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Charge structures and cloud-to-ground lightning discharges characteristics in two supercell thunderstorms

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Abstract The charge structures and temporal and spatial characteristics of cloud-to-ground (CG) lightning discharges in two supercell thunderstorms have been analyzed based on the data of three-dimensional VHF radiation sources with high time and space resolution produced by lightning discharges. The results indicate that the charge structures in main part (convective region) of the thunderstorms were inverted tripole while a number of positive CG lightning discharges were occurring in the two thunderstorms. The positive CG lightning discharges occurred in main part of the thunderstorms and originated from the positive charge region located at the middle part of the thunderstorms. While a number of negative CG lightning discharges were occurring, the negative CG lightning discharges occurred in the anvil of the thunderstorm. The charge structure is inverted dipole in the region due to the slant of charge structure in main region toward anvil region. The negative charge region located at the upper part of anvil produced a lot of negative CG lightning discharges. No or less CG lighting was produced directly by the charge region located at the lower part of the thunderstorm. The charge region in lower part of the thunderstorm plays an important role for the occurrence of CG lightning from charge region above it.

Keywords: supercell thunderstorm, charge structure, CG lightning.

The characteristics of CG lightning discharges have been studied because they often result in the disaster and are easier to be observed than intracloud discharge. In early stage, the locations of charges in cloud are determined based on the multi-stations measurements of electric field changes produced by CG lightning discharges. Then the charge structure in thunderstorm can be inferred. The results show that the charge structure in most of thunderstorms is dipole or tripole with the negative charges at the middle part of the thunderstorm[1]. As the systems locating CG lightning are developed, the temporal and spatial characteristics of CG lightning are understood gradually. Combining radar and other data with data of CG lightning location, it is revealed that most of thunderstorms produce mainly negative CG lightning and they occur during the middle and final stages of the thunderstorm development. The positive CG lightning discharges occur in dispersing stage of the thunderstorms. Meanwhile, the observing results show that a number of positive CG lightning discharges appear in some supercell thunderstorms, especially in thunderstorms producing severe processes such as hail and tornado[1]. The VHF radiation sources produced by lightning discharges were measured and located recently and it was found that the charge structure was inverted polarity in some supercell thunderstorms at their maturating stage, being positive charge at middle part of thunderstorm. It was inferred that the charge structure resulted in the occurrence of a number of positive CG lighting discharges[2−4]. However, the negative CG lightning discharges occurred mainly in some severe thunderstorms producing hail as normal thunderstorms. There is significant difference for different geography areas. The sound measurements of electric fields show that the electric charge structures in thunderstorms are very complex and the multilevel structures often exist[1)]. Because the occurrence of CG lightning discharges is related to the charge structures in thunderstorms, the researches on relativity between them are very significant to understand the occurring and developing processes of the lightning discharges based on the temporal and spatial characteristics of CG lightning and charge structure in thunderstorms. The characteristics of lightning occurring in two supercell thunderstorms on July 22, 2000 were analyzed by using the data observed by the Lightning Mapping Array(LMA) and CG lightning location system in this

1) Stolzenburg, M., An observational study of electrical structure in convective regions of mesoscale convective systems, Ph.D. Diss., Univ. of Oklahoma, Norman, 1996, 137.

paper. The relativity between charge structure and characteristics of CG lightning and the effect of charge region in lower part of thunderstorm on the occurrence of CG lightning were discussed.

1 Observation and analysis

The LMA system developed by New Mexico Institute of Mining and Technology takes advantage of GPS technology to measure the arrival time of impulsive VHF radiation events of lightning at each remote location. The spatial and temporal development processes of lightning are described in 3-dimasion by measurement of the system with high time resolution (50 ns) and space precision (50—100 m)[3−5]. The system can detect several hundred to several thousand radiation events for an individual lightning discharge. The 3-dimasion structure of lightning discharges can be mapped precisely in certain extension. The system has a central receiving frequency of 63 MHz and bandwidth of 6 MHz. In the Severe Thunderstorm Electrification and Precipitation Study (STEPS) in the summer of 2000, thirteen measurement stations were deployed over a four-county area in northwestern Kansas and eastern Colorado of USA[4,6]. Lightning discharges within 300 km away from the center of network, being the coordinate origin in the plan view projection, could be detected. The parameters of CG lightning were obtained from the data of National Lightning Detection Network (NLDN).

Two thunderstorms passed the observation domain on July 22, 2000. Thunderstorm A occurred at 18:40 in north of observation network and moved toward southeast. The thunderstorm lasted 4 h. Thunderstorm B started at 21:00 in northwest of observation network and moved toward southeast. The thunderstorm also lasted 4 h. A lot of lightning discharges were produced in the two thunderstorms even though no sever processes occurred. Especially the characteristics of CG lightning were different for the two thunderstorms.

1.1 Characteristics of CG lightning discharges

Fig. 1 (a) and (b) show the variations of CG light-

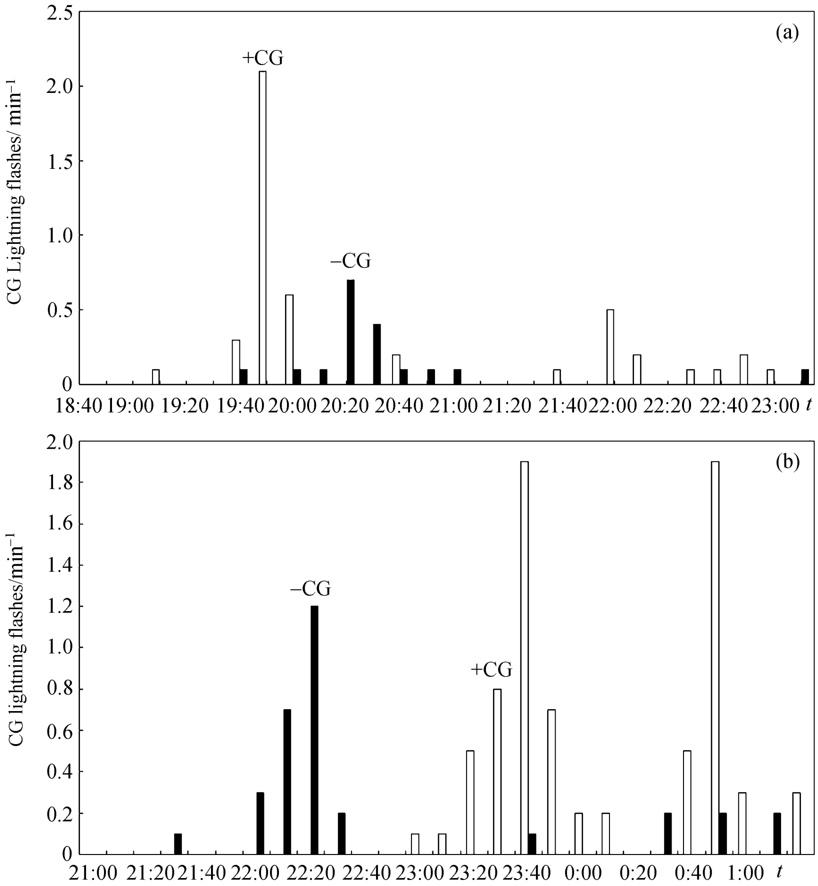

Fig. 1. Number of CG lightning discharges for thunderstorms A (a) and B (b) on July 22, 2000.

ning discharges rate with time for thunderstorms A and B respectively. In thunderstorm A, the positive CG lightning discharges were produced firstly and the peak of its rate with a value of 2.3 min appeared at 19:50. The negative CG lightning discharges occurred 10 min later and no positive CG lightning occurred during 30 min after that. The peak of negative CG lightning discharges rate appeared at 20:20, being 0.7 min. Positive CG lightning occurred three times at about 20:40. There was an intermission of the CG lightning after 21:00 and another peak of positive CG lightning discharges rate with lightning frequency less than before did not occur until 22:00.

