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Spatial relationship between lightning narrow bipolar events and parent thunderstorms as revealed by phased array radar

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[1] Phased array radar with unprecedented high temporal and spatial resolution is used for the first time to analyze structures of thunderstorms producing lightning narrow bipolar events (NBEs). Locations of NBEs generally correspond well with the deepest convection, but in some thunderstorms extending higher than 15 km, positive NBEs cluster around, rather than right at the center of the core of deep convection. Negative NBEs are generally higher than positive NBEs and are usually produced at the cloud top of the thunderstorm. Positive NBEs, on the other hand, are always located well inside the thundercloud. It seems that negative NBEs can only be produced in very vigorous thunderstorms with cloud tops higher than about 14 km. Numerous thunderstorms with lower height produce few negative NBEs, indicating a height threshold for NBE production. On the basis of these findings, it becomes very convenient and accurate to monitor severe thunderstorms with negative NBEs. **Citation:** Wu, T., Y. Takayanagi, S. Yoshida, T. Funaki, T. Ushio, and Z. Kawasaki (2013), Spatial relationship between lightning narrow bipolar events and parent thunderstorms as revealed by phased array radar, *Geophys. Res. Lett.*, *40*, 618–623, doi:10.1002/grl.50112.

1. Introduction

[2] Narrow bipolar event (NBE) is a special type of intracloud lightning discharge with many distinguishing characteristics. For example, NBEs produce extremely energetic VHF radiation that is one order of magnitude larger than that produced by normal discharge events [*Thomas et al.*, 2001; *Jacobson*, 2003]. NBEs are usually found temporally isolated from other discharges, but sometimes they occur as the initiation process in otherwise normal lightning discharges [*Rison et al.*, 1999; *Wu et al.*, 2011]. Discharge height of negative NBE is close to, or even larger than, the height of the tropopause [*Smith et al.*, 2004; *Wu et al.*, 2012]. The estimated channel length of NBE is smaller than 1 km [*Smith et al.*, 1999; *Liu et al.*, 2012]. For this reason, NBE is also called compact intracloud discharge (CID).

[3] Due to the fact that the strong high frequency radiation produced by NBE can penetrate the ionosphere and can be conveniently observed by satellite, NBE is a potential candidate for monitoring severe convective activities from space. However, such satellite-based monitoring cannot be realized until the relationship between NBE production and thunderstorm activities is well established. Over the last decade, many studies have contributed to examining such relationship [*Suszcynsky and Heavner*, 2003; *Jacobson and Heavner*, 2005; *Wiens et al.*, 2008]. Overall result indicates that NBEs tend to occur in the most vigorous thunderstorms, but statistical analysis on the relationship between NBE rate and various parameters of thunderstorm does not show a strong correlation. On the other hand, case studies on thunderstorms producing NBEs are still rare, and such studies mainly focus on positive NBEs [*Fierro et al.*, 2011; *Lu et al.*, 2012]. As demonstrated by *Wu et al.* [2011], the percentage of negative NBEs has the tendency to increase with increasing convective strength. In other words, vigorous thunderstorms are more likely to produce negative NBEs. Therefore, it is important to classify positive and negative NBEs when analyzing the relationship between NBE and thunderstorm, and special attention should be paid to thunderstorms producing negative NBEs.

[4] A significant and somehow mysterious feature of negative NBE is its large discharge height. Discharge height of negative NBE is generally larger than that of positive ones and normal intracloud discharges. Some negative NBEs are estimated to be significantly higher than the tropopause [*Smith et al.*, 2004; *Nag et al.*, 2010], which is difficult to understand because thundercloud has little chance to develop to such height. *Wu et al.* [2012] calculated discharge heights of thousands of NBEs in two regions and demonstrated that all NBEs, including negative NBEs, are produced inside thundercloud, and extremely large results in previous studies are probably due to computation errors. However, so far, there is still no direct evidence to prove that negative NBEs, occurring higher than 15 km or even close to 20 km, are inside thundercloud.

[5] In this paper, we will show observations of NBEs by low frequency (LF) lightning location system comprising nine stations and simultaneous observation of thunderstorms by a phased array radar (PAR) with the highest temporal and spatial resolutions in studies of NBE. Such coordinated observation provides the best chance so far to examine the relationship between NBE production and thunderstorm structure. As an initial report of the first observation in the summer of 2012, this paper deals with spatial relationship between NBE and parent thunderstorm.

