Discharge height of lightning narrow bipolar events

Ting Wu,[1,2] Wansheng Dong,[1] Yijun Zhang,[1,3] Tsuyoshi Funaki,[2] Satoru Yoshida,[2] Takeshi Morimoto,[2] Tomoo Ushio,[2] and ZenIchiro Kawasaki[2,4]

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[1] Discharge heights of thousands of narrow bipolar events (NBEs) observed in Guangzhou and Chongqing of China are calculated using time delays between the direct wave signals of NBEs and their ionospheric reflection pairs. The result shows that most positive NBEs occur between 8 and 16 km while most negative NBEs occur between 16 and 19 km. Very few negative NBEs are above 19 km or below 14 km. It is inferred that positive NBEs are produced between main negative charge layer and upper positive charge layer while negative NBEs are produced between upper positive charge layer and negative screening charge layer at the cloud top. Variations of NBE discharge heights in two thunderstorms are analyzed. It seems that NBEs can be produced at any position between corresponding charge layers. Positive NBEs are generally higher in the periods when negative NBEs are also occurring. For a given short time period in a single thunderstorm, negative NBEs are always observed to occur at a higher altitude than positive NBEs, indicating a dividing charge layer between positive NBEs and negative NBEs. The possibility of some NBEs as upward discharges from cloud tops mentioned by previous studies is discussed. Supported by multiple evidences, we believe such possibility is very low; instead, NBEs are produced in vigorous convective surges that develop to the height comparable to the discharge height of NBEs. Differences in height distributions in Guangzhou and Chongqing are analyzed and a hypothesis is put forward that both positive NBEs and negative NBEs can only be produced above certain height. The relationship between this hypothesis and the mechanism for NBE production is discussed.

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1. Introduction

[2] Narrow bipolar event (NBE) is one of the most special types of lightning discharge events. It is largely different from regular cloud-to-ground and intracloud lightning in many respects. The pulse width of electric field waveforms produced by NBEs is only a few microseconds [*Le Vine*, 1980; *Smith et al.*, 1999], much smaller than that of return strokes; NBEs produce extremely powerful radiation in the HF and VHF radio bands, which is at least one order of magnitude larger than that produced by normal intracloud discharges [*Smith et al.*, 1999; *Jacobson*, 2003]; NBEs are usually found isolated with other discharge processes [*Le Vine*, 1980; *Smith et al.*, 1999], but positive NBEs are sometimes found to be the initiation of otherwise normal intracloud lightning discharges [*Rison et al.*, 1999; *Wu et al.*, 2011]; the channel length of NBEs is inferred to be less than 1 km [*Smith et al.*, 1999; *Nag and Rakov*, 2010], much shorter than that of normal intracloud lightning discharges; negative NBEs mostly occur above 15 km [*Smith et al.*, 2004; *Wu et al.*, 2011], where few regular lightning discharge processes are observed.

[3] NBEs are also called "compact intracloud discharges" (CIDs) [*Nag and Rakov*, 2010; *Wu et al.*, 2011] because of small spatial extent of their discharge channels. However, it is unclear whether such discharge events are always accompanied by narrow bipolar electric field pulses which are indicative of large-scale charge transfers [*Jacobson*, 2003]. Since in this study the identification of such special discharge events is based on electric field change records, that is, the characteristics of narrow and bipolar pulses, we will refer to such discharge event as NBE.

[4] Although a large amount of NBEs have been observed with both ground-based and space-born observations and analyzed in various ways since they were first reported in 1980 [*Le Vine*, 1980], NBE remains one of the most mysterious lightning discharge processes. One interesting problem concerns the discharge height of NBEs. *Smith et al.*

[1]Laboratory of Lightning Physics and Protection Engineering, Chinese Academy of Meteorological Sciences, Beijing, China.
[2]Division of Electrical, Electronic and Information Engineering, Graduate School of Engineering, Osaka University, Osaka, Japan.
[3]State Key Laboratory of Severe Weather, Chinese Academy of Meteorological Sciences, Beijing, China.
[4]Electronics, Communications and Computer Science Engineering, Egypt–Japan University of Science and Technology, Alexandria, Egypt.

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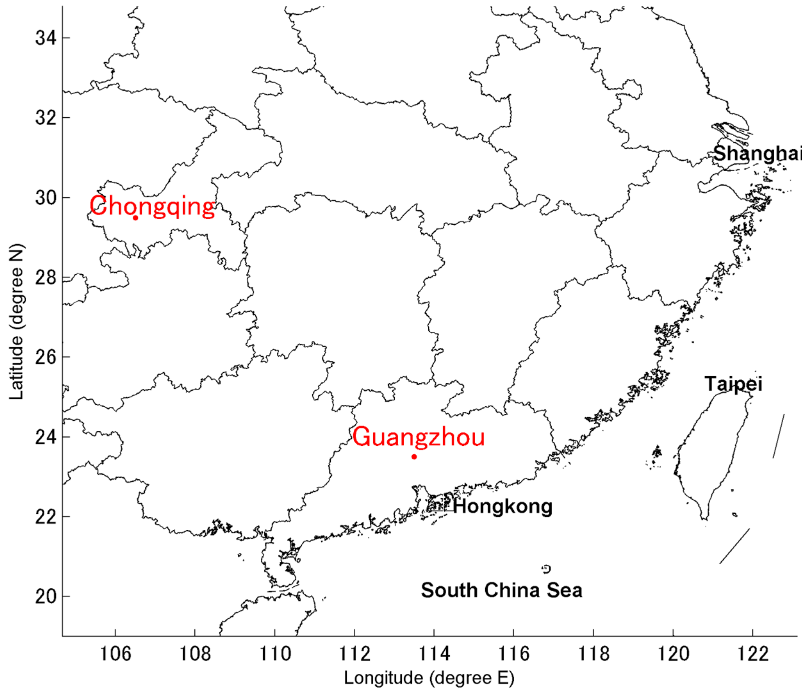

Figure 1. Map of Chongqing and Guangzhou in China.

[2004] calculated heights of over 100,000 NBEs observed by LASA [*Smith et al.*, 2002] and the result showed that positive NBEs were mostly between 7 and 15 km and negative NBEs between 15 and 20 km. *Wu et al.* [2011] calculated heights of hundreds of both polarities of NBEs observed in south China and had similar result. However, in the result shown by *Smith et al.* [2004], a small percent of negative NBEs were higher than 20 km and some of them were even as high as 30 km, which is difficult to explain because cloud tops can rarely reach 20 km. *Nag et al.* [2010] also reported several NBEs that were higher than 20 km in their height estimation of 48 positive NBEs. They further discussed the result and put forward the possibility that very high NBEs could be associated with gigantic jets [*Krehbiel et al.*, 2008].

[5] NBEs above 20 km generally account for a very small percent of all NBEs in previous studies; most of negative NBEs, however, are found to occur between 15 and 20 km [*Smith et al.*, 2004; *Wu et al.*, 2011], which also raises questions as the tropopause is around 17 km in tropical region and lower in higher latitudes, so a considerable amount of negative NBEs seem to occur above the tropopause. *Jacobson and Heavner* [2005] stated that some NBEs were truly occurring above the tropopause; they might be occurring in clear air as blue jets or in convective surges transiently overshooting the tropopause.

[6] In this paper, a method previously described by *Wu et al.* [2011] is modified to calculate the discharge height of thousands of NBEs that are observed in two different regions in China. We will show that the height distributions of both polarities of NBEs are similar to that documented by *Smith et al.* [2004] and *Wu et al.* [2011], but we will demonstrate that most of negative NBEs occur between 16 and 19 km and very few are above 19 km. Variations of NBE discharge height in two thunderstorms will also be presented. Further, we will try to demonstrate that NBEs are occurring inside vigorous thunderstorms rather than in clear air above cloud tops as mentioned by *Jacobson and Heavner* [2005] and *Nag et al.* [2010]. Finally, some inferences drawn from differences in height distributions of NBEs between two regions will be discussed.

