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Nowcasting CG Lightning Activity for Hainan Island during the Spring and Summer seasons

Guo Dongyan, Chen Youlong, Cai Qinbo
Hainan Meteorological Service
Haikou, China
Dongyan_g@live.cn

***Abstract*—The main purpose of this study is to explore predictability of cloud-ground (CG) lightning activity using Doppler weather radar data and high-density meteorology automatic stations for the purposes of nowcasting CG lightning within a 2 hour time frame during the spring and summer seasons for the Hainan Island. Results indicate the influence of sea-land breeze is likely one of the important reasons as to explain why lightning mostly occurs during afternoon over most of the areas of Hainan but during the nighttime in the southern areas. Some radar echo reflectivity threshold values associated with lightning activities (such as echo top at the elevation of the -30℃ isotherm, echo top of 35-dBZ reflectivity at the elevation of the -20℃ isotherm and the maximum reflectivity at 50dBZ) are concluded in this study. The mean lead times of these thresholds ranged from 11 to 33 minutes. The mean Vertical Integrated Liquid Water (VIL) values increases obviously with increasing flash rate. The testing results from nowcasting predictability studies in 2013 suggested that the nowcasting skills of echo top at -30℃ and echo top of 35-dBZ reflectivity at -20℃ are over 60%, while the maximum reflectivity at 50dBZ is the lowest at 40%.**

Keywords—Lightning characteristics, Sea-land breeze, Nowcasting, Radar reflectivity

I. Introduction

Hainan Island is located in the southernmost part of China. It is surrounded by the South China Sea and is facing the mainland China to the north. Hainan Island is one of the places most often struck by lightning in China (Guo Dongyan, 2008; Lin Jian and Qu Xiaobo,2008). Gao Yi and Zhang Yijun(2012) have found that Hainan and Guangdong provinces have the highest average cloud-ground flash density and casualty rate in China. According to their study, from 1997 to 2010, the casualty rate in Hainan province was 21.93 persons per year, and the lightning disaster frequency was 53.14 times per year. This founding is equivalent to the approximate number of 50 times per year in Hainan from 2003 to 2009 (Guo Dongyan, 2010)). Each year, lightning causes large losses to life of people, infrastructure, and the environment while our capability in forecast lightning, especially for the CG lightening for the Hainan Island remains limited.

It is necessary to understand the characteristics of lightning when attempting to forecast lightning activity over a certain area. Much work from all over the world that has studied the characteristics of lightning has focused on the distribution of lightning intensity, diurnal evolution, and influence by land-sea breeze. Lin Jian and Qu Xiaobo (2008) found that thunderstorms over China usually began at 12:00-24:00 from April to September. Lin Liangxun and Liang Qiaoqian (2006) found that in Guangzhou city, (Guangdong, China) lightning frequently occurs from April to October; during these months it occurs most frequently from the afternoon until midnight. B.Kucieniska(2010) has found that the diurnal lightning patterns over the Subtropical and Tropical Pacific are very similar, and that the maximum lightning over the Pacific coast of southern Mexico coincide with the maximum frequency of land breeze (observed at about 6 a.m). This finding affirms the land-sea breeze circulation data done by Baumgardner et al.(2006) in the coastal town of Salina Zruz.

There has also been a lot of research done that has focused on using radar products to forecast lightning activity. Emphasis has been placed on the combination of radar reflectivity values at different isothermal levels. Table 1 shows the results from previous studies of lightning forecasting using radar reflectivity(Richard M. Mosier, 2011, with Richard M Mosier's results). Using radar- derived parameters such as VIL(vertically integrated liquid) to forecast CG lightning has also been attempted in many studies (Greene and Clark, 1972; Waston et al. 1995, and MacGorman et al. 2007), while some other people (such as Richard M. Mosier (2011)) has tried to forecast lightning by using another radar derived product (vertically integrated ice(VII)).

In order to protect people's life and property from lightning attack, it is very important to know where and when lightning is most likely to strike. Additionally, a good lightning warning system is necessary in order to properly help decision makers to plan in advance. From the above discussion it should now be clear that the most efficiency way to forecast and nowcast lightning activity thus far is by using radar reflectivity and radar-derived products.

