Characteristics of a multi-stroke “bolt from the blue” lightning-type that caused a fatal disaster

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\textbf{ABSTRACT}

Observational data from the low-frequency electric-field detection array (LFEDA) and radar were used to study the precise location of a fatal accident caused by a lightning in Conghua, Guangzhou, China, 2017. Based on a comprehensive analysis, the lightning was concluded to be a negative “bolt from the blue” ground flash with seven return strokes. The first return stroke was on June 3 at 16:36:49.219 with a peak current intensity of $-30.9$ kA. The LFEDA system mapped the development of the lightning channel. The horizontal distance from the edge of the cloud anvil area (0 dBz) to the return stroke point was about 0.3 km, the horizontal distance from the edge of the precipitation area (18 dBz) to the return stroke point was about 1.8 km, and the return stroke channel extended as far as 3 km out of the cloud. There was no cloud cover above the head of the victim. The electric field waveform of the return strokes detected by the LFEDA system showed multi-peak characteristics, and all seven return strokes were multiple-termination strokes. The most probable mechanism for the lightning injuries was the side flash.

\textbf{1. Introduction}

In recent years, people have begun to pay more and more attention to lightning that causes casualties and property losses (Selvi and Rajapandian 2016; Hajikhani et al. 2016; Bhardwaj et al. 2017). In developed countries, lightning deaths in the last century have been significantly reduced by populations migrating from labour-intensive agriculture in rural areas to urban regions and rapid economic development that has provided better lightning protection measures (Holle 2016a). However, lightning continues to be a major meteorological cause of death and injury, with 6000–24,000
people killed and 10 times that number injured each year worldwide. Currently in the US, lightning appears as the third cause of weather fatalities: [http://www.nws.noaa.gov/om/hazstats.shtml](http://www.nws.noaa.gov/om/hazstats.shtml). Developing countries report a higher number of lightning casualties (Cardoso et al. 2014), due to the large number of industrial and agricultural labourers who work outdoors (Holle 2016a) and insufficient awareness of the hazards of lightning. At the same time, many developing countries lack of systems for accurately recording lightning deaths and injuries (Holle 2015), so their numbers should be the most conservative estimate. Dlamini (2009) analysed data on casualties from lightning strikes in Swaziland in 2000–2007 and noted that the most common lightning strikes occurred in rural homes (17%), followed by walking outdoors (16%) and under trees (14%). Navarrete-Aldana et al. (2014) found that 62.2% of deaths caused by lightning were scattered in surrounding rural areas by analysing data on lightning disasters in Colombia in 2000–2009. The highest mortality rate was in Vaupés of eastern Colombia with 7.69 deaths per million people per year, while the mortality rate for all Colombians during the same period was only 1.78 per million people per year. Shrigiriwar et al. (2014) indicted that 87% of 31 deaths from lightning strikes in the Nagpur region of Maharashtra state in India were farmers and farm workers. Dewan et al. (2017) analysed data on lightning casualties in Bangladesh from 1990 to mid-2016 and showed that 93% of lightning deaths occurred in rural areas. Lightning disasters occurred mainly during open field activities, followed by activities at home or walking in open fields.

In China, lightning is the third-deadliest meteorological disaster after rainstorms and floods. Lightning casualties reach thousands of people every year. Ma et al. (2008) analysed a database on lightning disasters from 1997 to 2006 in China and satellite lightning detection data. By studying the characteristics of lightning disasters and related factors, they found that the type of lightning disaster is closely related to the type of disaster-bearing body and that farmland has the highest lightning death toll. Zhang et al. (2011) further used the China lightning disaster database to analyse lightning disasters from 1997 to 2009 and found that, although the casualties and losses caused by lightning in China have declined since 2008, the residents in rural areas are still the main victims of lightning. Labour-intensive agriculture and living in shelters with imperfect lightning protection measures are still the main causes of lightning casualties. The most common causes of death from lightning strikes are cardiac arrest and hypoxic brain damage; such injuries to survivors of lightning strikes cannot be reversed or reduced (Holle and Cooper 2016). Many cases of lightning casualties are due to staying or choosing the wrong place as shelter under the tree during electrical storm activity. Elsom et al. (2016) analysed a lightning strike that killed two people in the United Kingdom in 2015. In this accident, the two victims were 1.7 km apart; the lightning location system could not identify whether the accident was caused by two separate flashes of lightning or from a single forked lightning flash with ground termination points at both peaks. None of the victims’ companions saw or heard lightning before the victim was hit.

