Anticipating the Initiation, Cessation, and Frequency of Cloud-to-Ground Lightning, Utilizing WSR-88D Reflectivity Data

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Abstract

Cloud-to-ground lightning ranks as one of the most frequent, damaging, and deadly weather hazards in the United States. Real-time information about the imminent threat of lightning is not routinely provided to the public, perhaps due to the seemingly unpredictable nature of lightning, and the sheer number of thunderstorms that occur each year.

Based on smaller prior studies, a larger study was completed in 2006, involving over 1,164 convective cells from over 21 different thunderstorm days. The study focused on radar clues suggesting the imminent onset of cloud-to-ground lightning strikes, as well as the onset of numerous strikes. The study confirmed the results of previous studies, finding a probabilistic relationship between thunderstorm intensity, as suggested by the height of the 40 dBZ echo in relation to the estimated -10°C level, and the occurrence and frequency of cloud-to-ground lightning. The results suggest that probabilistic guidance could be generated, based on each scan of volumetric radar reflectivity data, leading to real-time lightning alert information.

1. Introduction

Cloud-to-ground (CG) lightning is second only to floods in terms of annual weather-related fatalities in the United States. A study of 36 years of data, from 1959-1994, found an annual average of about 90 reported fatalities and nearly 300 injuries due to CG lightning (Curran et al. 2000). Lightning-related casualty statistics are believed to be underestimated as many occurrences are not reported (Lopez et al. 1993). Reported lightning fatalities have decreased over the past two decades, while the number of reported injuries has been constant, though highly variable from year to year, as illustrated on Fig. 1 (Curran et al. 2000). Economic losses due to lightning damage vary substantially by source, ranging from the tens of millions of dollars to a few billion dollars. Regardless of the source accepted, property damage from lightning is considerable.

CG lightning is the most frequent weather-related threat to life and property. As suggested by data from the National Lightning Detection Network (NLDN), which detects most, but not all, CG strikes (Cummins et al. 1998), over 20 million CG strikes per year occur across the United States (Orville and Huffines 2001, Zajac and Rutledge 2001). The threat exists across the U.S., and is most persistent across the southeastern third (Figs. 2 and 3, Zajac et al. 2000). Despite this, real-time guidance on the imminent threat of CG lightning or numerous CG strikes is not provided to the public.

The results of a large study completed at NWS Jacksonville, Florida are presented. The study examined the utility of generating probabilistic CG lightning guidance in an operational setting using real-time WSR-88D data.

2. Relating CG Lightning Onset to Vertical Reflectivity Structure: Previous Studies

A considerable number of studies relating CG lightning onset to radar reflectivity data have been completed as far back as the 1970s (Larsen and Stansbury 1974, Marshall and Radhakant 1978, Goodman et al. 1988, Dye et al. 1989, Michimoto 1990, Gremillion and Orville 1999, Vincent et al. 2003). These studies were based on the hypothesis that volumetric radar data could be utilized to anticipate when ice (graupel) is introduced in a turbulent convective updraft, leading to the initiation of CG lightning.

The studies shared a common conclusion that the imminent threat of CG lightning is suggested by the appearance of the 40 dBZ echo near or above the environment -10°C level (E-10L). This guideline suggested a sufficient precipitation mass in the mixed-phase cloud region to support lightning. A detailed discussion on the processes that lead to CG lightning is beyond the scope of this paper, but can be found in MacGorman and Rust (1998) and Vincent et al. (2003).

3. NWS Jacksonville FL Study

Unlike prior studies, which focused on databases of 50 thunderstorms or less, the current study includes over 1,164 convective cells from over 21 different archived thunderstorm events in the southern U.S., which occurred from 2001-2006. A majority of the cases were in Georgia and northern Florida, but several cases were utilized from other areas. The cases included a mix of supercell, multi-cell, and pulse single-cell events. Archived data, replayed on the station's Weather Event Simulator (Magsig and Page 2003), were used to complete the study. For each event, a cell was included in the study if the 40 dBZ echo height reached at least 3.1 km (10,000 ft) above ground level (AGL), and the echo top reached at least 6.7 km (22,000 ft) AGL.

In the study, 297 cells (26 percent) produced no CG lightning, an equal number produced "frequent" CG strikes (defined here as greater than 10 strikes per 5-minute period), and the remainder produced "isolated" (1-4 strikes per 5-minute period) or "scattered" (5-10 per 5-minute period) CG strikes. About 50 percent of the cells producing "frequent" CG strikes as previously defined (13 percent of all cells in the study) produced over 20 strikes in a 5-minute period, defined here as "numerous". The terms used here are not based on definitions in any previous study.

The primary difference with prior studies was the focus on the approximate -10°C level within the turbulent thunderstorm updraft (Davies-Jones and Henderson 1975), referred to as U-10L, rather than the ambient environment, or E-10L. The U-10L level was determined by plotting a surface-based updraft parcel on a Skew-T/Log P diagram, as illustrated on Fig. 4. This technique excluded the impact of environmental entrainment, or vertical density differences. This level was rounded to the nearest 0.3 km (1,000 ft) for simplicity. Actual or model-forecast soundings, modified using surface observation data, were used in the study.

4. Results

The results of the NWS Jacksonville study, as shown on Tables 1 and 2, and Figs. 5 and 6, reveal a pattern of increasing CG lightning probability and frequency with increasing 40 dBZ height, similar to prior studies. The study provides evidence that supports the utilization of WSR-88D reflectivity data, and model or observed soundings, to anticipate the onset and frequency of CG strikes.

Using the U-10L, and the updraft -6°C level (U-6L), yielded the following probability of detection (POD, ratio of CG cases to total) and false alarm rate (FAR, ratio of unverified cases to total) results for anticipating CG strike onset:

	CG	*No CG*	*Total*	*POD*
U-10L	*834*	*34*	*868*	*96%*
U-6L	*863*	*5*	*868*	*99%*

	Verified	*Unverified*	*Total*	*FAR*
U-10L	*834*	*99*	*933*	*11%*
U-6L	*863*	*210*	*1073*	*20%*

As illustrated on Table 2, note the increase in CG lightning probability for 40 dBZ heights two to four thousand feet below the U-10L, approximating the U-6L, where temperatures may be low enough to support ice nucleation (Stewart and Crawford 1995, Zerr 1997). Coincidently, in moderately unstable environments (assuming a uniform thermodynamic profile in all updrafts), the U-6L is often near the E-10L referred to in prior studies. The statistics for the U-6L show a higher POD and higher FAR compared to those for the U-10L.

For frequent/numerous (F/N) strike cases (> 10 strikes per 5-minute period), the following results were achieved using 40 dBZ echo heights of 4,000 ft (U-10L+4k) and 8,000 ft (U-10L+8k) above the U-10L:

	F/N	*No F/N*	*Total*	*POD*
U-10L+8k	*284*	*12*	*296*	*96%*
U-10L+4k	*296*	*0*	*296*	*100%*

	Verified	*Unverified*	*Total*	*FAR*
U-10L+8k	*284*	*136*	*420*	*33%*
U-10L+4k	*296*	*266*	*562*	*47%*

If verifying the F/N strike cases with at least scattered strikes rather than F/N strikes, the FAR for U-10L + 8k (4k) would have been only 10% (17%).