2. Data

[7] Records of NBEs used in this study were collected in Guangzhou (23.5°N, 113.5°E) and Chongqing (29.5°N, 106.5°E), as shown in Figure 1. A very low frequency and low frequency (VLF/LF) lightning location network consisting of 7 stations of fast electric field change meters was established in Guangzhou in 2007. Six of the stations covered an area with a radius of about 10 km, and the other station was about 32 km from the center of the network, forming a relatively long baseline [see *Wu et al.*, 2011, Figure 1]. In 19 days of observation, a total of 11,876 NBEs comprising 7,882 positive NBEs and 3,994 negative NBEs were recorded. Classification criteria for NBEs are the same as *Wu et al.* [2011] and similar with previous studies [*Smith et al.*, 2002; *Hamlin et al.*, 2007].

[8] A similar network consisting of 9 stations was established in Chongqing in 2010, covering an area with a radius of about 30 km. As shown in Figure 2, locations of lightning discharges correspond well with the area of high radar reflectivity. It should also be noted that, as the storm is outside the network, the detection efficiency for intracloud lightning is relatively low. However, in this study, only records of NBEs are utilized, so discrepancy in the detection efficiency for different types of lightning discharges is not a problem. This network had kept operating for about two months in the summer of 2010, recording 36,442 positive NBEs and 7,893 negative NBEs.

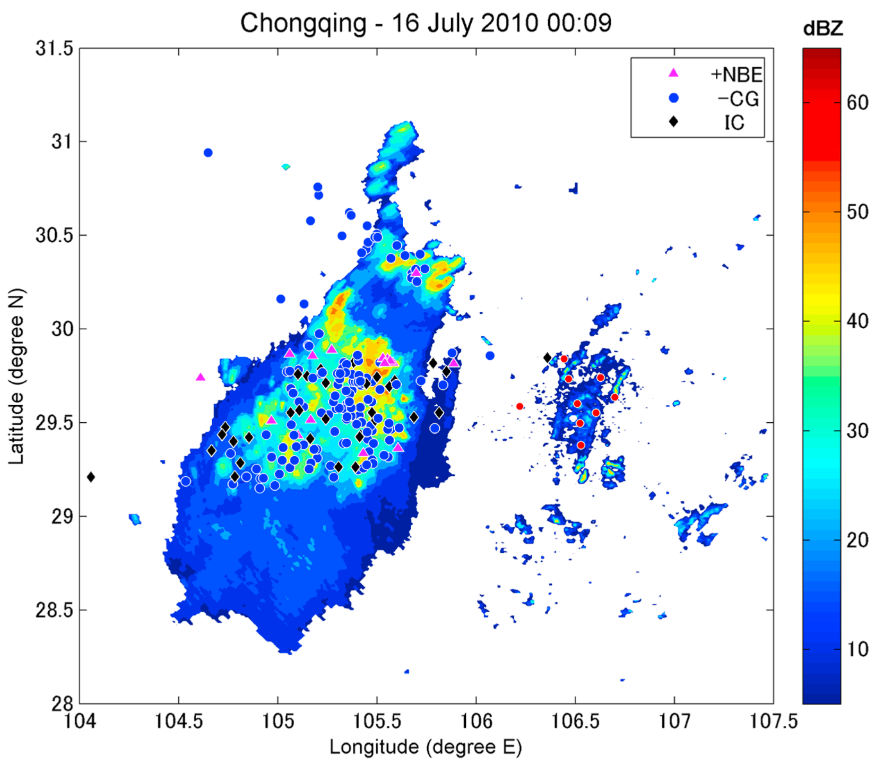

Figure 2. Composite radar reflectivity with locations of lightning discharge events within 6 min of the radar scanning time. Different types of lightning discharges are represented by different symbols as indicated by the legends. No negative NBE or +CG was detected in this time period. Red dots represent the observation stations of the lightning location network.

[9] The electric field change systems of the two networks were identical with each other, operating at 200 Hz to 500 kHz, having a decay time constant of 1 ms and a sampling rate of 10 MHz. Each output record had duration of 1 ms with pre-trigger time of 0.3 ms. A typical record of negative NBE is shown in Figure 3. Detailed description of the system is discussed by *Wu et al.* [2011]. Physics sign convention for electric field change polarity is used throughout this paper, thus a negative cloud-to-ground return stroke produces a negative polarity electric field change signal and a positive NBE corresponds to discharge between upper positive charges and lower negative charges. Such a definition is consistent with most of previous studies on NBEs.

3. Method for Determining Discharge Height of NBEs

[10] The method used in this study to calculate the discharge height of NBEs is similar to that used by *Wu et al.* [2011] and is developed from the method used by *Smith et al.* [1999]. The basic principle is to use the time delays between the original signal of an NBE and its ionosphere and ground reflection signals to determine the source height. As in Figure 3, pulse 0 is produced when the wave signal of

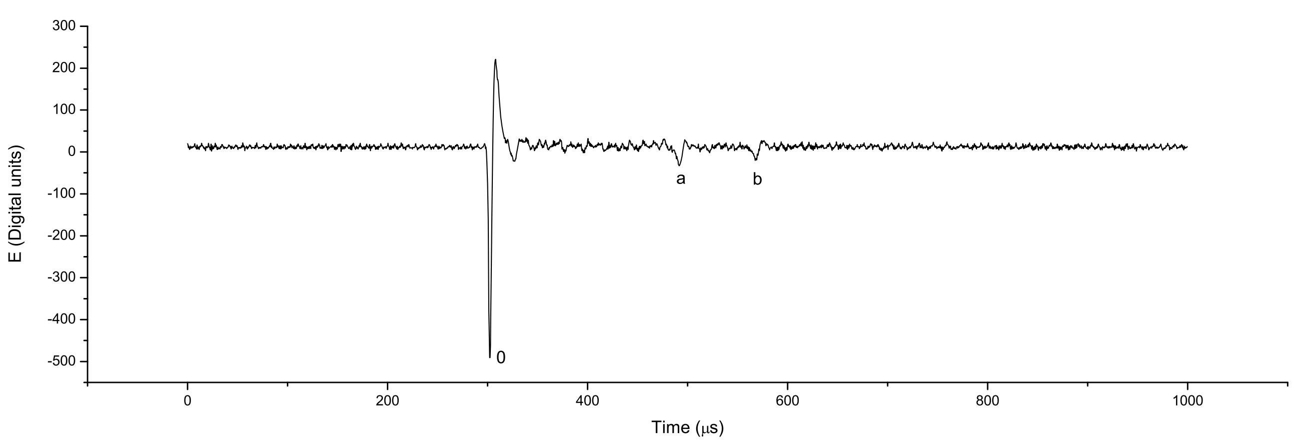

Figure 3. Electric field record of a typical negative NBE.

an NBE is directly received by the observation station, and pulses a and b correspond to the signals that are reflected by the ionosphere and ground-ionosphere, respectively, before they are captured by the observation station. Time delays of pulses a and b with respect to pulse 0 is associated with the 3-D position of the NBE and ionospheric virtual height (that is, ionospheric reflection height for VLF/LF signal of NBE), which can be inversely retrieved based on simultaneous observations of the NBE by multiple stations.

