Point to point response

By Jianguo Wang, Si Cheng, Li Cai

First of all, the authors wish to thank all reviewers for the comments which significantly improved the content of the manuscript. The authors have addressed all the comments raised by the reviewer and incorporated them in the revised manuscript wherever required.

Reviewer Comments:

#Reviewer 2

This paper titled, Characterizing the dynamic movement of thunderstorms using VLF/LF total lightning data over the Pearl River Delta region, describes the use of lightning location data to characterize thunderstorms in various ways. The authors provided detailed discussion of the methodology related to the storm clustering algorithm, with nice visuals to clearly illustrate what was done. The figures are generally well made and professional looking. However, due to my major concerns with the paper that I outline below, I believe there should be major revisions done. If the authors can address my concerns, I do believe this work can be a positive contribution to the literature.

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.

Major comments:

I am concerned that the authors have not done a thorough literature review for the background of this study. They state that no other studies have used lightning data to study thunderstorm characteristics, which is simply not true. Below I list several after just a few minutes of online research. I think the authors need to take the time to properly review the literature to understand what research has been completed in this domain.

Authors' Response

Thanks for your comments. As the reviewer says, there are indeed many papers that are concerned about the thunderstorm characteristics by using lightning data. However, most of these thunderstorm characteristics researches are about the number of total lightning flashes, the ratio of IC to CG, the ratio of positive CG, the lightning 'jump', the relationship between radar and lightning flashes and so on. Also, the clustering of thunderstorm is mostly based on the radar reflectivity, instead of total lightning data. The main point of our paper is to study the movement of thunderstormsrm by using the total lightning data, including the duration time, valid area, movement velocity, farthest distance and direction. We have made some revisions topinpointt our main purpose. We have also enhanced the literature review and added a more detailed description of the thunderstorm movement characteristics.

My biggest concern with the paper is that much of the discussion relates to statistics (max, min, median, etc.) and makes some generalized claims relating to these quantities. However, the sampling size of this study is extremely small with only 8 storms. Because of this, I think the authors need to refrain from making generalized claims.
Authors' Response
The authors would like to express our appreciation for the reviewer's suggestions. We have revised the generalized claims in the article to make our conclusion more precise.

There seems to be no discussion about whether the results could be influenced or biased by the methodology. The most obvious example relates to the storm velocities (Figure 6). In my opinion, the large variability is more an indication that the 12-min windows are simply too large to properly resolve the fast, but smoothly changing velocity of the storms. There should be more discussion about how there may be biases introduced by the data and/or the methodology.
Authors' Response
Thanks for your comments. The reviewer is right. We have also noticed the change of velocity and already made some discussion in the manuscript. 'In this paper, velocities are calculated by the discharge centroids of the thunderstorm. Owing to the instability of updraft and non-inductive electrification in the convective cloud, the discharge centroid is not always the barycentre of thunderstorm clusters. As the movement metrics are obtained through the lightning events, which represent the electrification in the cloud, the discharge centroid can better reflect the electrification variations in the storm.'
As the reviewer says, this method is very likely to bring about the bias of velocity, leading to a relatively fluctuant variation. The time interval also may cause the fluctuation of velocity. Some severe thunderstorms like supercells last for a short time and move extremely fast. A large time interval may be not able to well monitor the movement of the thunderstorm. We have added the corresponding discussion in the manuscript.

The fluctuation of velocity is very likely to result from the calculation method of centroid discharge. In addition, the different time intervals may cause the bias of velocity. Some severe thunderstorms like supercells last for a short time and move extremely fast, leading to poor monitoring results.

Finally, I found that the Discussion and Conclusions section to be significantly lacking discussion of the results. It was often difficult to follow what the authors were trying to point out. The authors need to spend more time expanding the discussion.
Authors' Response
Thanks for your comments. We have made the corresponding revisions in the manuscript based on your comments.

See my line numbered comments below for more details on my major concerns.

Comments by line number:

Line 15: first distribution should be plural

Authors' Response

Thank you very much for your carefulness. The corresponding revision has been made in the manuscript.

Line 51: hail should be singular

Authors' Response

Thank you very much for your carefulness. The corresponding revision has been made in the manuscript.

