THUNDERSTORM EVOLUTION ANALYSIS AND ESTIMATION USING RADAR AND TOTAL LIGHTNING DATA

Jianhua Dai[1,2] *, Yuan Wang[1], Lei Chen[2] , Lan Tao[2], Hong Lin[2]

1. Department of Atmospheric Sciences, Key Laboratory of Mesoscale Severe Weather of the Ministry of Education, Nanjing University, Nanjing 210093, China
2. Shanghai Meteorological Center, Shanghai Meteorological Bureau, Shanghai 200030, China

1. INTRODUCTION

In their life cycle, thunderstorms often cause lightning strokes, heavy rain, strong wind gusts, and even hail or tornadoes. These severe weather phenomena may occur in different stages of a thunderstorm life cycle. In thunderstorm nowcasting operations, it is possible to predict the location of a thunderstorm in a 0-2 hour period using echo tracking and extrapolation techniques. However, it is hard to predict the change of thunderstorm severity and impact due to thunderstorm evolution when using tracking and extrapolation techniques alone. The aim of this paper is to analyze storm structure and lightning activity during its life cycle, and to find some indicators for supporting storm evolution nowcasting.

Thunderstorms present different structure and accompany different lightning activity in their different stages of life cycle. Radar and lightning have been used in analyzing storm structure and evolution. Toracinta (1996) discovered lightning characteristics using comparisons of radar and lightning data. Parker et al. (2001) found different lightning activity during mesocale convective systems' lifetimes. Total lightning including CG (Cloud-to-Ground) lightning and IC (Intra-Cloud) lightning has also been used in thunderstorm detection and nowcasting (Goodman et al. 2005; Murphy and Demetriades 2005). Steiger et al. (2007a and 2007b) investigated total lightning activity in supercells and mesocale convective systems. Total lightning flash rate can improve severe storm probability of detection and lead time (Williams et al., 1999).

In this paper, about 200 thunderstorms cases are analyzed using observations of the Shanghai WSR-88D Doppler radar and the SAFIR total lightning localization system. Some radar products, such as storm structure products and vertical reflectivity distribution products, are used to depict thunderstorm structure. Some lightning data, including CG flash rate, IC lightning flash rate, and IC height, are analyzed to depict the life cycle stage of thunderstorms. These products show the clues to thunderstorm evolution.

2. DATA

About 200 thunderstorms from the Yangtze River Delta during 2004 to 2006 are selected based on the criterion that thunderstorm's VIL reaches 25 kg · m^{-2} at least once in its life cycle. The derived products of the Shanghai WSR-88D

* *Corresponding author address*: Jianhua Dai, Shanghai Meteorological Center, Shanghai Meteorological Service, Shanghai 200030, China； Email: djhnn@sina.com

Doppler radar and the total lightning products observed by the Shanghai SAFIR 3000 total lightning localization system are used. Radar products and lightning products are compared in 6-min intervals during the life cycle.

The radar products used in this research include storm structure (SS), Echo Top (ET), Echo Base (EB), Vertically Integrated Liquid (VIL), Maximum Reflectivity (MxRef), and Height of Maximum Reflectivity (HgtMR). A new indicator of storm structure, difference of HgtMR and EB (DMRB) (in 0.1 km), is developed for describing the difference between the height of the maximum reflectivity and the echo base of a cell.

Based on radar observation time interval of about 6 minutes, some lightning products, such as average IC height (HgtIC), max IC height (MxHgtIC), total lightning flash rates (NLTG), positive lightning flash rate (NumPosCG), and negative lightning flash rate (NumNegCG), are derived from total lightning data.

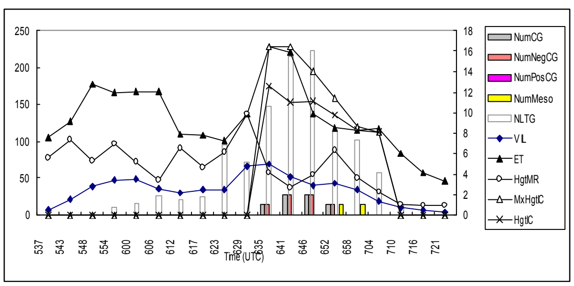

Fig 1 Time series of a thunderstorm's structure information and lightning activity in 6-min intervals from 05:27 UTC to 07:31 UTC on Sep. 21, 2005. White histograms stand for counts of total lightning flashes. Gray, orange, and purple histograms stand for number of all, negative, and positive CG lightning flashes. Yellow histograms stand for number of mesocyclones (M). Curves with white (black) circles stand for height of maximum reflectivity - HgtMR (vertically integrated liquid-VIL), curves with black triangles for echo top - ET, curves with white triangles (Xs) for maximum (average) height of IC lightning.