Utilizing "no CG" as a false alarm measure for the CG strike onset alert (focused on U-10L), and "none/isolated CG strikes" as a false alarm measure for the F/N CG alert (focused on 2.4 km, or 8,000 ft, above the U-10L), both alerts caught at least 95 percent of the respective events, with only 10-15 percent of alerts unverified using NLDN output.

Specifically, as suggested by Tables 1 and 2, and Figs. 5 and 6, the results included the following:

a) Minimal CG lightning probability until the 40 dBZ echo reached a height of the E-10L, or 0.6 to 1.2 km (2,000 to 4,000 ft) below the U-10L as an approximation in moderate instability environments;
b) A sharp reversal of probability from favoring "no CG" to favoring "CG" as the 40 dBZ echo reached the U-10L;
c) Minimal probability of F/N CG strikes (> 10 per 5-minute period) until the 40 dBZ echo height exceeded 1.2 km (4,000 ft) above the U-10L;
d) A sharp increase in F/N CG strike probability as the 40 dBZ echo exceeded 3.1 km (10,000 ft) above the U-10L;

e) Minimal probability of numerous CG strikes (> 20 per 5-minute period) until the 40 dBZ echo height reached 2.4 km (8,000 ft) above the U-10L;
f) A sharp increase in numerous CG strike probability as the 40 dBZ echo reached 4.6 km (15,000 ft) above the U-10L;
g) There were only a few cells in the study with no CG lightning detected when the 40 dBZ echo height exceeded 1.5 km (5,000 ft) above the U-10L.

Though not part of the initial focus of the study, a few other observations were noted in the course of the study's completion:

a) The "no CG strikes" probabilities, shown on Table 2, could be useful for anticipating CG lightning cessation. Further study is needed here, as this assumes the principles of water mass buildup in the mixed phase cloud region to initiate CG strikes also applies to water mass reduction leading to CG lightning cessation.
b) Although the focus of the study was the one to two radar-scan period prior to CG lightning and F/N strike occurrence, lead times were noted to range from none to 20 minutes, with an average of five to ten minutes, similar to prior studies referenced (e.g. Gremillion and Orville 1999).
c) A lag period, averaging one radar volume scan (5 minutes) was noted between the maximum CG lightning probability and the detection of CG lightning, as well as between the diminishing of CG lightning probability to zero and the cessation of CG lightning. Further study is needed to determine if the lag is due to physical reasons (charge development/separation) or technological reasons (data processing/delivery delay).

To build confidence in these results, two simulations were run, based on archived events, using the alert criteria described. Each simulation was attempted twice, first focusing on CG lightning onset, and then focusing on F/N CG strike onset. Several hours of data were included in each simulation. The first case was a multi-cell/supercell convective event in northern Florida and southern Georgia on March 22, 2005. NLDN data were not viewed when lightning alerts were made, based on the height of the 40 dBZ echo in relation to the U-10L (8,000 ft, 2.4 km, above the U-10L for F/N strike alerts). Alerts were verified using NLDN 5-minute CG lightning data. The results were as follows:

Alert	*CG*	*no CG*	*Total*	*POD*
CG Onset:	*43*	*1*	*44*	*97%*
F/N CG:	*16*	*0*	*16*	*100%*

Alert	*Verified*	*Unverified*	*Total*	*FAR*
CG Onset:	*12*	*58*	*70*	*17%*
F/N CG:	*21*	*16*	*37*	*57%*

Longer-lived storms supported average lead times near 16 minutes. Most of the CG lightning onset cases were alerted. All of the F/N CG cases were alerted, with a FAR of 57%. However, verifying F/N CG alerts with at least scattered CG strikes yielded a FAR of only 20%.

The second simulation was a pulse single-cell event in northern Florida on June 18, 2005. The results were as follows:

Alert	*CG*	*no CG*	*Total*	*POD*
CG Onset:	*21*	*3*	*24*	*88%*
F/N CG:	*11*	*1*	*12*	*92%*

Alert	*Verified*	*Unverified*	*Total*	*FAR*
CG Onset:	*27*	*1*	*28*	*4%*
F/N CG:	*9*	*4*	*13*	*31%*

Average lead times were just below 5 minutes, much shorter than the prior simulation given the shorter lifecycles of the thunderstorms in this case. Most of the CG onset cases were alerted, with a very low FAR. Most of the F/N CG cases were also alerted, with all alerts followed by at least scattered CG strikes.

These simulations were performed entirely without the benefit of real-time NLDN output, and with a limited number of archived radar elevation slices. Real-time lightning detection data, and automated scan-by-scan plots of 40 dBZ echo relative to a user-defined U-10L, would further improve CG lightning alert skill.

While the Jacksonville study focused on the southeastern United States, it is believed that the results would work in other areas of the country, and in various weather patterns. Future studies are encouraged to confirm this.

5. Discussion: Probabilistic CG Lightning Guidance and Alerts

The Jacksonville study confirmed prior studies in suggesting the utilization of WSR-88D reflectivity data to anticipate CG lightning initiation, cessation, and to some extent, frequency. The results show favorable scores when using the U-10L for anticipating CG lightning strikes. The study also suggested that better POD scores would be realized by utilizing the E-10L (approximately the U-6L) where ice may be introduced in a turbulent updraft, even though the resultant FAR may be slightly higher compared to using the U-10L. The results suggest that a 40 dBZ height at least 8,000 ft (2.4 km) above the U-10L (about 3.1-3.5 km, or 10,000-11,000 ft, above the E-10L) would be useful for anticipating the cells that will produce F/N CG strikes.

Failure of this technique was noted in the stratiform region of mesoscale convective systems, as well as in large convective anvils. 40 dBZ echo may not be present near the CG strike locations, but the advection of graupel into the MCS stratiform region, or thunderstorm anvil, suggested by upstream 40 dBZ cores, can lead to CG strikes. However, such charge advection may not be the dominant process (Rutledge and Petersen 1994, MacGorman and Rust 1998). Failure can also occur when utilizing a radar that is running slightly out of calibration, or when basing this concept on distant cells, for which few vertical reflectivity slices may be available.

Several potential sources of error may have impacted the results, including:

1) limited elevation slices archived for the events used in the study, and the potential error associated with interpolation between available slices;
2) uncertainty of environment changes in time and space that may have altered updraft –10°C heights; and
3) error associated with NLDN output. This study utilized CG lightning rather than other lightning observations (in-cloud, cloud-to-cloud, and cloud-to-air strikes). These other observations may be better predictors of the CG lightning threat.

The impact of these potential error sources on the study's results is not known. As a result, a probabilistic approach was taken with the results.

As illustrations of CG lightning predictability, Figs. 8 through 13 show consecutive radar volume scans for two cases in Georgia and northern Florida. CG lightning probabilities (F/N strike probabilities in parentheses, when above 10 percent) were assigned to many (but not all) of the storms on the display, based on the scale shown on Fig. 7. The images show increasing probabilities, occasionally followed by decreasing probabilities (recall the lag noted previously), just prior to CG lightning onset (small dashes represent NLDN CG strikes). A sharp decrease in CG lightning probabilities to zero suggested imminent cessation of CG lightning.

