Characteristics of upward lightning from a 325-m-tall meteorology tower

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ABSTRACT

Comprehensive observations of lightning flashes striking at a 325-m-tall meteorology tower were conducted in Beijing, China, during the summer of 2012. The images from high speed camera and normal video camera and the measurements of electric field changes were examined to investigate the characteristics of upward negative lightning initiated from the tower. Among eight upward lightning flashes documented during two thunderstorms, four were self-initiated events without lightning activity nearby prior to their initiation, two were triggered by the nearby positive cloud-to-ground lightning (+CG) with the initiation of the upward leaders from the tower lagged 0.4 ms and 5 ms behind, respectively, and the remaining two were triggered by nearby intra-cloud lightning activities. The average 2-D speed of the upward positive leader was $1.0 \times 10^5$ m/s within several hundred meters above the tower tip. When the upward lightning occurred, the tower was swept by a radar echo zone with not very strong peak intensity of about 35–45 dBZ, which exhibited as a secondary convective area in the trailing stratiform region of the mesoscale convective system. The vertical cross section revealed a relatively low altitude of the radar echo center, indicative of a low charge center of the cloud which was favorable for initiating tower lightning.

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CG flash

1. Introduction

Upward lightning initiated from tall buildings or towers has received increasing attention in recent years, on account of the increase of high structures, in particular, large buildings and windmills all over the world (e.g., Fuchs et al., 1998; Miki et al., 2005; Flache et al., 2008; Wang et al., 2008; Pichler et al., 2010; Lu et al., 2012; Warner, 2012; Zhou et al., 2012). This type of lightning discharges generally start with the initiation of upward leaders from the top of tall structures, then the leaders propagate toward the cloud and result in an initial continuous current. After the current cutoff of the channel, downward dart leaders and subsequent return strokes may occur (and sometimes not). The vast majority of upward flashes are negative discharges lowering a negative charge from the cloud to the ground. Diendorfer et al. (2011) examined the upward lightning from the Gaisberg Tower in Austria during 2000–2009, finding that 94% of the 651 upward lightnings were of negative polarity, and the remaining 4% and 3% were positive and bipolar, respectively.

The propagating features and triggering mechanism of upward leaders are of great significance in the investigation of upward lightning. The early studies on 20 upward positive leaders from the Empire State Building revealed a mean propagating speed of $2.5 \times 10^5$ m/s (McEachron, 1939). The later research also found that the speeds of the upward leaders generally ranged between $10^4$ m/s and $10^6$ m/s (Berger and
Berger and Vogelsanger (1969) attributed the high electric field for upward leader initiation to the in-cloud discharge (prior to the upward lightning) which could cause a rapid electric field change, rather than the cloud electrification with a slower process of charge buildup. However, Orville and Berger (1973) observed an upward lightning flash which was most likely triggered by a high electrostatic field, as there was no optical evidence showing the occurrence of a triggering flash. In Japan, both possibilities of initiating the upward leaders were confirmed.

Wang et al. (2008) firstly suggested a classification (“other-triggered” and “self-triggered”) of the upward flashes, based on whether or not they were triggered by prior lightning activity near the high structure. Warner et al. (2012a) analyzed the data observed during 2004–2010 for the upward lightnings from 10 towers at Rapid City, South Dakota, USA, and found that most of the upward lightning involved preceding flash activity, especially the +CG stroke. They interpreted that the triggering of the upward leader (by +CG stroke) was due to the negative field change caused by the return stroke traveling up through the flash channel network or the negative leader horizontally approaching the tower after the stroke reached the channel extremity at the upper region. Zhou et al. (2012) studied the upward lightning at the Gaisberg Tower during 2005–2009. Of the 205 samples, 87% belonged to the “self-initiated” type whereas 13% belonged to the “nearby-lightning-triggered” type. The relatively low charge region of thunderstorm in non-convective season and being considerably higher of the Gaisberg Mountain than the surrounding terrain, which lead to a field enhancement, were considered to be the main factors that result in the dominance of “self-initiated” upward lightning at the Gaisberg Tower.