Figure 1 shows the life cycle of a thunderstorm on Sep. 21, 2005 with radar products and lightning products by 6-min intervals. Based on VIL and ET products, two periods of strong development of the cell in its life were found at 06:00 UTC and 06:36 UTC. The VIL peaked twice at 40 kg・m^{-2} and 50 kg・m^{-2}, while ET reached 13 km and 16 km, respectively.

Compared to the peaks, lightning activity of the thunderstorm seemed to be different. Total lightning flash rate NLTG reached it peak with a value of about 220 flashes per 6 min at 06:42-06:48 UTC, while during the first strong phase of the storm development NLTG was very low with a value of only about 20 flashes per 6-min. CG flashes were found only near the second peak of cell development. Because the thunderstorm was out of the SAFIR 3000's IC height detection range, all height data of IC were processed as 0 meters before 06:30 UTC. Two to three volume scans of WSR-88D after the peak of NLTG, two mesocyclones (M) that caused strong surface wind gusts and heavy rain were found. In this case, IC lightning had a lead time of about 30 minutes relative to the CG lighting strokes.

The height of maximum reflectivity (HgtMR) of the cell climbed to 5-7 km in the initiation stages of the cell, and reached it peak at 10 km in its second period of strong development. This indicates that the core's height was lifted by the updrafts. After the burst of lightning in the second strong development phase, HgtMR had a significant drop and remained near 1 km in the last stages. Figure 1 also shows HgtIC and MxHgtIC had a very high correlation with ET, which reveals that the storm was dominated by IC at high levels.

Therefore, VIL, ET, HgtMR, DMRB, NLTG, HgtIC, and MxHgtIC can be used as indicators for identifying of thunderstorm evolution.

3. THUNDERSTORM LIFE CYCLE CATEGORIES AND STAGES

Life cycle can be defined using radar echo structures. Wakimoto (1992) defined four-stage life cycle of a thunderstorm gust front using radar vertical cross reflectivity and Doppler velocity information. In this paper, the entire life cycle of a thunderstorm is defined as a duration when it is identified by the WSR-88D Storm Cell Identification and Tracking (SCIT) algorithm [Johnson et al., 1998]. For finding average characteristics of thunderstorm evolution, the 200 thunderstorm cells are categorized into 3 categories by the duration of life-cycle: Category I (48 - 72 minutes), Category II (78 - 102 minutes), and Category III (108 - 132 minutes). Category I (III) are mainly the pulse or local thunderstorms (long-lived thunderstorms), and Category II are the mix of I and III.

Then, a normalized processing scheme is used for normalizing a general storm life cycle into 10 stages. Each stage has duration of about 6 minutes, 12 minutes, or 18 minutes, based on the 3-category life cycle. The stages include the initiation (1 to 3 stages), mature (4 to 7 stages), and decaying (8-10) phases of thunderstorms. Radar and 6-min lightning data within 10 km of the cells are collected and compared during their life cycle.

4. RESULTS

4.1 General Life cycle

Figure 2 to figure 4 show the time series of cell structure information and lighting activity for those thunderstorms with life cycle about 60 minutes, 90 minutes, and 120 minutes. Compared with the average life cycle of all researched thunderstorms, VIL and ET have a normal distribution in the life cycle, which shows good correlation with storm evolution: increasing in the initiation and development stages, reaching a high level in the mature stage, falling in the decaying and dissipating stages. VIL can depict storm vertical extent and intensity and ET can depict storm vertical extent.

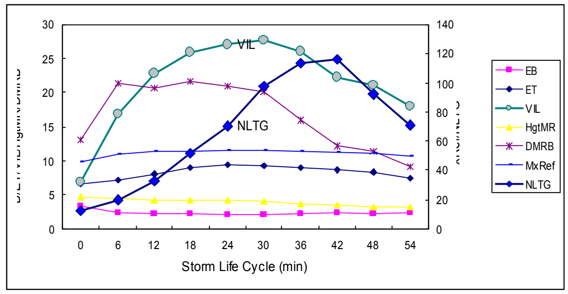

Fig 2 Cell structure and lightning activity of thunderstorms with a life cycle of about 60 minutes.

