Referee Comment 2

This manuscript employs total lightning observations from the Foshan total lightning locating system to characterize the movement and size of eight thunderstorms in 2014. However, it isn't clear how they are useful or novel. Additionally, I have concerns about the data processing leading to their conclusions. For instance, some of the storm velocities touted by the paper are physically unrealistic (e.g., >200 km h^{-1}). I recommend rejection in the present form.

Authors' Response

The authors thank the reviewer for providing all the suggestions and sincerely accept that these have turned out to be indispensable in pushing and improving the standard of the current work.

There are two innovation points of this article. Firstly, it is the total lightning data derived from the VLF/LF Lightning Location System (LLS) that we use to reveal the characteristics of thunderstorms in the PRD region. In the literature, the lightning and thunderstorm-related research for a region is usually based on the radar data, CG LLS, Very High Frequency (VHF) Lightning Mapping Array and the satellite (Chen et al. 2014; Chen et al. 2015; Liu et al. 2014; Xu et al. 2009; Zhang et al. 2014). There has not been comprehensive research about the characteristics of total lightning in the PRD region. Few literature has used the total lightning data to reflect the movement of thunderstorms. The VLF/LF total lightning data enriches data sources and provide a new perspective to study the thunderstorm in this region.

Secondly, the authors put forward five parameters, including the duration time, valid area, movement velocity, movement direction, and FD in longitude and latitude to reveal the kinematic features of thunderstorms in the region. The duration reflects how long the storm will last. The movement velocity helps to exhibit how fast the thunderstorm travels and predict how long it will take to move to other places. The movement direction represents where the thunderstorm will go. The valid area shows the range the thunderstorm will affect. The farthest distance shows how far the thunderstorm will go. The lifetime and spatial movement of thunderstorms in the region can be clearly depicted with these characteristic parameters, which are beneficial to the thunderstorm prediction.

We want to clarify that the velocities are calculated by the discharge centroids of the thunderstorm. Owning to the instability of updraft and non-inductive electrification in the convective cloud, the discharge centroid is not always the barycenter of thunderstorm clusters. In some cases, as the discharge center lies on the left of the clusters at first, the cluster moves forward after 12 minutes with the discharge center moving to the right. The velocity may be relatively larger compared with the velocity calculated by the movement of the barycenter. However, as the movement metrics are obtained through the lightning events, which represent the discharge in the cloud, the authors believe that the discharge centroid can better reflect the electrification variations in the storm. The corresponding discussion has been added to explain the high value of speed.

Major comments:

1. While the paper indicates eight storms were selected for analysis, there is no justification given for why these eight storms were retained and others discarded. With only eight storms this study is missing the sample size to make generalizable conclusions while simultaneously lacking the detail of a case study. There either needs to be a larger number of storms considered, or these eight storms must be analyzed in greater detail (i.e., compare to convective environmental conditions, synoptic wind fields, etc). For instance, it is hard to conduct a thunderstorm morphology study without characterizing the environmental conditions (e.g., CAPE, wind shear, etc) since those parameters are influential determinants of the size and longevity of convection.

