell, contains between 1 and 120 blue discharges. Every cluster is classified as containing only slow blue discharges or both fast and slow blue discharges to see if the cells differ in either CTT or CAPE. 4495 events come from cells generating both fast and slow events while 7130 events come from cells generating only slow events. Given an average uncertainty on the CTT of 7.5 K (Landolt et al., 2004), and knowing that we have 50 to 150 events per bin of 1° width we estimate the uncertainty on the histogram in Figure 5a to be about ± 1 K $(7.5/\sqrt{50} \approx 1)$. When an overshooting top occurs, a part of the cloud cell expands above the tropopause height which cools it below the tropopause temperature. A CTT below the tropopause temperature can therefore be used to characterize an overshooting top and as we can see in Figures 5a,

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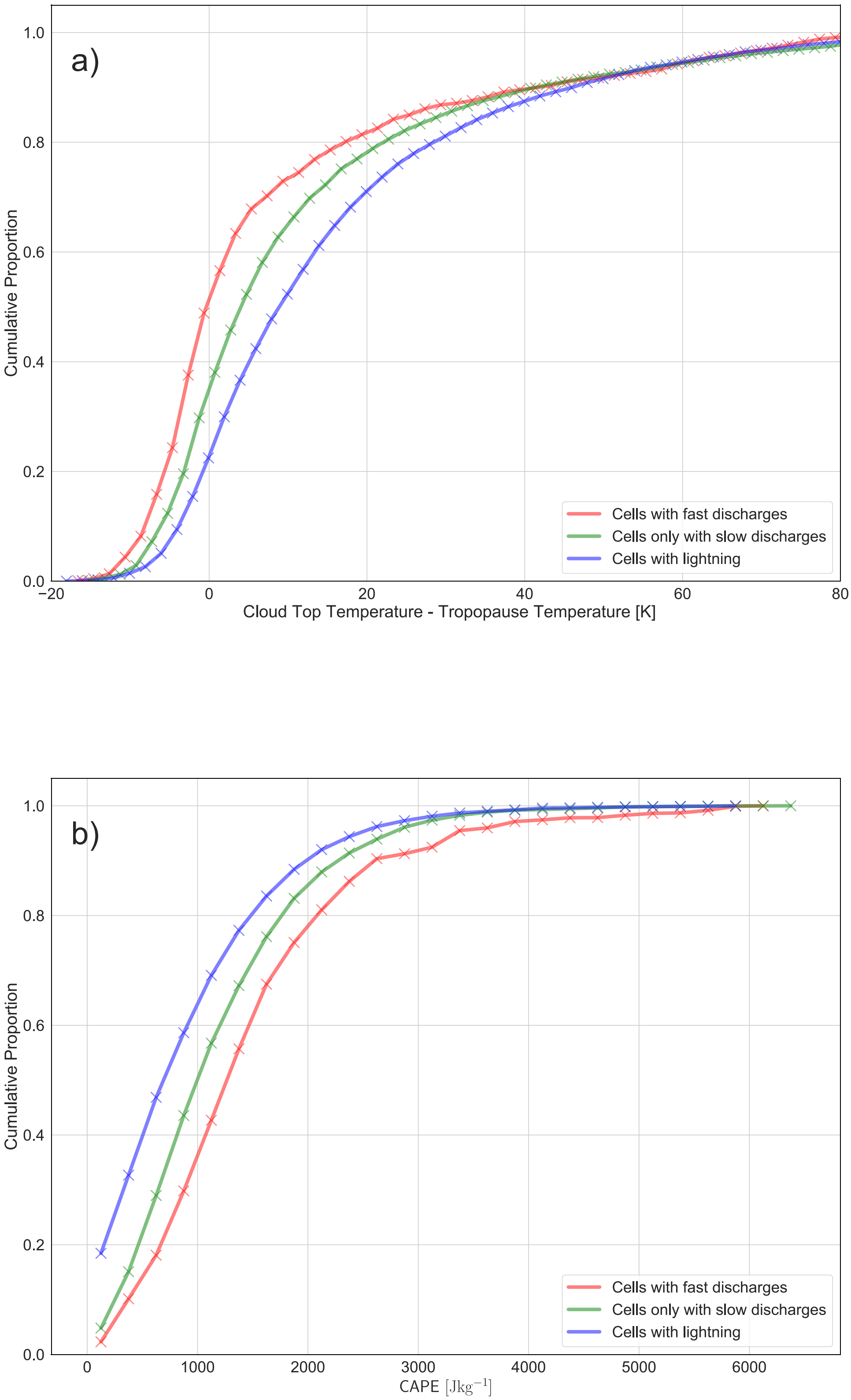

Figure 5.

44%–54% (1987–2431 events) of cells which generate fast blue discharges come from overshooting tops. For the cells only with slow discharges 27%–36% (1955–2536 events) are overshooting while cells containing only lightning consists of 16%–23% (1560–2254 events) overshooting tops. Both cells generating fast blue discharges and cells generating only slow discharges are significantly more likely to be overshooting tops than regular lightning cells. There is a clear link between the both the fast and the slow blue discharges and overshooting tops, with both classifications showing that the discharges are significantly more likely to come from overshooting tops than regular lightning. Given the proportion of cells with fast discharges associated with overshooting tops the cells are likely to be linked to more severe weather systems than that of cells only with slow discharges. However, both types are also associated with more severe weather than that of lightning.