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TABLE 1. RESULTS FROM PREVIOUS STUDIES OF LIGHTNING FORECASTING WITH RADAR REFLECTIVITY.

Study	No.of Cells	Location	Criteria		Lead time (min)
			Reflectivity (dBZ)	*Isotherm (℃)*	
Buechler and Goodman(1990)	20	FL,AL, NM	40	-10	4-33
Michimoto(1991)		Japan	30	-20	5
Hondl and Eilts(1994)	23	FL	10	-10	15
Gremillion and Orville(1999)	39	FL	40	-10	7.5
			25	-15	14.8
Vincent et al.(2004)	50	NC	35	-10	17.5
			40	-15	11.0
Wolf(2007)	1,100	FL,GA	40	-10*	N/A
Clements and Orville(2008)	37	TX	30	-10	16.14
Richard M. Mosier and Courtney Schumacher(2011)	67,384	HT	30	-15/-20	10
			30	-10	19.1

* The isotherm level for Wolf(2007) if the updraft temperature, not the environmental temperature.

The main purpose of this study is to improve the forecasting abilities of cloud-to-ground(CG) lightning activity over Hainan Island. The characteristics of CG lightning over Hainan Island from April to September, using some combinations of the radar reflectivity forecast method and warning predictors based on radar products have been proposed in this study and the case studies have been discussed.

II. DATA AND METHODS

A. Lightning Data

The CG lightning data used in this study was provided by the Hainan Lightning Detection Network(HLDN) (which is owned by Hainan Meteorological Service on Hainan island, China). The lightning data analyzed in this paper cover the period 2007,2008, and 2013. The lightning data obtained from HLDN has been verified (Chen Youlong, 2010). The results show that the data can give forecast information on the path, occurrence, and development trends of thunderstorms.

B. Radar Data

Three years (2007,2008,2013) of the Haikou Weather Doppler Radar (WSR-98D) data from Hainan Meteorological Service for the spring and summer seasons (April-September) were analyzed within 150 km from the Radar site (Fig.1).

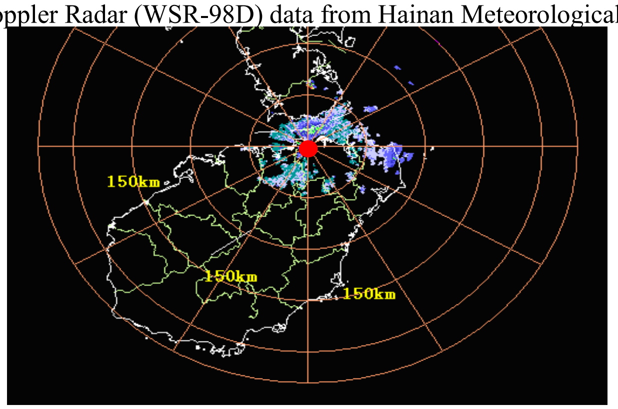

Fig.1 Location of the study area and the location of WSR-98D（Red dot）

Since the weather events over Hainan Island occur mainly as a result of convection, and rainy day occurs so often, Hainan Meteorological Service runs VCP(volume control patterns)-21 for most situations. The Radar scans for 9 levels every 6mins. Horizontal revolution of the Radar product is 1 km.

C. Wind Data

The wind data used in this study is from high-density Hainan meteorology automatic stations, which have 371 stations in total spreading over the whole Hainan Island. The wind data is observed every 10 minutes. The hourly wind data has been used in this study. When verifying the data, wind speed data extremely high or low are compared to the nearby stations for over 2 consecutive hours. If such data are found to be inconclusive, they are excluded from this study..

D. Lightning Disasters Data

Lightning disasters data has been obtained from the meteorological disasters database of Hainan Meteorological Service. The lightning disasters data in the database include the numbers of disasters that have occurred, and casualty and property losses (which are specifically described during the study periods). Since there are still a few lightning disasters which might not have been reported (or might not have been recorded correctly), the lightning disasters data from the databases (for Hainan lightning disasters characteristics) provide a partially incomplete set of statistics.