Lines 58-60: I actually disagree with this statement and feel that the authors did not do a thorough literature review before making this statement. After a few minutes of investigation, I found multiple papers that specifically look at the lightning characteristics over the course of individual thunderstorms. Here are a few that I was able to find within a few minutes of online searching.

Soula, S., & Chauzy, S. (2001). Some aspects of the correlation between lightning and rain activities in thunderstorms. Atmospheric research, 56(1-4), 355-373.

Williams, E., Boldi, B., Matlin, A., Weber, M., Hodanish, S., Sharp, D., ... & Buechler, D. (1999). The behavior of total lightning activity in severe Florida thunderstorms. Atmospheric Research, 51(3-4), 245-265.

Wang, C., Zheng, D., Zhang, Y., & Liu, L. (2017). Relationship between lightning activity and vertical airflow characteristics in thunderstorms. Atmospheric Research, 191, 12-19.

Authors' Response

Thanks for your comments. Indeed, there are many articles about lightning characteristics over the course of individual thunderstorms. However, these characteristics are mostly about the number of total lightning, the lightning 'jump' and the relationship between radar and lightning flashes. Seldom papers concentrate on the kinematic characteristics of every single thunderstorm, such as the direction and speed of movement or cell sizes and severity.

The article you mentioned above 'Wang, C., Zheng, D., Zhang, Y., & Liu, L. (2017). The relationship between lightning activity and vertical airflow characteristics in thunderstorms.' is related to the thunderstorm identification which is a meaningful reference for our paper. But, it is not concerned about the movement of thunderstorms and it is an analysis of the overall 22 storms from 2010 to 2012, instead of the individual thunderstorm.

We put forward five kinematic parameters (duration time, valid area, movement velocity, farthest distance and direction) to quantify the movement of clusters in various periods of a day. This is exactly the key point of this paper. We have revised to explain this.

However, up to now, there have been few formal studies that individually analyze such fundamental kinematic characteristics of every single thunderstorm.

Line 80: The use of heights for classifying IC versus CG flashes is problematic and can lead to many misclassified CGs as ICs. Combining this with waveform classification will improve this, however, this is very little information provided regarding the details or the efficacy of the algorithm. Can the authors provide some literature review as to how accurate this method is as well as the expected false classification rate?

Authors' Response

Thanks for your comments. We have stated in the manuscript that 'The validation of the system has been guaranteed through the comparison of rocket-triggered lightning experiments and the application of transmission lines (Cai et al., 2019; Wang et al., 2019).'

Specifically, from the initial operation result, it has shown good three-dimensional location accuracy and detection efficiency. A total of 27 lightning strokes, with 168 field waveforms included, were recorded by FTLLS to explain the transmission-line fault in the Foshan area (Wang et al., 2019). In the rocket-triggered lightning experiment in Guangzhou, 38 return strokes in six triggered flashes were observed by nine sites of FTLLS to compare the differences between rocket-triggered lightning and subsequent return strokes in natural flashes(Cai et al., 2019).

In addition, the detection efficiencies and peak-current estimation of the FTLLS and the LLS of Guangdong power grid in Guangdong Province were examined and were compared based on the directly measured current data at the triggering lightning site. It is shown that the detection efficiencies of the FTLLS for flashes and for return-strokes were 87.5% (7/8) and 93.0% (40/43), respectively. The peak-current estimation error reported by the FTLLS was 8% on average (Li et al., 2021).

We have added the following reference to explain the accuracy of FTLLS in the manuscript.

Li et al. (2021) examined the detection efficiencies using the directly measured current data at the triggering lightning site. The result shows that the detection efficiencies of FTLLS for flashes and for return strokes were 87.5% and 93.0%, respectively.

Line 82: This type of network does not inherently detect lightning flashes. Because it is an VLF/LF network, it is detecting charge motion occurring from current pulses. Therefore, there must be some pulse clustering occurring to clustering these pulses into flashes. This clustering methodology is important to this analysis since it can impact the number of flashes and flash rates. Therefore, the authors need to describe the flash clustering algorithm used in the paper.

Authors' Response

Thanks for your comments. The reviewer is right. We cannot directly get the number of flashes from the FTLLS. The current pulse detected by the FTLLS in this paper is defined as a lightning event. However, the main aim of this paper is to study the movement of the thunderstorm. We do not need to cluster the lightning events into flashes and still can get the centroid and valid area of the thunderstorm. We have added the definition of the lightning event in 'Foshan total lightning location system' part.