In reverse order of thunderstorm A, it can be seen from Fig.1 (b) that thunderstorm B produced firstly the negative CG lightning and its rate gradually increased. The peak of negative CG lightning rate appeared at 22:20, being 1.3/min. After that, the negative CG lightning rate decreased rapidly. After an intermission of about 30 min, thunderstorm B started to produce the positive CG lightning and its peak with a value of 1.9/min appeared at 23:40. Only one negative CG lightning discharge occurred during the period. The positive CG lightning discharges were dominant in the finial stage of the thunderstorm.

The time and location of the thunderstorms A and B were different. However, they produced mainly the positive CG lightning discharges and the positive and negative CG lightning discharges appeared alternately in reverse order. A thunderstorm may consist of several cells and the conditions of formation, development and dissipation for each cell were different. This results in the difference of charge structure in thunderstorm. The differences of CG lightning characteristics result from the collocation of different polarity charge regions.

1.2 Charge structure characteristics

The observation results indicate that the VHF radiation of the lightning discharges is produced mainly by the negative polarity breakdown in processes of lightning initiation and development. The VHF radiation produced by positive breakdown is 20dB less than that by negative breakdown and is too weak to measure [5, 7]. The LMA system mainly detects and locates the VHF radiation sources produced by the negative breakdown. So, the distributions of positive charge regions in the thunderstorm can be mapped precisely. Meanwhile, the negative charge regions can be located by using the propagation characteristics of the K processes involving intracloud discharges and interval processes between return strokes in CG lightning. (These processes develop toward the starting region of the lighting from the front of the lightning channel tip in a retrograde manner in negative charge regions and the lightning channels are extended. Sometimes, some processes pass the starting region of the lightning into the positive charge region.) [3, 8, 9]. So, the charge regions involving lightning discharges in the thunderstorms can be inferred based on the distributions of the VHF radiation sources produced by the lightning, especially individual lightning. The main charge structure in thunderstorms is revealed.

Fig. 2 shows that lightning radiation events for 10 min from 19:49 to 19:59 occurred in thunderstorm A on July 22, 2000. The number of radiation sources shown in Fig. 2(c) was 128101 during the period and they were located mainly at about 8 km height. Some radiation sources appeared at 14 km height. It is seen from Fig. 2 (b), (d) and (e) that the storm was moving toward the southeast direction. The positive CG lightning discharges occurred just below the thunderstorm and in main part of the thunderstorm.

Fig. 3 shows the radiation events of three small intracloud discharges at about 19:59 in thunderstorm A on July 22, 2000. In Fig. 3 (a) and (d), IC1, IC2 and IC3 indicate the three intracloud discharges respectively. It can be seen that the three discharges occurred in different regions of thunderstorm A. The results observed reveal that the intracloud discharge shows bilevel structure corresponding to the positive and negative charge regions respectively. Most of radiation points appear in positive charge region and less in negative region[8]. The discharges IC1 and IC3 were inverted polarity and indicated that the positive and negative charge regions were located between 8 and 10 km, and between 11 and 12 km respectively. The discharge IC2 was normal and indicated that the positive and negative charge regions were located between 8 and 9 km, and between 5 and 7 km respectively. These discharges indicated clearly the charge structure involved in the lightning discharges in thunderstorm A. Therefore, the positive charge region was located at the middle of the thunderstorm and the two negative charge regions were located above and below the positive charge region respectively. The charge structure in thunderstorm A during this period was inverted tripole. Fig. 4 shows the distribution of VHF radiation sources produced by a positive CG lightning occurring during the period. The