E. Lightning Nowcasting Criteria and Statistics

A typical nowcasting process of Hainan lightning warning systems includes the following steps: 1) Identify and track cells; 2) for each cell, the reflectivity values are to be obtained at different heights; 3) if the reflectivity values meet the given thresholds, a yes warning for the following 0-2h should be made.

III. RESULTS

A. Characteristics of CG Lightning Activity

The CG lightning activity over the Hainan Island is studied based on the observational data from HLDN. Over 178,483 flashes were recorded during the AMJJAS (April, May, June, July, August, September) of 2007-2008. Among them, 2,824 flashes are positive and 175,659 flashes are negative.

The Fig. 2a shows the average CG lightning density in number of lightning strikes per square kilometer during the spring and summer seasons per year over Hainan Island. These

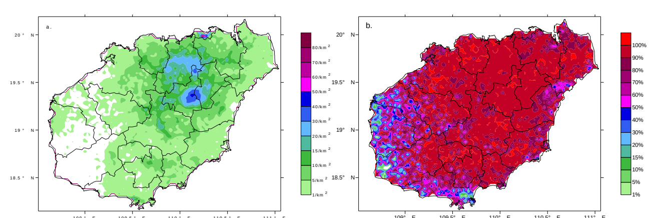

Fig.2a The number of CG lightning strikes per square kilometer in the spring and summer months over Hainan Island. b. Percentage of lightning occurrence during the daytime over Hainan Island

results were calculated from data from 2007-2008 obtained by HLDN. It can be seen that lightning occurs more frequently over inland areas than coastal areas, more frequently over northern areas than southern areas, and more frequently over eastern than western areas. For the whole Island, the lightning occurs much more frequently in the north half of the inland area than over other areas with the number of lightning strikes per square kilometer ranging from 10-40. The areas which have the highest frequency of lightning strikes are the northwest inland area (which is about 50 km from the coastline) and the northeast part of the middle area (which is 50-100 km from the coastline). The mean values range from 20 to over 40 flashes per square/km, while flashes rarely occurs over the western area of the island, with the number of lightning strikes per square/km are less than 5.

The Fig.2b shows the percentage of lightning occurrences during the daytime. It can be seen that lightning occurs mainly during the daytime throughout most areas except for southern and western coastal areas of Hainan Island where lightning occurs mainly during the nighttime. The northwest inland and the south-central mountainous regions have the highest frequency of lightning strikes during the daytime. The percentage is as high as over 90%, while the percentage in southern coastal and western areas is lower than 40%.

The number of CG lightning strikes per square kilometer during the spring and summer months of 2007-2008 is presented in Fig.3. It can be seen from Fig.3a that flashes start to be active in April, and that the occurrence area is very centralized over the northern part of the middle area (with lightning strikes5-20 times per square kilometer). The lightning activity becomes larger more frequent from May to June (Fig.3 b-c) and reaches its most active in June (with the number of lightning strikes per square kilometer per year in June ranging from 1 to 15 over most areas). Differing with May

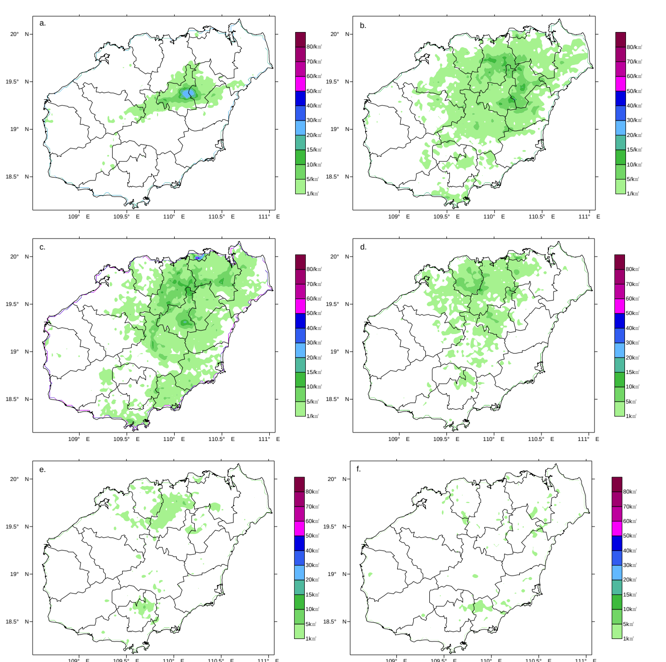

Fig.3 The number of CG lightning strikes per square kilometer in the spring and summer months over Hainan Island. (a. April, b. May, c. June, d. July, e. August, f. September)