Lightning generally occurs in cumulonimbus clouds with vigorous convection development. It is rare for lightning strikes to occur without thunder or clouds
overhead, but it does happen and is often referred to as a “bolt from the blue.” NOAA defines a bolt from the blue as a cloud-to-ground (CG) flash that typically comes out of the back side of a storm cloud, travels a relatively large distance in clear air away from the cloud, and then angles down and strikes the ground. Because there is a certain distance between the lightning strike point and thunderstorm cloud body of the bolt from the blue, people usually do not take any precautions to prevent lightning damage because the sky is clear overhead. However, serious casualties can easily occur. Cherington et al. (1998) used a ground flash positioning system to analyse an accident in which a single-stroke bolt from the blue struck the victim directly in the head. The lightning was probably originated from a thunderstorm about 16 km away. They examined the neurological consequences of the lightning strike on the victim’s health and the environmental characteristics of thunderstorms at the time of the accident. Very high-frequency (VHF) mapping observations showed that a bolt from the blue discharge begins as regular and upward-developing intracloud flashes in normally electrified storm (Rison et al. 1999; Thomas et al., 2001). This type of CG lightning is classified as a bolt from the blue discharge because it differs from normal negative CG lightning (Krehbiel et al. 2008). Lu et al. (2012) used a lightning mapping array (LMA) to locate 48 instances of bolts from the blue and found that this type of lightning usually has only one return stroke.

This article presents an analysis on a lightning-caused death that occurred in Conghua District, Guangzhou City, China on 3 June 2017. The precise location and approximate time of the accident came from the description of a witness. The low-frequency electric-field detection array (LEFDA), Guangdong lightning location system (GLLS), and Guangdong–Hong Kong–Macao Lightning Location System (GHMLLS) were utilised for the analysis. Based on weather radar observation data, the lightning that caused the disaster was determined to be from thunderstorm clouds that were a few kilometres away. At the time of the disaster, the sky was clear and cloudless. According to the definition of NOAA and the classification method in the above references, this lightning accident can be considered as a multi-stroke bolt from the blue fatal event. This article considers three aspects of the lightning case: the thunderstorm weather characteristics, the lightning discharge characteristics, and an analysis of the cause of death.

Figure 1. Post-disaster photos.
2. Disaster description

On the morning of 3 June 2017, Conghua District in Guangzhou City was fine with occasional clouds. In the afternoon, the weather was mostly cloudy with thunderstorms. According to an eyewitness, he and a 44-year-old man named Wu from Gaotian Village, Taiping Town, were touring farmland and a litchi forest at about 16:36 local time. There were clouds in the sky a few kilometres southwest of the two people, but the weather was clear overhead, and they were surrounded by a litchi forest, a small cluster of bamboo trees, and a small ditch. At that moment, Wu passed by a big tree and suddenly fell down and lost consciousness. The witness was less than 10 m away from the victim and was unharmed, and no thunder was heard beforehand. After the scene was investigated, no obvious lightning strike points were found. A tree about 13 m tall was located 1 m from where the victim fell to the ground; this tree was the highest point in the surrounding area. There were burn marks on some overhead branches and leaves of the tree. Another tree about 8 m tall and 4.0 metres away from the previous tree also had burnt leaves. The two trees were covered with branches and bark. There was a hat with a burnt hole at the scene that was consistent with the small hole in the forehead of the victim. Figure 1 shows two photos related with the scene after the disaster. A forensic investigation showed that the victim’s hair and clothes were burnt. The whole body was black, and there was a hole in the forehead from lightning accompanied by bleeding. The hole was surrounded by lightning striations. The victim was bleeding from his ears. The cell phone in his trousers was burned together with the victim’s skin, and the death was preliminarily identified as characteristic of a lightning strike. The witness rushed to the victim after he was struck by lightning and fell to the ground and performed artificial respiration and cardiopulmonary resuscitation. The victim did not die immediately but was not fully conscious. After the victim was sent to the hospital, he died within an hour from being stricken by lightning. Figure 2 shows a schematic diagram of the lightning accident scene.
3. Materials and methods

We extracted location data from GDLLS and GHMLLS to obtain accurate information on the time, return stroke current, and other parameters of the lightning accident to analyse the disaster process. Based on the approximate time information presented above, data on changes in the electric field were extracted from LFEDA for the corresponding period, and positioning analysis was carried out on the development process of the lightning channel.

GDLLS is a business monitoring system established by the Department of Power of Guangdong Province. It has 16 detection stations and uses orientation and time difference joint positioning technology. The positioning error of GDLLS has certain regional differences: the Pearl River Delta has high positioning accuracy, while the northern and eastern Guangdong Mountains and southwest Guangdong have somewhat poor accuracy. This is mainly related to the distribution of lightning detection stations, the distances between stations, and the terrain (Fan et al. 2004). An evaluation of the system with artificially triggered lightning showed that GDLLS has a lightning detection efficiency of about 93%, return stroke detection efficiency of about 42%, average positioning error of about 760 m, and relative error of the peak current inversion of the lightning stroke of about 14% (Chen et al. 2009).