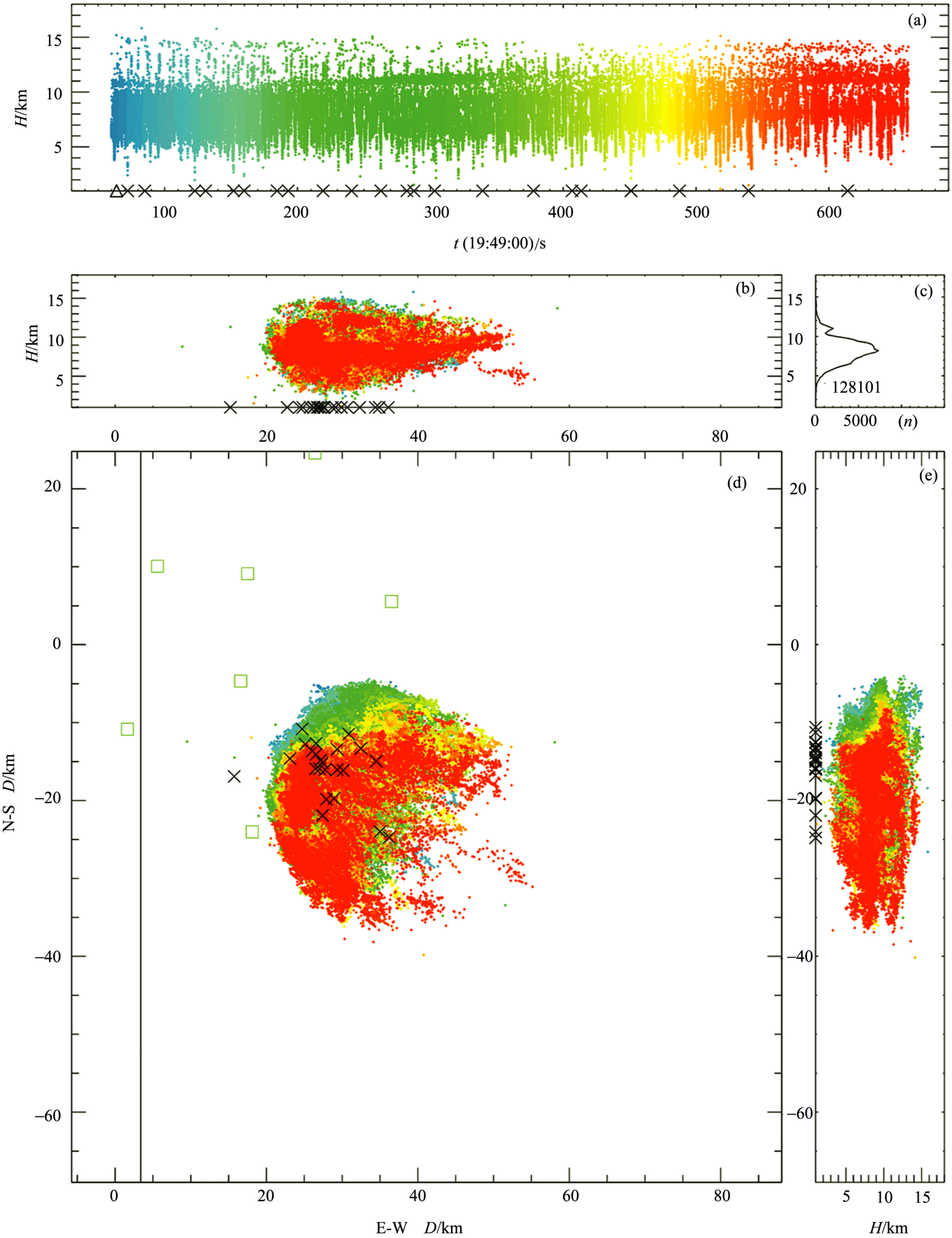

Fig. 2. Distribution of lightning radiation events for 10 min from 19:49 to 19:59 in thunderstorm A on July 22, 2000. The changes of color from blue, green, yellow to red in figure indicate the variations of VHF radiation events with time. (a) Height-time plots, (b) north-south vertical projections, (c) height distribution of number (N) of radiation events, (d) plan views, (e) east-west vertical projections. △, time and location of occurrence of negative; ×, positive CG lightning; □, location of measurement station; D, distance away from the coordinates origin.

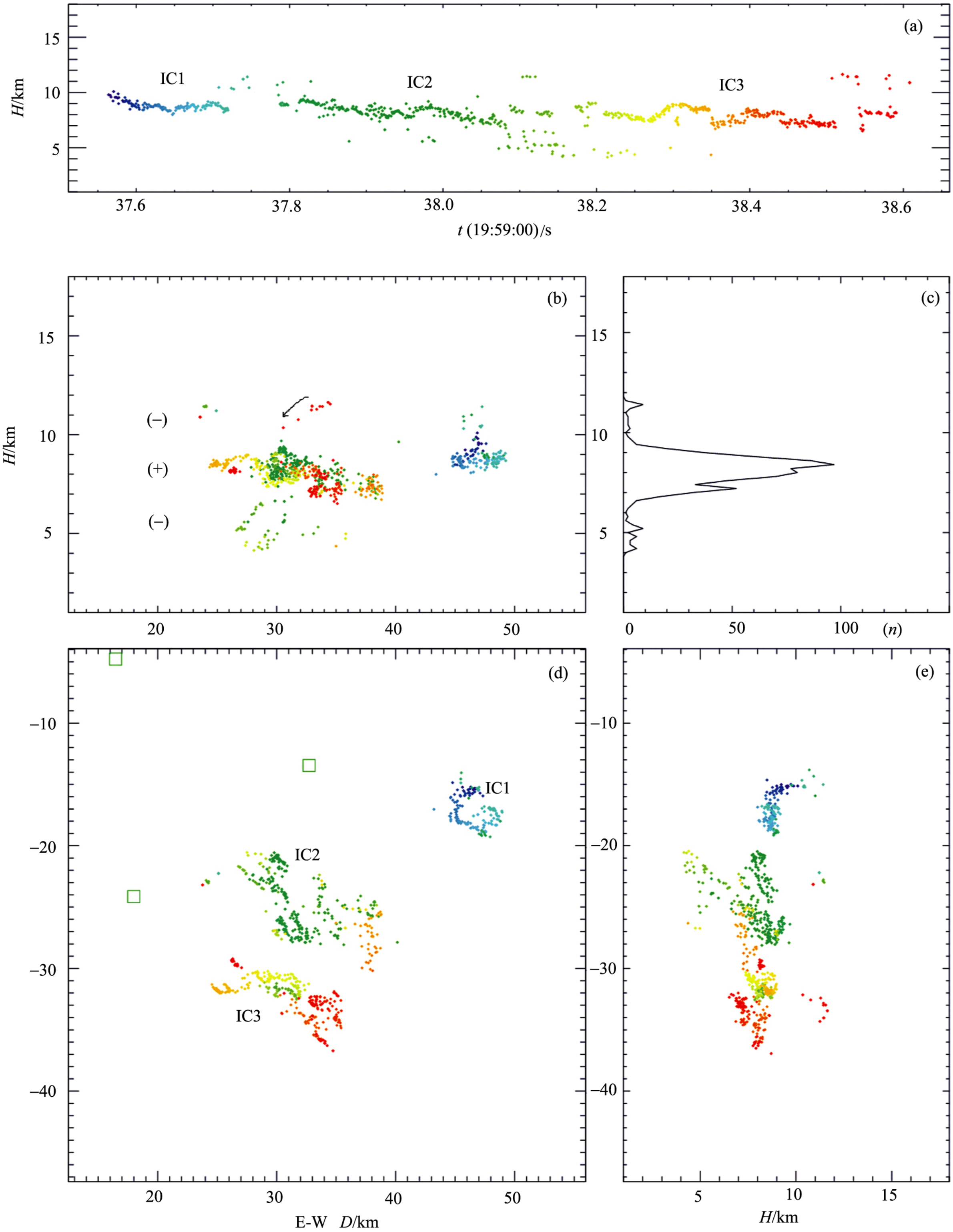

Fig. 3. Distribution of lightning radiation events of three intracloud lightning discharges at 19: 59(UTC) in thunderstorm A on July 22, 2000, with the same format as Fig. 1.