and June, lightning rarely occurs over eastern and southern coastal areas in July. From August to September, the number of lightning strikes over the whole island is significantly reduced with few flashes occurring throughout the entire inland. This finding is also in agreement with a previous study done on lightning activity by Li Fan and Guo Dongyan(2010). The study found that a high density of lightning flashes are distributed inland in the northwest and north mid-area regions of the island.

The diurnal variation of lightning frequency and density studied during the spring and summer of 2007-2008 in 3 hour intervals. Fig. 4 indicates that diurnal distribution of lightning for the Hainan Island exhibits the highest and second highest number of strikes from 14:00-17:00 and 17:00-20:00. This result is similar with the results from Li Fan and Guo Dongyan (2010). They found that 82.4% of lightning over Hainan Island occurs from 13:00 to 20:00 which also coincides with Guo Dongyan's (2010) results that the Lightning disasters over Hainan Island occur mainly in the afternoon (14:00-18:00). We also notice the difference with other areas of Hainan where lightning mainly occurs during the daytime (especially during the afternoon hours). It is important to note that lightning over southern and western coastal areas might be more active in the morning and midnight than during other times.

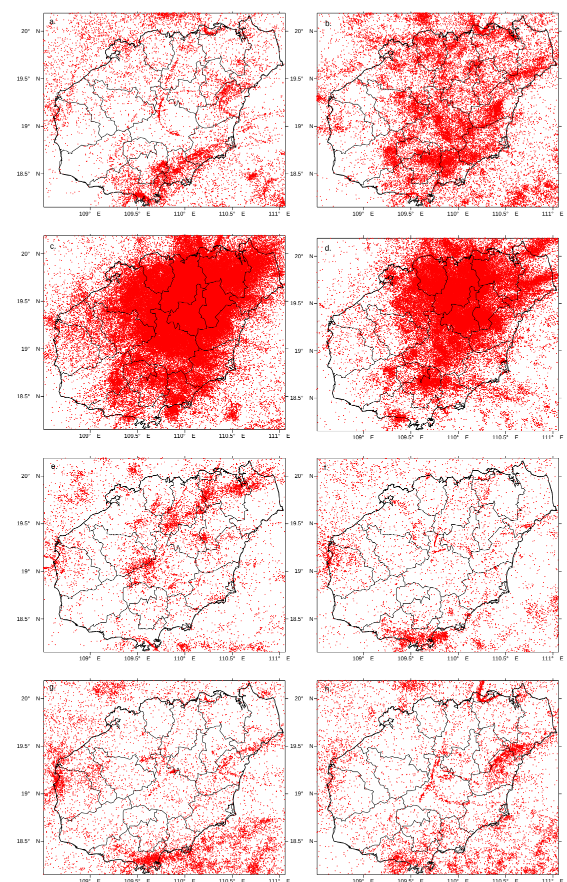

Fig.4 The number of CG lightning strikes every 3h during the spring and summer season of 2007-2008 over Hainan Island. (a. 08-11h, b. 11-14h, c. 14-17h, d. 17-20h, e. 20-23h, f. 24-02h, g. 02-05h, h. 05-08h)

B. Sea-land Breeze Influence

Much work has been done studying the influence of sea-land breeze on lightning activity. University of Florida lightning research group studies have found that thunderstorms caused by powerful sea breeze fronts frequently occur in Florida during the wet season (which typically lasts from June through September/October). Every direction that the wind blows in Florida is always off of the water, thus making Florida the place most often struck by lightning in the United States (and one of the most often struck places on Earth). Afternoon thunderstorms are observed along the coasts of the Indonesian islands. Converging land breezes, enhanced by mountain breezes, produce nighttime and morning thunderstorms over the Straits of Malacca and the African Great Lakes(Katrina S. Virts and John M. Wallace, 2013). For Hainan Island, Guo Dongyan and Zhai Panmao (2011) have found that the land-sea breeze convection shear induces thunderstorms frequently during the summer in northwest coastal areas, especially during the afternoon. The main cause is the convection of the local northerly from sea and large-scale southerly of the general circulation. In Sanya, thunderstorms mainly happen at night is just because of the convection of the local northerly from land-sea breeze and the large-scale environmental southerly in nighttime.