Authors' Response

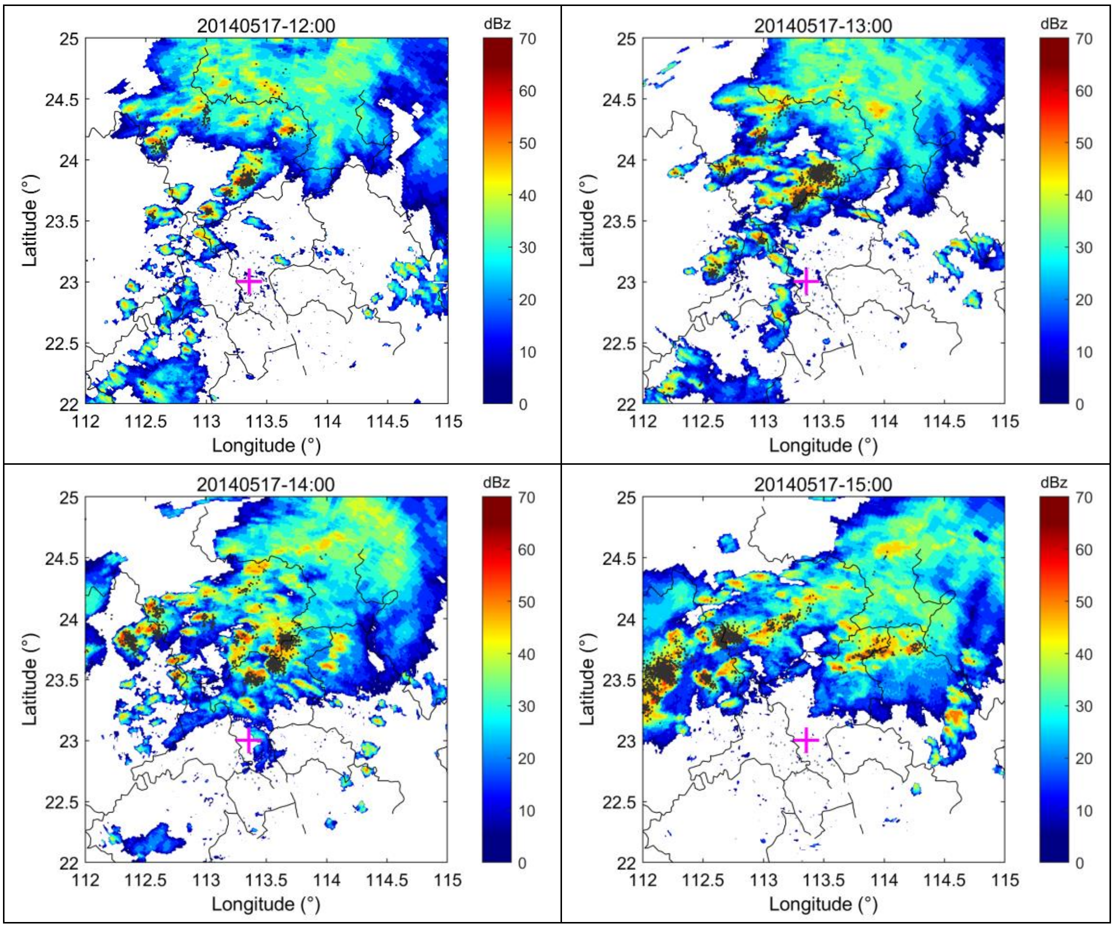
Thanks for your comments. We want to clarify that there are two thresholds and limitations of thunderstorms we choose. As has been explained in the article, 'To better capture the main spatial movement of the thunderstorm, clusters less than 25 km^2 and the duration of storm less than 60 min are removed based on the scale of thunderstorms in the PRD region.' The less strong thunderstorms are not considered in the article since it is the strong thunderstorms that pose great damage.

In the literature, some analyze only one or two storms specifically (Betz et al. 2008; Meyer et al. 2013; Strauss et al. 2013), the others analyze thousands of thunderstorms without details, such as the track or the area (Rigo et al. 2010). In this article, the authors analyze eight thunderstorms at different times of the day with different intensities in detail. It not only shows the thunderstorm diversities in the PRD region, such as thunderstorms with heavy precipitation on 17 May and 23 May and mild storms in other cases (The authors have added the precipitation in 24 h to show the intensity of thunderstorms in the article), but also retains the details of storm and represents some common characteristics, such as the durations and directions of storms. The authors believe that this is another creativity in the article.

In order to verify the validation and explain the rationality of using total lightning data to characterize the movement of the thunderstorm, the authors have added the stacking map of reflectivity scan by DSR research radar and spatial distributions of total lightning data on 17 May 2014. We can see that prominent areas of higher reflectivity are simultaneously covered by lightning events. The authors believe that clusters of lightning events and their variations can effectively illustrate the thunderstorm evolution. Lightning-related research can definitely enrich the study of thunderstorm morphology.

In view of the reviewer's comment, the following description and figures have been added to the revised version of the manuscript.