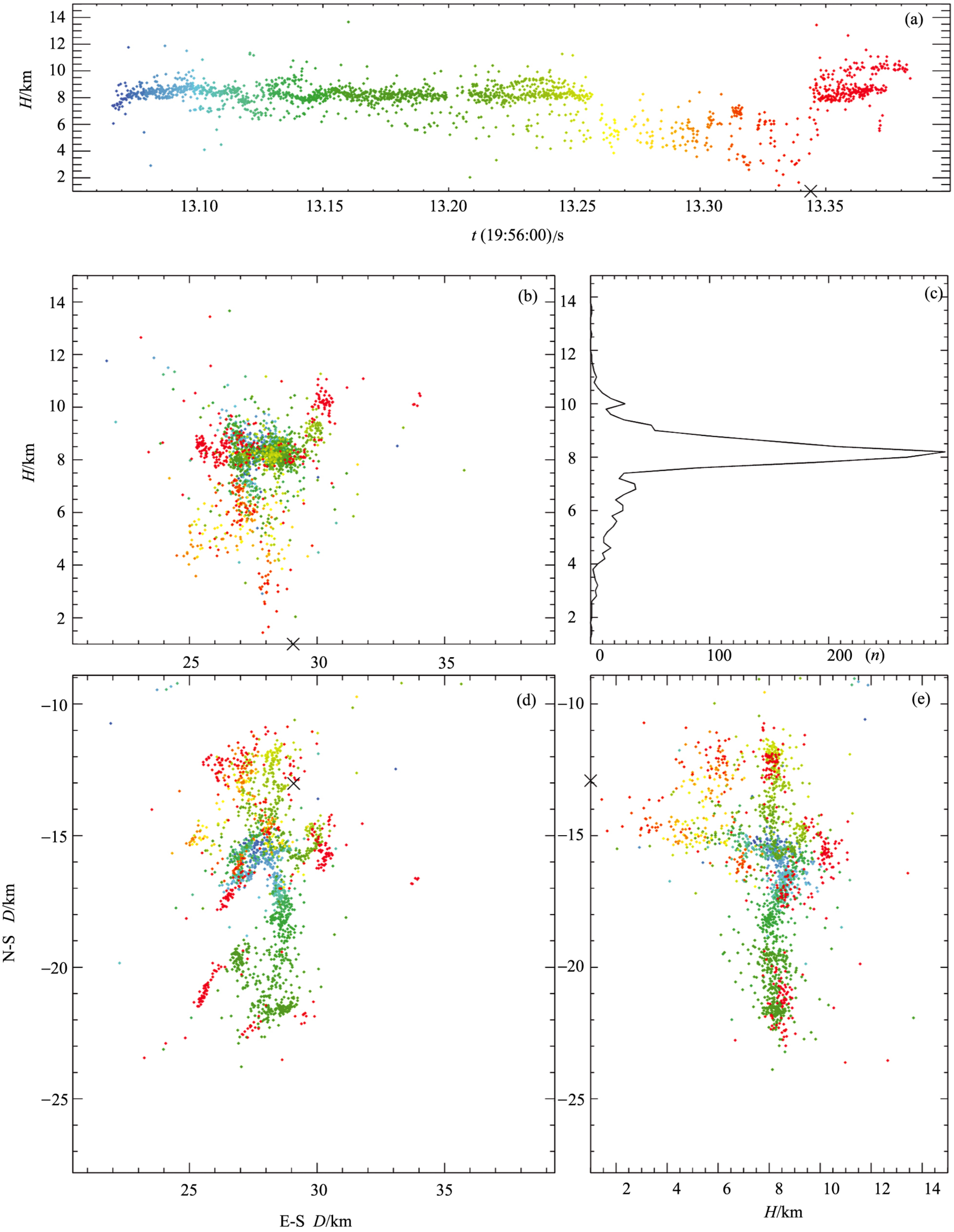

Fig. 4. Distribution of lightning radiation events of a positive CG lightning discharge at 19:56(UTC) in thunderstorm A on July 22, 2000, with the same format as Fig. 1.

lightning discharge initiated at 6 km height and developed upward to 8.5 km height. Most of radiation points occurred at about 8 km height. This is in agreement with that shown in Fig. 3. This indicates further that the positive charge region in thunderstorm was located at about 8 km height and produced the positive CG lighting. The only negative CG lightning occurring in this period was analyzed and the results indicated that the discharge originated from the upper negative charge region.

Fig. 5 shows that the distributions of VHF radiation sources for 10 min from 20:19 to 20:29 in thunderstorm A on July 22, 2000 during a amount of negative CG lightning occurring. It is shown in Fig. 5 (c) that less radiation sources occurred during the period, being 38344. However the peaks of a number of radiation sources appeared at 9 km height. A obvious overshooting of radiation sources appeared between 12 and 14 km corresponding to a overshooting processes of updraft in main part of the thunderstorm [3, 10]. This indicates that the convective processes continued to occur during the period. However it is indicated from Fig. 5(b), (d) and (e) that the radiation sources of lightning moved from main part to anvil of the thunderstorm and the height of the radiation sources gradually decreased. A amount of negative CG lightning occurred in anvil of the thunderstorm.

Fig. 6 shows that the distributions of VHF radiation sources produced by a negative CG lightning at 20:31 in thunderstorm A on July 22, 2000. Comparing to Fig. 5, the negative CG lightning discharge occurred in anvil of the storm. The discharge started from 10 km height and propagated downward. The lightning channel developed horizontally and fell from 10 km to 8 km height. The structure of the lightning indicates the location of negative charge region in the thunderstorm. The structures of more individual intracloud and CG lightning discharges revealed that the charge structures were inverted tripole and dipole in the main part and anvil of storm respectively at this stage. The inverted dipole charge structure with upper negative and lower positive charge in anvil part of the thunderstorm was formed due to the slant of the charge structure in main part of the thunderstorm. The height of negative charge region fell gradually from near main part to anvil of the storm, being from 10 km to 8 km. The height of lower positive charge region also fell from 8 km to 5 km.

Fig. 7(a) and (b) shows the sketches of charge structures at the two stages shown in Figs. 2 and 5 respectively. A lot of positive charges were located at the middle of the thunderstorm and negative charges distributed above and below the positive charge respectively during the positive CG lighting occurring. The positive CG lightning discharges originated from the positive charge region. The charge structure with the positive charge in middle of the main part of the thunderstorm did not change during the negative CG lightning discharges occurring. With the development of the thunderstorm, the anvil part of the thunderstorm was augmented and the charge structure became more obvious in anvil of the thunderstorm. The positive and negative charge regions inclined from the main part to anvil of the thunderstorm. The inverted polarity dipole structure was formed in anvil, being upper negative and lower positive charge. The negative CG lightning discharges originated from the upper negative region. It is revealed from the analysis above that the CG lighting discharges were produced by the middle or upper charge region and the lower charge region did not produce the CG lightning.

Fig. 8 shows the distribution of the radiation sources for 10 min from 22:19 to 22:29 in thunderstorm B on July 22, 2000 during the negative CG lightning occurring. Fig. 8(c) shows that the number of radiation sources was 27604, with a peak at 9 km height. It can be seen from Fig. 8 (b), (d) and (e) that the thunderstorm was divided into main part and anvil. The distribution of the radiation sources inclined gradually from the main part to anvil of the thunderstorm toward southeast. The negative CG lightning discharges occurred in main part and anvil. It is found by analyzing the structures of individual negative CG lightning discharges that the negative CG lightning occurring in main part of the thunderstorm started from 8 km height and developed directly downward with shorter horizontal channel in main part of the cloud. Most of the negative CG lightning occurred in anvil and near the main part of the thunderstorm and started from 8 km height with longer horizontal channel in anvil region. Fig. 9 shows an example of negative CG lightning. The discharge leader initiated from 8 km height and developed directly downward. After the return stroke, the channel of the discharge developed horizontally in cloud at 8 km at the starting stage and at 6 km at the final stage, corresponding to the main part and anvil of the storm respectively. This indicates that the heights of the negative charge regions in main part and anvil of the storm were different. The results analyzed indicated