As for Figure 4, it not only shows the variation of the number of lightning events in each thunderstorm, but also reflects the difference between thunderstorms. As the

FTLLS is the new system that can first detect the total lightning events over the Pearl River Delta region. We believe that more studies about the flash clustering algorithm and the comparison with other LLS can be done in the future.

Line 89: Cai et al., **2019**

Authors' Response

Thanks for your comments. We have revised the mistake.

Line 109: wording here is unclear, please rephrase.

Authors' Response

Thanks for your comments. We have revised the sentence as follows.

The analysis of total lightning is in progress with a 12-minute time interval, which was twice of the Doppler Radar scans.

Lines 137-142: There seems to be no way for a thunderstorm to split and may affect the results since this does happen in real thunderstorms. Have the authors considered this? I think this is worth discussing in the paper.

Authors' Response

Thanks for your comments. We have added the split situation of the thunderstorm in the '2.2 Data and Meterology' part. The process of the thunderstorm is shown as follows.

As the coordinates of discharge centroids within a time interval are obtained, two clusters whose discharge centroid is less than 10 km merge as one cluster. For the split of the thunderstorm, if there is more than one cluster within the analysis region, the cluster with the largest area is set as the main body of the thunderstorm. The cluster whose discharge centroid is more than 10 km away from the main cluster's discharge centroid will be seen as the split part of the thunderstorm and be discarded.

Lines 170-171: Check grammar.

Authors' Response

Thanks for your comments. We have revised the sentence as follows.

The midday and afternoon thunderstorms keep relatively strong and stable, with more than twelve thousand lightning events per hour, while the morning thunderstorms are much more gentle and weaker, with around ten thousand lightning events per hour.

Line 190: This phrasing makes it seem like the thunderstorm initiation and dissipation is decided by radar data. Is that true? If so, the previous methodology made it sound like the lightning was the only deciding factor for clustering flashes into thunderstorms. If not, please rephrase.

Authors' Response

Thanks for your comments. We have added the definition of the starting time and ending time of the thunderstorm in 'Data and Methodology' part. The thunderstorm started with the appearance of the valid area (>25 km^2), while the ending time of the thunderstorm is when the cluster is less than 25 km^2 and can not be depicted by the algorithm any longer. So, the analysis period of the thunderstorm we choose is not decided by radar data. The reason why we mention the radar data is to reconfirm that the lightning data is reliable. The corresponding revision is as follows.

The thunderstorm started with the appearance of the valid area (>25 km^2), while the ending time of the thunderstorm is when the cluster is less than 25 km^2 and can not be depicted by the algorithm any longer.

Line 191: You should state explicitly that the IC and CGs are for the storm only, not the entire dataset.

Authors' Response

Thanks for your comments. We have added the relative description in the manuscript as follows.

The blue line and red lines represent the IC events and CG events produced by the chosen thunderstorm, respectively.

Lines 192-194: I do not agree with this statement. It is true that the CG rate usually peaks near the middle to end, but so does the IC rate. Maybe the authors meant to say that the IC:CG ratio is highest at the beginning of the storm? I am not sure that is true either, but to show that you could add a curve for the IC:CG ratio on the plots as well.

Authors' Response

Thanks for your comments. Indeed, we cannot compare the occurrence between the IC peak and the CG peak. There is also no obvious evidence that the IC:CG ratio is highest at the beginning of the storm. So, we revise the conclusion from Figure 4 as follows.

The thunderstorm occurred at 18:00 on 17 May produced the largest number of total lightning events per 12 minutes, with the number being more than 8000 times. Another night storm occurred at 19:12 on 19 May is much weaker, whose scale is slightly smaller than the morning storm occurred at 8:36 on 20 May, with a smaller peak of total lightning per hour and a smaller number of total lightning events.

Line 196: "visions to the horizon" does not make sense. Maybe "The footprint, trajectory, and flash density of thunderstorms" is more accurate?

Authors' Response

Thanks for your comments. The reviewer is right. We have revised the corresponding description as follows.

The footprint, trajectory, and flash density of thunderstorms are displayed in Figure 5.