2. Experiment

[6] LF lightning location system in Osaka region of Japan has been set up since the summer of 2011. During the

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summer of 2012 (period for this study), there were 9 stations, shown as red squares in Figure 1. Each station was equipped with a fast antenna with frequency range of 400 Hz to 1 MHz and decay time constant of 200 μs. Electric field change signals were digitized with 4-megasample/sec sampling rate and 12-bit resolution. All stations are synchronized by GPS receivers. Details of this system were described by *Takayanagi et al.* [2011].

[7] 3-D locations of lightning discharges are automatically determined by interferometry technique, and real-time monitoring of lightning activities in the Osaka region has been realized since the summer of 2012. Locations in Figure 1 are from results of real-time monitoring. However, NBEs have very clear peaks, so it is better to use time-of-arrival (TOA) technique to locate them. In this study, locations of NBEs are all determined with TOA technique. Because of relatively small sample of NBEs in this study, we manually checked waveforms and location results of all NBEs to make sure there is no apparent error. 3-D location error for NBE should be smaller than 1 km, as *Takayanagi et al.* [2011] compared location results determined by this system, which only contained four stations at that time, with those determined by a VHF interferometry system, and the difference was no larger than 1 km.

[8] The PAR started working since July 2012. It is a single-faced phased-array system located in Suita campus, Osaka University (34.82°N, 135.52°E; origin in Figure 1). In our system, the beam is electronically steered in elevation direction by transmitting a fan beam and receiving scattered signals as multibeam using digital beam–forming technology [*Yoshikawa et al.*, 2013]. In this way, one rotation of the antenna can cover a whole volumetric scan, and the time for volumetric updates can be significantly reduced. The current system can work in two scanning modes: fast-observation mode and wide-observation mode. Currently, the PAR is operated under the wide-observation mode, which takes 30 seconds for a whole volumetric scan, and the largest scanning range is 60 km. Its temporal resolution of 30 seconds is far better than conventional weather radar with parabolic antenna. Its spatial resolution is 100 m in radial direction, 1.2° in azimuthal direction and 0.9° in elevation direction. Such spatial resolution is also much better than conventional weather radar.

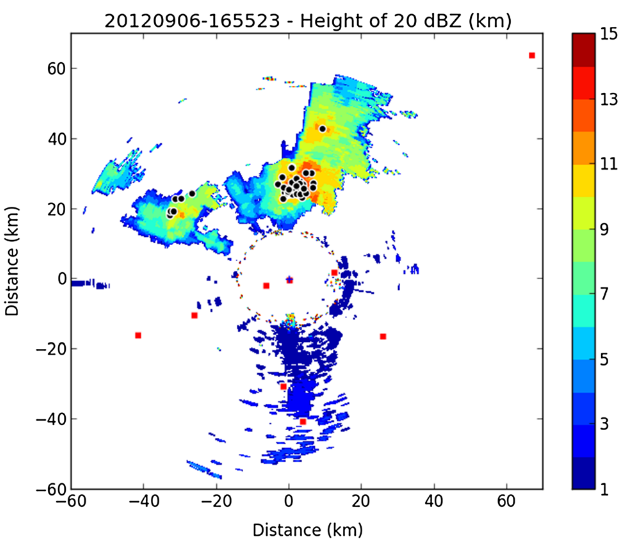

Figure 1. Height of 20 dBZ calculated from PAR reflectivity data. The PAR is represented by blue "+". Nine stations of LF lightning location system are represented by red squares. Black points represent lightning locations within ±15 seconds of the radar time.

[9] Data quality has not been fully controlled. The reflectivity data commonly contain some contaminations from ground clutter, such as the dark blue region in the lower part of Figure 1. Echoes from such contamination have strong intensity (larger than 50 dBZ), but they only occur at a low altitude (lower than 2 km). Therefore, we use height of 20 dBZ to indicate evolution of thunderstorms as shown in Figure 1. Another problem is that observation within about 10 km of the PAR is not very accurate due to some unsolved problems on pulse compression in this newly built system. So data within 10 km of the PAR are not shown as in Figures 1 and 2.

3. Results

[10] There are more than ten thunderstorms observed by the PAR during the summer of 2012. In Osaka region of Japan, each thunderstorm usually lasts for less than 1 hour with cloud top height of around 12 km. A total of 232 positive NBEs and 22 negative NBEs were observed during the summer of 2012, which had simultaneous observation by the PAR. Physics sign convention is used throughout this paper, so positive NBE corresponds to the discharge between upper positive charge and lower negative charge.