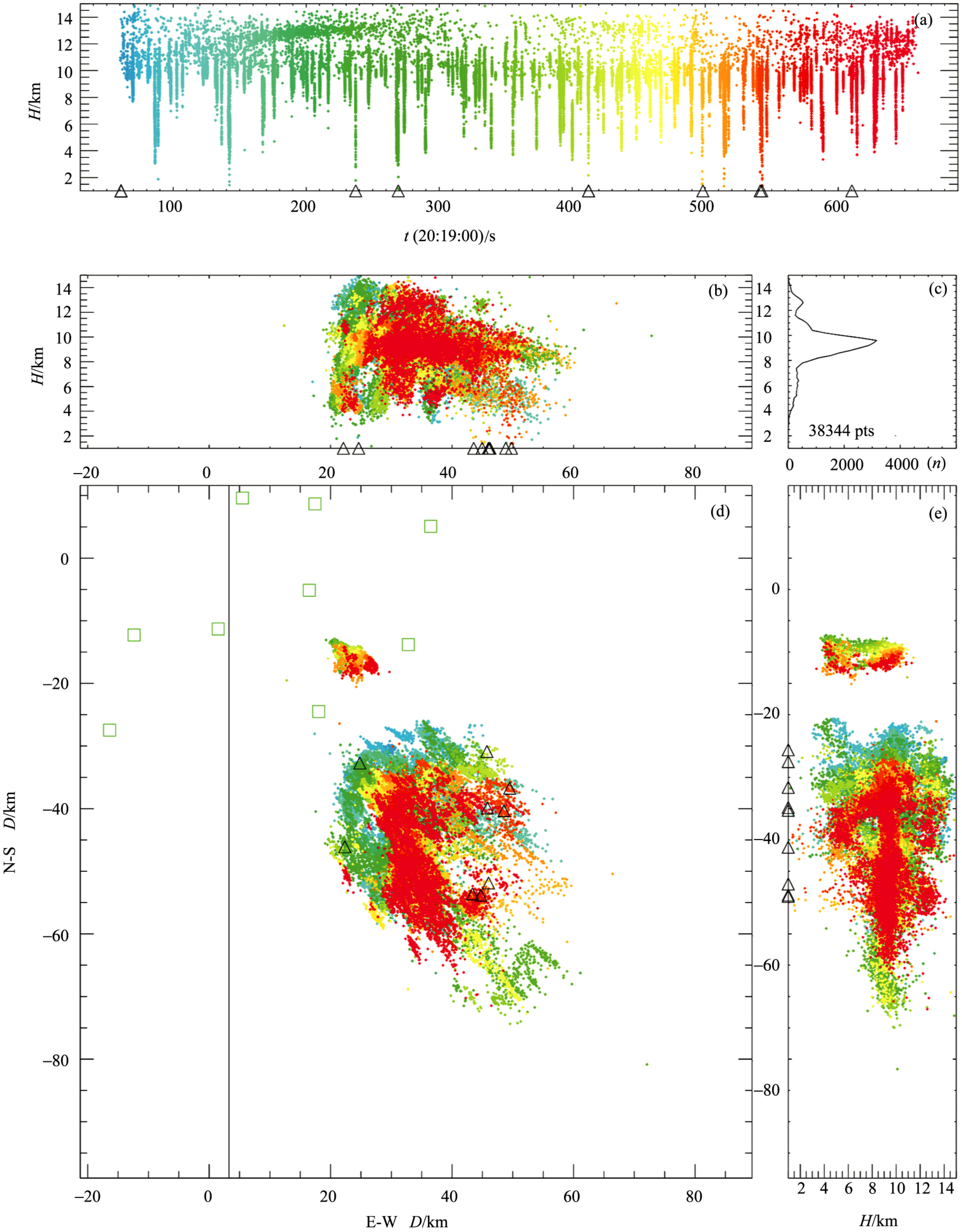

Fig. 5. Distribution of lightning radiation events for 10 min from 20:19 to 20:29 in thunderstorm A on July 22, 2000, with the same format as Fig. 1.

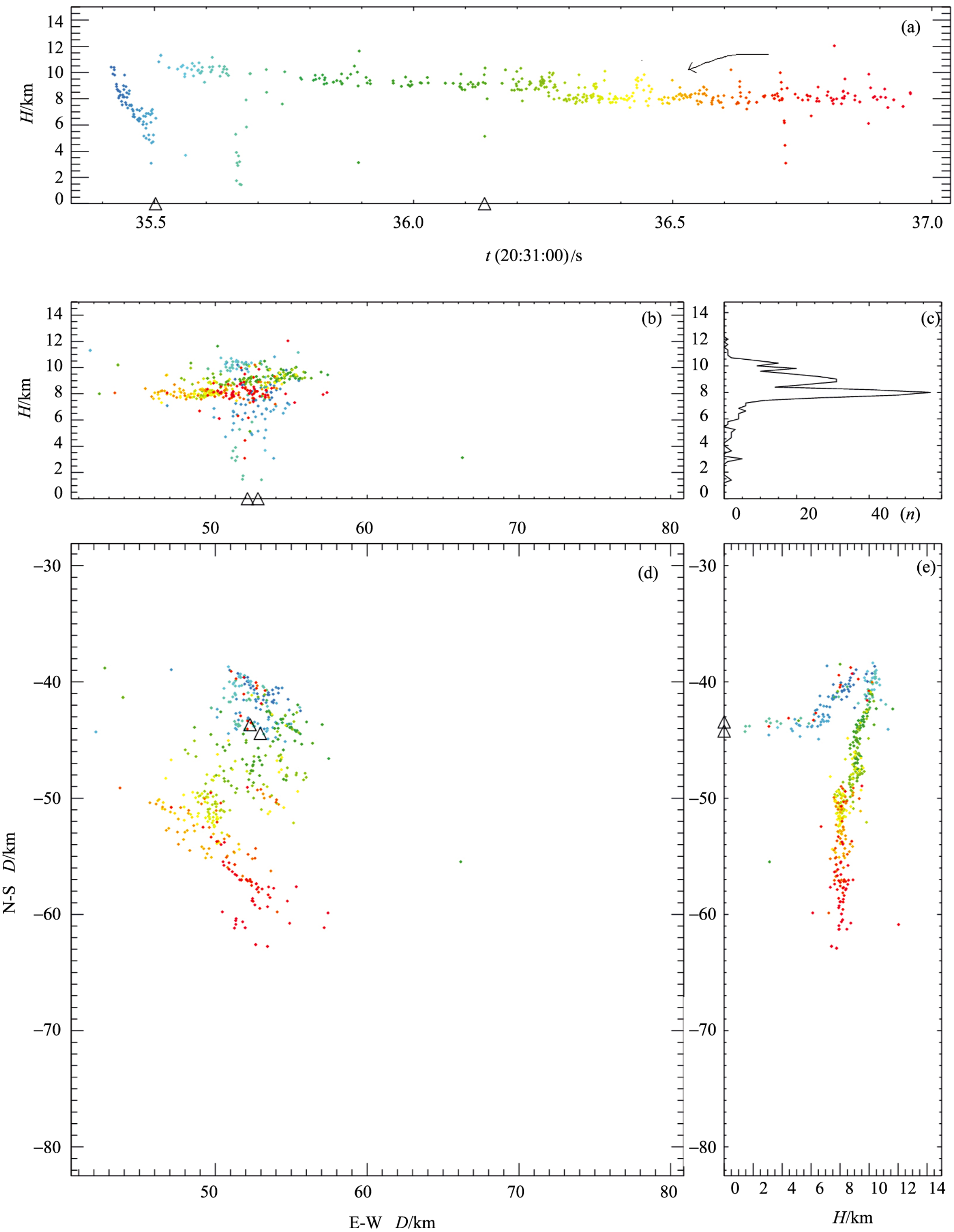

Fig. 6. Distribution of lightning radiation events of a negative positive CG lightning discharge at 20:31(UTC) in thunderstorm A on July 22, 2000, with the same format as Fig. 1.