During the monsoon period (in May on average) in the PRD region, the South China Sea Summer Monsoon (SCSSM) enhances the precipitation owing to the southwesterly monsoon flow, especially the southwesterly low-level jets, carrying abundant water vapor to South China (Chen and Luo, 2018; Bei et al., 2002). More than 50% of heavy rainfall events in South China occur in April–June period, in which precipitation is primarily related to fronts and monsoon flows (Wu et al., 2011). Persistent heavy rainfall occurred from 17 May 2014 to 23 May 2014, especially in the central and eastern part of the PRD region. It was found that 62 automatic weather stations recorded heavy precipitation of more than 100 mm on 17 May, while Huizhou and Shenzhen stations recorded 24-h rainfall of 377. 9 mm and 274. 6 mm (Bingzhi Zheng, 2015). Severe thunderstorms occurred in the PRD region with a record-breaking 24-h rainfall of 477.4 mm starting from 2000 LST (local standard time = UTC + 8 h) 22 May during this heavy rainfall week. The hourly precipitation in Conghua station surpassed 60 mm at 1300 LST on 23 May (Xinyu Zhou, 2017; Zhongqing Liang, 2015). Figure. 2 showed general radar characteristics and lightning distributions on 17 May. The lightning events are located in the area with radar reflectivity higher than 30 dBz, which has been verified as the threshold on the south of China (Xu et al., 2010). Consecutive precipitations within one week include the extremely severe thunderstorms and the relatively mild thunderstorms which serve as great cases for comparison.



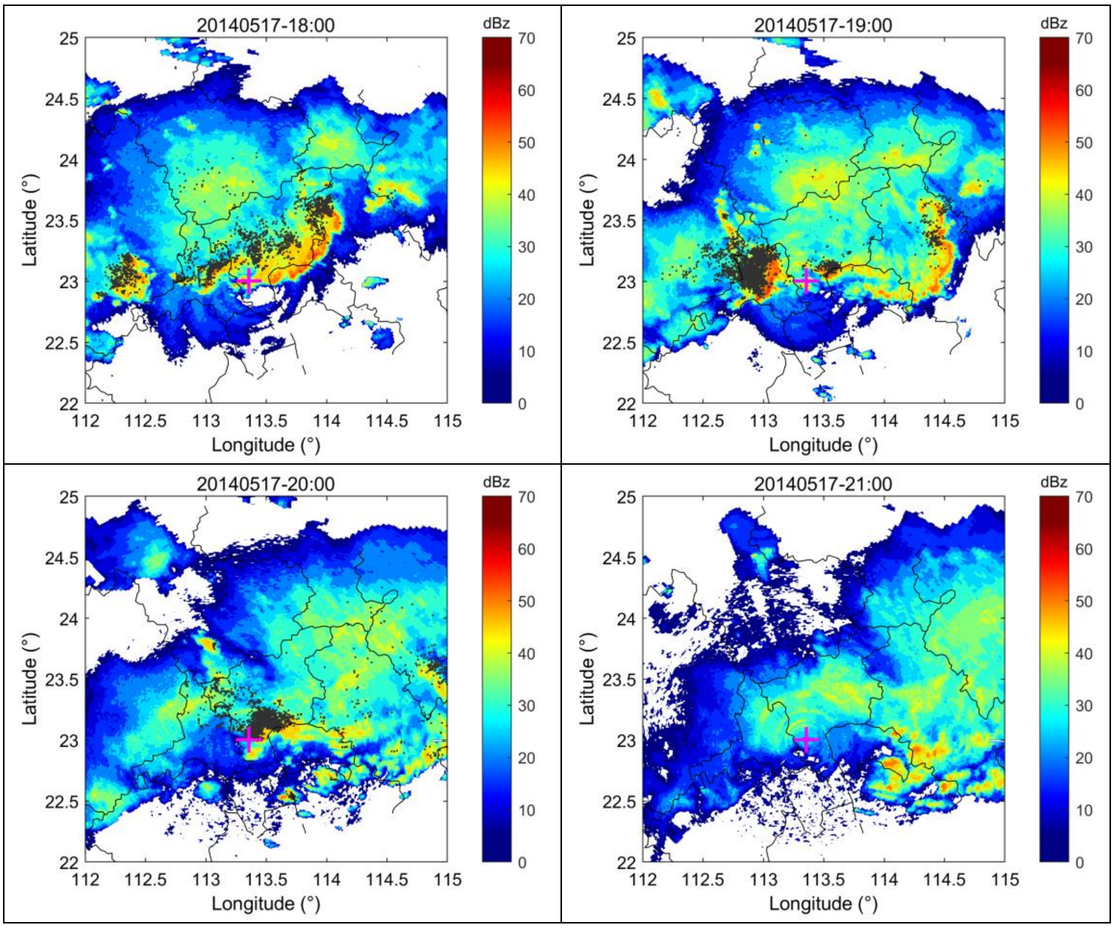


Figure. 2 The stacking map of reflectivity scan by WSR-98D research radar and spatial distributions of total lightning data on 17 May 2014. Prominent areas of higher reflectivity are simultaneously covered by lightning events. The red plus represents the radar station which is situated on the east side of the FTLLS.