[11] In the study by *Wu et al.* [2011], the following function is constructed:

$$f(H, h, x_0, y_0) = \sum_{i=1}^{n}\left[ct_{ia} - \sqrt{(2H - h - z_i)^2 + r_i{}^2} + \sqrt{(h - z_i)^2 + r_i{}^2}\right]^2 + \left[ct_{ib} - \sqrt{(2H + h - z_i)^2 + r_i{}^2} + \sqrt{(h - z_i)^2 + r_i{}^2}\right]^2 \quad (1)$$

where H is the ionospheric virtual height, and x_0, y_0 and h are the latitude, longitude and height of NBE, which are four unknowns of the function. t_{ia} and t_{ib} are time differences between pulse 0 and pulses a and b, respectively, in Figure 3. c is the speed of light. r_i is the horizontal distance between NBE and the ith station, given by the following relationship:

$$r_i = R\cdot \arccos[\sin(x_0)\sin(x_i) + \cos(x_0)\cos(x_i)\cos(y_0 - y_i)]$$

where R is the radius of the earth, and x_i and y_i are the latitude and longitude of the ith station.

[12] With simultaneous observations by multiple stations, 3-D position of NBE and ionospheric virtual height can be determined by minimizing the function using optimization method.

[13] In this study, as a modification of the original method, the ionospheric virtual height H is set as a constant: $H = H_0 = 90$ km. Therefore the function (1) is rewritten as:

$$f(h, x_0, y_0) = \sum_{i=1}^{n}\left[ct_{ia} - \sqrt{(2H_0 - h - z_i)^2 + r_i{}^2} + \sqrt{(h - z_i)^2 + r_i{}^2}\right]^2 + \left[ct_{ib} - \sqrt{(2H_0 + h - z_i)^2 + r_i{}^2} + \sqrt{(h - z_i)^2 + r_i{}^2}\right]^2 \quad (2)$$

Function (2) has only three unknowns that determine 3-D position of NBE.

[14] There are two reasons for such a modification. First, with the ionospheric virtual height set as a constant, the number of unknowns decreases from four to three and as a result, the computational accuracy is improved. Figures 4a and 4b show results of NBE locations computed with function (1) and function (2), respectively. In Figure 4a, most NBEs are located close to high-reflectivity cores, but some of the location results such as the ones in the white area obviously involve large errors. However, in Figure 4b, almost all NBE locations are quite well corresponded with high-reflectivity cores, showing much higher accuracy for the results computed with function (2). Since the latitude, longitude and height of an NBE are determined simultaneously with function (2) using optimization method, it is believable that results of NBE discharge height will also have higher accuracy when computed with function (2). Second, NBEs with ionospheric reflection pairs in this study were all observed at night when the variation of the ionospheric virtual height is relatively small. *Smith et al.* [2004] showed that variation of the ionospheric virtual height for radiation waves of NBEs is most significant during the transition between day and night. Relevant studies also showed that ionospheric virtual height at VLF/LF frequencies is around 90 km at night [*Bracewell et al.*, 1951]. In order to determine the influence of possible variation of ionospheric virtual height (H_0) on the result of NBE discharge height (h), we repeated computation with function (2) with different choices of H_0 from 85 km to 95 km. Figure 5 shows variations of h with different choices of H_0 for 10 NBEs in different altitudes. With ±5 km variation of H_0, variation of the result of h ranges from 0.27 km to 0.87 km. Therefore, setting H as a constant will not have a significant influence on the result of h but will increase accuracy of the result, and we believe it is a reasonable treatment.

[15] This method only utilizes time delays between different pulses in the same waveform record, so differences of arrival times of the signal to different observation stations, which are essential in the traditional time-of-arrival technique, are irrelevant with the computation. The error of the computation in this method mainly comes from misidentifications of the reflection pulses (pulses a and b in Figure 3), which have been avoided in several ways in this study. First, NBEs far away from the network, which produce polarity reversal of ionospheric reflections or multiple-hop reflections [*Smith et al.*, 2004], are not utilized for computation. In this study, most NBEs producing clear reflection pulses and used for computation are between about 100 km to 300 km from the network. In this range, reflection pulses largely resemble the one in Figure 3 and are easy to be automatically identified. Second, all the automatic identifications of reflection pulses are manually checked to make sure that there is no apparent misidentification. Such re-examination ensures that there are no large errors in the computation. Finally, the residual of function (2) can also indicate error magnitude in the computation, and results with large-than-normal residuals will be excluded.

[16] In order to estimate errors in the results of NBE discharge height due to inaccuracy in determining reflection pulses, we made the following test. For a typical NBE observed by five stations, up to 4-μs error is intentionally added in the identification of ionospheric reflection pulse recorded by two of the five stations. Under such condition, 2-D location (latitude and longitude) of the NBE is up to 40 km from the original position, which is a significant error. However, the height result shows no larger than 0.5 km variance from the original result, indicating that the height result is much more stable than the results of latitude and longitude. This can also be qualitatively seen from function (2), in which r_i, determined by latitude (x_0) and longitude (y_0) of NBE, is a much larger quantity (~200 km) than the height (h, ~15 km). The value of r_i (and the value of x_0 and y_0), therefore, has the largest variation through the process of searching the minimum of the function, while the value of h has relatively small variation. For the same reason, if function (1) is utilized, results of ionospheric virtual height (H, ~90 km) will also have relatively large variations [see *Wu et al.*, 2011, Figure 7]. Since errors in 2-D locations of

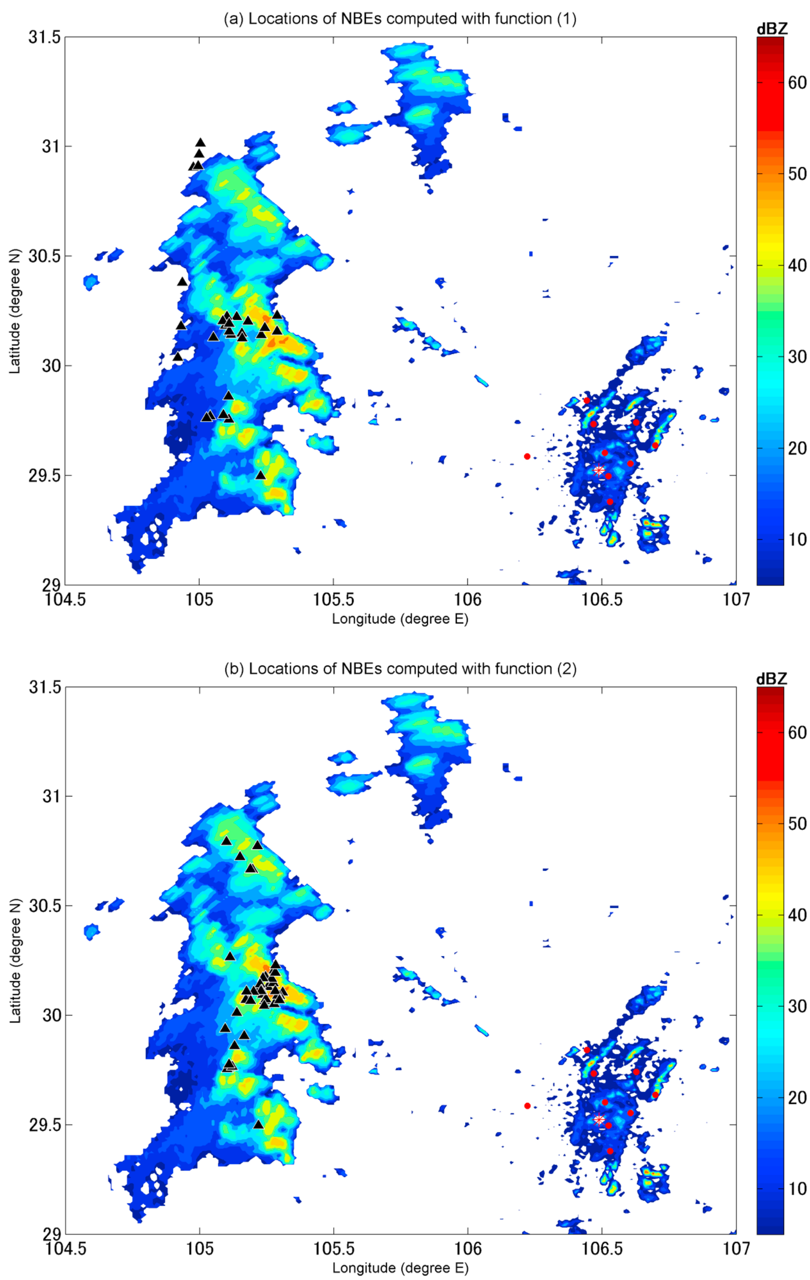

Figure 4. Composite radar reflectivity with locations of NBEs within 6 min of the radar scanning time. Black triangles represent NBE locations computed with their ionospheric reflection pairs using (a) function 1 and (b) function 2.