Warner (2012) analyzed the radar echo upon the occurrence of the upward lightning. The results indicated that the tall towers were generally located in the area with a relatively weak echo intensity, while the triggering flashes (+ CG or cloud discharge activity) could be located inside, on the edge of or sometimes outside the echo cell with strong reflectivity. It is reasonable that the charge structure of the thundercloud may significantly influence the upward lightning behavior, not only its initiation, but also the channel formation and the discharge process.

In the summer of 2012, comprehensive observations were conducted concerning the lightning flashes initiated from a 325-m meteorology tower in Beijing, China. In this paper, optical observations by high speed camera and electric field measurements by BLnet (Beijing Lightning Observation Network) were used to study the characteristics of upward lightning from the tower. The corresponding cloud structure was also briefly analyzed based on the radar echo data.

2. Experiment and data description

The meteorology tower, with a height of 325 m, is located at the Institute of Atmospheric Physics (IAP), Chinese Academy of Sciences, Beijing, China. Fig. 1 shows a picture of the tower and map of the observation sites around the tower. The optical observation system, including a normal video camera and a high speed camera, was located at the 9th floor (about 30 m above ground) of IAP 40# building, 910 m apart from the tower. The normal video camera with a spatial resolution of 720 × 576 pixels was connected to a computer and controlled by dedicated software with a window trigger mode and a data recording length of 1 s. The high speed camera Fastcam SA1 was operated at 10,000 fps with a spatial resolution of 960 × 528 pixels. A single pixel of the high speed images is equivalent to an area of 1.25 × 1.25 m² at the distance of the meteorology tower. The electric field changes produced by the upward lightning were detected by the Beijing Lightning Observation Network (BLnet). Fast and slow antennas, with an upper frequency response of 5 MHz and 2 MHz and a time constant of 1 ms and 3 s, respectively, were installed at ten sites, as shown in Fig. 1. An S band Doppler radar located at 20.3 km away, southeast to the tower, provided the radar echo data of the thunderstorm, with a monitoring radius of 230 km. The radar completes routinely a volume scan in every 6 min.

Eight upward lightning flashes initiated from the tower were observed during the summer of 2012, the corresponding optical images and electric field change data were analyzed in detail to investigate the characteristics of the lightning discharge, and the radar echo data were also used for a discussion on the thunderstorm intensity during which the upward lightning occurred.

3. Analysis and results

Table 1 shows the general properties of eight upward lightning flashes observed during two thunderstorm systems on June 21 and September 27, respectively. Here the flashes were named by the local time of their occurrence (e.g. the flash 0621_2212 occurred at 22:12, June 21). All the lightning flashes lowered negative charges to the ground, which were initiated with an upward positive leader from the tower tip that propagated toward the charged cloud. Six of these flashes only involved the initial continuous current without any subsequent return strokes, and the remaining two were multi-stroke flashes with the dart leader traversing the primary channel to the ground after the current cut off of the initial stage. The triggering mechanism of these eight lightning flashes was examined carefully. Four of them were found to be self-initiated without any lightning activity prior to the initiation, two were triggered by the nearby positive cloud-to-ground lightning (+CG), while the remaining two were triggered by the nearby cloud lightning activities. Based on the lightning channel patterns revealed by the optical images, the upward lightning flashes can be divided into two types: those involved just a single channel within the field of view of the camera (about 200 m above the tower tip), as shown in Fig. 2a, and those branched immediately from the tower tip, as shown in Fig. 2b. As indicated in Table 1, there seems to be a relationship between the triggering mechanism of the upward lightning and complexity of the channel development. That is, the self-initiated lightning corresponded to the “branched” type while the other-triggered one corresponded to the “single-channel” type, except for lightning 0927_1354. This will be discussed in the following section.

3.1. Initiation and leader propagation of upward lightning

Fig. 3 shows the images of the upward lightning 0621_2225 triggered by a nearby cloud-to-ground lightning flash. As revealed by the electric field change waveform shown in
This CG flash was of positive polarity. The strike point of this +CG flash was within 2 km from the tower, as estimated by a time difference of 5–6 s between the thunder and light at the camera site and a known distance of 910 m between the tower and the camera. Fig. 3a shows the frame just prior to the occurrence of a return stroke of the +CG flash. The downward positive leader which was propagating to the ground with a single channel exhibited relatively

Table 1
General properties of the upward lightning flashes initiated from the meteorology tower.