2. I am concerned about the method of calculating the thunderstorm's direction, velocity, and furthest distance parameters. There is no mention of how thunderstorms spanning multiple 12-min grids are joined into a single multi-grid thunderstorm. While connected neighborhoods labeling can be performed in three dimensions, the paper does not indicate this capability was utilized. Figure 4 shows that 12-min increments were joined, but this aspect of the methodology is important and not discussed at all. Without a clear method of joining multi-timestep storms, it is hard to account for storm splits and mergers that could easily sway the velocity, duration, and FD calculations that span multiple 12-min grids. In fact, the maximum velocity reported in the abstract of >200 km h^{-1} (a physically unrealistic value), as well as the highly variable storm velocities in Figure 5, suggests the methodology is not joining thunderstorms across multiple 12-min frames effectively. While the storm velocities are touted as a finding with "great significance" in lines 200-205, I believe it is more likely a deficiency in the methodology.

Author Response

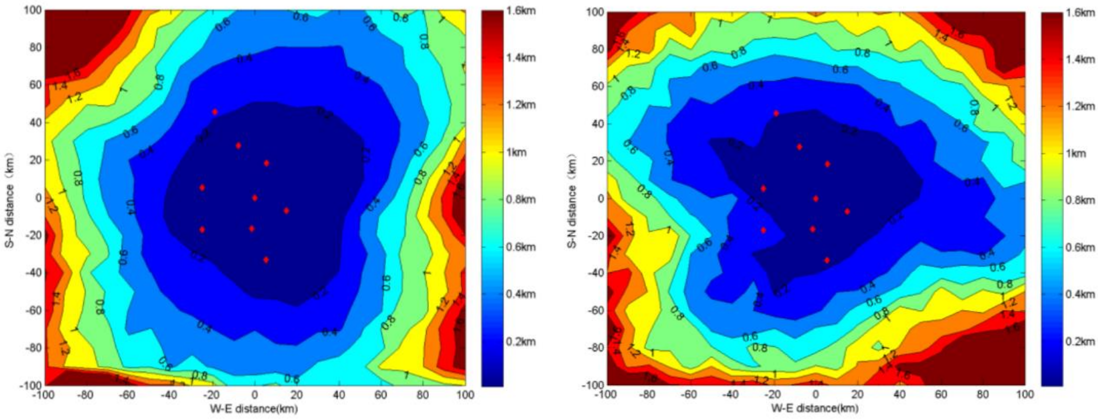
Thanks for your comments. We have to clarify that we have explained how the thunderstorm clusters are identified and selected. Firstly, lightning events are collected in 12-minute time interval and put into the 0.01*0.01 grid. The grids with more than one event are retained as the valid grid. The area of each grid is 1 km^2. Then, using the 8-adjacent connected-neighborhood labeling method, we can obtain clusters of lightning events within the analysis area, including the discharge centroid and the valid area. Clusters less than 25 km^2 are removed based on the scale of thunderstorms in the PRD region. Two clusters whose discharge centroid is less than 10 km merge as one cluster. Afterwards, each time the window advances 12 minutes, the cluster is updated and also its centroid. If the distance from the previous cluster to the current cluster is less than 50 km, or the current cluster exhibits an overlap with the previous cluster, they can be regarded as the same thunderstorm. At last, we obtain the coordinates of all clusters in the area and we choose the thunderstorms whose lifetime is longer than 60 minutes. The tracks are defined by the sequence of centroid positions. The more detailed explanation has been added to the manuscript.

As we have explained above, velocities are calculated by the discharge centroids of the thunderstorm. Owning to the instability of updraft and non-inductive electrification in the convective cloud, the discharge centroid is not always the barycenter of thunderstorm clusters. In some cases, as the discharge center lies on the left of the clusters at first, the cluster moves forward after 12 minutes with the discharge center moving to the right. The velocity may be relatively larger compared with the velocity calculated by the movement of the barycenter. However, as the movement metrics are obtained through the lightning events, which represent the discharge in the cloud, the authors believe that the discharge centroid can better reflect the electrification variations in the storm. Therefore, the velocity we calculated is reasonable.