NBEs rarely exceed 40 km according to comparisons of NBE locations with radar reflectivity, we believe that errors in discharge heights of NBEs due to inaccuracies in determining reflection pulses are generally smaller than 0.5 km.

4. Results

4.1. Statistical Results of Discharge Height of NBEs

[17] With the method introduced in section 3, discharge heights of thousands of NBEs were calculated. In Guangzhou, there are a total of 1318 and 625 height results for positive NBEs and negative NBEs. The geometric means (GMs) of discharge height are 12.1 km and 17.3 km, and the arithmetic means (AMs) are 12.3 km and 17.3 km. In Chongqing, there are a total of 5489 and 1400 height results for positive NBEs and negative NBEs with GMs of 9.9 km and 17.5 km and AMs of 10.0 km and 17.5 km, respectively. Statistics of discharge height of NBEs observed in these two regions are summarized in Table 1. All the results are given as above ground level (AGL), but they should not have much difference with the heights above mean sea level (AMSL) because all station elevations in Guangzhou are smaller than 100 m and the ones in Chongqing are mostly around 300 m.

[18] Figure 6 shows distributions of discharge heights of NBEs observed in Guangzhou and Chongqing. It clearly

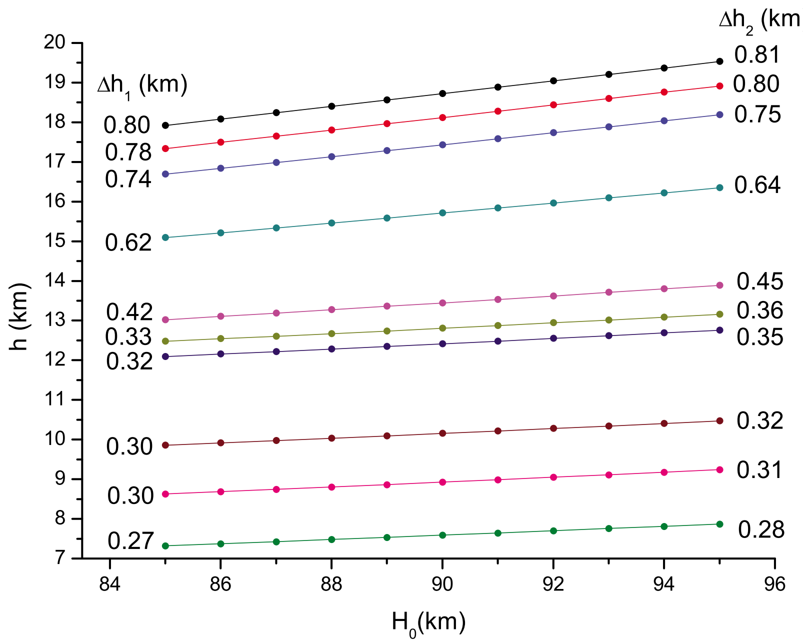

Figure 5. Variation of NBE discharge height (h) with different choices of ionospheric virtual height (H_0) for ten NBEs in different altitudes:Δh_1 is difference between results of h computed with H_0 = 90 km and H_0 = 85 km and Δh_2 is difference between results of h computed with H_0 = 95 km and H_0 = 90 km.

shows that positive NBEs and negative NBEs occur in two different altitudes, with negative NBEs mostly higher than positive NBEs. Most positive NBEs occur between 8 and 16 km while most negative NBEs occur between 16 and 19 km in Guangzhou. The distribution in Chongqing is quite similar, with positive NBEs converging in lower altitudes compared with that in Guangzhou. Such distribution is also consistent with the result of *Smith et al.* [2004], further confirming that negative NBEs occur at a region higher than positive NBEs.

[19] An interesting result in our calculations is that very few NBEs are above 19 km as shown in the height distribution in Figure 6. As summarized in Table 1, the highest NBE in Guangzhou is 19.6 km, and the highest one in Chongqing is 19.9 km. However, there are only 6 NBEs (0.31%) in Guangzhou and 18 NBEs (0.26%) in Chongqing above 19 km, all of which are negative polarity. The majority of negative NBEs occur between 16 km and 19 km with a peak between 17 and 18 km, both in Guangzhou and Chongqing. The result given by *Smith et al.* [2004] also showed a peak around 17 km in height distribution of negative NBEs [see *Smith et al.*, 2004, Figure 5]. According to their distribution curve, which shows a sudden decrease above 20 km, it seems very likely that most NBEs above 20 km are resulted from errors probably caused by misidentifications of reflection pulses in their automatic identification routine. *Nag et al.* [2010] also showed several positive NBEs that were above 20 km. In our study, the maximum heights of positive NBEs are 17.5 km and 17.8 km, respectively, in Guangzhou and Chongqing, and the majority of positive NBEs are below 15 km. *Smith et al.* [2004] also showed very few positive NBEs were above 17 km. Considering their very small sample (48 positive NBEs), it seems that results of positive NBEs above 20 km found by *Nag et al.* [2010] may have some problem.

[20] The minimum height of negative NBE in Chongqing is 7.0 km, much smaller than that in Guangzhou. However, there are only 5 negative NBEs (0.073%) below 14 km in Chongqing, among which 2 were around 12 km and 3 were from 7 to 7.5 km. Other than these 5 cases, the minimum height of negative NBE in Chongqing is 14.1 km, similar to that in Guangzhou. As for the five negative NBEs with exceptionally low height, we checked their waveforms and re-examined the computation procedure, and we believe the height results are accurate. However, we are not sure whether they are truly NBEs, which produce not only narrow and bipolar pulses in low frequency radio bands but also very strong radiation in high frequency radio bands. It is possible that they are polarity-inverted intracloud discharges produced below the main negative charge layer [*Qie et al.*, 2005]. Such intracloud discharges may produce large bipolar electric field change waveforms that are similar to NBEs. Since we do not have observations in VHF bands to help identify NBEs, such misidentification is possible. Even if they are truly NBEs, they should have some special characteristics or are produced in special conditions as they are significantly lower than other negative NBEs and only account for an extremely small percent (0.073%).