<table>
<thead>
<tr>
<th>Date</th>
<th>Flash no.</th>
<th>Polarity</th>
<th>Number of RS</th>
<th>Triggering mode</th>
<th>Channel pattern</th>
</tr>
</thead>
<tbody>
<tr>
<td>2012/06/21</td>
<td>0621_2212</td>
<td>Negative</td>
<td>0</td>
<td>Other-triggered (+CG)</td>
<td>Single channel</td>
</tr>
<tr>
<td></td>
<td>0621_2225</td>
<td>Negative</td>
<td>0</td>
<td>Other-triggered (+CG)</td>
<td>Single channel</td>
</tr>
<tr>
<td>0927_1354</td>
<td>Negative</td>
<td>0</td>
<td>Self-triggered</td>
<td>Single channel</td>
<td></td>
</tr>
<tr>
<td>0927_1402</td>
<td>Negative</td>
<td>0</td>
<td>Self-triggered</td>
<td>Branched</td>
<td></td>
</tr>
<tr>
<td>0927_1405</td>
<td>Negative</td>
<td>6</td>
<td>Self-triggered</td>
<td>Branched</td>
<td></td>
</tr>
<tr>
<td>0927_1408</td>
<td>Negative</td>
<td>0</td>
<td>Other-triggered (CC)</td>
<td>Branched</td>
<td></td>
</tr>
<tr>
<td>0927_1411</td>
<td>Negative</td>
<td>6</td>
<td>Self-triggered</td>
<td>Branched</td>
<td></td>
</tr>
<tr>
<td>0927_1415</td>
<td>Negative</td>
<td>0</td>
<td>Other-triggered (CC)</td>
<td>Single channel</td>
<td></td>
</tr>
</tbody>
</table>

*a “Single channel” means that the upward lightning developed a single channel within the field of view of the camera, while “branched” means that the upward lightning branched immediately from the tower tip.*
weak luminosity. Then the leader reached the ground and the return stroke of the +CG flash quickly lighted up the discharge channel in the field of view of the camera. In the fifth recorded frame after the return stroke as shown in Fig. 3c, a luminous segment emerged at the tower tip, indicating the inception of an upward positive leader. The leader sustained to propagate upward and reached an altitude of 135 m above the tower tip 1.8 ms later, as shown in Fig. 3d. It can be determined by the recorded images that the upward leader from the tower was triggered at 0.4–0.5 ms after the return stroke of the + CG

Fig. 2. Images of upward lightning: (a) event 0927_1354 with a single lightning channel appearing in the field of view of the camera, and (b) event 0927_1402 with multiple channels emerging immediately from the tower tip.

Fig. 3. Images of upward lightning 0621_2225 triggered by a nearby positive cloud-to-ground flash: (a) the frame prior to the return stroke, (b) the second frame as the return stroke occurred, (c) the fifth frame as the return stroke occurred, showing the initiation of an upward leader from the tower tip, and (d) the eighteenth frame as the return stroke occurred, showing that the upward leader had propagated to an altitude of 135 m above the tower tip.
flash. Warner et al. (2012b) proposed two hypotheses of how +CG flash trigger tower lightning. One is that the upward return stroke in the form of a negative charge density wave rapidly neutralized the positive charge deposited along the channel, the other is that the return stroke continued to develop in the form of a negative leader as it reached the upper extremity of the channel branches in the cloud. Both processes would result in transient negative enhancement of the ambient electric field, especially when the channel network was near the tower or the negative leader extension was toward the tower. Since the time interval between the initiation of the upward leader and the occurrence of the nearby positive return stroke for 0621_2212 was considerably short, it is reasonable that the first hypothesis (return stroke traversing the already channel) was the dominant causality of the upward leader initiation. As for 37 cases of upward lightning flashes being triggered by nearby +CG flashes, Warner et al. (2012a) found that the time intervals exhibited the geometric mean, maximum and minimum values of 50 ms, 267 ms and 1 ms, respectively. Here we examined another flash 0621.2212 which was also triggered by a +CG flash, and found the corresponding time interval of 5 ms, being also obviously shorter than the mean value obtained by Warner et al. (2012a).