From the results, it is believed that a radar-based algorithm could be developed to produce real-time CG lightning (and F/N strike) probabilities, utilizing a user-input E-10L. The algorithm results could be incorporated into programs like the System for Convective Analysis and Nowcasting, or SCAN (Smith et al. 1998), and could be provided to customers through an internet webpage. Fig. 7 reflects a probability scale that could be used based on the probabilistic results of the Jacksonville study. Lead times could be extended slightly by providing rapid updates after each elevation scan is completed.

Probability guidance generated using this technique could be utilized for automated or human-developed CG lightning alerts, to fulfill the NWS mission. In particular, "electrical storm warnings" (Fig. 14) could be a product of the future for non-severe thunderstorms expected to produce F/N CG strikes that could cause damage and power outages. A continuously-updated web page with real-time CG strike, and F/N strike, probabilities (as illustrated on Fig. 15) could also prove useful to various customer segments.

Further technological advances (e.g. dual polarization radar) will serve to increase the accuracy and timeliness of CG lightning alert information in the future, perhaps to the extent to support deterministic lightning alerts rather than probabilistic guidance proposed from this study.

6. References

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7. Author

Peter Wolf received a B.S. degree in Meteorology from the Pennsylvania State University in 1990. He has been employed in the NWS since 1990, serving as an meteorological intern at NWS Richmond, Virginia, through 1993, a journeyman forecaster at NWS Tulsa, Oklahoma, through 1996, a senior forecaster at NWS Jackson, Mississippi, through early 1998, science and operations officer at NWS Wichita, Kansas, through the end of 2004, and science and operations officer at NWS Jacksonville, Florida, since the start of 2005.

Mr. Wolf has published several papers in NWA/AMS journals focused on severe weather threat recognition. He has received numerous awards for severe weather operations and forecaster training, including a Dept. of Commerce Bronze Medal in 2001, and more recently, a NOAA Administrator's Award in 2006 for work on the national polygon warning evaluation team.

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9. Tables

Table 1. Number of cases comparing CG lightning activity to the height of the 40 dBZ echo one or two radar scans prior to the observed CG lightning.

Item	No CG	Isold CG	Sctd CG	Freq CG	Nmrs CG
# of strikes/5min:	0	1-4	5-10	> 10	> 20
# of cells in study:	297	319	252	296	148
# of cases with 40 dBZ level:					
-10°C – 8+ kft	20	0	0	0	0
-10°C – 5 to 7 kft	67	2	2	0	0
-10°C – 2 to 4 kft	111	24	5	0	0
-10°C +/- 1 kft	72	104	25	0	0
-10°C + 2 to 4 kft	23	96	51	0	0
-10°C + 5 to 7 kft	1	53	76	12	0
-10°C + 8 to 10 kft	2	22	54	37	3
-10°C + 11 to 14 kft	1	14	27	39	16
-10°C + 15 to 18 kft	0	3	9	117	67
-10°C + 18+ kft	0	1	3	91	62

Table 2. Based on data from Table 1 above, probabilities of no CG lightning, any CG lightning, and frequent/numerous CG strikes, as related to the height of the 40 dBZ echo one or two radar scans prior to the observed CG lightning.

	No CG	CG	“Frequent” CG	“Numerous” CG
Probability with 40 dBZ to:				
-10°C – 8+ kft	100%	0%	0%	0%
-10°C – 5 to 7 kft	94%	6%	0%	0%
-10°C – 2 to 4 kft	79%	21%	0%	0%
-10°C +/- 1 kft	36%	64%	0%	0%
-10°C + 2 to 4 kft	14%	86%	0%	0%
-10°C + 5 to 7 kft	1%	99%	8%	0%
-10°C + 8 to 10 kft	2%	98%	32%	2%
-10°C + 11 to 14 kft	2%	98%	48%	20%
-10°C + 15 to 18 kft	0%	100%	91%	52%
-10°C + 18+ kft	0%	100%	96%	65%

10. Figures

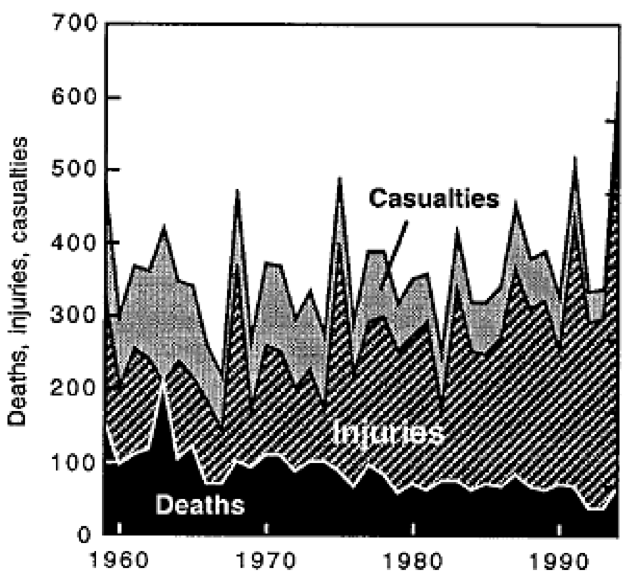

Fig. 1. Time series of US annual lightning-related deaths and injuries (Adapted from Curran et al., 2000).

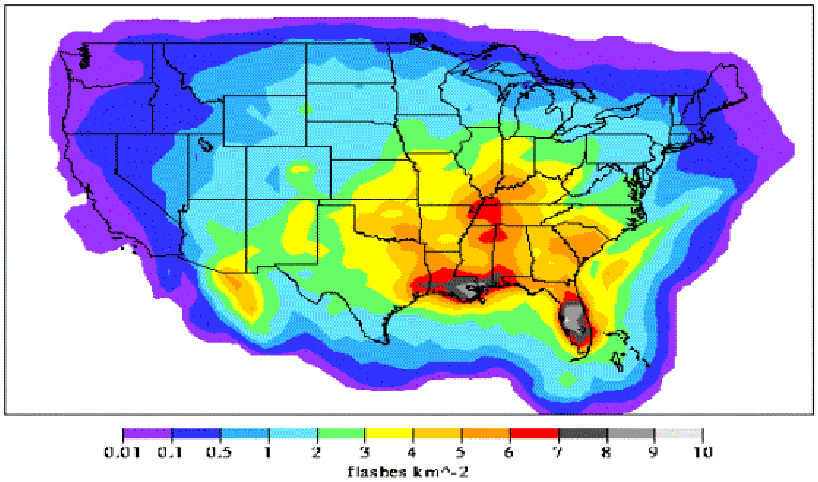

Fig. 2. Annual CG lightning density (flashes km^{-2}) across the contiguous United States (Adapted from Zajac et al., 2000).