[21] In summary, we state that negative NBEs mostly occur between 16 and 19 km; few are above 19 km or below

Table 1. Statistics of Discharge Height of NBEs

	Polarity	Number	GM (km)	AM (km)	Maximum (km)	Minimum (km)
Guangzhou	+NBE	1318	12.1	12.3	17.5	7.0
	-NBE	625	17.3	17.3	19.6	14.6
Chongqing	+NBE	5489	9.9	10.0	17.8	6.4
	-NBE	1400	17.5	17.5	19.9	7.0

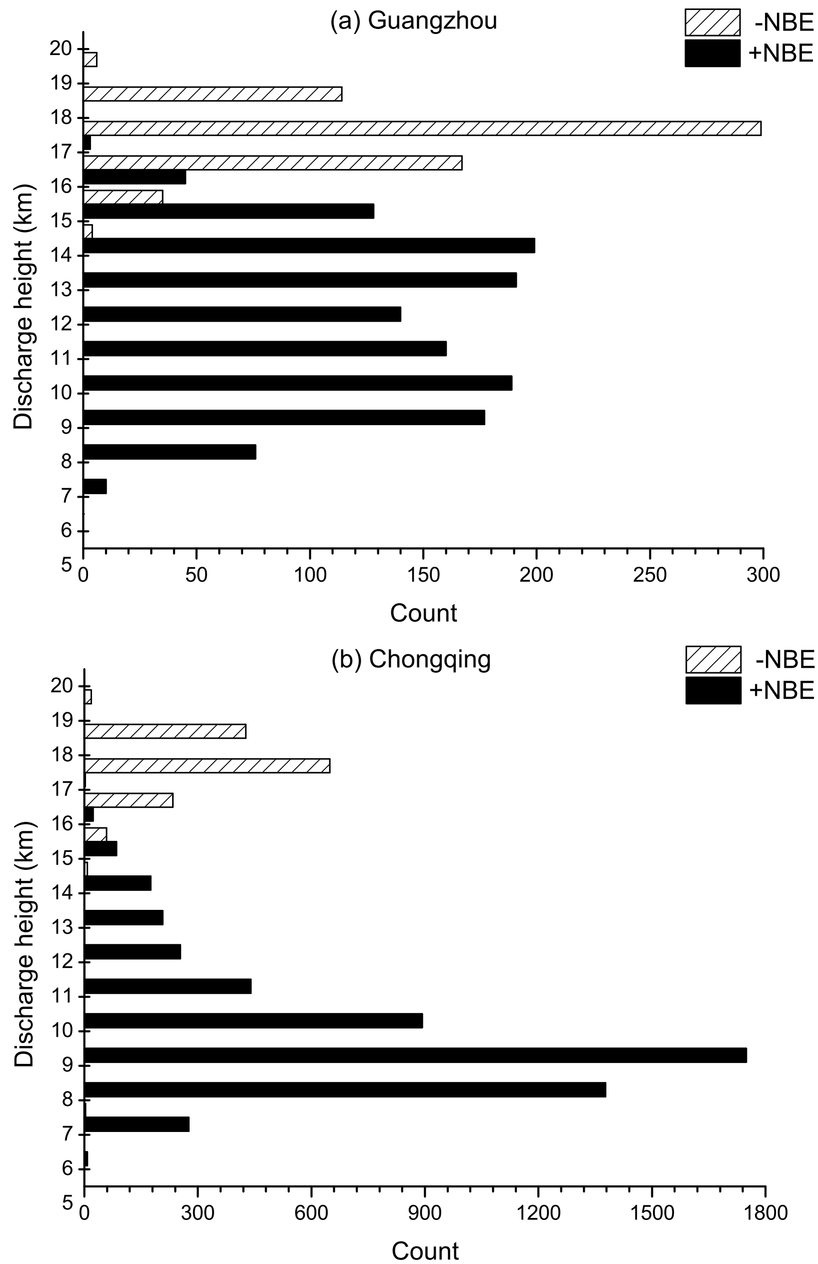

Figure 6. Distributions of discharge heights of NBEs observed in (a) Guangzhou and (b) Chongqing.

14 km. Positive NBEs occur in a wider range, mostly between 7 and 16 km. On the basis of discharge height distributions and discharge polarities, we conclude that positive NBEs are probably produced between the main negative charge layer and the upper positive charge layer while negative NBEs are probably produced between the upper positive charge layer and the screening negative charge layer at the cloud top as roughly illustrated by Figure 7. Such a charge structure is consistent with typical charge distributions in updraft regions of thunderstorms [*Stolzenburg et al.*, 1998].

4.2. Variations of NBE Discharge Height in Thunderstorms

[22] *Fierro et al.* [2011] discussed variation of NBE discharge heights in Hurricanes Rita and Katrina, but NBEs in their study were all positive polarity. Here we present the first analysis of height variations of both polarities of NBEs in two thunderstorms. Both of these two thunderstorms occurred at night with a distance of about 200 km from the lightning location network, so most of NBEs were recorded with well-defined ionospheric reflection pairs and could be located with the method introduced in section 3. Although radar observations of these two thunderstorms are available, which can be used to relate NBEs with the thunderstorm producing them, the radar stations were too far away in most periods of the thunderstorms and therefore could not give accurate information on the structure of the thunderstorms. So this section only discusses variations of NBE discharge height and next section will include a discussion on the structure of NBE-producing thunderstorms using the ones at more appropriate distances with radar stations.

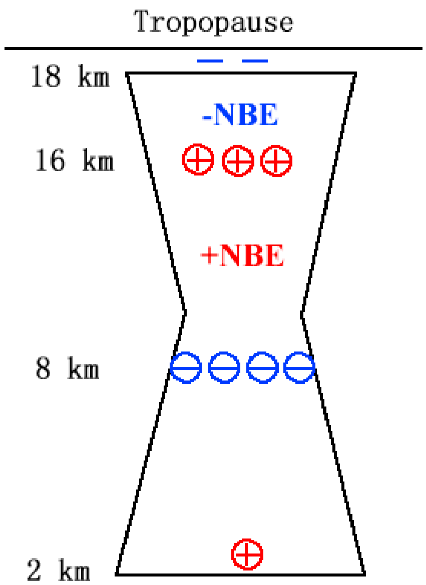

Figure 7. Illustration of discharge heights of positive NBE and negative NBE with respect to the charge layers in a thunderstorm.

[23] The first thunderstorm was observed in Chongqing, which was the only one in the observation in Chongqing that produced more negative NBEs than positive NBEs. As in Figure 8, there are 615 positive NBEs and 1108 negative NBEs, most of which are produced in the period from 23:30 to 02:30.

[24] Similar to the height distribution in Figure 6b, height of positive NBE shows a much larger variation than that of negative NBE. In the period from 00:00 to 02:00, height variations of positive NBEs are as large as 8 km in several minutes. *Fierro et al.* [2011] shows that in each NBE burst in Hurricanes Rita and Katrina, height variations of positive NBEs are only 2 to 3 km. However, at the end of the Hurricane Rita, the height variation is as large as 12 km [see *Fierro et al.*, 2011, Figure 3], very similar to our result. The reason for such large height variation is currently unknown. It may be simply because NBEs can be produced in any place between corresponding charge layers as illustrated in Figure 7. Relatively small height variations of negative NBEs indicate narrow space between upper positive charge layer and the screening charge layer. It is also reported that these two charge layers are sometimes partially mixed with each other [*Riousset et al.*, 2010].

[25] Each 15 successive positive NBEs and negative NBEs, respectively, are grouped together (the last group may contain less than 15 positive NBEs or negative NBEs), and the average height of each group is computed and represented by blue and green triangles in Figure 8. The density of triangles can also indicate NBE rate. Rate of positive NBE and negative NBE generally correspond with each other, both of which reach very large values in the period from about 00:00 to 02:00. In this period, a considerable amount of positive NBEs are occurring at relatively large heights (above 13 km). At the end of this thunderstorm (after about 03:00), few negative NBEs are produced, and all positive NBEs are occurring at lower heights (no positive NBE is above 10 km after 03:00). In the periods when no negative NBE is produced (indicated by shaded rectangles in Figure 8), there are 87 positive NBEs with an average height of 10.1 km, while in the periods with negative NBEs, there are 528 positive NBEs with an average height of 11.0 km. So positive NBEs are generally higher when negative NBEs are produced at the same time.