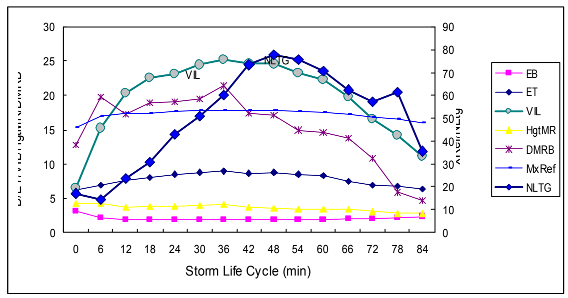

Fig 3 Cell structure and lightning activity of thunderstorms with a life cycle of about 90 minutes.

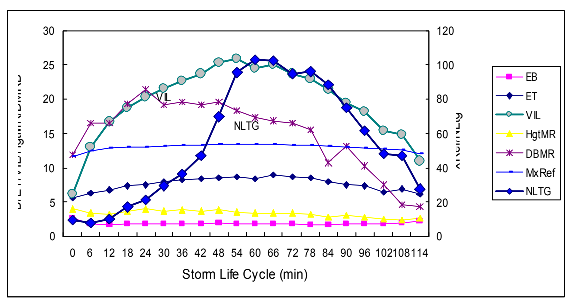

Fig 4 Cell structure and lightning activity of thunderstorms with a life cycle of about 120 minutes.

In the initiation and developing stages, the updraft extends and intensifies. It dominates the storm and makes the storm develop vertically. In the initiation stages (0-12 minutes), VIL has a rapid increase, and ET climbs gradually.

During the mature stage, precipitation and downdraft appear and compete with updraft. After reaching their maximum values in the early mature stage, ET and VIL do not change a lot.

After the mature stage, downdraft and precipitation start to dominate the storm. VIL starts to decline as the storm top, the storm maximum reflectivity and its height are falling. During the decaying and dissipating stages, most of storm structure indicators have a rapid drop except that the echo base (EB) is climbing slightly due to the evaporation of low level precipitation.

Compared to VIL and ET, however, lightning activity reaches its peak later than storm top and VIL. In all three categories, total lightning flash rate NLTG is increasing in the initiation stage and reaches it peak in the late mature stage, which is about 1-3 scans (6-18 minutes) later than does VIL. In category III, a lightning burst occurs just after VIL's maximum. During the burst of lightning, some severe weather may occur, such as surface wind gusts caused by the downdraft, hail, even tornado. Mesocyclone can be identified by Doppler radar.

4.2 Normalized life cycle

Using the normalizing scheme, three normalized 10-stage storm life cycles for the three categories thunderstorms are given (Figure 5 for the thunderstorms with a life cycle about 90 minutes). The average distributions of VIL, ET, DMRB, and NLTG are similar to the general life cycle. The DMRB first reaches its highest, about 1 to 3 scans earlier than VIL and ET reaches their highest, and 2-4 scans earlier than NLTG. These results support combining these parameters into an indicator for evaluating storm life cycle.

4.3 Life cycle indicator and nowcasting scheme

From the statistical result of 200 thunderstorms, the height difference between maximum reflectivity and echo base (DMRB) can be a good indictor of storm's life cycle. DMRB has a high value when storm just initiates. When a storm initiates, its core develops at an altitude of 3-5 km, which can be detected by weather radar. The average HgtMR (height of maximum reflectivity) is around 4 km and EB (echo base) is about 2-3 km. With the rapid development of the storm, cell core is intensified and lifted slightly by the updraft, while the echo base (precipitation) of the cell is descending. Before the top of the cell reaches it highest, the cell core intensifies to its maximum and the updraft can not lift it any more. HgtMR reaches its maximum just in the very beginning of the storm initiation. Therefore, DMRB has reached its maximum before VIL and ET do.

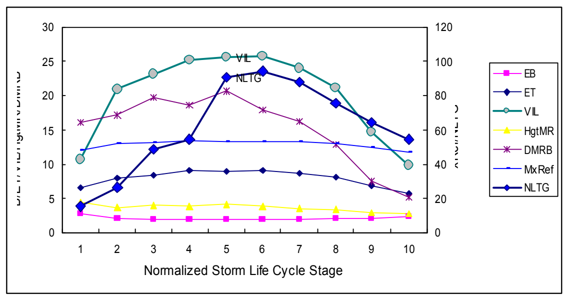

Fig 5 Cell structure and lightning activity of thunderstorms with a normalized life cycle of about 90 minutes.

During the mature stage, the core is intensifying and begins to descend slightly even if the updraft is still strong. DMRB stops climbing. After the mature stage, a downdraft starts to dominate the storm evolution. The storm is decaying with a descending cell core while the base of the cell still touches the ground. DMRB declines as storm decays. When the storm is dissipating, the outflow cuts off the supply of updraft. The maximum reflectivity falls rapidly while the storm base is slowly climbing because the precipitation stops. DMRB reaches its lowest value when the storm dissipates.