GHMLLS is a business monitoring system established by the meteorological departments of Guangdong, Hong Kong, and Macao in 2005. Since September 2012, it has had 17 detection stations. The system applies the direction and time difference integrated positioning method to detect the longitude and latitude, GPS time, lightning current amplitude, and polarity of the CG lightning return stroke in real time. A comparison of the results for lightning observation tests showed obvious improvements in the detection efficiency and positioning accuracy of GHMLLS after the number of detection stations was increased in 2012. The system has a lightning detection efficiency of 97%, ground flash return stroke detection efficiency of 91%, and average positioning error of 600 m. The estimated peak current of the return stroke was shown to have a systematic error (Zhang et al. 2016).

LFEDA comprises 10 electric field change detection substations distributed in and around Conghua. Figure 2a shows the layout of the station network. Each station can record changes in the waveform of the electric field and locates the pulse of the change in waveform with a lightning electric field by the time of arrival (TOA) method. The system was completed by the Chinese Academy of Meteorological Sciences in 2015 and is mainly used for lightning physics and thunderstorm electricity research. The change in electric field probe at each station uses the traditional fast electric field change measurement instrument for lightning (fast antenna) (Kitagawa et al. 1960). It has a bandwidth of 160–600 kHz, time constant of 1 ms, and synchronization between different stations by a GPS clock with a time precision of 50 ns. The acquisition device has a sampling accuracy of 12 bits, sampling rate of 10 MHz, sampling time of 1 ms, and pre-trigger time of 20%. The system has detection efficiencies for artificially triggered lightning and return strokes of 100% and 95%, respectively, and it can be used to describe the development process of lightning (Shi et al. 2017). After the positioning algorithm was improved, the system was proven to be able to depict the lightning development channel in fine detail with an increased positioning accuracy of less than 60 m (Fan et al. 2018).
The radar data for the analysis of the lightning process came from the Panyu meteorological radar station in Guangzhou, which is a Doppler weather radar operating from 2001. The radar station is about 70 km away from the location of the lightning accident, and it completes the body scanning process every 6 min.

Fuelberg et al. (2014) measured the horizontal development distance of different types of lightning channels that extend from a thunderstorm cloud; three are used for the ground flash process, and three are used for the cloud flash process. There are two ways to measure the horizontal development distance of a lightning channel: the horizontal distance from the edge of the anvil to the lightning strike point (0 dBz) or from the edge of the precipitation area (18 dBz) to the lightning strike point. Ward and Merceret (2004) defined a cloud body as having an edge characterized by a thin stratiform cloud with a radar echo of 0 dBz. Merceret et al. (2005) and Punkka and Bister (2005) proposed that the precipitation area were defined as the area of a cloud with a radar echo that is greater than 18 dBz.

4. Analysis and results

4.1. Lightning time confirmation

At noon on 3 June, the weather was clear in most areas of Conghua District in Guangzhou and cloudy in some areas. The 500 hPa height field had a westerly
shortwave trough crossing eastward. The 850 hPa height field was controlled by the southwest wind field. The ground was controlled by a low-pressure trough. Weak cold air infiltration caused unstable weather, and the heat flow in the afternoon easily stimulated the thunderstorm process.

According to the Panyu weather radar in Guangzhou, scattered thunderstorm clouds began to move from Baiyun District to Taiping Town in Conghua District at about 16:40 on 3 June and moved out to Taiping Town at 17:30. According to monitoring data from the nearest automatic weather station (Taipingfeie station in Gaotian Village), Taiping Town recorded 0.5 mm of precipitation at 16:50 and 8 mm of precipitation at 17:30.

Figure 3 shows the ground flash location data between 16:30 and 17:00 for a 1 km radius around the victim. Within this spatiotemporal range, GDLLS detected nine negative ground flash return strokes. According to the spatiotemporal relationship between the locations of the lightning (Shao et al. 2006), they were determined to come from three lightning discharge events. One lightning event had seven return strokes; the other two lightning events occurred after 16:50, and each contained a single return stroke. GHMLLS detected eight negative return strokes in the same spatiotemporal range. According to the above criteria, they were determined to belong to three different lightning discharges. One lightning process included six return strokes, and the other two ground flashes coincided with the times detected by GDLLS. The multi-stroke flash process detected by the two lightning location systems occurred at 16:36:49 on 3 June 2017, which coincides with the time described by the witness.

The first return stroke in the lightning discharge recorded by GDLLS occurred at 16:36:49.219 and is represented by the circled mark in Figure 3. This location is closest to the 13-m-tall tree at the disaster accident. The current intensity of the first return stroke was about −30.9 kA. The current intensities of the six subsequent return strokes ranged from −5.2 to −21.7 kA. GHMLLS also gave consistent positioning results but had less information than GDLLS with regard to the return stroke (Table 1). Therefore, this article only refers to the time and location information provided by GDLLS.