3.1. Horizontal Structure

[11] Locations of NBEs usually correspond well with the region of strongest convection (indicated by the largest 20 dBZ height) as shown in Figures 2a and 2b. In Figure 2a, the 20 dBZ height is 9.0 km, and NBE height is 5.9 km. In Figure 2b, the 20 dBZ height is 13.6 km, and NBE height is 10.7 km. The region where NBE is produced has the largest cloud top height at that moment. It appears that NBE is selective for the deepest convection. Such corresponding relationship has been suggested and reported by many studies [*Jacobson and Heavner*, 2005; *Wiens et al.*, 2008].

[12] However, the actual situation is more complicated. Figures 2c–2f are from two independent thunderstorms on 14 August 2012. Cloud tops of these two thunderstorms stayed higher than 15 km for a long time, which is not common in the Osaka region. These two thunderstorms produced 150 positive NBEs (65%) and 11 negative NBEs (50%). Positive NBEs in these two thunderstorms are apparently not selective for the deepest convection; instead, they converge around, and outside of, the region with deepest convection. In Figures 2c and 2d, locations of several positive NBEs form a circle right around the region with the highest cloud top, and all NBEs are located in regions with 20 dBZ height lower than 15 km. In Figure 2e, four positive NBEs are located at one side of the 15 km contour. In Figure 2f, two negative NBEs (with the same location, also shown in Figure 3d) are located almost right at the center of the thunderstorm, but seven positive NBEs are scattered near the edge of the thunderstorm. Such feature can also be found in other thunderstorms, but it seems most pronounced in very deep convections.

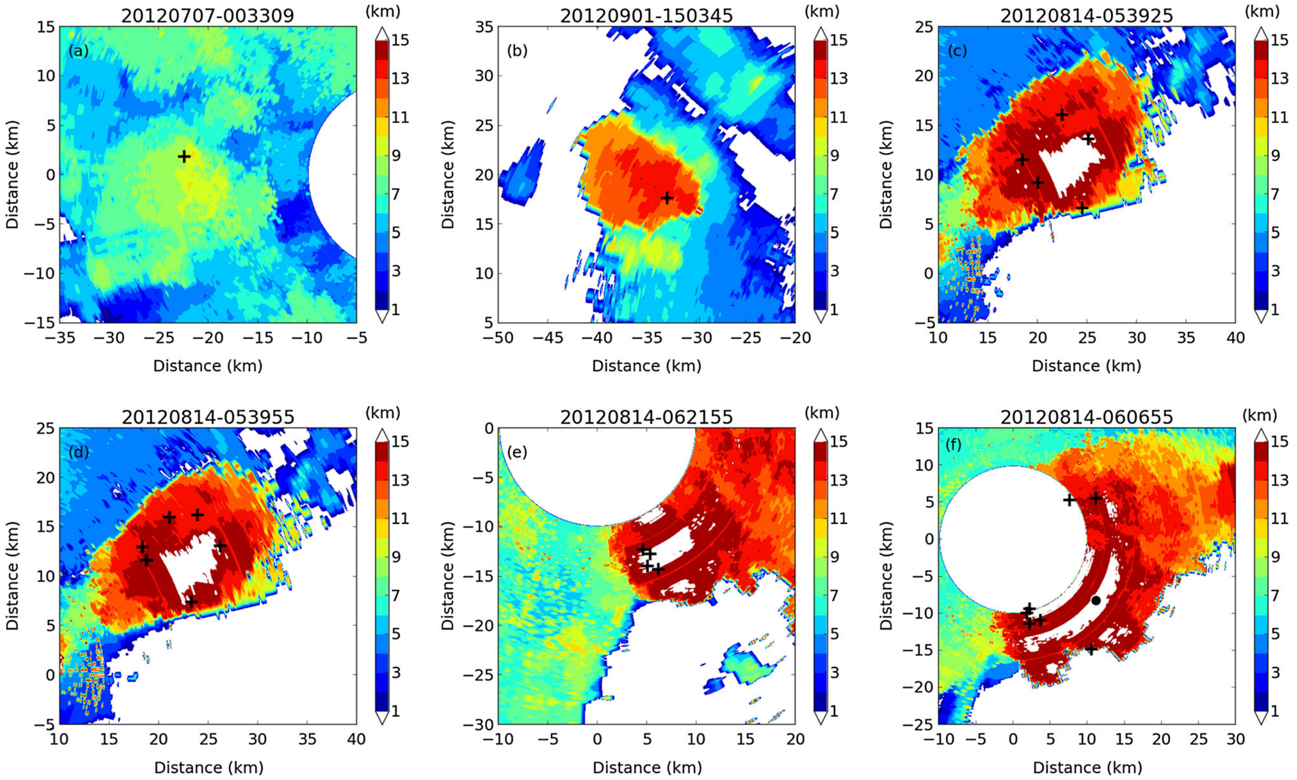

Figure 2. Height of 20 dBZ calculated from PAR reflectivity data. The PAR is located at (0, 0). Black pluses represent positive NBEs and black points represent negative NBEs within ±15 seconds of the radar time.