Line 225-229: I find the discussion of the velocity results to be somewhat biased in that there is no discussion that they could be a result of the method or sampling of the methodology. When observing the motion of a storm in real-time, there is no apparent drastic changes in motion of typical storms. They generally move quite smoothly. I believe the result that the velocity seems to vary so much is more related to the methodology. It could indicate that the 12-min windowing is sampling the motion of the storm too slowly, resulting in these results not being able to resolve the proper smooth changes of the storm.

Authors' Response

Thanks for your comments. As we have mentioned above. We have also noticed the change of velocity and made the corresponding discussion in the manuscript.

Owing to the instability of updraft and non-inductive electrification in the convective cloud, the discharge centroid is not always the barycentre of thunderstorm clusters. As the movement metrics are obtained through the lightning events, which represent the electrification in the cloud, the discharge centroid can better reflect the electrification variations in the storm. The storm with the highest speed occurred on the morning of 20 May, with a value of 204.8 km/h. The lowest maximum speed was 115.3 km/h occurred on the evening of 19 May. The velocity does not show the same tendency as the variation of VA during the lifetime of thunderstorms. It oscillates severely compared with the valid area which shows a steady increase or decrease during the lifetime of thunderstorms. The fluctuation of velocity is very likely to result from the calculation method of centroid discharge. In addition, the different time intervals may cause the bias of velocity. Some severe thunderstorms like supercells last for a short time and move extremely fast, leading to poor monitoring results. A relatively large velocity variation is also seen in the Mediterranean storm (Betz et al., 2008), but with a general upward trend in some cells during the whole movement. Meyer et al. (2013) proposed that long-lived storms are most likely fast propagation as the storms with velocities around 80 km/h spent 150 min to 240 min to cross the domain, however, this was under-represented because of the insufficient statistics. The eight cases in this study also do not show this trend.

Lines 268-272: These references all relate to radar data and seem inappropriate to reference the characteristics used for lightning data. As I mentioned above, there are previous papers that have used lightning data to estimate thunderstorm characteristics.

Authors' Response

Thanks for your comments. The purpose of this paper is to analyze the movement characteristics of thunderstorms, instead of the characteristics of lightning itself. The thunderstorm evolution and movement can be obtained both by the lightning data and radar data. Meyer et al. (2013) provide a hybrid method that combines the radar data and lightning data to assess, track, and monitor a more comprehensive picture of thunderstorms. We believe that it is necessary to compare and discuss the kinematics features of thunderstorms with various data sources. And it also enriches the method to analyze thunderstorm movement.

In Line 268-272, we have discussed the different thresholds used in the literature. Some papers used radar data or both radar and lightning data to identify the thunderstorm with different thresholds including the radar reflectivity, pixel area and duration. The pixel area and duration thresholds are also used in our paper. It is worthwhile to discuss the differences.

Line 286: Please re-state what the mean was for this study so that the reader does not need recall what it was or to go back and find it.

Authors' Response

Thanks for your comments. We have revised the corresponding description as follows.

The lifetime was between 54 min to approximately 8h, with the average thunderstorm duration of the whole evolution process being about 3.5 h, which is slightly longer than this study.

Line 287: 6-minute time interval? I thought the time intervals for this paper were 12-minutes.

Authors' Response

Thank you very much for your carefulness. The sentence 'The average area was 509 km^2 in a 6-minute time interval, with the biggest cluster area in the mature stage.' in line 287 is the description of the literature. It is the finding of Rigo et al. (2010) who analyzed the thunderstorm at the 6-minute time interval.

Line 289: This is not a discussion, this is simply stating what others have found. Please include discussion on how this compares to the current study. It sounds like the storms in this study had an average area equal to the maximum area of a supercell (which is defined as an extremely strong thunderstorm). That seems very unlikely. This raises several concerns related to the methodology of the paper. The authors need to provide much more detailed discussion.

Authors' Response

Thanks for your comments. The maximum cell area of the June supercell reported by Meyer et al. (2013) was found to be nearly 500 km^2 in the 3-min interval. We have mistakenly treated it as 15 minutes, which is actually very unlikely. The average area of 66 Catalonia warm-season thunderstorms was 509 km^2 in a 6-minute time interval (Rigo et al., 2010). In our study, the average area of eight thunderstorms is 336 km^2 per 12 minutes. The differences derive from the geographic position, the severity of thunderstorms and the clustering methodology. We have added the discussion in the manuscript.