3. The detection efficiency of the FTLLS will vary with distance from the network. Storms that move into the periphery of the detection area will experience inconsistent detection efficiency and the calculation of the movement metrics will be biased at these ranges. For instance, according to the longitudes in Figure 4, the storm in pane (a) extends nearly an entire degree east of the FTLLS domain in Figure 1. The detection efficiency, particularly for IC flashes, must erode at this distance, and making the calculations of FD, VA, and velocity questionable. The effect of the FTLLS detection efficiency on the thunderstorm classification needs to be investigated.

Author Response

We want to clarify that FTLLS can locate the lightning radiation source within a distance of 100 km in the Foshan area accurately, from which the data provides valid reference information for analyzing lightning strike faults on power transmission lines (Cai et al. 2019b). Cai et al. (2019a) has reported that the average horizontal error within a distance of 100 km is less than 1.5 km and the corresponding vertical error is less than 1000 m (seen in Figure 9). The stacking map shows that the lightning events is well corresponded with the radar reflectivity over 30 dBz within the analysis area. As a result, we have the reason to believe that the FTLLS is highly reliable for the detection of lightning events and the result is acceptable for the analysis of the thunderstorm movement.



(**a**) Estimated horizontal location errors

(**b**) Estimated vertical location errors

Figure 9. The estimated locating errors at an altitude of 10 km ((**a**) horizontal error, (**b**) vertical error).

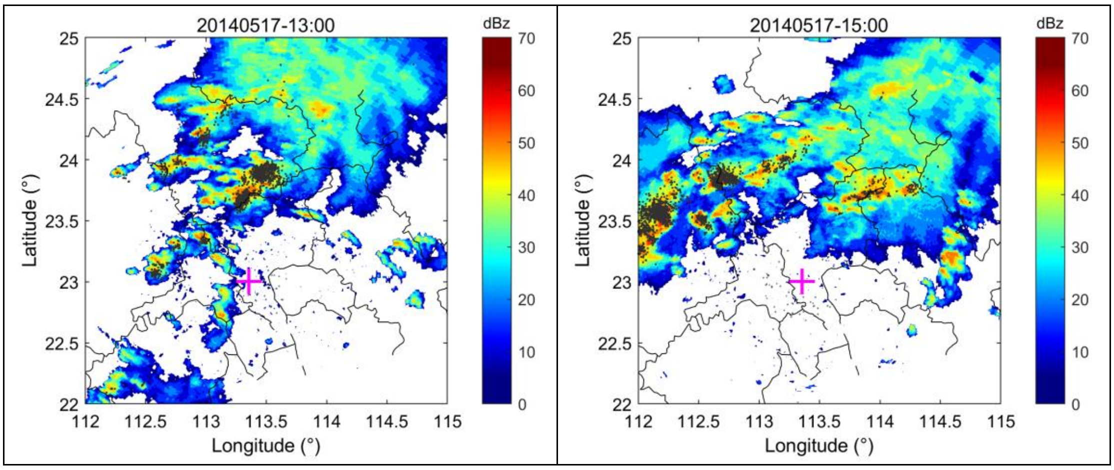


Figure. The stacking map of reflectivity scan by WSR-98D research radar and spatial distributions of total lightning data on 17 May 2014.

Minor comments:

- Line 51-52: Citation?

Authors' Response

Thanks for your comments. We have revised the description of the article we cited.

- Lines 53-55: I don't follow this reasoning

Authors' Response

Thanks for your comments. In the conclusion of the article 'Thunderstorm occurrence and characteristics in Central Europe under different synoptic conditions' (Wapler and James, 2015), it says 'The detailed analysis of convective cell characteristics shows that there is a significant dependence between various cell attributes and the GWLs. E.g., those types associated with broadly westerly flow tend to have high cell speeds and relatively narrow distribution of cell directions. Those Grosswetterlagens which have lower average cell speeds tend to have a higher likelihood of hail.' The Grosswetterlagens in the article means the large-scale weather conditions in Central

Europe. We have revised the description of the article we cited. And we believe the citation is reasonable.

- Line 111: How many thunderstorms are excluded by this condition?

Authors' Response

Thanks for your comments. There is no specific number of thunderstorms excluded by the threshold mentioned in the article. The authors believe that it is unnecessary to study the discarded storm because the less strong thunderstorms are not considered in the article since it is the strong thunderstorms that pose great damage. We mainly focus on eight cases instead of all storms in the PRD region. The discarded thunderstorms could be study separately.