[13] One possible explanation for such phenomenon is that under intense updraft, ice crystals with positive charges are elevated to a higher altitude while graupels (larger and heavier) carrying negative charges still stay in the mixed-phase region, so the distance between the upper positive charge layer and the main negative charge layer increases and discharges in this region are less likely to occur. Another reason may be that as cloud top extends into higher altitude, it becomes easier to form the screening negative charge layer due to increase of atmospheric conductivity [*Riousset et al.*, 2010]. Such screening negative charge layer can reduce the net electric field between the main negative charge layer and the upper positive charge layer and reduce the possibility of positive NBE production in this region. As a result, positive NBEs are more likely to occur outside of the deepest convective region.

3.2. Vertical Structure

[14] According to the results of NBE discharge height calculated by *Smith et al.* [2004] and *Wu et al.* [2012], it is speculated that positive NBEs are produced between the main negative charge layer and the upper positive charge layer, while negative NBEs are produced between the upper positive charge layer and the screening charge layer at the cloud top. However, due to some results of NBEs that are much higher than normal cloud top [*Smith et al.*, 2004; *Nag et al.*, 2010], such speculation is still questionable. Here we compare locations of NBEs, especially negative NBEs, with vertical structures of thunderstorms revealed by the PAR to examine this issue.

[15] Figure 3 shows some examples of range-height indicator (RHI) of reflectivity with NBE locations. Figure 3a shows a positive NBE of 5.7 km inside a thundercloud with top height of about 9 km. Figure 3b shows a much more vigorous thunderstorm with top height of about 14 km. Three positive NBEs are produced at the upper part of the thundercloud. In fact, all positive NBEs analyzed in this study are found to be well inside thunderclouds regardless of storm-top heights.

[16] The situation for negative NBEs is quite different. Figure 3c shows two negative NBEs right at the upper boundary of the thundercloud. Because the PAR is designed for observation of up to 15 km altitude, only fragments of reflectivity above 15 km can be captured by the end of some beams as shown in Figure 3. However, the upper cloud boundary can still be roughly figured out. In Figure 3c, one negative NBE is at the inner side and the other at the outer side of the upper boundary. A positive NBE is produced outside of the reflectivity core similar with those analyzed in section 3.1. Figure 3d is only 30 seconds from Figure 3c, and two negative NBEs occurred again at almost the same location. Figure 3e shows another two negative NBEs. The cloud top is higher than 15 km and difficult to discern, but the two NBEs seem to be quite close to the cloud top. Figure 3f shows similar situation with Figure 3e. It also shows a positive NBE at the edge of the reflectivity core. The negative NBE in Figure 3g is well inside, and the one in Figure 3h is well outside of the thundercloud, somehow different from other cases. The one inside the thundercloud may be due to lower altitude of the upper positive charge layer, and the one outside thundercloud may be due to transient overshooting that is not captured by