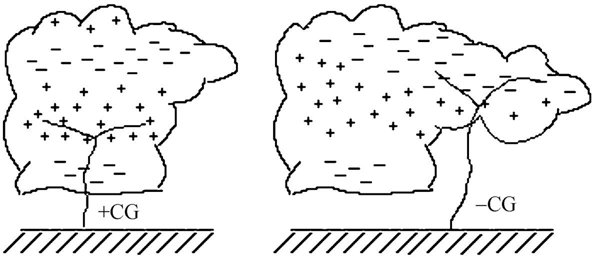

Fig. 7. Sketches of the charge structures in thunderstorm A during the periods shown in Figs. 2 and 5 respectively.

that the multi-levels charge structure appeared in the main part of the thunderstorm at this stage, being middle negative charge region, upper and lower positive charge regions and another negative charge region at the top of the thunderstorm. The middle negative charge region produced the negative CG lightning in main part of the thunderstorm. The charge structure in anvil of the thunderstorm was inverted dipole and the upper negative charge region produced the negative CG lightning.

Fig. 10 shows the distribution of the radiation sources for 10 min from 23:29 to 23:39 in thunderstorm B on July 22, 2000 during the positive CG lightning occurring. Fig. 10(c) shows that the number of radiation sources was 315932 and its peak occurred at 10 km height. From Fig. 10 (b), (d) and (e), it can be seen that the positive CG lightning discharges appeared in main part of the storm and the number of radiation sources increased much more than that shown in Fig. 8. This reveals that the lightning discharges were more active. However the obvious bilevel charge structure still existed in the anvil of the thunderstorm. In the main part of the thunderstorm, the charge structure was inverted tripole and the positive charge region in middle of the storm increased obviously.

Fig. 11 (a) and (b) shows the sketches of charge structures in two stages shown in Fig. 8 and 10 respectively. The negative charge region was located at the middle part and two positive charge regions were located at the upper and lower parts of the thunderstorm in the main part of the storm during the negative CG lightning occurring. There was another negative charge region at the top of the main part of the thunderstorm in this stage. The charge structure inclined toward southeast. The charge structure was inverted dipole with the upper negative charge and lower positive charge in anvil of the storm. The positive charge region increased at the middle part of the thunderstorm and the negative charge regions were located at the upper and lower parts of the thunderstorm during the positive CG occurring. No CG lightning originates from lower charge region. Krehbiel *et al*.[3] and Hamlin *et al*.[4] found that no CG lightning occurred during the period of 1—2 h in some thunderstorms, even in whole thunderstorm process. A number of intracloud discharges occurred between middle and lower charge regions, being large in magnitude and extensive in dimension. The results analyzed in this paper revealed that the charge region in lower part of the thunderstorm produced less CG lightning directly and played an important role in the occurrence of CG lightning originating from the charge region above it. The occurrence of CG lightning from the middle or upper charge regions needs an amount of charge with opposite polarity below it.

Comparing Figs. 2 and 5 to 8 and 10, the numbers of radiation sources were obvious more during the positive CG lighting occurring than those during the negative one. The negative breakdown processes produce more intensive VHF radiation than the positive breakdown. For positive CG lightning, the less VHF radiation is produced by the positive leaders and a number of negative breakdown processes occur after the positive return stroke in the positive charge region. For negative CG lightning, only negative leaders produce intensive VHF radiation and the channels of lightning are extended horizontally by the K breakdown processes in a retrograde manner in negative region[5, 11]. So, more VHF radiation sources are produced due to the occurrence of a number of positive lightning discharges.

2 Conclusions and discussion

The results analyzed above reveal that the temporal and spatial distribution and polarity of the CG lightning discharges depend on the charge structure in the thunderstorm. The charge structure in the main part of the thunderstorm was inverted tripole during the positive CG lightning discharges occurring. The positive CG lightning discharges originated from the middle positive charge region. The polarity of CG lightning discharges depended on the polarity of middle charge region. With the development of the thunderstorm, the charge structure in anvil of the storm was inverted dipole due to the slant of the charge structure in the main part toward the anvil of the storm. A number of the negative CG lightning discharges were produced and