- Lines 124-135: I'm confused where the subscripts 1 and 2 come from. It seems like each storm would receive one Clat and one Clon, so how are two Clat's and two Clon's being calculated to derive the direction and velocity? If this is referencing Clats and Clons from multiple 12-min grids, how were the joined into a single storm?

Authors' Response

Thanks for your comments. As has been explained in the article, we can obtain the coordinate of discharge centroid at each 12-min interval through the 8-adjacent connected-neighborhood labeling method. Two clusters whose discharge centroid is less than 10 km merge as one cluster. Each time the window advances 12 minutes, the cluster is updated and also its centroid. If the distance from previous cluster to the next cluster is less than 50 km, they can be regarded as the same thunderstorm. We obtain the coordinates of all clusters in the area and we choose the thunderstorms whose lifetime is longer than 60 minutes. The tracks are defined by the sequence of centroid positions. The subscripts 1 and 2 represent the discharge center of storm clusters at different times. For example, we calculate the coordinates of discharge centroids at 14:00 and 14:12 respectively. We define the coordinate at 14:12 as the (C_{lon2}, C_{lat2}), and the coordinate at 14:00 as the ($Clon_1$, $Clat_1$). After getting two coordinates, we can calculate to obtain the direction and velocity. The corresponding explanation has been revised to make it clearer in the manuscript.

- Line 164: What is the significance of comparing each storm's lightning to the rest of the lightning observed by the FTLLS?

Authors' Response to the comments in Line 111 and 164

Thanks for your comments. As the referee has mentioned, there are some storms that have been excluded. However, it is unnecessary to study the discarded storm. It is the total lightning data that we use to characterize the dynamic movement of thunderstorms, this is why we show the number of lightning events excluded by the condition in Figure 3. It shows the result of lightning events excluded by the thresholds. The corresponding explanation has been added to the manuscript.

- Line 128: Normally true North serves as the benchmark. This decision results in some hard-to-interpret graphics later in the paper. For instance, west-to-east moving storms (as these appear to be from Figure 4), receive directions of ~0 or ~360 degrees, as opposed to 270 degrees that we normally associated with westerly wind.

Authors' Response

The issue pointed out by the reviewer is very important. The authors decide to change the expression of direction to the true North benchmark to better combine the influence of the summer monsoon. The corresponding revision has been made to make it more acceptable in the manuscript.

- Line 141: Are lightning events the same thing as flashes? Or are they strokes? Please clarify in text.

Authors' Response

The authors would like to express our appreciation for the reviewer's suggestions. As we all know, lightning flashes include the IC flashes and CG flashes, and each CG flash consists of one or more leaders followed by one or more return strokes. The FTLLS detects electromagnetic waves associated with lightning discharges and locates VLF/LF (200 Hz–500 kHz) radiation sources. The remote sub-stations acquired triggered waveforms with a duration of 0.5 ms and a resolution of 12-bits. The discharge which meets the threshold will be considered as a lightning event. Therefore, an IC or CG flash consists of several IC or CG events. The type of lightning event is classified by the waveform characteristics and the height information (Cai et.al 2019). The corresponding explanation has been added to the manuscript.

- Line 186, 208: "Severe" storms have a particular meaning (i.e., producing some sort of surface hazard that makes them severe), and surface hazards were not mentioned in the analysis.

Authors' Response

The issue pointed out by the reviewer is very important. In 2014, A total of 12 heavy rainfall events occurred during the flood season, including the period from 15 May ti 23 May. From the night of May 22 to 23, 2014, there were heavy rainstorms in Guangzhou. The center place of precipitation appeared in the PRD region, more specifically, the central and northern parts of Conghua, central and northern Zengcheng, and eastern Huadu. The precipitation in some areas exceeded historical extremes. From May 16 to 17, 2014, severe thunderstorms occurred in most parts of Guangdong accompanied by heavy local rains and strong winds of magnitude 7 to 9.

In view of the reviewer's comment, the following description and figures have been added to the revised version of the manuscript.

Persistent heavy rainfall occurred from 17 May 2014 to 23 May 2014, especially in the central and eastern part of the PRD region. It was found that 62 automatic weather stations recorded heavy precipitation of more than 100 mm on 17 May, while Huizhou and Shenzhen stations recorded 24-h rainfall of 377. 9 mm and 274. 6 mm (Bingzhi Zheng, 2015). Severe thunderstorms occurred in the PRD region with a record-breaking 24-h rainfall of 477.4 mm starting from 2000 LST (local standard time = UTC + 8 h)

22 May during this heavy rainfall week. The hourly precipitation in Conghua station surpassed 60 mm at 1300 LST on 23 May (Xinyu Zhou, 2017; Zhongqing Liang, 2015).