Table 1. Location results of the multi-stroke ground flash obtained by GDLLS and GHMLLS. The X and Y values of the location results are based on centre station CHJ (E113.615, N23.569) of the LFEDA system as the origin (0, 0) and the current intensity of the return stroke. The precise time of the return stroke positioned by the LFEDA system is also given; the LFEDA system is currently more focussed on the fine positioning of lightning and does not provide information on the return stroke current of the ground flash.

| Return stroke | GDLLS | GHMLLS | LFEDA |
|---------------|-------|--------|-------|
|               | Time (s) | X (m) | Y (m) | Current (kA) | Time (s) | X (m) | Y (m) | Current (kA) | Time (s) |
| 1             | 49.219  | −8765.5 | −17958.6 | −30.9 | 49.219612 | −8836.8 | −18103.2 | −19.7 | 49.220280 |
| 2             | 49.331  | −9071.3 | −18080.9 | −8.8  | 49.331892 | −8938.7 | −17769.6 | −5.9  | 49.331892 |
| 3             | 49.382  | −8999.9 | −18069.8 | −19.7 | 49.382333 | −8633.0 | −17769.6 | −12.9 | 49.382334 |
| 4             | 49.407  | −8999.9 | −18381.2 | −5.2  | 49.407042 | −8531.1 | −17769.6 | −3.5  | 49.407043 |
| 5             | 49.448  | −8663.6 | −18125.4 | −14.5 | 49.448075 | −8531.1 | −17658.4 | −9.1  | 49.448075 |
| 6             | 49.496  | −8898.0 | −17992.0 | −18.8 | 49.496856 | −8429.1 | −17658.4 | −12.5 | 49.496857 |
| 7             | 49.547  | −9142.6 | −18203.3 | −21.7 | 49.547213 |  |  |  |  |
As shown in Figure 4, the radar combined reflectivity maps at 16:36, 16:42, and 16:48 indicated no cloud cover at 16:36 above the accident position. The accident position was not completely covered by storm clouds until 16:48. Figure 3 indicates that one ground flash discharge event with seven return strokes was distributed at 16:36 in the vicinity of the accident, and only after 16:48 did two more ground flashes occur within 1 km of the accident.

4.2. Positioning of the lightning process

Based on the temporal information on the preliminary judgment of the lightning disaster, we extracted data on the multi-station synchronous electric field of the LFEDA system for the corresponding time period and carried out a location analysis on the development process of the lightning channel. According to the positioning results of LFEDA system, the starting time of the flash was at 16:36:48.655, and the first return stroke occurred at 16:36:49.219. According to the changes in the lightning electric field waveforms and positioning results, the process had six subsequent return strokes in addition to the first stroke. The time interval between strokes was consistent with the positioning results given by GDLLS and GHMLLS. The lightning classification algorithm (Shao et al. 2006) was used to determine that these return strokes belonged to the same ground flash event. The LFEDA system identified the locations of 224 discharge pulse events during the flash process and was used to depict the three-dimensional development pattern of the flash discharge event, as shown in Figure 5.
The changes in the lightning electric field and position height over time confirmed seven grounding processes for the return strokes as indicated by the arrows in Figure 5(a) and corresponding to the return stroke electric field waveform in Figure 6. Figure 5(b, c) shows the radar vertical cross-sections and combined reflectivity plots, respectively, at 16:36 and superimposed on the lightning location results of the LFEDA system. The radar vertical cross-section in Figure 5(b) was taken along the lightning strike point to the convection core (greater than 30 dBz), which is shown by the dashed straight lines in Figure 5(c), and through the centre of the strongest echo. Figure 5(b) shows that there was no cloud cover directly above where the lightning disaster occurred, which is consistent with the witness description. The lightning location results showed that the distance between the lightning leader–return stroke channel and edge of the cloud body was greater than the distance between the strike position and cloud body itself. In other words, the lightning channel extended as far as 3 km from the cloud.

The initial height of the lightning event was about 8 km, and the initial breakdown process developed upward to a height of nearly 15 km. Based on the channel
development of the lightning, the lightning initiation characteristics were consistent with observations using VHF frequency band detection equipment, which have indicated that bolt from the blue begin as regular and upwardly developing intracloud flashes in normally electrified storms. After vertical downward development to a height of 7 km, the lightning event transformed in the horizontal direction and developed from southwest to northeast for 5 km. Then, the lightning event extended horizontally from the cloud about 3 km. At the same time, some channels in the cloud continued to develop in the northeast and southeast directions, and the leader–return stroke channel developed some distance to the cloud itself before landing, as shown in Figure 5(b). The form of this lightning development is very similar to that of the bolt from the blue lightning type (Krehbiel et al. 2008; Lu et al. 2012), which was observed by the LMA system running in the VHF band. As shown in Figure 5(a), the first return stroke occurred approximately 600 ms after the initial development with a total of six subsequent return strokes occurring over the next 350 ms. Figure 6(h) compares the seven return strokes located by the LFEDA system and the actual lightning strike point of the accident. The maximum error between the position results of the seven return strokes and the lightning strike point was 57.3 m, the minimum error was only 2.67 m, the average error was 26.7 m, and the standard deviation for the position results of the seven return strokes was 16.98 m. This indicates good convergence for the position results (Figure 7).