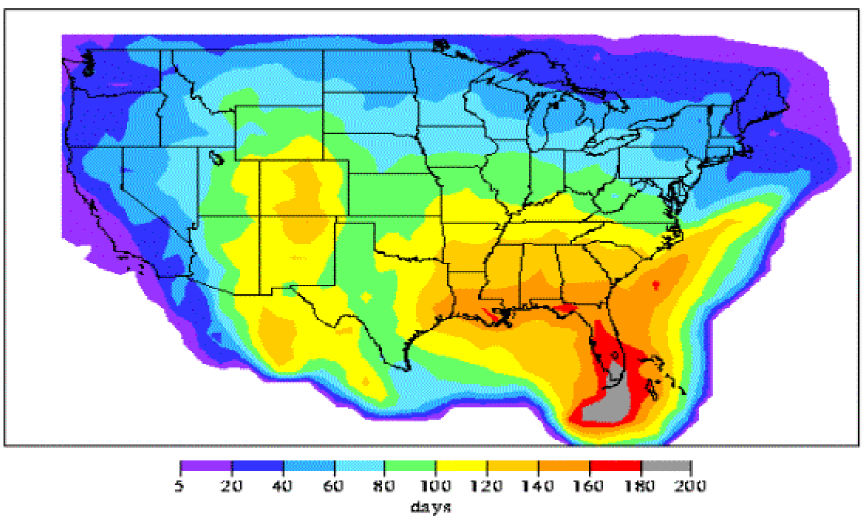

Fig. 3. Annual number of days per year with 1 or more CG lightning strikes (Adapted from Zajac et al., 2000).

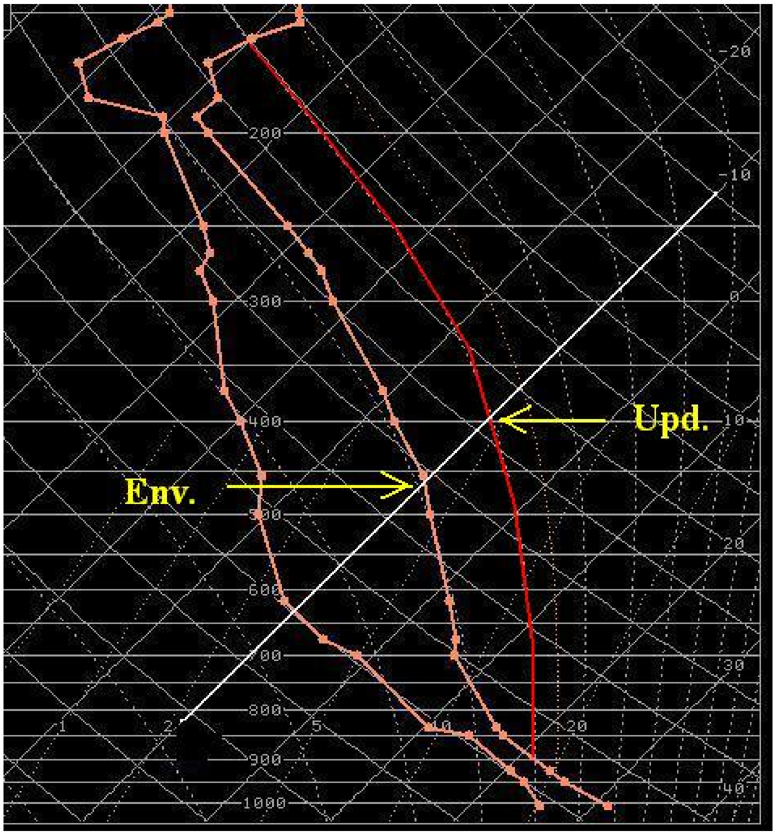

Fig. 4. Comparison of environment (Env.) -10°C level and the approximate -10°C level within a theoretical thunderstorm updraft (Upd.). The -10°C isotherm (white) and updraft parcel trace (red) are also displayed.

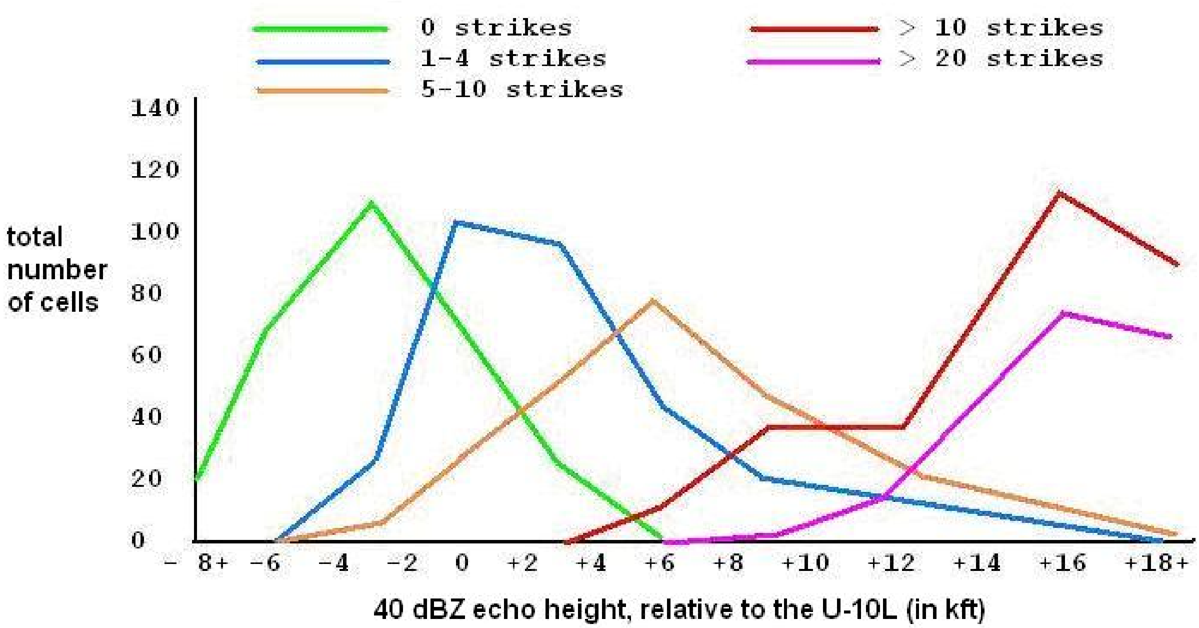

Fig. 5. NWS Jacksonville study results showing a relationship of CG lightning frequency to 40 dBZ echo height (relative to the U-10L),