Rigo et al. (2010) reported the duration and the average area of 66 Catalonia warm-season thunderstorms. The lifetime was between 54 min to approximately 8h, with the average duration of the whole thunderstorm evolution process being about 3.5 h, which is slightly longer than this study. The average area of 66 thunderstorms was 509 km^2 in a 6-minute time interval, with the biggest cluster area in the mature stage. A June supercell propagated north of Munich in the eastern direction was reported by Meyer et al. (2013) to illustrate the area, velocity and farthest distance of storms, showing that the maximum cell area was nearly 500 km^2 in the 3-min interval. The average area of eight thunderstorms in this paper is 336 km^2 per 12 min. The differences derive from the geographic position, the severity of thunderstorms, the clustering methodology and so forth.

Line 294-295: How is this conclusion found? Once again, there is not enough discussion provided for the reader to follow this statement.

Authors' Response

Thanks for your comments. We have added the specific date of Meyer's case. The conclusion was from Figure 9 of Meyer et al. (2013). It shows the lifetime of selected cell parameters for the thunderstorm case study from 25 June 2008. We can see that the area variation of Meyer's case occurred on 25 June 2008 appears to be more fluctuant with a sharp decrease in the developing stage and many peaks during the whole evolution process. The corresponding revision had been shown as follows.

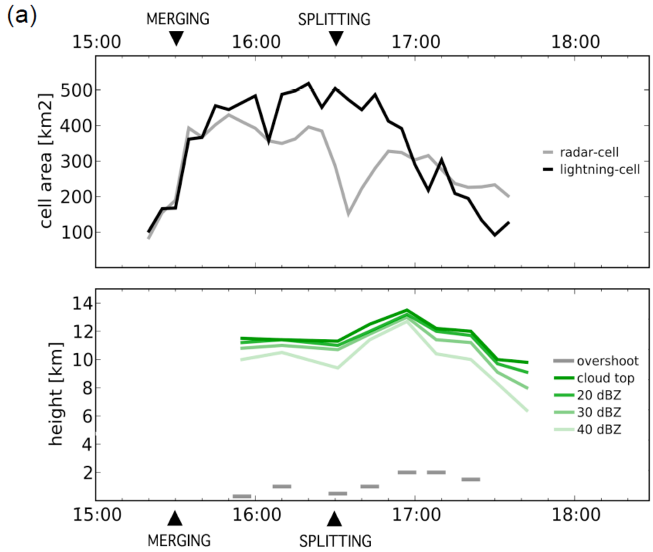


Fig. 9. Lifetime diagrams of selected cell parameters for the thunderstorm case study from 25 June 2008. **(a)** Radar- and lightning-cell areas (top) and iso-reflectivity heights a.g.l. (green) and overshooting top height relative to the mean anvil top height estimated from POLDIRAD radar data (grey bars) (bottom, shared axis). **(b)** 3 min TL stroke rates per cell (top) and per respective lightning-cell area (bottom). **(c)** IC fraction to TL stroke rate (top) and precipitation "intensity" per radar-cell area as described in text (bottom).

The area variation of Meyer's case occurred on 25 June 2008 appears to be more fluctuant, with a sharp decrease in the developing stage and many peaks during the whole evolution process.

Line 304: "Owning" should be "Owing"

Authors' Response

Thank you very much for your carefulness. The corresponding revision has been made in the manuscript.

Line 318: Are the authors sure that the direction angle are in the same reference frame as this study? Storms in the USA also generally move from West to East.

Authors' Response

Thanks for your comments. We have deleted contents about the direction of thunderstorm in the USA and added possible causes of the thunderstorm movements over the PRD region. We believe that the influence factors are more relevant and worthwhile to be disccused in this paper. The discussion is shown as follows.

The orientation of thunderstorms can be affected by the topographic relief (Miller and Mote, 2017). Lin et al. (2011) found that the warm season afternoon thunderstorm over Taiwan Island frequently occurred in a narrow strip, parallel to the orientation of the mountains, along the lower slopes of the mountains. The urban heat island effects and northern mountains in Guangzhou city may influence the movement of thunderstorms over the PRD region (Yin et al., 2020).