According to the images frame by frame, the propagating speeds of upward positive leaders were calculated. Fig. 5 shows the 2-D partial speeds of the leaders of 0621.2212 and 0621.2225 (both being triggered by the nearby +CG flashes). Within an altitude of 210 m above the tower tip, the 2-D partial speeds of these two leaders were estimated to range between 0.13 and 1.5 × 10^5 and 0.4–1.6 × 10^5 m/s, respectively, exhibiting an evident acceleration during their upward extension. It is interesting to find that both leaders ascended at an average speed of 1.0 × 10^5 m/s, which is consistent with the study of McEachron (1939) and Berger and Vogelsanger (1969) for the upward leaders from the Empire State Building and towers at Monte San Salvatore, respectively. Takagi et al. (2006) studied nine upward positive leaders from two windmills and their lightning protection tower in winter thunderstorm. Five samples exhibited the average speed on the order of 10^6 m/s and the rest four on the order of 10^5 m/s, with the minimum speed being 3.9 × 10^5 m/s, which is larger than the result of this study.

As shown in Fig. 4b, the electric field change exhibited somehow chaotic waveform upon the initiation of the upward

![Fig. 4. Electric field change due to the +CG flash and the relevant upward lightning flash 0621.2225: (a) the waveform on 0.7 ms timescale showing the positive return stroke (+RS) of the CG flash, and (b) time expanded waveform as the upward lightning initiated from tower, 0.4–0.5 ms after the +RS. (The waveform was detected at site "SY", 20.7 km away from the tower).](image1)

![Fig. 5. Evolution of 2-D partial speeds of upward positive leaders of flashes 0621.2212 and 0621.2225.](image2)

![Fig. 6. Electric field changes at 910 m during the very initial stage of the upward positive leader of 0927.1402.](image3)
positive leader of flash 0621_2225 from the tower, which was
due to the discharge processes of both the positive return
stroke and the upward leader. In order to avoid the possible
influence of the nearby discharge process, and investigate only
the electric field that was produced by the upward leader. Fig. 6
shows the electric field change waveform of a self-initiated
upward flash 0927_1402, which was detected at 910 m away
from the tower with respect to the very initial stage of the
leader. As shown in the figure, the electric field waveform
exhibited a positive slope, indicating a transportation of
positive charge into the newly formed leader channel. The
time expanded waveform showed that several pulses were
superimposed on the positive slope, with the time intervals
of the 10–50 μs, indicating a step-like process of the upward
positive leader during the initial stage as it emerged from the
tower tip. Such pulsed electric field waveform is also valid
for the other three self-initiated flashes, during the initial
stage of their leader development. This is to some extent similar
to the upward positive leaders in rocket triggered lightning,
which resulted in the pulsed channel base current and the
associated E-field pulses that superimposed on the positive
slope (Willett et al., 1999; Wang et al., 2012; Jiang et al., 2013),
and accordingly, with the leader steps being imaged (Biagi et
al., 2011). Since in this study, three self-initiated upward flashes
branched immediately from the tower tip while the other one
did not, it is not sure whether the electric impulses were related
to the branches. On the other hand, Warner et al. (2013) found
that the upward positive leaders with weak luminosity usually
involved luminous steps if they did not branch immediately
from the tower tip, and these steps were more irregular than
the negative leader steps observed by the same high speed
camera (54000 fps). This is not really the same with the result
above. Nevertheless, by combining the observation of Warner et
al. (2013) and this study, it seems that in the tower initiated
lightning, the stepwise (or step-like) development is possibly a
common phenomenon for the upward leaders during their very
initial stage as they emerge from the tower tip.

Regarding the propagation of the upward positive leaders
in tower-initiated lightning, Wang and Takagi (2012) observed
luminous pulses by using ALPS (Automatic Lightning
Progressing Feature Observation System). They found that
the rise time of those optical pulses were more than ten
times longer than the negative leader steps, and for emphasis
of such difference, they termed those optical pulses as LVEs
(luminous-variation-events). In this study, by checking the
observed electric field data, we found the rise time of the
E-field pulses to be ranged mostly between 0.4 and 0.6 μs.
Although this result is longer than that of the negative stepped
leaders with a typical rise time of 0.2–0.4 μs (based on the
same E-field sensor), it is still considerably short, which
tends to support the speculation of a step-like development
during the very initial stage of the upward positive leader.
Nevertheless, for a more solid confirmation, additional
detailed observations including channel current and optical
images with a faster time resolution are expected.