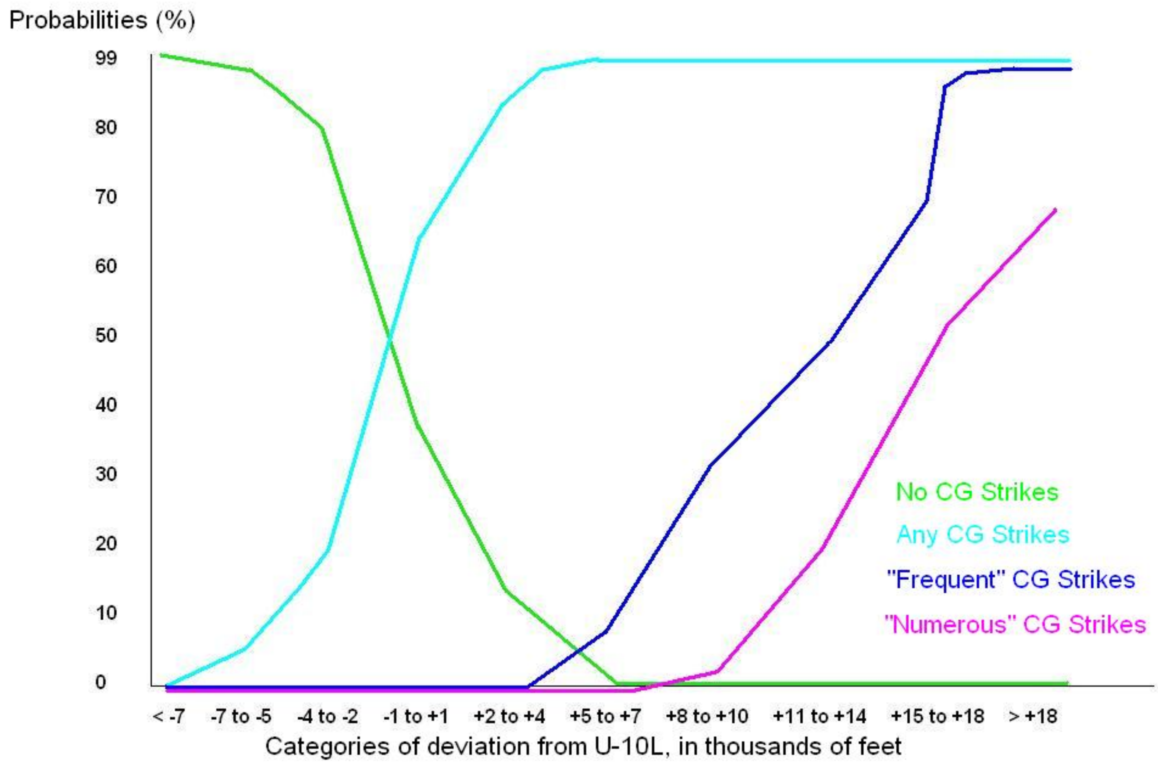

Fig. 6. NWS Jacksonville study results showing a relationship of CG lightning frequency probability to 40 dBZ echo height (relative to the U-10L).

PROBABILITIES USED IN EXAMPLES

40dBZ height relative to updraft -10C level	Prob of CG lightning (1+ per 5 min period)	Prob of numerous strikes (> 10 per 5 min period)
-8+ kft		
-7 kft	5%	
-6 kft	10%	
-5 kft	15%	
-4 kft	20%	
-3 kft	30%	
-2 kft	40%	
-1 kft	50%	
0 kft	60%	
+1 kft	70%	
+2 kft	75%	
+3 kft	80%	
+4 kft	85%	5%
+5 kft	90%	10%
+6 kft	95%	15%
+7 kft	95%	20%
+8 kft	95%	25%
+9 kft	95%	30%
+10 kft	99%	40%
+11 kft	99%	50%
+12 kft	99%	60%
+13 kft	99%	70%
+14 kft	99%	80%
> +14 kft	99%	90%

Fig. 7. Probabilities for CG lightning and F/N CG strikes, based on the U-10L height, used in case examples.

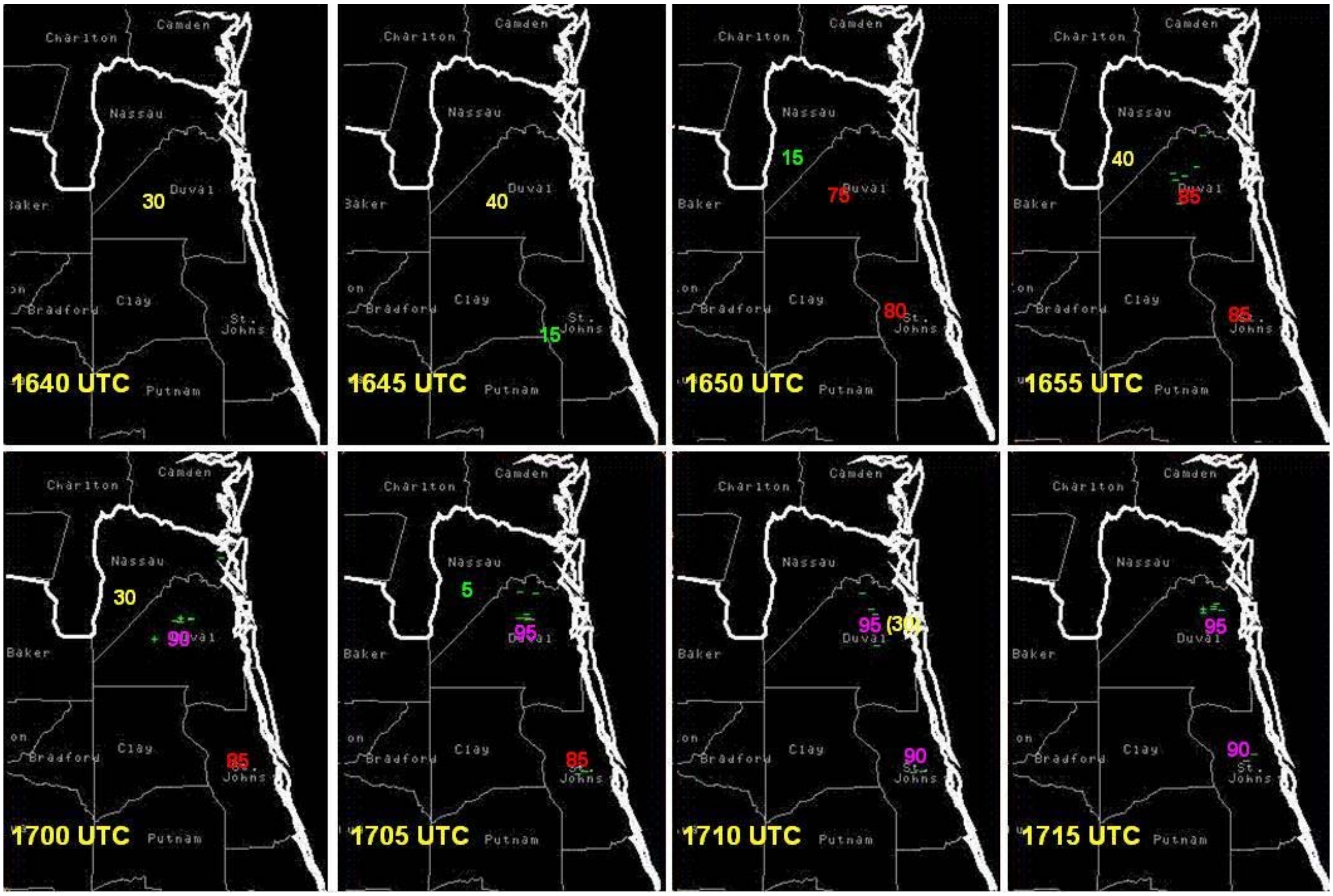

Fig. 8. Mosaic of consecutive 5-minute displays of cell-based CG lightning probability (F/N strike probabilities in parentheses when above 10 percent), from 1640-1715 UTC 22 Mar 2005, across northeast Florida. NDLN strikes are shown as small dashes on the images.