[26] The black curve in Figure 8 divides positive NBEs and negative NBEs into two sides, representing possible heights of the upper positive charge layer (see charge structure in Figure 7). It is interesting to note that all negative NBEs are above the curve and all but two positive NBEs are below the curve, indicating that negative NBEs are always above positive NBEs at the same moment, consistent with the charge structure for NBE productions in Figure 7. It also indicates that height results in Figure 8 do not have significant errors, otherwise there should be at least some

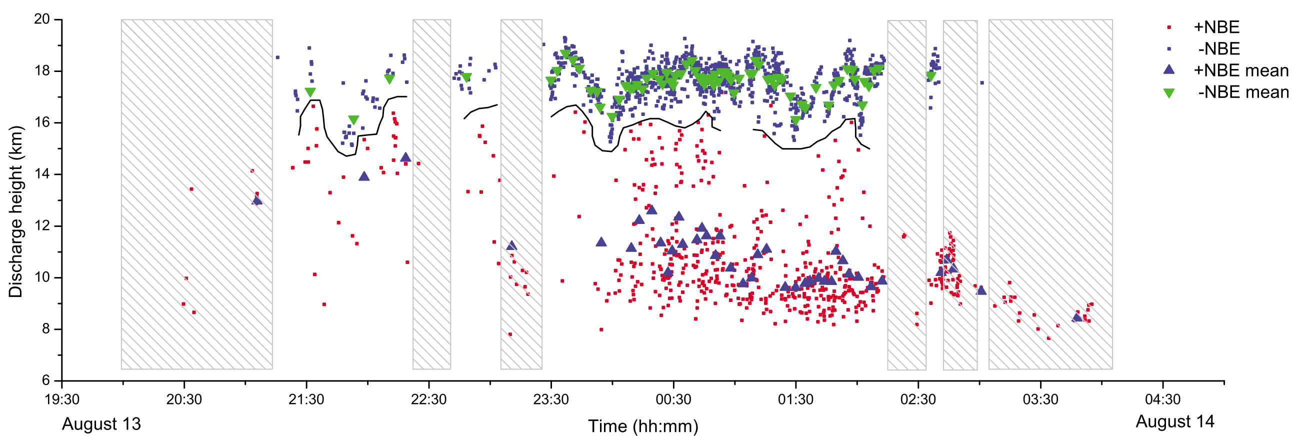

Figure 8. NBE discharge heights in a thunderstorm in Chongqing. Blue and green triangles represent average heights for each 15 successive positive NBEs and negative NBEs, respectively. Shaded rectangles indicate the periods when no negative NBE is produced. Black curve represents the possible location of the upper positive charge layer, dividing almost all positive NBEs and negative NBEs into two sides.

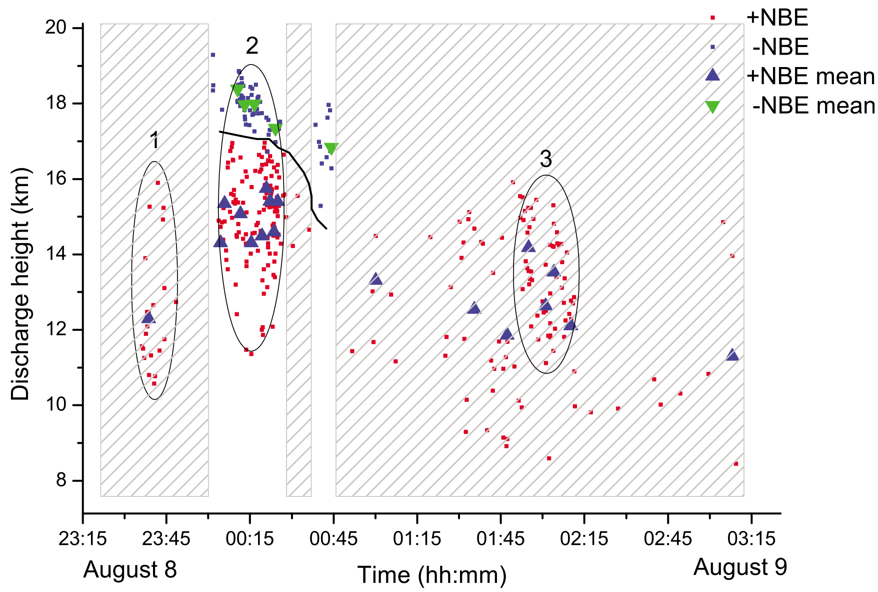

Figure 9. As in Figure 8, but for a thunderstorm in Guangzhou. The black ovals labeled 1 to 3 highlight NBE bursts.

positive NBEs and negative NBEs mixed together and it would be impossible to draw such a dividing curve.

[27] The second thunderstorm was observed in Guangzhou, which was predominated by positive NBEs. As shown in Figure 9, negative NBEs are only produced in a short period. There are a total of 262 positive NBEs and 69 negative NBEs in Figure 9. Similar to the case in Figure 8, height variations of positive NBEs are very large, about 6 km in several minutes. The NBE production shows 3 bursts in this case in which relatively large number of NBEs are produced in short intervals, similar to that shown by *Fierro et al.* [2011]. In the burst 2, negative NBEs were also produced, and the overall height of positive NBEs in this period is larger than that in other periods. In the periods when no negative NBE is produced (indicated by shaded rectangles in Figure 9), the average height of positive NBEs is 12.7 km, much smaller than that in the periods with negative NBEs, which is 15.0 km. The black curve has the same function as in Figure 8. Note that all positive NBEs are below the curve and all but 1 negative NBE are above the curve.

[28] Summarizing the above two cases, we have the following conclusions. First, NBEs seem to be able to occur in any position between corresponding charge layers, making height variations very large in most periods of a thunderstorm, especially for positive NBEs. However, at the end of a thunderstorm, when elevations of charge layers are probably decreasing, heights of NBEs are also decreasing and usually have small variations. Second, discharge heights of positive NBEs are generally higher when negative NBEs are occurring in the same period. This indicates that when negative NBEs are occurring, updraft is stronger, lifting charge layers responsible for positive NBE production to a larger altitude. Third, for a given short time period in a single storm, negative NBEs are always observed to occur at a higher altitude than positive NBEs, supporting the conclusion that positive NBEs are below the upper positive charge layer while negative NBEs are above the upper positive charge layer.

5. Discussions

5.1. Possibility of NBEs Occurring Above Thunderclouds

[29] *Jacobson and Heavner* [2005] and *Nag et al.* [2010] both mentioned the possibility that some NBEs may be produced above the cloud top because of their high discharge heights. However, we think that NBEs are all produced inside thunderclouds as indicated by Figure 7, at least for those observed in our study. We have the following evidences to support our opinion.

[30] First, upward discharges from thundercloud tops including blue jets and gigantic jets are different from NBEs in many respects. For example, both of blue jets and gigantic jets are optically visible [*Wescott et al.*, 1995; *Su et al.*, 2003], and their structural features have been well characterized; on the contrary, the "appearance" of NBEs is still unclear although it is commonly recorded by electric field measurements in various radio bands. The vertical extents of blue jets and gigantic jets are tens of kilometers, bridging the thundercloud top and lower ionosphere [*Pasko et al.*, 2002; *Su et al.*, 2003], but the spatial extent of NBEs is inferred to be less than 1 km. Except that some NBEs occur at an altitude comparable to the initiation height of blue jets or gigantic jets, they generally have no similarities.

[31] Second, as discussed by *Krehbiel et al.* [2008], blue jets and gigantic jets are produced as a result of certain special charge structures in the thundercloud. For example, large positive charge at the upper level and mixing of the screening negative charge with the upper positive charge are conducive to gigantic jets, while upper positive charge larger than the main negative charge added with screening negative charge is favorable for the production of blue jets. *Krehbiel et al.* [2008] also showed a jet produced in a decaying storm system. Here we will show that NBEs, different from

jets, are closely related with deep convections. The relationship between NBEs and thunderstorms has been discussed by many studies [*Suszcynsky and Heavner*, 2003; *Jacobson and Heavner*, 2005; *Wiens et al.*, 2008]. Here we will mainly demonstrate that when negative NBEs are produced, thundercloud tops are usually higher than 15 km, comparable to the discharge height of negative NBEs.