3.2. Characteristics of radar reflectivity

Fig. 7 shows the radar reflectivity of the thundercloud on
September 27 when the upward lightning occurred. As indi-
cated by the overall view of the radar echo, the tower was not
located in the severest convective region of the whole thunder
system. Two strong centers with the radar echo intensity up to
60 dBZ (convective region with the maximum reflectivity of
60 dBZ) were located in the southwest and east to the tower,
respectively, with the distances of more than 50 km from the
tower. The whole mesoscale convective system (MCS) exhib-
ted a general movement direction from the northwest to the
southeast, and the tower was just under the trailing stratiform
region with considerably weaker intensity of the radar echo.
When the tower-initiated upward lightning occurred, a
radar echo zone with peak intensity of about 35–45 dBZ was
covering the tower, exhibited as a secondary convective area in
the trailing region of MCS. As shown in the expanded view of a
radar echo in Fig. 7b, the tower was located under the southern
development of this secondary convective area at 13:54, around which
time the first upward lightning flash occurred, then this area
swept the tower. At 14:12, the tower was under the northern
development, as shown in Fig. 7c. Fig. 8 further gives the vertical cross
section of the radar echo through the white line in Fig. 7. When
the upward lightning occurred, the thundercloud was observed
to involve small rainfall intensity, due to not very strong
convection of the trailing stratiform region. It is clear in Fig. 8
that the height of the intensity center of the radar echo
(40 dBZ–45 dBZ) at the tower region was only about 2–3 km,
which is relatively low. Generally, the trailing stratiform cloud
does not involve very intensive lightning activity, which was
also observed in this study. However, the cloud would still carry
a certain number of charges, as transferred from the convective
region and generated by the weak convection inside the cloud
(Carey et al., 2005; Liu et al., 2013). In association with the low
altitude of the radar echo center and with the small updraft in
the region, the charge density of the cloud would consequently
exhibit a low center. Such situation is favorable for initiating
upward lightning from the tall tower. Note that on September
27, among the six upward lightning flashes that occurred
during a 20 minute interval, four were of the self-initiated type,
and none was triggered by the nearby CG lightning. This may be
due to that firstly, there were scarcely +CG flashes that
occurred at the area around the tower during the period, and
secondly, the lightning activity of the thunderstorm was less
active during the dissipating stage, which contributed to the
sustaining and the slow enhancing of the thunderstorm electric
field.

4. Discussion

The preceding occurrence of natural lightning activity in
the vicinity of the tower is a primary inducement of the
upward lightning initiated from the tower. These nearby
discharge processes resulted in a transient environmental
electric field change which would be significantly enhanced
at the top of the tower due to the field distortion. As the electric
field exceeded the threshold, leader breakdown occurred,
which finally developed into a sustained upward leader. This
scenario, of course, would be further influenced by the height
of the tower, the condition of the surrounding terrain, the
polarity and orientation of the discharge process, and the
distance between the tower and the discharge location, etc.
Observations indicated that the CG flashes triggering the
upward lightning from the tower were generally of positive
polarity, with the triggered upward lightning being of negative
polarity (Warner et al., 2012a; Zhou et al., 2012), which is the same as the two cases studied in this paper. There was only one case observed at the Gaisberg Tower that a $-$ CG flash triggered a tower discharge (Zhou et al., 2012).

Fig. 9 shows the images of a CG flash with the striking point being also not far from the tower. Based on the electric field change waveform observed by the BLnet, this flash was a single-stroke $-$ CG flash. The frame just prior to the return stroke of this flash (in Fig. 9a) shows that the negative leader was descending with two branches, marked as “Ch1” and “Ch2”. Fig. 9b, c shows the first and second frames just after the occurrence of the return stroke of the $-$ CG flash which was induced by the leader branch “Ch2” as it reached the ground. The return stroke quickly propagated upward and lighted up the leader channel. Meanwhile, the area around the tower tip was unaltered, without any observation of intermittent luminous events which may be associated with the initiation of the upward leader. In the following images, as the grounded stroke channel became faint and finally invisible, the tower tip remained unaltered consistently. As inferred by the time difference of also about 5–6 s between the thunder and the light at the camera site, the distance between the tower and the $-$ CG flash was similar to (or even closer than) that for the $+$ CG flash shown in Fig. 3.