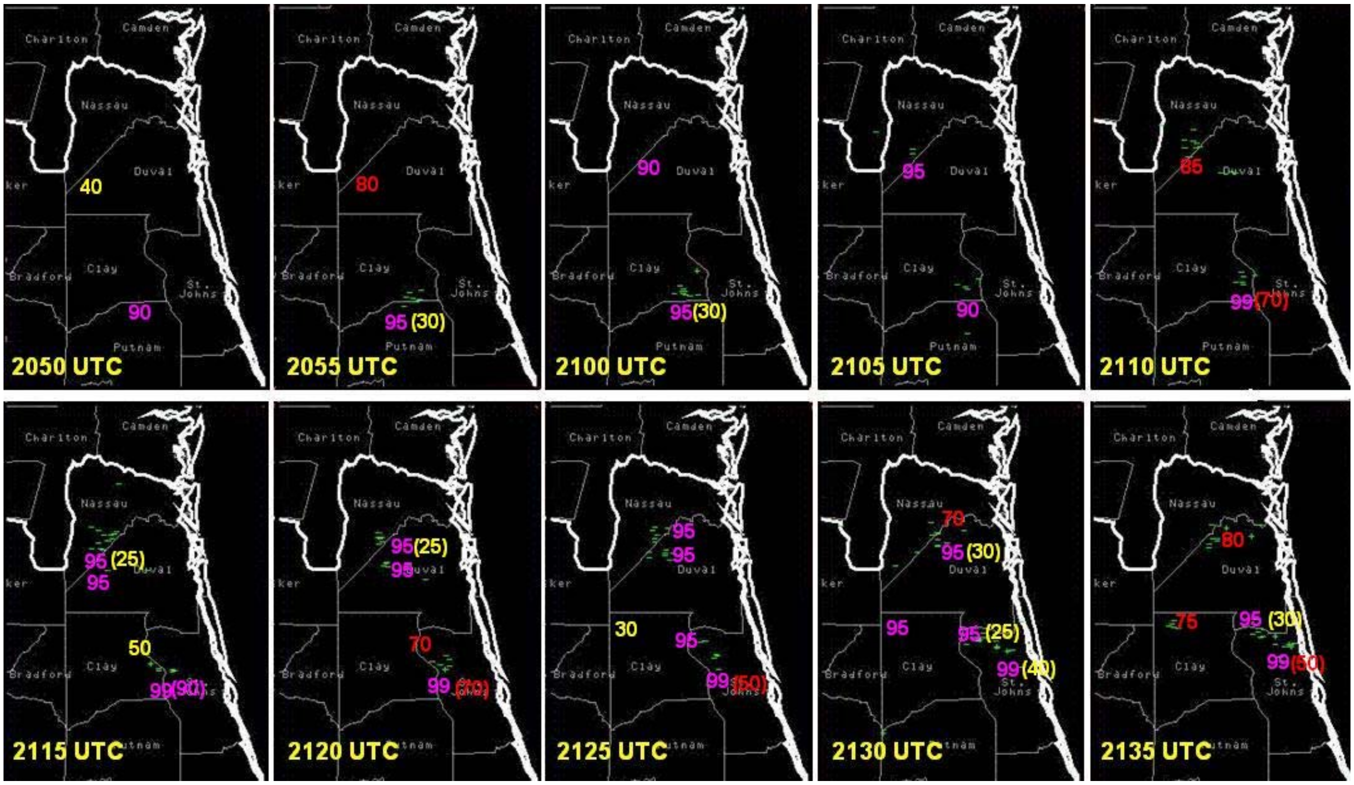

Fig. 9. The same as Fig. 8 except for 2050-2135 UTC 22 March 2005.

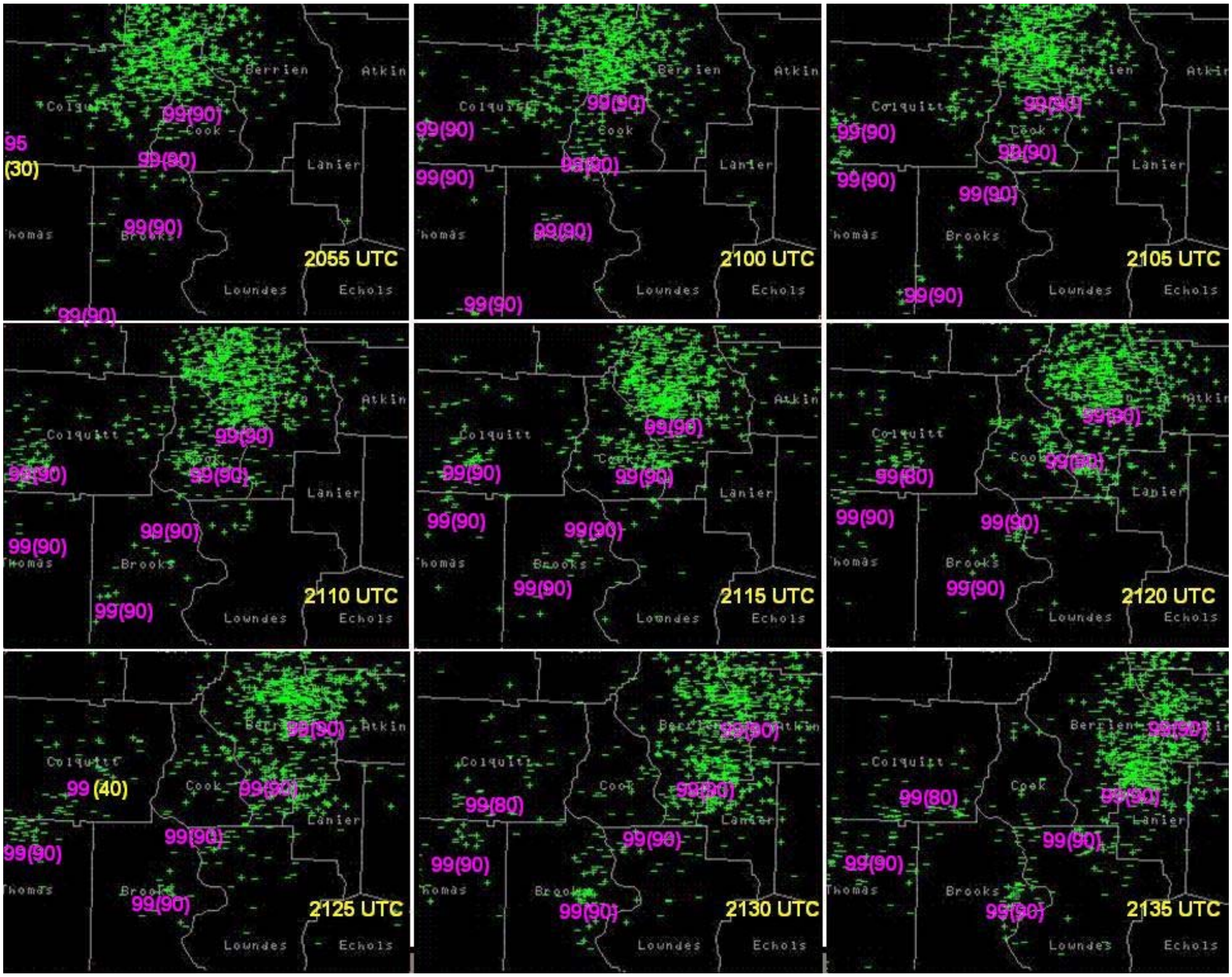

Fig. 10. The same as Fig. 8 except for 2055-2135 UTC 22 March 2005, across south-central Georgia.