Operationally, it is hard to nowcast if a storm reaches its mature stage just using VIL and ET. If a combination of VIL, ET, DMRB, and NLTG is used, however, it is possible to predict the tendency of storm intensity. When DMRB has not increased for 2-4 scans (12-24 minutes) or it is decreasing gradually, and NLTG has a sudden jump, it can be a signal that the storm has been in its mature stage and is decaying.

5. CONCLUSIONS

About 200 thunderstorm cases are categorized and analyzed using radar data and lightning data in different stages of their life cycle. The results show that thunderstorms' evolution can be presented with their structure and lightning activity. VIL leads a rapid increase in the initiation stage and peaks 0-15 minutes in the early mature stages ahead lightning activity. HgtMR has higher values in the early stages and mature stages than in the dissipating stages of thunderstorms. Differences of HgtMR and EB have a good correlation with thunderstorm life cycle stage. The combination of WSR-88D Doppler radar products and total lightning data can be used as an indicator of thunderstorm evolution. The thunderstorm life cycle indicator can describe the stage of thunderstorm life cycle. These results will improve the nowcasting for thunderstorm evolution and severity.

6. REFERENCES

Bunkers, M.J., M.R. Hjelmfelt, and P.L. Smith, 2006: An observational examination of long-lived supercells. Part I: Characteristics, evolution, and demise. Wea. Foreasting, **21**, 673-688.

Carey, L.D., T.L. McCormick, M.J. Murphy, and N.W.S. Demetriades, 2003: Three dimensional radar and total lightning structure of mesoscale convective systems. 31st Conf. on Radar Meteorology, Seattle, WA, Amer. Meteor. Soc., 80-83.

Goodman, S. J., R. Blakeslee, H. Christian, W. Koshak, J. Bailey, J. Hall, E. McCaul, D. Buechler, C. Darden, J. Burks, T. Bradshaw, and P. Gatlin. 2005: The North Alabama Lightning Mapping Array: Recent Severe Storm Observations and Future Prospects, *Atmos. Res.*, **76**, 423-437.

Johnson, J.T., P.L. MacKeen, A. Witt, E. D. Mitchell, G. J. Stumpf, M. D. Eilts, and K. W. Thomas, 1998: The Storm Cell Identification and Tracking (SCIT) algorithm: An enhanced WSR-88D algorithm. *Wea. Forecasting*, **13**, 263-276.

Murphy M.J., and N.. Demetriades, 2005: The role of total lightning in thunderstorm nowcasting. The World Weather Research Programmes' symposium on nowcasting and very short range forecasting (WSN05), Toulouse, France, Sep. 2005. P4.21.

Parker, M.D., S.A. Rutledge and R.H. Johnson, 2001: Cloud-to-ground lightning in linear mesoscale convective systems. *Mon. Wea. Rev.*, **129**, 1232-1242.

Steiger S.M., R.E. Orville, and L. D. Carey, 2007a: Total lightning signatures of thunderstorm intensity over North Texas. Part I: Supercells, *Mon. Wea. Rev.*, **135**, 3281–3302

Steiger S.M., R.E. Orville, and L. D. Carey, 2007b: Total lightning signatures of thunderstorm intensity over North Texas. Part II: Mesoscale Convective Systems, *Mon. Wea. Rev.*, **135**, 3303–3324

Toracinta, E. R., K. I. Mohr, E. J. Zipser, and R. E. Orville, 1996: A comparison of WSR-88D reflectivities, SSM/I brightness temperatures, and lightning for mesoscale convective systems in Texas. Part I: Radar reflectivity and lightning. *J. Appl. Meteor.*, **35**, 902–918.

Wakimoto, R.M., 1982: The life cycle of

thunderstorm gust fronts as viewed with Doppler radar and rainsonde data. Mon. *Wea. Rev.*, **110**, 1060-1082

Williams, E.R., B. Boldi, A. Matlin, M. Weber, S. Hodanish, D. Sharp, S. Goodman, R. Raghavan, and D. Buechler, 1999: The behavior of total lightning activity in severe Florida thunderstorms. Atmos. Res., **51**, 245-265.

Acknowledgements

This paper is jointly funded by the 2005 Doctoral Fund of Ministry of Education of China (No. 20050284035), the National Key Basic Research and Development Project of China (973: 2004CB418301), and China Meteorological Administration's New Technology Development Program (CMATG2006M16).