The return stroke of the $-$ CG flash, propagating in the form of a positive charge density wave, would quickly deplete the negative charge in the lightning channel and in the cloud. When it reaches the upper channel extremity, it may continue to propagate as a positive breakdown in the cloud. In this situation, if the tall tower initiates a lightning discharge, it should theoretically start with an upward negative leader, and consequently, a lower positive charge from the cloud to ground. Such a conceptual process involves much lower possibility than that nearby $+$ CG flashes triggering upward lightning from the tower, as judged by the comparison in this study, and by that vast majority of the reported CG flashes which triggered tower lightning were of the positive polarity (Warner et al., 2012a; Zhou et al., 2012). Generally, $+$ CG flash
involves a considerably larger peak current and charge transfer than $-\text{CG}$ flash. Meanwhile, the $+\text{CG}$ flash was found to possess a much larger continuing current (following the return stroke) than the $-\text{CG}$ flash (Brook et al., 1982), which is associated with the channel extension in the form of in-cloud leader propagation (Lu et al., 2009). As for the leader inception with different polarities, the laboratory experiments revealed that the breakdown process or the streamer occurring at the negative end of the electrode demands a higher threshold electric field than that at the positive end (Castellani et al., 1998), indicating an easier inception of the positive leader than the negative leader. These two factors may help explain why $-\text{CG}$ flashes are less conducive to trigger tower-initiated lightning than the $+\text{CG}$ flashes.

As mentioned above, the eight upward lightning flashes in this study likely demonstrate a relationship between the triggering mechanism and the channel pattern. In all but one case, the “self-initiated” flashes branched immediately from the tower tip, while those “other-triggered” flashes involved a single channel within the field of view of the camera. It is reasonable that for different types of tower lightning, the strong ambient electric fields sufficient for the initiation of upward leaders may not be similarly reached. For the “self-initiated” type, it was accumulated slowly due to the cloud electrification; while for the “other-triggered” type, the previous discharge processes in the cloud or between cloud and ground would result in a transient electric field enhancement. Though it is speculative, the different ways in reaching the threshold electric

![Fig. 8. Vertical cross section of radar echo through the white line in Fig. 7: (a) at 14:00, and (b) at 14:06.](image)

![Fig. 9. Images of a nearby $-\text{CG}$ lightning flash that did not trigger any discernible lightning discharge from the tower tip.](image)
field of the leader initiation, would possibly further influence the discharge behavior of the upward lightning. For a further investigation, more observations by different detecting means and the associated theoretical studies are expected.

5. Conclusion

The characteristics of eight upward lightning flashes from a 325-m meteorology tower were studied. By inspecting whether or not there was a nearby lightning activity prior to the initiation of these upward lightning flashes, it was found that four of them initiated spontaneously, two were triggered by nearby cloud lightning discharge processes, and the other two were triggered by nearby +CG flashes. The time interval between the initiation of upward leaders and the nearby return strokes of the CG flashes was about 0.4 ms and 5 ms, respectively. These two upward positive leaders both ascended at an average 2-D speed of $1.0 \times 10^5$ m/s, with the partial speeds, exhibiting an evident acceleration during the extension and ranging between $0.13-1.5 \times 10^5$ and $0.4-1.6 \times 10^5$ m/s, respectively. The upward positive leader exhibited impulsive electric field waveform superimposed on the positive slope during its very initial stage, indicating a step-like leader development. The meteorology tower was located in the trailing stratiform region with not very strong radar echo intensity when the upward lightning occurred, and a radar echo zone indicative of a secondary convective area swept the tower within a period of about 20 min. The thundercloud over the tower exhibited a low echo center of about 2–3 km, with the charge center inside the cloud being relatively low either. The environment electric field sufficient for initiating an upward leader, which was slowly built-up by the cloud electrification, or abruptly enhanced by the nearby lightning discharge, may possibly influence the discharge behavior of upward lightning.

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