The study cases below show the sea-land breeze influence of lightning activity for the Hainan Island. The large-scale wind directions of all three cases in Fig.5 are all blowing in a southward direction.

Fig.5a shows hourly wind direction, wind speed, and flashes changing from left to right during 14:00 to 16:00 on April 22nd. It is clear from the map that the sea breeze front had formed over the north coastal area beginning at 14:00, and becoming even more pronounced throughout the next two hours; in other words the flashes started at 14:00 and became much more frequent as 16:00 approached. 1 person was reportedly struck dead by lightning at about 16:00 near the highest density lightning-strike area.

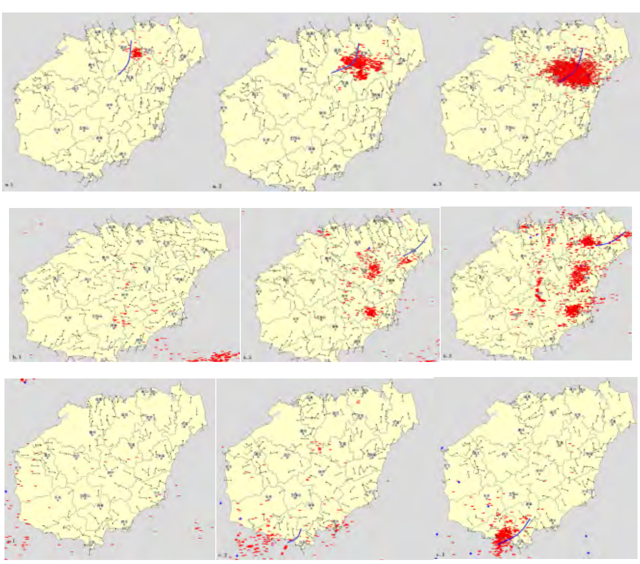

Fig.5 the hourly wind direction, wind speed and the flashes of three cases showing sea/land breeze fronts effect the lightning activities. (a. 14:00,15:00 and 16:00 on 22 April, 2007 from left to right, b. 13:00,14:00 and 15:00 on 4 June, 2008 from left to right, c. 03:00,04:00 and 05:00 on 27 May, 2007 from left to right. The red "-" and blue "+" stands for negative flash and positive flash, respectively)

Fig.5b shows the change in hourly wind direction, wind speed, and flashes from 13:00 to 15:00 on 4 June, 2008. It also can be seen that the sea breeze front had formed at 13:00 over northeast coastal area, and became stronger at 15:00, which lead to lightning occurrences being the most frequent after 15:00. 2 people reportedly died from lightning strikes in the northeast area at about 15:00.

At night, the sea-breeze usually changes to a land breeze due to a reversal of the same mechanisms. The Fig. 5c shows a land breeze front which led to a lightning disaster in southern coastal areas. The same as Fig.5a and Fig.5b, the hourly wind and flash changes are represented in the picture from left to right. The northern winds were blowing from land, and the environmental south winds formed a front in southern coastal areas during late night hours (around 03:00). Maximum lightning activity occurred after 05:00, which led to 3 people dying from lightning strikes at about 05:30.

C. Nowcasting of CG Lightning

From the above study, it is evident that most lightning over Hainan Island occurs within 150 km from the Haikou Radar site. In order to improve the nowcasting skill of CG lightning over Hainan island, the predictors of lightning nowcasting were found based on the analysis of radar products.

In order to find the predictors by using radar products mainly for the area mentioned above, the 118 high frequency lightning events were selected under the criteria that the numbers of lightning strikes over the Island exceeds 500 per day. Radar reflectivity values and VIL values from these high frequency lightning events within 150km from the Haikou Radar site are calculated from composite reflectivity products. Additionally, disasters caused by lightning strikes during the spring and summer of 2007-2008 are also used to help determine the thresholds.