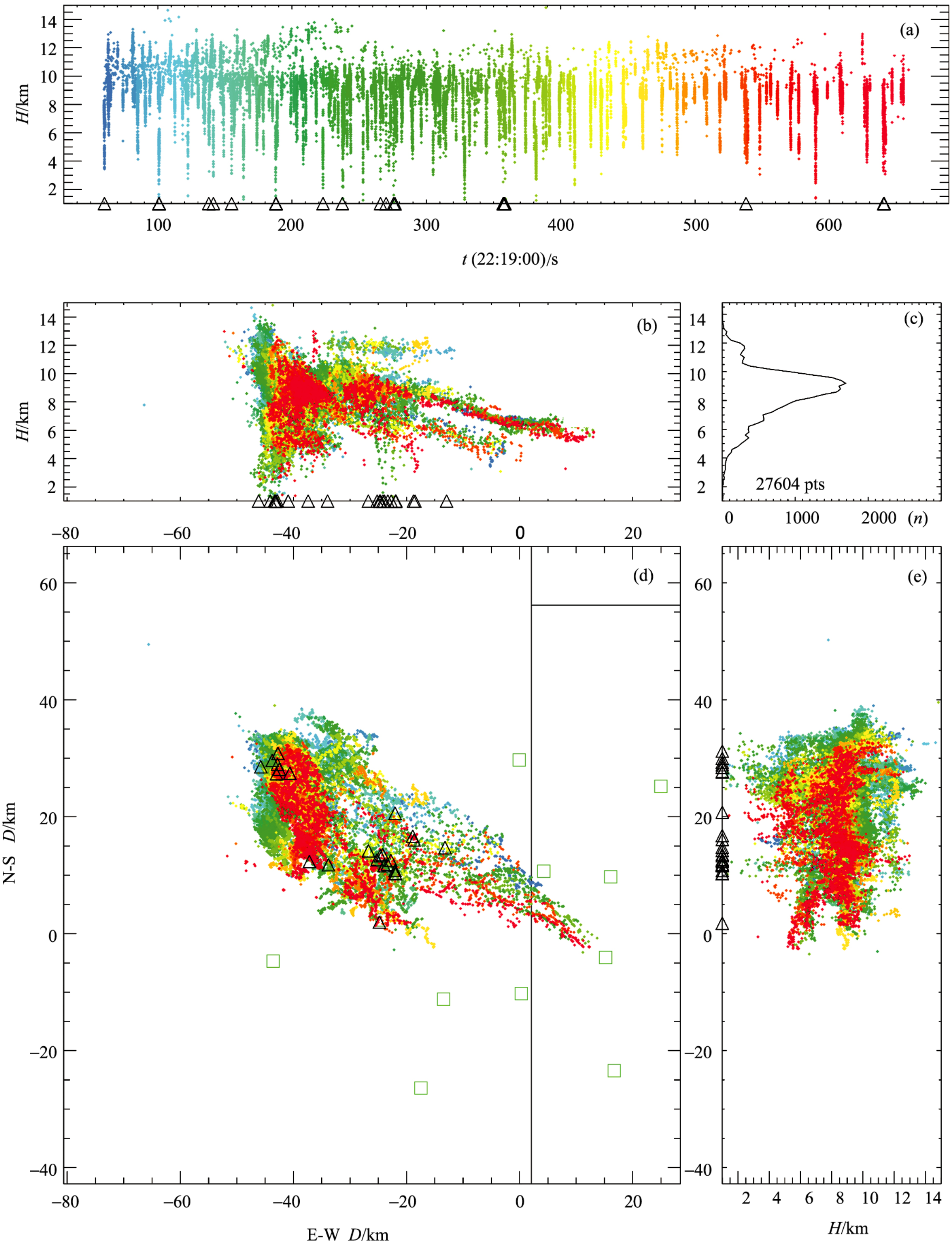

Fig. 8. Distribution of lightning radiation events from 22:19 to 22:29 for thunderstorm B on July 22, 2000, with the same format as Fig. 1.

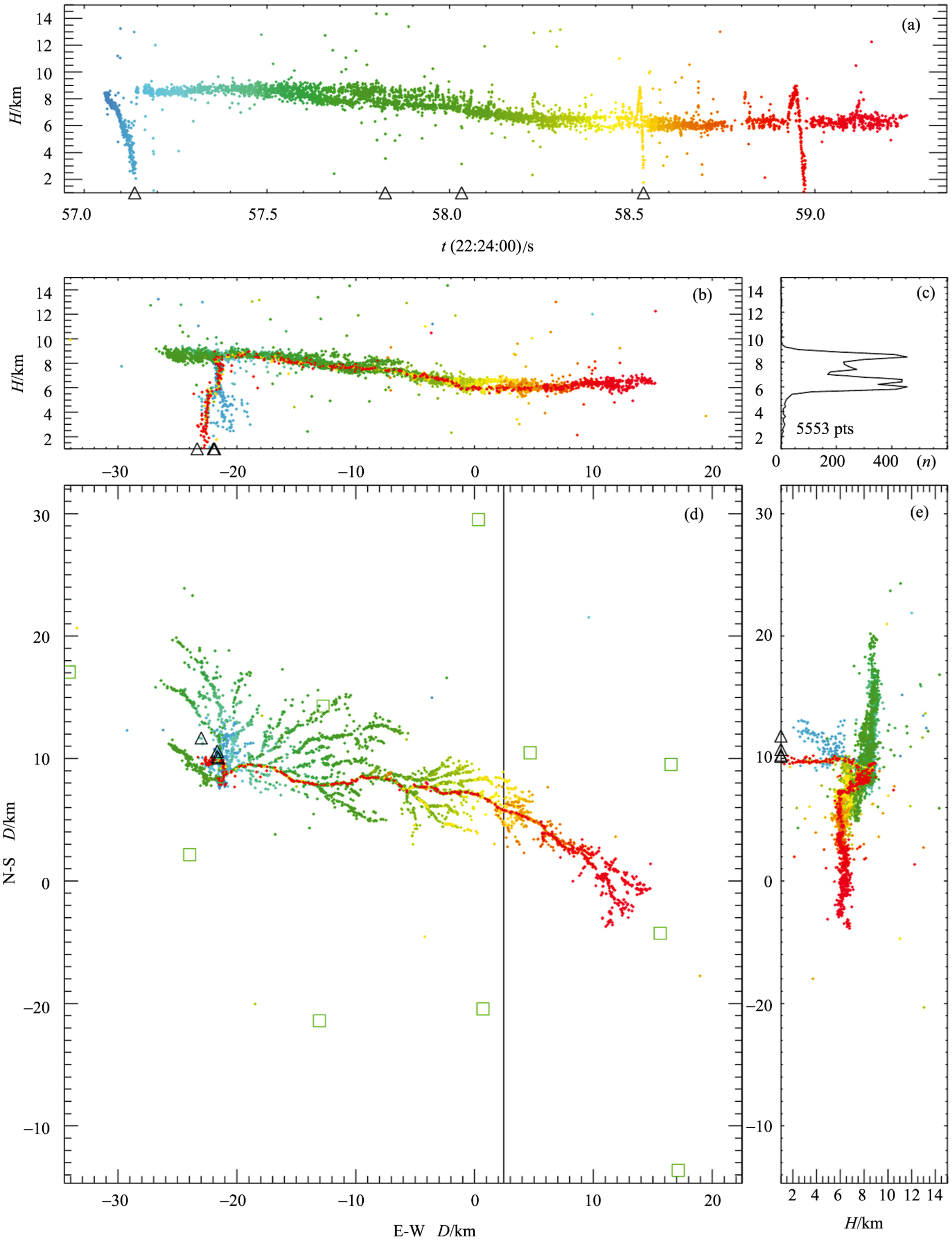

Fig. 9. Distribution of lightning radiation events of a negative positive CG lightning discharge at 22:24(UTC) in thunderstorm B on July 22, 2000, with the same format as Fig. 1.