As shown in Figure 5, the return stroke ground point was not covered by the cloud anvil. Before being grounded, the lightning channel extended out of the cloud and then vertically downwards. It developed a distance 3 km below and close to the cloud body before finally being grounded. We used two methods introduced by Fuelberg et al. (2014) to calculate the horizontal extension distance of a bolt from the blue lightning channel after it extends from the cloud. The horizontal distance

![Figure 6. (a)–(g) Electric field change waveforms of seven return strokes detected by station XTC of the LFEDA system (22.9 km from lightning strike point). (h) Comparison of the LFEDA system’s return stroke positioning results with the victim’s position.](image-url)
between the cloud anvil edge (0 dBz) and strike point (location of the victim) was about 0.3 km, and the horizontal distance between the precipitation edge (18 dBz) and strike point was about 1.8 km. According to Fuelberg et al. (2014), the extended distances of 70 bolt from the blue lightning flashes occurred in 17 thunderstorm days after passage out of the cloud in their statistical study. The average horizontal distance from the edge of the cloud anvil to the strike point was found to be 2.5 km, and the horizontal distance of 13 cases (18.6%) was between 0 and 1 km. The average horizontal distance between the edge of the precipitation area and the strike point was 4.8 km; nine cases had a horizontal distance of 2–3 km, and 22.9% had a horizontal distance from the edge of the precipitation area to the strike point of less than 3 km. After the lightning channel exits the cloud, the case of relatively small

Figure 7. Schematic diagram for the mechanism between the lightning, the trees and the victim together.
4.3. Electric field waveforms of the return strokes

Based on the exact time of the lightning disaster as confirmed by the lightning location results presented above, we extracted the fast changes in the electric field waveform of the LFEDA system. Figure 6(a)–(g) shows the electric field waveforms of all seven return strokes detected by station XTC of the LFEDA system (22.9 km from the lightning strike point). Except for the electric field waveform of the first return stroke (Figure 6(a)), which showed multi-peak characteristics, the electric field waveforms of the six subsequent return strokes showed double peak characteristics. The electric field waveforms of the return strokes detected by all stations of the LFEDA system showed the same characteristics as described above. This multi-peak characteristic of the electric field waveforms of the ground flash return strokes is quite different from that of the ground flash return stroke waveform when the strike point is on flat ground or for artificially triggered lightning, which usually has only one peak (Baba and Rakov 2005; Rachidi et al. 2002). Some studies have shown that the electric field waveform of the lightning return stroke shows multi-peak characteristics in two cases. The first case is tall buildings subjected to lightning strikes, which has been observed and verified by relevant physical models (Rakov 2001; Baba and Rakov 2005; Rachidi et al. 2002). When lightning strikes a tall object, the resistances among the lightning channel, object, and ground are different, which leads to the current being reflected at the interfaces between the lightning channel, object, and ground. This causes the multi-peak characteristics of the electric field waveform of the return stroke. In this case, the time interval between multiple peaks is mainly determined by the height of the building. In the second case, two leader branches reach the ground at almost the same time to form connections. This may show up as multi-peak characteristics in the electric field waveform of the return stroke (Thottappillil et al. 1992; Rakov and Uman 2003); when subsequent strokes are initiated by the newly established connection (i.e., multiple termination flash (MTF)) or from a main stepped leader channel, multiple leader branches are induced and eventually connect to the ground (i.e., multiple termination stroke (MTS)) (Willett et al., 1995; Ballarotti et al. 2005; Qie et al. 2005, Qie and Kong 2007; Kong et al. 2009; Sun et al. 2016). In this case, the time interval between multiple peaks is determined by the time difference between the different leader branches reaching the ground to form a connection.

Table 2 presents statistical data on the characteristic parameters for changes in the electric field waveforms of the LFEDA system according to the seven return strokes detected by station XTC. In particular, $\Delta E_s / \Delta E_f$ of $R_1$ was 34.5% and $\Delta E_s / \Delta E_f$ of $R_4$ was only 14.6%. The value of $\Delta E_s / \Delta E_f$ for the other five return strokes was around 23.6% on average. Considering that $R_4$ was the weakest of the return strokes, the noise signal had a large influence on the calculation of the change in electric field, which may have led to a larger deviation of the eigenvalue. Table 2 indicates that the two parameters of the other five return strokes excluding $R_1$ and $R_2$ were all close
with standard deviations of 0.46 and 0.36 μs, respectively. This conforms to the deviation characteristics for the time with high-frequency noise in the LFEDA detection signal (Fan et al., 2018). For the return stroke electric field waveform when lightning strikes high buildings, the sub-peak width $T_s$ and interval between the primary peak and sub-peak $ΔT$ are related to the propagation speed and length of the reflected current in the object (i.e., object height). For MTF and MTS, the sub-peak width $T_s$ and time interval $ΔT$ between the primary peak and sub-peak are related to the development distance of the ground leader and difference in grounding times of different leaders, respectively. In the case of MTF, $ΔT$ is usually on the order of milliseconds, while in the case of MTS, $ΔT$ can reach the order of microseconds. In contrast to the observation and model results for lightning strikes on high buildings (Rakov 2001; Baba and Rakov 2005; Rachidi et al. 2002), the tallest tree had a height of only 13 m, which is much shorter than the wavelength (300 m) corresponding to 1 MHz, which is close to the highest frequency of lightning return stroke current waveforms. A 13 m tall tree is likely to behave as a lumped circuit; in other words, no reflections should be discernible in the corresponding current and field records. Therefore, the multi-peak feature of the return stroke waveforms can only be attributed to the simultaneous presence of two grounding points in the leader–return stroke channel. The splashes between some branches of these trees could have caused the phenomena.