1) Radar reflectivity

As is demonstrated in table 2, the results in this study show that for at any time 1) the echo top of 35 dBZ reaches the elevation of the -20℃isotherm (which is equal to 9 km), or 2) the echo of a cell reaches nearly -30℃(at above 11 km), 3) when a maximum echo reflectivity that reaches above 50 dBZ with a minimum track count of 2, be identified within 100 km(the studied area is within 150km from radar site, but in order to improve the nowcasting accuracy, the nowcasting will be considered with 100 km from the radar site), there is a potential for CG flashes.

When using radar reflectivity to forecast lightning, there are some results from previous studies, such as the "Larsen area" of Larsen and Stansbury (1974). In this study the "Larsen area" was defined as an area with more than 43 dBZ above 7km. Gremillion and Orville(1999) found 40 dBZ at -10

℃ to be the best predictor pair while Richard M. Mosier (2011) found 30 dBZ at -20℃ to be the best for Houston.

TABLE 2. THE RADAR REFLECTIVITY THRESHOLDS OF LIGHTNING NOWCASTING OVER HAINAN ISLAND

Predictor	Echo top of 35 dBZ	Echo top	Maximum reflectivity
Threshold	-20℃	-30℃	50dBZ

2) VIL

Using radar-derived parameters-vertically integrated liquid(VIL) to forecast CG lightning has also been attempted in this study. Many studies on using VIL to forecast lightning have been done. Greene and Clark (1972), Waston et al. (1995), and MacGorman et al. (2007) found that there was a large scatter of lightning occurrence as VIL values increased, and the mean and mode VIL values increase with an increasing flash rate.

In order to find the relation between VIL and lightning, the cells based on VIL have been calculated during the lightning disasters events during spring and summer from 2007 to 2008. The finding is in agreement with the result from Waston et al. (1995), and MacGorman et al. (2007), that for Hainan Island, the VIL values also increases remarkably(from 10 to 40 kg/m2 in average) with increasing flashes. It has also been found that when mean VIL value in the cell increased from 10 to 30, flashes occurred after average 22mins in 65% cells. The VIL can go up to 40 in average. Additionally, it is also found that the VIL increasing has high related to radar reflectivity values changing before first flash.

However, there are also findings from Watson et al.(1995) and MacGorman et al.(2007) that VIL alone cannot be used to forecast lighting (the VIL threshold was found in this study). Additionally, Petersen et al. (1999) gave a result that VIL can also be biased by high-reflectivity echo at low levels in storms with warm-rain processes that are not necessarily related to storm electrification. Therefore, the mean VIL values of cells can be a secondary consideration to forecast the lightning.

3) Lead time

The lead times to the first flashes are calculated for the radar reflectivity threshold methods. It has been found that the mean lead times of these thresholds ranged from 11 to 33 min (Table 3). The number of cells analyzed in different case studies is the main cause of the difference between the previous studies and this study.

4) Tesing

For testing the forecast capabilities of the predictors given in this study, the Radar products and lightning data during the spring and summer of 2013 have been investigated. Consider the fact that when the weather forecasters gave the lightning nowcasting, the yes or no warning given by the lightning warning system (which is based on the predictors given in this study) was not the only factor that they considered. They had to also consider other factors, such as how the influence of

TABLE 3. THE LEAD TIMES OF THRESHOLDS

Echo top of 35 dBZ at -20℃			Echo top at -30℃			Maximum reflectivity > 50 dBZ		
Min	***Max***	***Mean***	***Min***	***Max***	***Mean***	***Min***	***Max***	***Mean***
5	15	11.4	10	30	16.9	20	59	33.7

sea-land breeze and current effect weather systems, etc. which need to be discussed together in order to make a final warning. So, testing work has been done in three ways. The first way is to select high frequency lightning events (which are the days on which lightning occur more than 500 times per day) and then calculate the radar reflectivity values and VIL values to see whether or not the values met the thresholds given. The second way is to calculate all of the history radar reflectivity values and VIL values from the radar composite reflectivity products and then to select the values which meet the thresholds and then check if lightning occurs after 11 to 33 minutes. The third way is to analyze the radar reflectivity values of all of the lightning disasters which occurred in the spring and summer in 2013 and determine how many of them met the thresholds given.