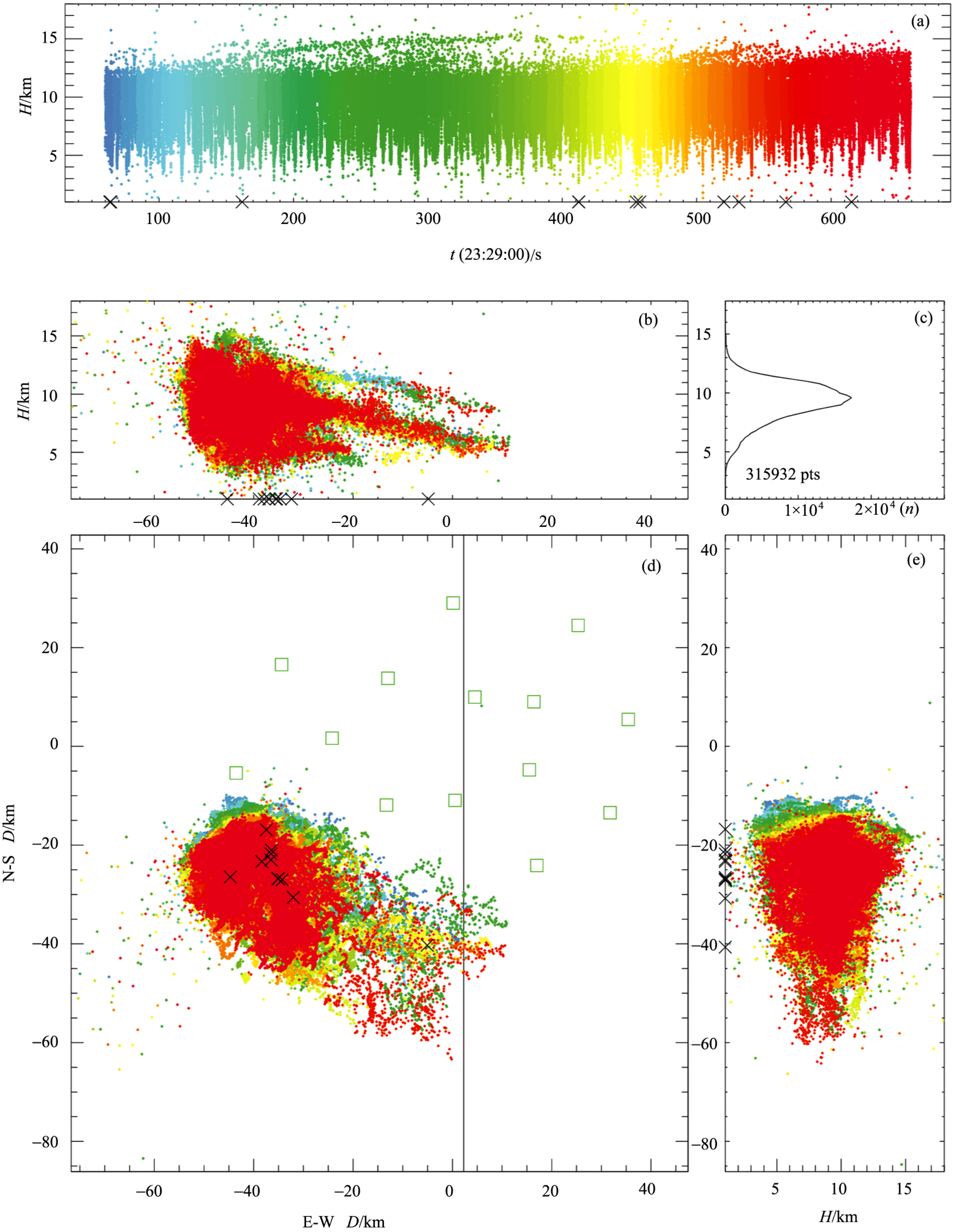

Fig. 10. Distribution of lightning radiation events for 10 min from 23:29 to 23:39 in thunderstorm B on July 22, 2000, with the same format as Fig. 1.

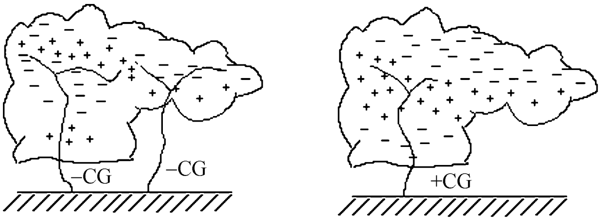

Fig. 11. Sketches of the charge structures in thunderstorm B during the periods shown in Figs. 8 and 10 respectively.

their polarity depended on the polarity of upper charge region. Less CG lightning discharges originated directly from the charge region in lower part of the thunderstorm. However the charge region played an important role in the occurrence of CG lightning originating from the charge region above it.

The results analyzed in this paper show that the charge region in lower part of the thunderstorm produced less CG lightning directly. So, a number of the positive CG lightning discharges occurring in the sever thunderstorm may not originate from the lower positive charge region and there is a positive charge region, being large in magnitude and extensive in dimension in the middle part of the thunderstorm. The positive CG lightning discharges originate from the middle positive charge region. The lower negative charge region provides the condition for the occurrence of the positive CG lightning from the upper positive charge region. The results observed indicate that the lightning discharges usually initiate from the common boundary with most intensive electric field between positive and negative charge regions in thunderstorms. The positive and negative charge regions produce the intensive electric field together and the lightning discharges initiates easily from the common boundary. Ma1) introduced the discharge process into the electrification model of the thunderstorm based on the concept of the bidirectional leader. The calculated results indicated that the charge region in lower part of the thunderstorm did not produce directly the CG lightning. If there was not the lower charge region (sometimes it was very small in magnitude and extensive in dimension), the charge region in middle part of the thunderstorm could not produce the CG lightning. This is in agreement with the results analyzed in this paper. However to clarify whether the lower charge region provides only an intensive electric field or plays other roles in the occurrence of the CG lightning from the middle charge region, more researches need to be conducted.

Based on the concept put forward by Kasemir[12], the initiations of any lightning discharges produce the positive and negative leaders simultaneously and the leaders develop toward opposite direction. The observations of VHF radiation produced by lightning reveal that the negative leaders propagate toward the positive charge region after the lightning discharges initiate. The channels of the lightning discharges develop horizontally after they enter into the positive charge region. The bidirectional leader concept has not been proved by observations up to now because the VHF radiation produced by the positive breakdown is too weak to measure. Kawasaki *et al*.[13] reported the verification of bi-directional leader concept by broadband interferometer observations for lightning VHF radiation. They found that the intensive negative breakdown occurred in the positive charge region for the positive CG lightning with the continuing current after the return strokes and the correctness of bi-directional leader concept was inferred. The bi-directional leader concept seems reasonable based on the model calculation and the analysis results in this paper. However the more observations and theoretic studies are needed in order to obtain unambiguous conclusion on the bi-directional leader concept.

The results obtained in this paper also indicate that the charge structures vary with the development of the thunderstorm. The anvil part of the thunderstorm was augmented due to the intensive wind shear. The charge regions located at the upper and middle parts of the thunderstorm inclined toward the anvil. The CG lightning discharges will occur when the charge structure in anvil forms a certain allocation. This may be a reason why a amount of CG lightning occurs at the final stage of the thunderstorm. MacGorma and Rust[3] have summarized two reasons for high rate of positive CG lightning in severe thunderstorms. (1) The charge structure in thunderstorms is a slant dipole resulting from wind shear, i.e. the positive charge region in upper part of thunderstorm extends horizontally beyond the negativecharge below it and effectively exposes to the ground, making the positive CG lightning flash increase. (2) The positive charge region in lower part of

1) Ma Ming, Study on relationship between lightning activities and climate change, Ph.D. Diss., University of Science and Technology of China, 2004, 131－132.

the thunderstorms might be intensified and positive CG lightning discharges are produced by this lower positive charge. However the results obtained in this paper are not in agreement with their suggestions. Even though the charge structure in anvil part of the thunderstorm is changed by the wind shear with the development of the thunderstorm, the polarity of the CG lightning occurring in the anvil depends on the charge structure of the anvil part of the thunderstorm, i.e. the polarity of the upper charge region. The second reason was not supported by the observations in the paper.

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