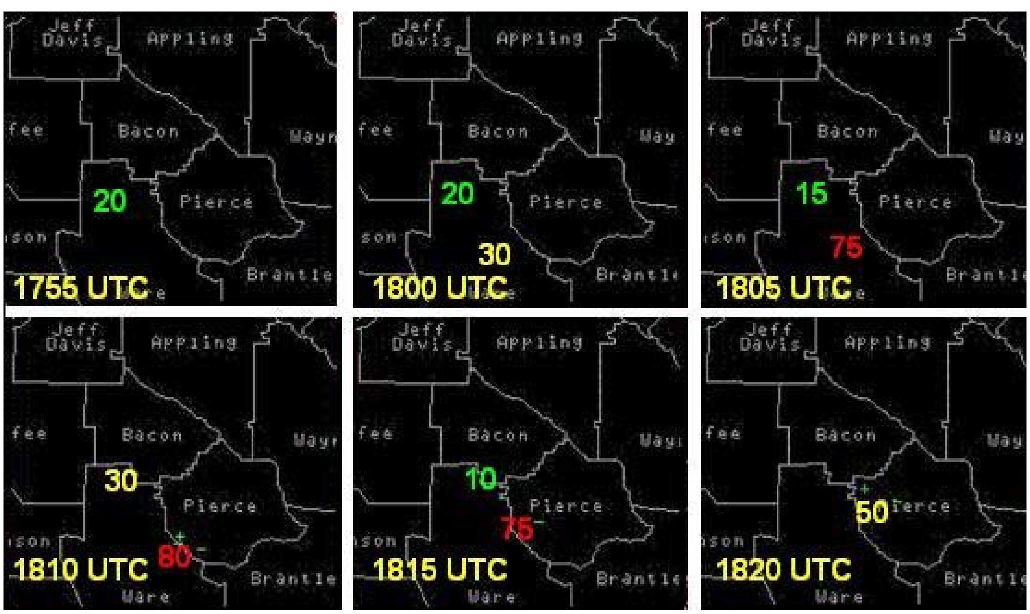

Fig. 11. The same as Fig. 8 except for 1755-1820 UTC 22 March 2005, across southeast Georgia.

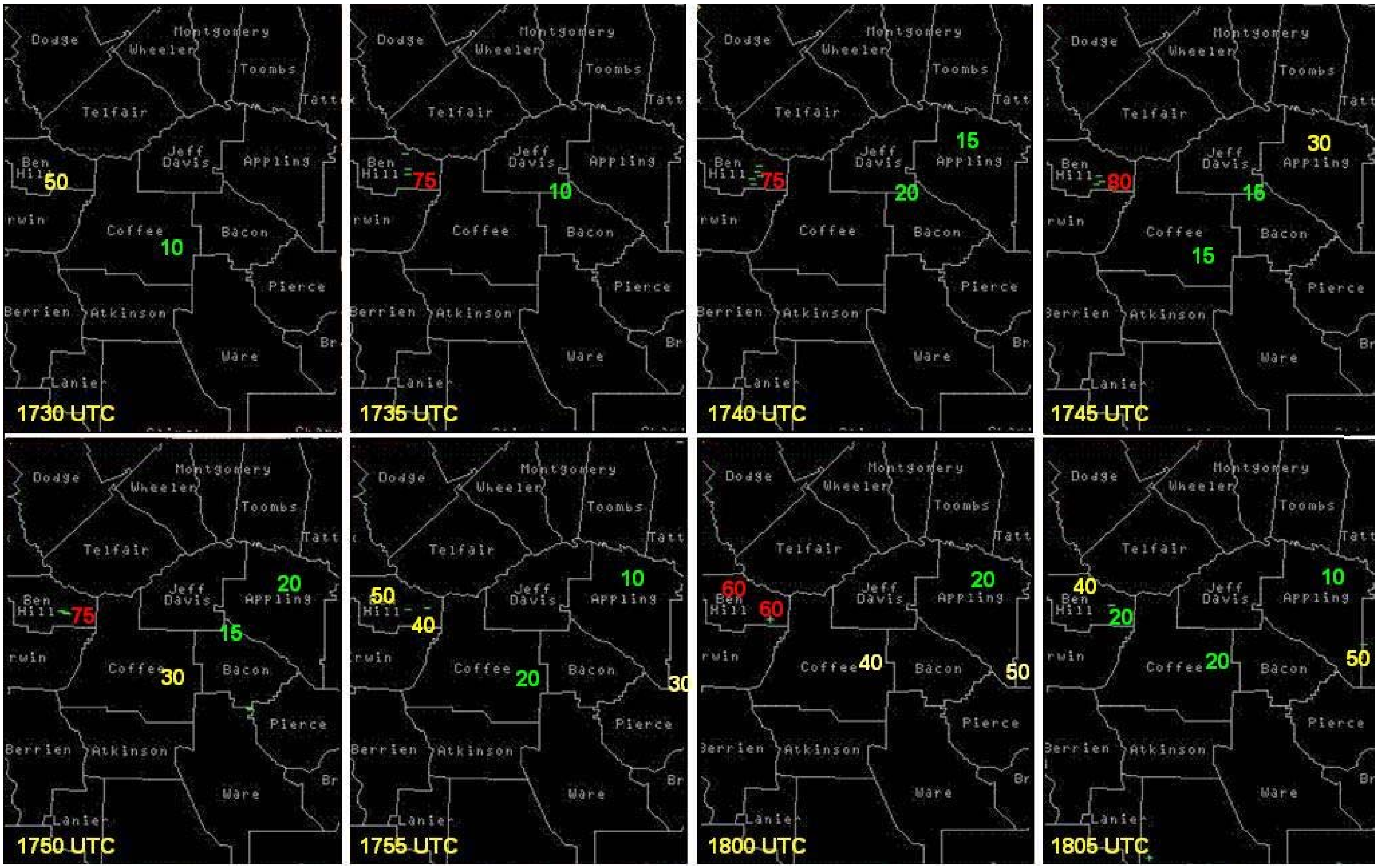

Fig. 12. The same as Fig. 8 except for 1730-1805 UTC 27 June 2005, across southeast Georgia.