[32] Observations of a conventional S-band Doppler weather radar are employed here. Since radar observations of targets at high altitudes (roughly above 15 km in our data set) have low resolution reflectivity, making it seriously inaccurate to determine cloud top of higher than 15 km from radar echo top, here we define two quantities to roughly infer storm structures: total volume of reflectivity larger than 30 dBZ (V_{30}) and total volume of reflectivity larger than 30 dBZ above 15 km (V_{30-15}). Two adjacent thunderstorms producing more negative NBEs than positive NBEs observed in Guangzhou in August 8, 2007 are selected. These two thunderstorms are selected because they are in appropriate distances (between 60 and 100 km) from the radar station; they are close to the lightning location network (less than 120 km), so the location accuracy is high; and they both have clear boundaries, making the analysis easy. Figure 10 shows the time series of positive NBE rate, negative NBE rate and the value of V_{30} and V_{30-15}. Bursts of negative NBEs are clearly associated with abrupt increases of V_{30-15}, but V_{30} does not show obvious variation accordingly, indicating that changes of the storms mainly occur above 15 km; that is, the storms are developing higher during the bursts of negative NBEs. Although it is so far unclear why variations of V_{30-15} are always several minutes ahead of variations of negative NBE rate, the connection between negative NBE production and deep convection is obvious, which is also consistent with the finding of *Wu et al.* [2011] that a thunderstorm has higher tendency to produce negative NBEs as it is more vigorous. It is important to note that in these two cases, 30-dBZ heights are higher than 15 km when $V_{30-15} > 0$, so thundercloud tops are probably comparable to the discharge height of negative NBEs (16 to 19 km) during bursts of negative NBEs. This phenomenon is also consistent with charge structure in Figure 7; when negative NBEs are produced, thunderclouds are developing higher, and charge layers are lifted to the height comparable to the discharge height of NBEs, supporting the conclusion that NBEs are produced inside thunderclouds.

[33] Finally, *Jacobson and Heavner* [2005] and *Nag et al.* [2010] mentioned the possibility of some NBEs occurring above thunderclouds mainly because some NBEs were found to occur at very large heights, which thundercloud tops could rarely reach. However, in this study, we have demonstrated that almost all NBEs are below 19 km. It seems that very high NBEs in previous studies are probably due to computation errors. Under such circumstances, the assumption of NBEs being upward discharges from cloud tops is unnecessary, because thundercloud tops of 17 to 18 km high do not seem to be rare, and that up to 19 km high is also possible. *Zipser et al.* [2006], summarizing over 7 years of TRMM observation, found that maximum height of 40 dBZ of about 0.01% events can reach above 14 km, and some can even reach up to 19 km. *Ushio et al.* [2001] also showed that cloud top heights up to 18 km are not rare according to the data from TRMM. In a recent study on the relationship between cloud top and the tropopause, *Pan and Munchak* [2011] showed that in the region of our study, tropopause height is close to 17 km [see *Pan and Munchak*, 2011, Figure 8] and cloud tops can be 0.5 to 2.5 km higher than the tropopause in summer [see *Pan and Munchak*, 2011, Figure 7].

[34] In conclusion, NBEs with discharge heights up to 19 km are totally possible to be produced inside thunderclouds. The fact that cloud tops have relatively small chance to reach the height of 16 to 19 km where negative NBEs occur results in the phenomenon that negative NBEs are usually much fewer than positive NBEs. The possibility of NBEs occurring above thunderclouds is very low.

5.2. Comparison of Height Distributions in Two Regions

[35] When comparing distributions of NBE discharge height in Guangzhou and Chongqing (Figure 6), it is interesting to note that height distributions of negative NBEs are almost the same, while that of positive NBEs are largely different in these two regions. Average heights of negative NBEs in these two regions are also very close, while that of positive NBEs differ by more than 2 km (Table 1). It seems that large number of positive NBEs cluster below 10 km in Chongqing, while positive NBEs in Guangzhou distribute relatively evenly between 9 and 15 km.

[36] Another difference worth noting is that the percentage of negative NBE is much larger in Guangzhou than in Chongqing. The number of negative NBEs in Guangzhou is about half of the number of positive NBEs, while that in Chongqing is only about one fifth of positive NBEs. According to the conclusion of *Wu et al.* [2011] that percentage of negative NBE increases as convective strength of the thunderstorm increases, it seems that thunderstorms in Guangzhou have stronger convection than that in Chongqing. This can also be inferred from frequencies of negative return stroke (–RS) in these two regions. In Guangzhou, 138,148 –RSs were detected in 19 days, equivalent to 7271 –RSs per day. In Chongqing, 174,756 –RSs were detected in about two months, equivalent to about 2913 –RSs per day, much smaller than that in Guangzhou. From another perspective, we compared 50 largest hourly rates of total discharge events and –RSs in Guangzhou and Chongqing. In Guangzhou, the 50 largest hourly rates of total discharge events range from 22215 to 3203 counts per hour, much larger than that in Chongqing, which range from 2410 to 1288 counts per hour. The 50 largest hourly rates of –RSs in Guangzhou range from 5826 to 853 counts per hour, also larger than that in Chongqing, which range from 1437 to 776 counts per hour. Given the fact that the lightning detection network in Chongqing has more observation stations and covers larger area than that in Guangzhou (see section 2), it should be concluded that thunderstorms are generally more vigorous in Guangzhou than in Chongqing.

[37] Combining these two differences, we speculate on a possible explanation. It is likely that negative NBEs can only be produced above certain height. When the charge layers responsible for negative NBE production are lifted above certain height, negative NBEs can be produced, otherwise negative NBEs can rarely occur. Such “critical height” is around 15 km according to the result of this study. Since