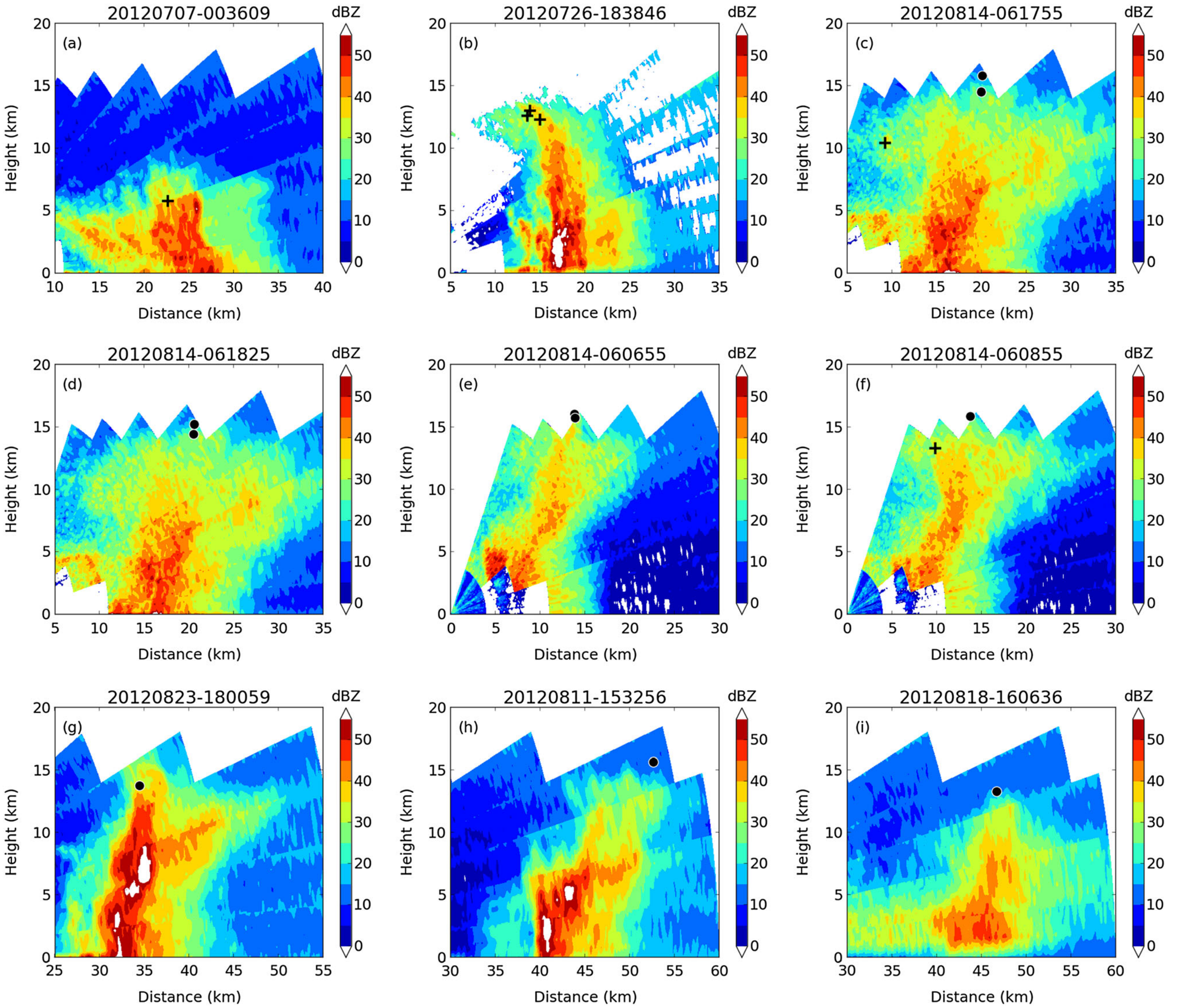

Figure 3. RHI of reflectivity observed by the PAR. The PAR is located at (0, 0). Black pluses represent positive NBEs and black points represent negative NBEs within ±15 seconds of the radar time.

the PAR. Figure 3i shows a very low negative NBE (13.3 km), which is also right at the top of the thundercloud.

[17] In summary, positive NBEs are always well inside thundercloud, while negative NBEs are usually at the upper boundary of the thundercloud. Sometimes negative NBEs are at the inner side of the boundary while sometimes they are at the outer side, which may be due to different situations analyzed above. Figure 4 shows a scatterplot of discharge height of all NBEs versus 20 dBZ height of parent thunderstorms. It should be noted that the actual storm-top height is a little higher than 20 dBZ height. Negative NBEs are generally higher than positive NBEs. One negative NBE is exceptionally low (8.1 km), which may be similar with three negative NBEs around 7 km reported by *Wu et al.* [2012]. It may indicate that negative NBEs can also be produced below the main negative charge layer, but it is more likely that such low negative NBEs are different from other negative NBEs in certain respect such as VHF radiation characteristics. However, such cases are very rare (0.073% in the study by *Wu et al.* [2012] and 1 in 22 in this study), and we will not further discuss them in this study.