The results show that: For CG lightning, the nowcasting accuracies of echo topped out at -30℃ and echo top of 35-dBZ reflectivity at -20℃were 60% and 70% respectively, while the maximum reflectance at 50dBz was the lowest with 40%.

5) Cases

The Fig. 6a,b present two cases on 17th May and 20th May, 2013, respectively. For case 1 showed in the Fig. 7a (17th May, 2013), the echo top of 35 dBZ reached 10 km (-30 ℃) at 16:55 roughly 15 minutes before the first flash was observed (table 4).

In case 2, two cells had been tracked on 20 May, 2013(Fig. 6b.1 and Fig. 6b.2), the first flashes both occurred at 16:30 over b1 area and b2 area(showed in the Fig. 6b.3). For the b1 area, the maximum echo reflectivity was 50dBZ at 16:02, then it kept going up until 60dBZ, which was satisfied the threshold of having a maximum echo reflectivity above 50dBZ, and gave a 28mins lead time ahead before the first flash occurred(table 4). For the b2 area, the maximum echo reflectivity was 50dBZ at 16:02, gave a 54 lead time ahead before the first flash occurred; the echo top reached 11km at 16:15, which gave a 15mins lead time(table 4).

It also can be seen from both the cases that both the echo top and the cells based VIL showed significant changing before the first flash occurred(e.g. In case 2, the mean VIL value of cell b.1 increased to 30 at 16:12, which was 18mins ahead the first flash occurred, while echo top reached 10km at 16:12).

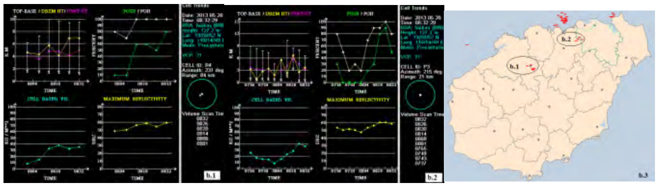

Fig.6 The cases of lead times. (a. The case on 17th May, 2013: a.1, the radar echo reflectivity section map at 15:55, a.2, the radar reflectivity products fo the cell, a.3, the flashes at 17:10; b. The case on 20th May, 2013: b.1, the radar reflectivity products of the cell 1, b.2, the radar reflectivity products of the cell 2, a.3, the flashes at 16:30)

TABLE 4. THE LEAD TIMES OF THRESHOLDS OF CASES STUDY

Case	**Predictor**	**Met threshold**	**Time (h)**	**Occurrence time of first flash**	**Lead time (min)**
a	Top of 35dBZ >10km	Y	16:55	17:10	15
	Echo topped out 11km	Y	16:55		15
	Max dBZ>50	Y	16:11		59
	Cell based VIL > 30 kg/m^2	/	16:31		39
b.1	Max dBZ>50	Y	16:02	16:30	28
	Echo top reached 10km	N	16:12		18
	Cell based VIL > 30 kg/m^2	/	16:16		14
b.2	Max dBZ>50	Y	15:36		54
	Echo top reached 11km	Y	16:15		15
	Cell based VIL > 30 kg/m^2	/	16:15		15

IV. DISCUSSION

From the results above, the combination of the radar reflectivity forecast method and the VIL forecast method can potentially be used to improve lightning nowcasting for the Hainan Island. In testing the warning abilities of the thresholds given in this study, the flashes and radar reflectivity values have been calculated.

Future studies are expected to concentrate not only on testing the hit rate, but also on examining the false and missing percentages of lightning warning alarms using operational Hainan lightning warning and nowcasting systems based on the thresholds given in this study. Additionally it is important to note that this study only focuses on an area within 150km from the Haikou Radar sites. The Haikou Radar is the only Doppler Weather Radar run by Hainan Meteorological Service in the study period. Since warning thresholds can vary from place to place, it is necessary to conduct similar study based on the Sanya Radra, which has been operated since 2011. Obviously, such effort will help to improve nowcasting of lightening of the entire island!

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