Figure 5b shows that by clustering the blue discharge data set as previously, cells which generate fast blue discharges have a median CAPE of 1390 Jkg^{-1} compared to 1128 Jkg^{-1} for cells generating only slow blue discharges, further indicating that stronger cells are more likely to generate fast blue discharge. For comparison, the median CAPE for regular lightning is 816 Jkg^{-1}. In particular the distributions differ around the low CAPE regime, wherein regular lightning is relatively common while the blue discharges are significantly rarer. A CAPE greater than 2000 Jkg^{-1} usually indicates deep convection. Cells generating fast blue discharges have 25% occur in the region of deep convection. For cells generating only slow blue discharges it is 17% while for regular lightning, only 10% of the events have a CAPE greater than 2000 Jkg^{-1}. Therefore, there is a strong link between deep convection and the generation of blue discharge events. All parameters presented here suggest that both fast and slow blue discharges are favored by more severe weather than that required for lightning strokes.

4. Discussions and Conclusion

The catalog presented here is the first of its kind to compare blue discharge cell systems with the meterological parameters of the cloud they originated from. To further the understanding of how lightning is triggered in clouds, it is important to determine if these systems are significantly different from those generating only regular lightning.

The geographical distribution of events show clear correlations between regions with higher average lightning activity and blue discharge generation. Furthermore, the blue discharges are usually generated near the coasts or near the ridges of mountains except in the central Africa region. There blue discharge events occur relatively evenly everywhere likely due to the extremely high atmospheric instability. Coastal regions are areas of significant atmospheric instability and it has been shown that the exact topography of the land-sea contrast can have large effects on the convection initiation in those regions (Bai et al., 2020). It is therefore likely that the relatively higher instability and propensity for convection is the cause of the abundance of blue discharges observed near coasts. While the link between mountains and convection is less well characterized, it is known that the topography of mountain ranges have an important role in understanding the properties of local convection (Kirshbaum, 2011; Serafin & Zardi, 2010). Furthermore the Andes mountain range is known to have a significant effect on the deep convective processes of South America (Insel et al., 2010). Both the fast and slow blue discharges appear to require the deep convective processes which are found mainly in areas with strong contrasting topography such as mountain ranges and coastlines as well as a moist environment.

Studies show that blue discharges are linked to NBEs which are known to occur at different cloud depths depending on the polarity of the NBE as is seen in this separate distribution of rise times of the blue discharges (Liu et al., 2018). A subset of blue discharges are likely a result of NBE events with a significant part of the shallow events coming from negative NBEs. The strong separation between the cloud depths as determined by the rise time distribution indicate that they are two separate types of events. It might be intriguing if we consider only the light scattering phenomenon as in that case the optical depth would increase regularly. However, if we consider the charge distribution we can expect a sharp transition between the two top charge layers and this would explain the separation of the two populations that we observe.

Figure 5. Cumulative distribution of CAPE and CTT difference of the blue discharges compared to regular lightning detected by MMIA normalized by total number of events. Individual blue discharge observations are clustered into cells via density clustering and considered coming from a cell generating fast blue discharges if there is at least one fast blue discharge in its cell. Of the cells generating fast blue discharges, 50% are overshooting tops, compared to 34% of the cells only with slow discharges. Cells containing only lightning consists of 21% overshooting tops. About 25% of cells with fast discharges occur during deep convection (CAPE greater than 2000 Jkg^{-1}), compared to 17% of cells only with slow discharges and 10% of lightning cells.

The first peak in the rise times is associated with negative NBEs and it is likely that the second peak contains many positive NBEs. This is further suggested by the large proportion of fast and slow blue discharges associated with overshooting tops. NBEs are often associated with overshooting tops and severe weather which is supported by the data presented here (Liu et al., 2021; Monette et al., 2012).

We have presented the first data set of blue discharges which compares important meteorological parameters of clouds producing these events with those of clouds producing only regular lightning. By inspecting the rise time distribution of the events, we see two separate event types characterized by the cloud depth of their source, strongly indicating a link between blue discharges and NBEs. Understanding how the generating systems differ from systems which produce only lightning is an important step in expanding the understanding of the deeper mechanisms which cause the blue discharges and therefore how lightning triggers in clouds.

Data Availability Statement

Data supporting this research are available at https://asdc.space.dtu.dk, with agreement from the ASIM Facility Science Team (FST), and are not accessible to the public or research community. Interested researchers should submit a research proposal to the FST through asdc@space.dtu.dk. GLD360 data may be obtained through agreement with VAISALA. ERA5 reanalysis data download and instructions are available at https://www.ecmwf.int/en/forecasts/datasets/reanalysis-datasets/era5 for registered users. All satellite images used can be accessed using MCFetch for registered users, with instructions available at https://mcfetch.ssec.wisc.edu/.

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