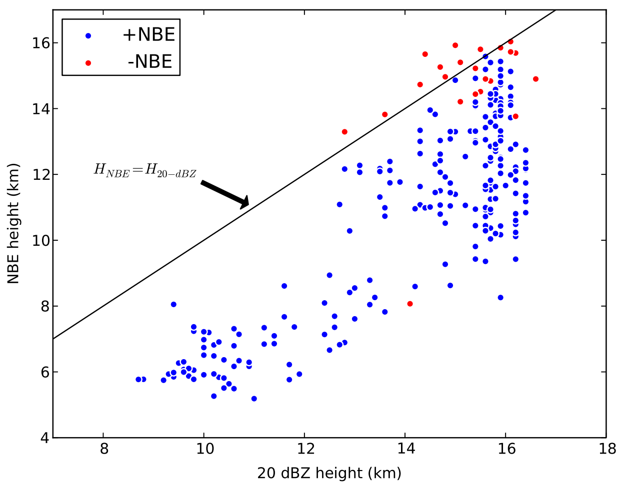

Figure 4. Height of all NBEs in this study versus 20 dBZ height of their parent thunderclouds. At the black line, NBE height equals 20 dBZ height.

[18] Apart from the exceptionally low one, the lowest negative NBE is 13.3 km, and the highest one is 16.0 km. Most of negative NBEs are clustered around the line of equal NBE height and 20 dBZ height, indicating negative NBEs occur near the upper boundary of thunderclouds. Positive NBEs, on the other hand, are usually much lower than the 20 dBZ height. As the 20 dBZ height increases, some positive NBEs also reach quite close to the cloud top, but all of them are still inside the thundercloud. Such result is consistent with the notion that positive NBEs are produced below and negative NBEs above the upper positive charge layer.

4. Discussion

4.1. Height Threshold for NBE

[19] *Wu et al*. [2012] proposed a hypothesis that NBEs can only be produced above a certain height ("critical height"). Our observation is consistent with such hypothesis, especially for negative NBE. Discharge heights of negative NBEs in this study range from 13.3 to 16.0 km (except for the especially low one), and most of them are between 14 and 16 km. Such distribution resembles the lower tail of the distributions in Guangzhou and Chongqing of China (see Figure 6 in *Wu et al*. [2012]). This hypothesis indicates that only when the charge layers responsible for production of NBEs are lifted above the critical height can NBEs occur. Since negative NBE is produced near the upper boundary of thundercloud, the thundercloud top has to develop to the critical height, which is probably around 14 km, before negative NBE can occur. However, thunderstorm with cloud top of higher than 14 km is very rare in Osaka region (the PAR is only designed for observation of up to 15 km). Most thunderstorms in Osaka region only developed to around 12 km or even lower, and no negative NBEs were produced. Cloud tops of some rare cases analyzed in section 3.2 exceeded the critical height and produced several negative NBEs. The highest negative NBE is only 16.0 km in this study, compared with larger than 16 km for majority of negative NBEs in south China [*Wu et al*., 2012], which is also a manifestation of much lower storm top in Osaka region than that in south China.

4.2. Significance for Monitoring Severe Thunderstorm with NBE

[20] When analyzing the relationship between NBE and thunderstorm, previous studies usually make no discrimination between positive and negative NBEs [*Jacobson and Heavner*, 2005; *Wiens et al*., 2008]. We suggest that negative NBE is more useful and accurate in indicating the deepest convection.

[21] As analyzed in this study, negative NBEs are only produced in the most vigorous thunderstorms (usually higher than 14 km), and negative NBEs always occur near the upper boundary of the thundercloud. Therefore, if we can detect negative NBE and determine its height, we can estimate the thunderstorm top height right from the negative NBE height. Even if we cannot determine NBE height, we can roughly decide the severity of thunderstorm by the presence of negative NBE. As long as negative NBE is produced, the thunderstorm has probably developed above at least 14 km, which is quite severe. In this way, severe thunderstorms can be conveniently monitored by detecting negative NBEs.

5. Conclusions

[22] Locations of NBEs detected by LF lightning location system are compared with thunderstorm structure observed by the PAR. It is found that NBEs usually correspond well with the deepest convection. However, in some thunderstorms with intense updraft extending above 15 km, positive NBEs are produced at the periphery, instead of the center, of the deepest convection. This may be because of decrease of electric field due to elevation of the upper positive charge layer or formation of screening negative charge layer in the region of the deepest convection.

[23] Positive NBEs are usually lower than negative NBEs. Positive NBEs are always produced well inside thundercloud, while negative NBEs are usually close to the upper boundary of the thundercloud. Negative NBEs were only produced in a few thunderstorms with the deepest convection, while numerous thunderstorms with shallower convection did not produce any negative NBE, a phenomenon consistent with "critical height" hypothesis proposed by a previous study. Such feature also makes negative NBE a perfect proxy for monitoring severe thunderstorm.

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