Figure 1: The colormap label is confusing. Seems to me the top two row colors are exactly the same or extremely similar. Please consider redoing it.

Authors' Response

Thanks for your comments. We have changed the top two row colors in Figure 1.

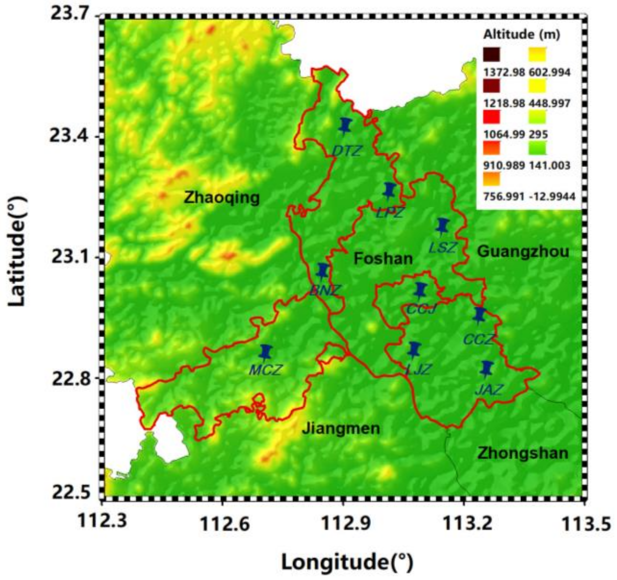


Figure 2: 16:00 is missing. Is that intentional? That is confusing and should be stated in the caption for readers to understand.

Authors' Response

Thanks for your comments. Considering that two thunderstorms have been chosen for study on 17 May (one is from 11:36 to 14:36, and another is from 17:48 to 20:36), we put the stacking map from 12:00 to 15:00 and 18:00 to 21:00 to display the location and variation of the thunderstorm. We have added the corresponding explanation in the manuscript as follows.

Figure 2 showed general radar characteristics and lightning distributions of thunderstorms from 11:36 to 14:36 and 17:48 to 20:36 on 17 May.

Figure 4: "during the thunderstorm process", it is unclear to me what you mean by this. Do you mean the lightning associated within each chosen thunderstorm? please rephrase for clarity.

Authors' Response

Thanks for your comments. We have revised the description in the manuscript as follows.

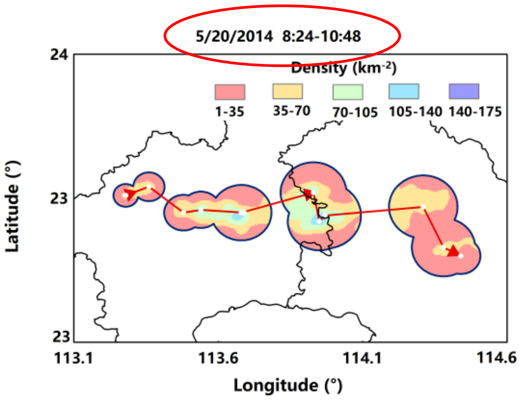
The light blue shaded areas represent total lightning events produced by the chosen thunderstorm.

Figure 5. Similar to Figure 4, you should add the Storm ID so that readers can easily compare. Also, the caption is wrong. The horizontal is actually longitude, while the vertical is latitude.

Authors' Response

Thank you very much for your carefulness. The corresponding revision has been made in the manuscript as follows. The Storm ID of Figure 5 is longer than that of Figure 4 because it includes the specific time. So, we put the Storm ID on the top of the figure.

The horizontal axis corresponds to the longitude with the vertical axis standing for the latitude.



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Miller, P. W. and Mote, T. L.: A Climatology of Weakly Forced and Pulse Thunderstorms in the Southeast United States, Journal of Applied Meteorology and Climatology, 56, 3017-3033, 10.1175/jamc-d-17-0005.1, 2017.

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Wang, J., Li, Q., Cai, L., Zhou, M., Fan, Y., Xiao, J., and Sunjerga, A.: Multiple-Station Measurements of a Return-Stroke Electric Field From Rocket-Triggered Lightning at Distances of 68–126 km, IEEE Transactions on Electromagnetic Compatibility, 61, 440-448, 10.1109/temc.2018.2821193, 2019.

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