- Line 287: How do the rivers affect the storms?

Authors' Response

The issue pointed out by the reviewer is very important. The rainy season in the south of China refers to the April–June period, in which precipitation is primarily related to fronts and monsoon flows. It is divided into the pre-monsoon and monsoon period. The latter is affected by the South China Sea Summer Monsoon (SCSSM) which breaks out in May on average. After the SCSSM outbreak (monsoon period), the southwesterly monsoon flow, in particular the southwesterly LLJ, carries abundant water vapor to South China, enhancing precipitation in the region.

A pertinent discussion on this aspect has now been added in the Data and Methodology as follows.

During the monsoon period (in May on average) in the PRD region, the South China Sea Summer Monsoon (SCSSM) enhances the precipitation owing to the southwesterly monsoon flow, especially the southwesterly low-level jets, carrying abundant water vapor to South China (Chen and Luo, 2018; Bei et al., 2002).

- Line 288: Figure 4 seems to indicate the storms move from west to east?

Authors' Response

Thanks for your comments. We have revised the clerical error in the Results.

- All – Needs editing and spelling check (e.g., "dimention" and "adjacenct")

Authors' Response

Thanks for your comments. The typing errors have been checked and revised throughout the article.

Betz, H. D., K. Schmidt, W. P. Oettinger, and B. Montag, 2008: Cell-tracking with lightning data from LINET. Adv. Geosci., 17, 55-61, https://doi.org/10.5194/adgeo-17-55-2008.

Cai, L., X. Zou, J. Wang, Q. Li, M. Zhou, and Y. Fan, 2019a: The Foshan Total Lightning Location System in China and Its Initial Operation Results. Atmosphere, 10, https://doi.org/10.3390/atmos10030149.

Cai, L., X. Zou, J. Wang, Q. Li, M. Zhou, Y. Fan, and W. Yu, 2019b: Lightning electric‐field waveforms associated with transmission‐line faults. IET Generation, Transmission & Distribution, 14, 525-531, https://doi.org/10.1049/iet-gtd.2019.0736.

Chen, X., K. Zhao, and M. Xue, 2014: Spatial and temporal characteristics of warm season convection over Pearl River Delta region, China, based on 3 years of operational radar data. Journal of Geophysical Research: Atmospheres, 119, 12,447-412,465.

Chen, X., K. Zhao, M. Xue, B. Zhou, X. Huang, and W. Xu, 2015: Radar‐observed diurnal cycle and propagation of convection over the Pearl River Delta during Mei‐Yu season. Journal of Geophysical Research: Atmospheres, 120, 12557-12575.

Liu, Y., and Coauthors, 2014: Physical and observable characteristics of cloud‐to‐ground lightning over the Pearl River Delta region of South China. Journal of Geophysical Research: Atmospheres, 119, 5986-5999.

Meyer, V. K., H. Höller, and H. D. Betz, 2013: Automated thunderstorm tracking: utilization of three-dimensional lightning and radar data. Atmospheric Chemistry and Physics, 13, 5137-5150, https://doi.org/10.5194/acp-13-5137-2013.

Rigo, T., N. Pineda, and J. Bech, 2010: Analysis of warm season thunderstorms using an object-oriented tracking method based on radar and total lightning data. Natural Hazards and Earth System Sciences, 10, 1881-1893, https://doi.org/10.5194/nhess-10-1881-2010.

Strauss, C., M. B. Rosa, and S. Stephany, 2013: Spatio-temporal clustering and density estimation of lightning data for the tracking of convective events. Atmospheric Research, 134, 87-99, https://doi.org/10.1016/j.atmosres.2013.07.008.

Xu, W., E. J. Zipser, and C. Liu, 2009: Rainfall characteristics and convective properties of mei-yu precipitation systems over South China, Taiwan, and the South China Sea. Part I: TRMM observations. Monthly Weather Review, 137, 4261-4275.

Zhang, C., Y. Huang, B. Mai, and N. Wen, 2014: Temporal and spatial characteristics of lightning in Guangdong region. 2014 International Conference on Lightning Protection (ICLP), IEEE, 1173-1176.