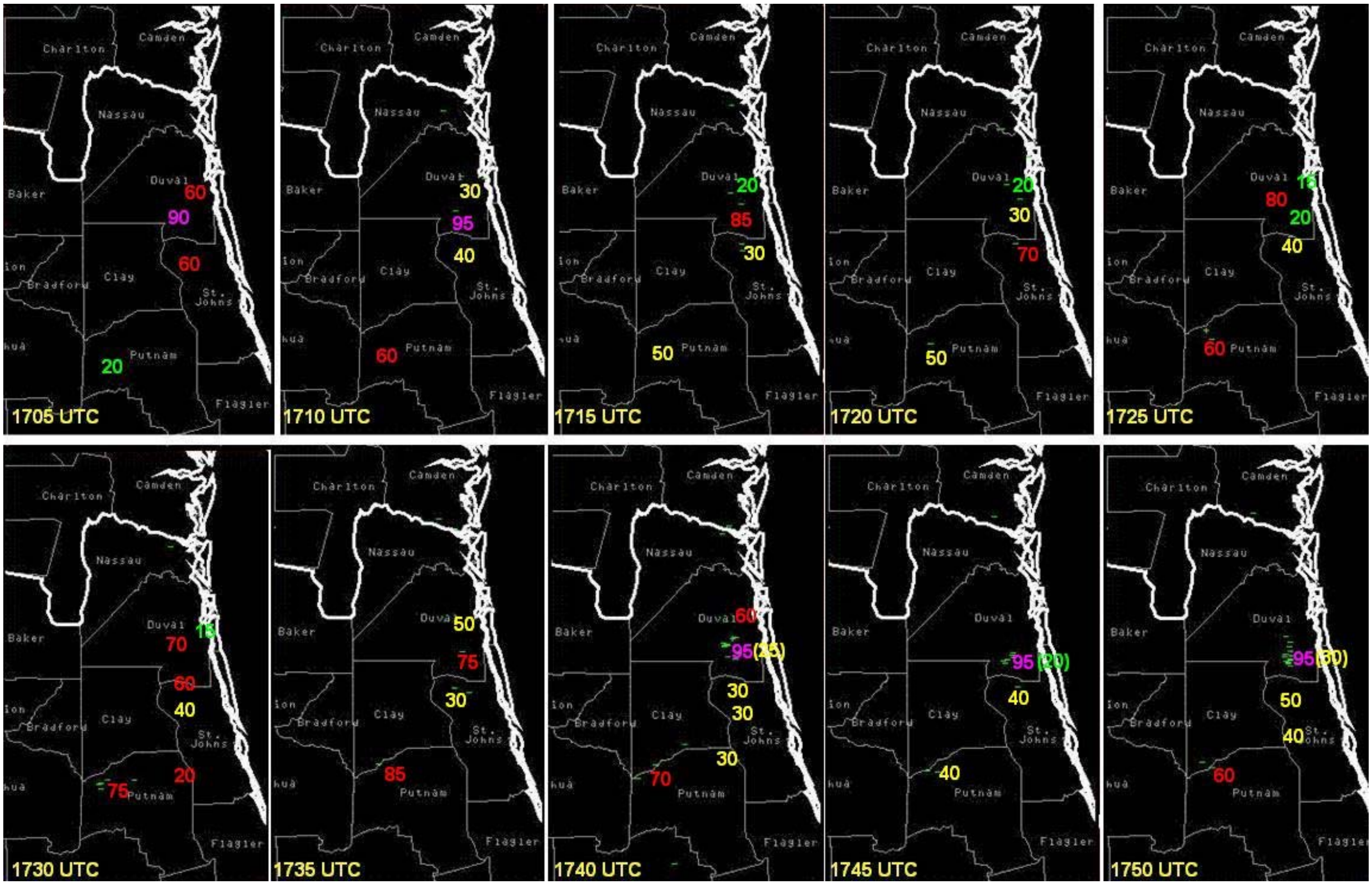

Fig. 13. The same as Fig. 8 except for 1705-1750 UTC, 27 June 2005, across northeast Florida.

ELECTRICAL STORM WARNING
NATIONAL WEATHER SERVICE, JACKSONVILLE, FLORIDA
500 PM EDT MON JUL 10 2006

THE NATIONAL WEATHER SERVICE HAS ISSUED AN ELECTICAL STORM WARNING EFFECTIVE UNTIL 600 PM EDT FOR...

CENTRAL DUVAL COUNTY
INCLUDING THE CITY OF JACKSONVILLE

NUMEROUS CLOUD-TO-GROUND STRIKES ARE EXPECTED FROM THUNDERSTORMS IN THE WARNED AREA. ELECTRICAL STORMS CAN CAUSE DAMAGE TO PROPERTY, INCLUDING ELECTRICAL EQUIPMENT, AND CAN CAUSE POWER OUTAGES. SEEK SHELTER UNTIL THE THUNDERSTORMS MOVE OUT OF YOUR AREA.

Fig. 14. Theoretical example of an "Electrical Storm Warning" product for storms expected to produce CG lightning at a rate greater than 10 strikes per five-minute period.

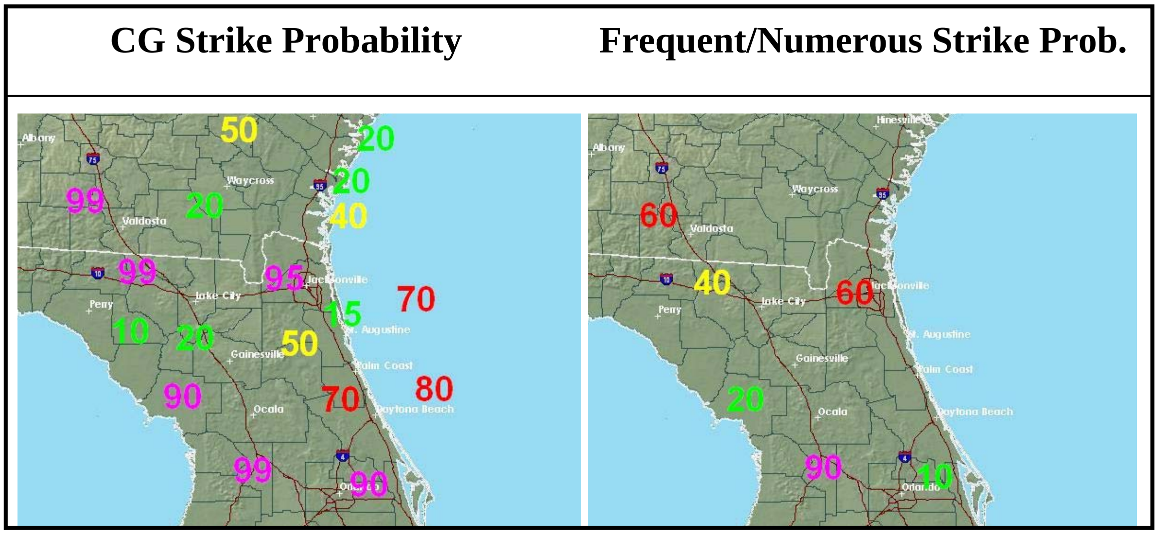

Fig. 15. Theoretical example of a web page image with color-coded real-time 15- or 30-minute CG lightning and F/N CG strike probabilities.