4.4. Analysis of the cause of death

After repeated confirmation from the detection data, we are sure that a multi-stroke bolt from the blue struck the tree during the accident. The question then becomes how this caused the death of the victim. Cooper et al. (2017) summarized five common situations in which lightning strikes cause casualties: an earth potential rise (EPR), a side flash or side splash, the contact potential, upward streams/leaders, and a direct strike.

A lightning current passes through the earth just like any other conductor. The earth has limited resistance, so the voltage is set up on the ground and decreases with the distance from the strike point. This causes EPR. The step voltage is a common form of EPR. If a person is standing in the EPR active area (i.e., near the location of the lightning strike), there will be a voltage between their feet, and current will enter the lower part of the body through the legs. A side flash or side splash occurs when lightning strikes an object such as a tree or building and “jumps” to nearby victims, with only a portion of the lightning current travelling down the object. When a person comes into contact with an object struck by lightning, this produces a contact potential that can cause casualties. Injuries may occur when a victim serves as a conduit for one of the usually multiple upward leaders induced by a downward stepped leader and its field. This mechanism accounts for only 10–15% of all deaths caused by lightning strikes. A direct strike occurs when the lightning stroke attaches directly to the victim. Direct strikes are often believed to be the most common cause of death related to lightning, but it actually has the lowest probability among the five mechanisms at 3–5% (Cooper et al. 2017).
According to the LFEDA positioning results, when the position of the victim was taken as the actual lightning strike point, the average positioning error of the seven return strokes was only 26.7 m, and the maximum positioning error was 57.3 m, as shown in Figure 6(h). There was no building in a radius of 60 m around the victim. A 13 m tall tree 1 m away from the victim was the tallest object in the vicinity, and the top of the tree had obvious burn marks after the accident. In addition, an 8 m tall tree was 4 m away from the tallest tree and also showed traces of a lightning strike and the electric field waveform of the ground flash return strokes was characterized by multiple peaks. This means that the lightning return strokes maybe directly struck the taller tree, and some branches of these trees could have facilitated the lightning currents splash from one to another. The death of the victim was not caused by a direct strike from the lightning stroke. However, according to the forensic identification results, the head of the victim was struck by lightning. There was no obvious trace of a strong current flowing through the trunks of the trees, the case scenario situation with the trees around, the condition of their trunks and branches, the consequences and marks left on the body and belongings, the witness report, the lightning data and the study of other previous reported accidents can indicate the injure mechanism that some or all of the current jumped to the victim. According to Cooper et al. (2017), EPR causes 40–50% of all lightning-related death. In this case, the victim was happening to pass under the tree when it was struck by lightning. At a distance of only 1 m, the step voltage would cause fatal harm to the human body. In this accident, we are not sure how much of the lightning current jumped to the victim, but if only a part of the current passed through the trunk, the victim would have been hurt by the step voltage. Thus, there are two possible mechanisms for the cause of death: side flash and step voltage. Because the victim had burn injuries on his body, the most probable mechanism was the side flash. Figure 7 shows a schematic diagram of the discharge mechanism for the victim.

5. Discussion
In this article, we combine data from the LFEDA, GDLLS, GHMLLS, and the Panyu radar station in Guangzhou City for an analysis on a fatal lightning accident that occurred in Conghua District on 3 June 2017.
A negative ground flash event with seven return strokes was successfully detected by multiple lightning location systems. According to the positioning results of the LFEDA system for lightning channels, there was no cloud cover overhead. The horizontal distance between the cloud anvil area (0 dBz) edge and strike point was about 0.3 km, and the horizontal distance between the precipitation area (18 dBz) edge and strike point was about 1.8 km. The lightning channel extended as far as 3 km from the cloud and was a bolt from the blue. The bolt from the blue struck a 13 m tall tree beside the victim, and the electric field waveform detected by the LFEDA system showed multi-peak characteristics. A field investigation showed that the 13 m tall tree and another 8 m tall tree 4 m away had traces of a lightning strike. The electric field waveform of the return stroke showed multi-peak characteristics. These various characteristics all prove that the return stroke channel of the bolt from the blue had the bifurcation phenomenon, and the seven return strokes were all multiple termination strokes. There are two possible mechanisms for the cause of death: side flash and step voltage. The most probable lightning injury mechanism was the side flash.