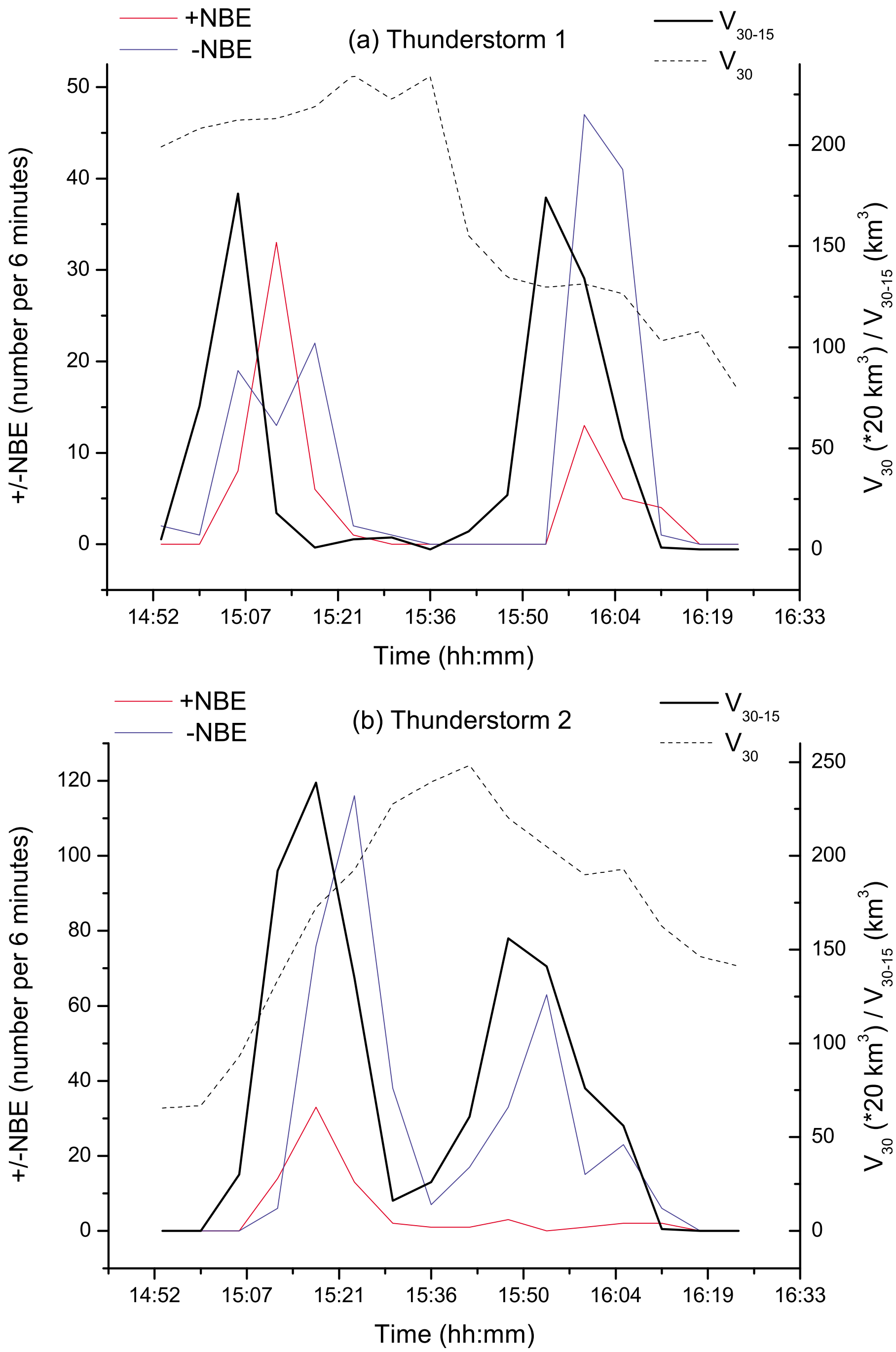

Figure 10. Time series of positive NBE rate, negative NBE rate and the value of V_{30} and V_{30-15} in two thunderstorms observed in Guangzhou: V_{30} and V_{30-15} share a scale, but the real value of V_{30} is the scale multiplied by 20.

thunderstorms in Chongqing are generally less vigorous than that in Guangzhou, thunderclouds in Chongqing are generally lower and the upper charge layers have less chance to develop above the critical height, resulting in much smaller percentage of negative NBEs in Chongqing. Normally the middle charge layers responsible for positive NBE production are also lower in Chongqing than that in Guangzhou, so positive NBE discharge heights in Chongqing are also lower. However, because of the limitation imposed by the "critical height," discharge heights of negative NBEs are almost the same in Chongqing and Guangzhou; the difference is that negative NBE percentage is much smaller in Chongqing because thunderclouds in Chongqing have less chance to develop to the critical height.

[38] The higher the upper charge layers are lifted above the critical height, the larger chance negative NBEs can be produced. However, it is difficult for thundercloud tops to penetrate the tropopause. Competition of such two limitations results in distribution peak between 17 and 18 km for negative NBE discharge height (Figure 6). Positive NBE

production should also have a critical height, which is possibly around 7 km. The upper limit for the height of middle charge layers responsible for positive NBE production seems to be around 17 km, so positive NBEs can occur between 7 km and 17 km, much larger a range than that of negative NBEs. Therefore positive NBEs have the "space" to show large difference in height distributions in two regions. However, although average discharge heights of positive NBEs in two regions differ by more than 2 km, the minimum values only differ by 0.6 km, indicating a lower height limit for positive NBEs. The minimum discharge heights of negative NBEs in these two regions are also very close (14.6 km and 14.1 km, see discussion in section 4.1), supporting our hypothesis.

[39] Under this hypothesis, negative NBE will rarely occur between the lower positive charge layer and the main negative charge layer (Figure 7), because these charge layers have very little opportunity to be lifted above the critical height of negative NBE (around 15 km). This also results in the fact that negative NBEs are usually much fewer than positive NBEs, because it is much easier for charge layers responsible for positive NBE production to reach the critical height.

[40] Such a hypothesis indicates an initiation mechanism of NBE in which there is energy injecting into thunderclouds from space. The higher a thundercloud develops, the larger energy it receives, and the larger chance there is that NBEs can be produced. Such notion is also consistent with the phenomenon that negative NBEs are usually more powerful than positive NBEs [*Wu et al.*, 2011]. A possible candidate for such mechanism is runaway breakdown mechanism [e.g., *Roussel-Dupré and Gurevich*, 1996] and likely included with relativistic feedback to increase multiplication of energetic electrons [*Dwyer*, 2003]. In such mechanism, cosmic ray particles play a critical role. There are also some studies trying to relate runaway breakdown mechanism to NBE phenomenology [*Gurevich and Zybin*, 2004; *Gurevich and Zybin*, 2005], but details are still missing to account for differences between positive NBE and negative NBE.

[41] If our hypothesis is true, a direct result is that NBEs will not be produced in thunderclouds with small vertical extent. *Sharma et al.* [2011] reported that no NBE was observed in Sweden (59.8°N, 17.6°E). According to our hypothesis, this result is likely due to lower tropopause at high latitude, limiting cloud tops below small altitude. It is also expected that in some regions with appropriate height of tropopause, only positive NBEs can be produced.

6. Summary

[42] Discharge heights of thousands of NBEs in two regions have been calculated employing time delays between direct radiation waves of NBEs and their ionospheric reflection pairs. The result shows that most positive NBEs occur between 8 and 16 km while most negative NBEs occur between 16 and 19 km. Few negative NBEs are above 19 km or below 14 km. It is likely that NBEs above 20 km reported by previous studies are due to errors in computations. According to discharge height distributions and discharge polarities, positive NBEs are probably produced between main negative charge layer and upper positive charge layer while negative NBEs are probably produced between upper positive charge layer and negative screening charge layer at the cloud top.

[43] Variations of NBE discharge heights in two thunderstorms are presented. It seems that NBEs can be produced at any position between corresponding charge layers, resulting in large variations of discharge heights. Positive NBEs are generally higher when negative NBEs are occurring in the same period, and for a given short time period in a single thunderstorm, negative NBEs are always higher than positive NBEs, supporting the charge layer structures for NBE production illustrated in Figure 7.

[44] The possibility of some NBEs as upward discharges from cloud tops mentioned by previous studies is discussed in many respects. Two thunderstorms producing more negative NBEs than positive NBEs are analyzed to demonstrate that negative NBE productions are closely associated with deep convections higher than 15 km. Supported by some other evidences, we concluded that such possibility is very low.

[45] Height distributions of NBEs in Guangzhou and Chongqing are compared, and it is found that height distributions of negative NBEs are almost the same in these two regions, but height distributions of positive NBEs have large difference. A hypothesis is put forward that there are "critical heights" for both positive NBEs and negative NBEs, and positive NBEs and negative NBEs can only be produced above their respective critical heights. Such hypothesis is consistent with many phenomena, and it also has some predictions. To further test this hypothesis, observations of NBEs of both polarities should be carried out in different regions over the world. Special attention should be paid to the discharge height of negative NBEs, studies of which are still scarce.

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W. Dong and Y. Zhang, Laboratory of Lightning Physics and Protection Engineering, Chinese Academy of Meteorological Sciences, Beijing 100081, China.

T. Funaki, Z. Kawasaki, T. Morimoto, T. Ushio, T. Wu, and S. Yoshida, Division of Electrical, Electronic and Information Engineering, Graduate School of Engineering, Osaka University, 2-1 Yamadaoka, Suita, Osaka, 565-0871 Japan. (wu.ting@comf5.comm.eng.osaka-u.ac.jp)