Lightning strikes cause death, which in itself is a small probability event. This kind of bolt from the blue extending a few kilometres from a thundercloud in clear sky is unusual. The low possibility of the event and the fact that it occurred to a pedestrian makes it seem unnecessary to take any protective measures, however, it is such a neglect of prevention that caused the disaster. This was a very unfortunate and deplorable incident, but the key factor leading to death was the large tree that the victim happened to be passing by at the time. Therefore, when people participating in outdoor activities realize that there are thunderstorms in the vicinity (i.e., within a few kilometres) or obtain relevant information, some sensible precautions to greatly reduce the probability of lightning damage would be to stay away from tall and prominent objects or not make yourself a prominent object within a certain radius.

6. Conclusions

Based on a comprehensive analysis, the lightning was concluded to be a negative “bolt from the blue” ground flash with seven return strokes. The first return stroke was on 3 June at 16:36:49.219 with a peak current intensity of $-30.9$ kA. The return stroke channel extended as far as 3 km out of the cloud. The electric field waveform of the return strokes detected by the LFEDA system showed multi-peak characteristics, and all seven return strokes were multiple-termination strokes. The bolt from the blue struck a 13 m tall tree beside the victim, and the most probable mechanism for the lightning injuries was the side flash.

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References
Baba Y, Rakov VA. 2005. On the use of lumped sources in lightning return strike models. J Geophys Res Atmos. 110:D03101 doi:10.1029/2004JD005202
Ballarotti MG, Saba MMF, Pinto O. Jr. 2005. High-speed camera observations of negative ground flashes on a millisecond-scale. Geophys Res Lett. 32:L23802.
Bhardwaj P, Singh O, Kumar D. 2017. Spatial and temporal variations in thunderstorm casualties over India. Singapore Journal of Tropical Geography. 38(3):293–312
Cardoso I, Pinto O, Pinto IRCA, Holle R. 2014. Lightning casualty demographics in brazil and their implications for safety rules. Atmos Res. 135-136(1):374–379.
Cooper, MA, Holle, RL, Andrews CJ. 2017. Distribution of lightning injury mechanisms. International Conference on Lightning Protection. IEEE.
Chen LW, Zhang YJ, Lu WT. 2009. Comparative analysis between LLS and observation of artificial-triggered lightning. High Voltage Eng. 35(8):1896–1902.
Cherington M, Krider EP, Yarnell PR, Breed DW. 1998. A bolt from the blue, lightning strike to the head. Neurology. 50(3):830.
Dewan A, Hessain MF, Rahman MM, Yamane Y, Holle RL. 2017. Recent lightning-related fatalities and injuries in bangladesh. Wea Climate Soc. 9:575–589.
Dlamini WM. 2009. Lightning fatalities in swaziland: 2000–2007. Nat Hazards. 50(1):179–191.
Elsom DM, Webb JDC, Enno SE, Horseman A. 2016. Lightning fatalities and injuries in the UK in 2015 and lightning safety advice for hill and mountain walkers. Int J Meteorol. 41(397):105–126.
Fan LM, Li ZF, He HM, Yang CM. 2004. Analysis of location error of Guangdong lightning location system. High Voltage Eng. 30(7):61–63.
Fan XP, Zhang YJ, Zheng D, Zhang Y, Lyu WT, Liu HY, Xu LT. 2018. A new method of three-dimensional location for low-frequency electric field detection array. J Geophys Res: Atmos. 123. https://doi.org/10.1029/2017JD028249
Fuelberg HE, Walsh RJ, Preston AD. 2014. The extension of lightning flashes from thunderstorms near Cape Canaveral, Florida. J Geophys Res Atmos. 119(16):9965–9979.
Hajikhani M, Ab-Kadir MZA, Izadi M, Gomes C, Jasni J. 2016. Lightning fatalities and injuries in Malaysia from 2008 to 2015. IEEE 2016 33rd International Conference on Lightning Protection (ICLP) - Estoril, Portugal (2016.9.25–2016.9.30); p. 1–6. IEEE.
Holle RL, Cooper MA. 2016. Lightning Occurrence and Social Vulnerability. Atmospheric Hazards—Case Studies in Modeling. In: Coleman, JSM, ed. Communication, and Society Impacts, In Tech 08, 18pp. https://www.intechopen.com/books/atmospheric-hazards-case-studies-in-modeling-communication-and-societal-impacts.
Holle RL. 2016. Lightning-caused deaths and injuries related to agriculture. 24th Int. Lightning Detection Conf. and Sixth Int. Lightning Meteorology Conf., San Diego, CA, Vaisala. p. 1–5.

Holle RL. 2015. A summary of recent national-scale lightning fatality studies. Weather Climate & Society. 8(1):150917121202003.

Kitagawa N, Brook M. 1960. A comparison of intracloud and cloud-to-ground lightning discharges. J Geophys Res. 65(4):1189–1201.

Kong XZ, Qie XS, Zhao, Y, Zhang T. (2009). Characteristics of negative lightning flashes presenting multiple-ground terminations on a millisecond-scale. Atmospheric Research, 91(2–4), 0–386.

Krehbiel PR, Riousset JA, Pasko VP, Thomas RJ, Rison W, Stanley MA, Edens HE. 2008. Upward electrical discharges from thunderstorms. Nature Geosci. 1(4):233–237.

Lu G, Cummer SA, Blakeslee RJ, Weiss S, Beasley WH. 2012. Lightning morphology and impulse charge moment change of high peak current negative strokes. J. Geophys. Res. Atmos. 117: D04212. doi:10.1029/2011JD016890

Ma M, Lyu WT, Zhang Y, Meng Q. 2008. Analysis of lightning disasters in china and their correlative factors. Adv. Earth Sci. 23(8):856–865.

Merceret FJ, Short DA, Ward JG. 2005. Radar evaluation of optical cloud constraints to space launch operations. J Spacecraft Rockets. 43(1):248–251.

Navarrete-Aldana N, Cooper MA, Holle RL. 2014. Lightning fatalities in colombia from 2000 to 2016. Nat Hazards. 74(3):1349–1362.

Punkka AJ, Bister M. 2005. Occurrence of summertime convective precipitation and mesoscale convective systems in Finland during 2000–01. Mon Weather Rev. 133(2):362–373.

Qie X, Kong X. 2007. Progression features of a stepped leader process with four grounded leader branches. Geophys Res Lett. 34:L06809.

Qie X, Kong X, Zhang G, Zhang T, Yuan T, Zhou Y, Zhang Y, Wang H, Sun A. 2005. The possible charge structure of thunderstorm and lightning discharges in northeastern verge of Qinghai-Tibetan Plateau. Atmos Res 76(1–4):231–246.

Rachidi F, Rakov VA, Nucci CA, Bermudez JL. 2002. Effect of vertically extended strike object on the distribution of current along the lightning channel. J Geophys Res Atmos. 107(D23), ACL1–ACL1-66.

Rakov VA. 2001. Transient response of a tall object to lightning. IEEE Trans Electromagn Compat. 43(4):654–661.

Rakov VA, Uman MA. 2003. Lightning: physics and effects, New York: Cambridge University Press.

Rison W, Thomas RJ, Krehbiel PR, Hamlin T, Harlin J. 1999. A gps-based three-dimensional lightning mapping system: initial observations in central New Mexico. Geophys Res Lett. 26(23):3573–3576.

Selvi S, Rajapandian S. 2016. Analysis of lightning hazards in india. Int J Disaster Risk Reduct. 19:22–24.

Shao XM, Stanley M, Regan A. 2006. Total Lightning Observations with the New and Improved Los Alamos Sferic Array (LASA). J Atmos Oceanic Technol. 23(23):1273.

Shi D D, Zheng D, Zhang Y, Zhang Y J, Huang Z G, Lu W T, Chen S D, Yan X. 2017. Low-frequency E-field Detection Array (LFEDA)—Construction and preliminary results. Science China Earth Sciences. 60(10):1896–1908. doi:10.1007/s11430-016-9093-9.

Shrigiriwar MB, Gadhari RK, Jadhao VT, Tingne CT, Kumar NB. 2014. Study of fatalities due to lightning in Nagpur region of Maharashtra. J Indian Acad Foren Med. 36(3):259–262.

Sun Z, Qie X, Liu M, Jiang R, Wang Z, Zhang H. 2016. Characteristics of a negative lightning with multiple-ground terminations observed by a VHF lightning location system. J Geophys Res Atmos. 121(1):413–426.

Thomas RJ, Krehbiel PR, Rison W, Hamlin T, Harlin J, Shown D. 2001. Observations of vhf source powers radiated by lightning. Geophys Res Lett. 28(1):143–146.

Thottappillil R, Rakov VA, Uman MA, Beasley WH, Master MJ, Shelukhin DV. 1992. Lightning subsequent-stroke electric field peak greater than the first stroke peak and multiple ground terminations. J Geophys Res. 97(D7):7503–7509.
Ward JG, Merceret FJ. 2004. Electric field magnitude and radar reflectivity as a function of distance from cloud edge, Tech. Rep. NASA/TM-2004-211530, NASA Kennedy Space Cent., Cocoa Beach, FL.

Willett JC, Le Vine DM, Idone VP. 1995. Lightning-channel morphology revealed by return-stroke radiation field waveforms. *J Geophys Res.* 100(D2):2727–2738.

Zhang W, Meng Q, Ma M, Zhang Y. 2011. Lightning casualties and damages in China from 1997 to 2009. *Nat Hazards.* 57(2):465–476.

Zhang Y, Lü W, Chen S, Zheng D, Zhang Y, Yan X, Chen L, Dong W, Dan J, Pan H. 2016. A review of advances in lightning observations during the past decade in Guangdong, China. *J Meteorol Res.* 30(5):800–819.