P4.16 LIGHTNING WATCH AND WARNING SUPPORT TO SPACELIFT OPERATIONS

Johnny W. Weems*, Clark S. Pinder, William P. Roeder, and Billie F. Boyd
45 Weather Squadron
Patrick AFB, FL 32925

1. INTRODUCTION

Environmental considerations are important for planning future spaceflight operations and/or new space launch vehicles. The most important environmental issue for the Cape Canaveral Air Force Station (CCAFS) and Kennedy Space Center (KSC) is estimating the impact of lightning. Lightning impacts are reviewed through three different methods: (1) climatology, (2) lightning detection, and (3) lightning advisories. Impacts of changes in weather support procedures on advisory performance are presented. Implications of advisory performance on forecasting, and opportunities for future improvements are also discussed.

2. BACKGROUND

Lightning has the greatest weather impact on day-to-day spacelift operations at CCAFS and KSC, particularly during the convective season from May through September. Other weather hazards are easier to identify, forecast, and mitigate. Lightning can strike from clouds several miles away, inducing damaging currents even when striking the ground or other structures tens of yards away, and is a definite death and injury threat. In one extreme case of long distance lightning, on May 18, 1998, a cloud-to-ground (CG) strike occurred 104km from the parent thunderstorm. This same event also had in-cloud lightning (IC) extending 141km through anvil clouds.

Continuous lightning surveillance is critical to personnel safety, resource protection, and system analysis. The 45th Weather Squadron (45 WS) provides watch and warning services for lightning within 5nm (9.26km) of 13 points of operational interest on CCAFS/KSC, Patrick AFB, and two nearby sites (Figure 1). A watch (Phase-1) is issued when lightning is expected within 5nm (9.26km) of any of the 13 points with a desired lead-time of 30 minutes. A warning (Phase-2) is issued when lightning is imminent or occurring within 5nm (9.26km) of any of the points. The 5nm (9.26km) "safety buffer" is based on the observed distribution of lightning strike distances (Roeder, 1995), (Cox, 1999). Since CG lightning frequently occurs so quickly after initiation of lightning aloft, it is extremely difficult to forecast the initial CG strike with sufficient lead-time. Therefore, watches and warnings are issued for all types of lightning, whether IC or CG.

*Corresponding author address: Johnny Weems, 45 WS/DOR, 1201 Edward H. White II St, MS 7302, Patrick AFB, FL 32925-3238; e-mail: johnny.weems@patrick.af.mil
web site: www.patrick.af.mil/45og/45ws/ws1.htm

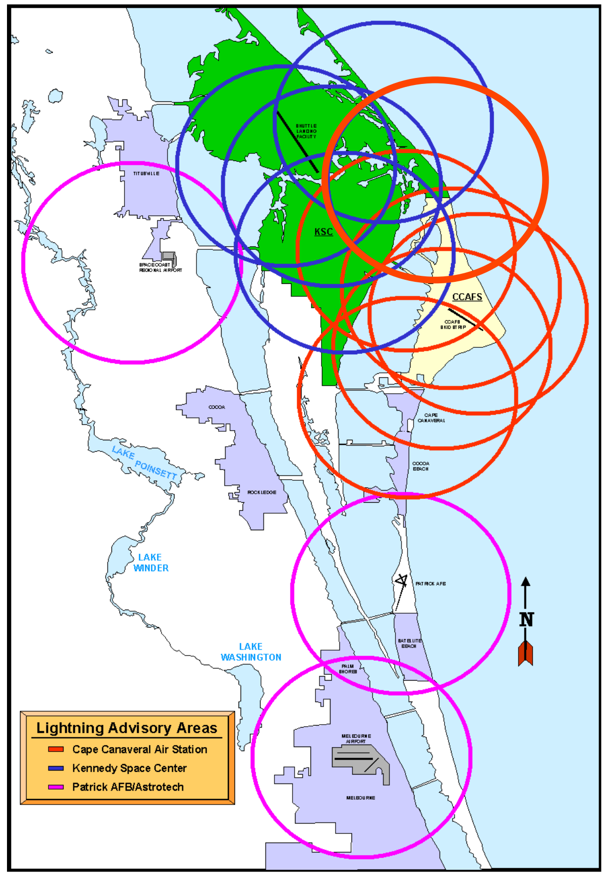

Figure 1. 45 WS Lightning Watch/Warning locations (5nm (9.26km) radii circles)

An extensive suite of lightning detection systems at CCAFS/KSC is used to aid in lightning forecasting and to accurately locate strikes in order to evaluate the impact of nearby lightning on mission critical electronics (Harms, et al., 1997). This article will analyze data only from the Cloud-to-Ground Lightning Surveillance System (CGLSS), one of four lightning detection and locating systems used by the 45 WS. The CGLSS consists of an array of six remote sensors located around the local area (Figure 2). They are the Improved Accuracy Through Combined Technology (IMPACT) sensors, which use both magnetic direction finding (MDF) and time of arrival (TOA) techniques for enhanced performance (Cummins, et al., 1998). The sensors are positioned to obtain excellent detection efficiency and location accuracy over the CCAFS/KSC Complex. The CGLSS is extremely well maintained, which contributes to excellent system performance. The CCAFS/KSC Complex also has a wealth of CG lightning ground truth, via routine videotape triangulation and launch pad strike detectors, with which to calibrate CGLSS and maximize performance. Current detection efficiency is near 98% with a locating accuracy of 250m (Roeder, et al.,2000).

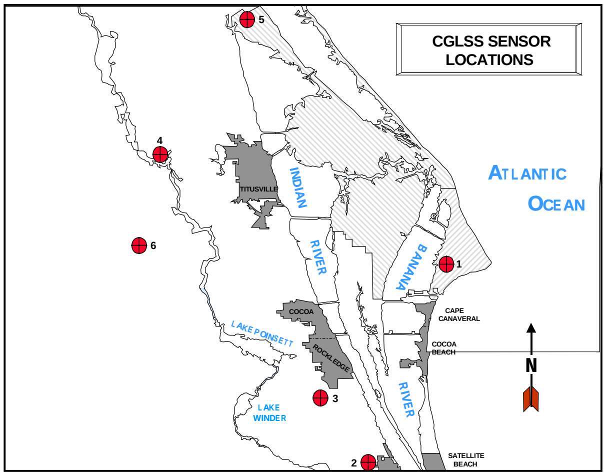

Figure 2. Location of CGLSS sensors

3. LIGHTNING IMPACT ANALYSIS

Several methods have been used over the years to assess the impact of lightning on operations. Those methods are, in order of increasing quality: climatology, lightning watches and warnings, and most recently, lightning flash density. These estimates of lightning impacts have been a vital component in planning spaceflight operations and future space launch vehicles.

3.1 *Thunderstorm-Day Climatology*

In the past, the data normally provided to estimate the lightning impact was the average number of thunderstorm-days obtained from climatic records from the Shuttle Landing Facility (KTTS) located on KSC or the Cape Canaveral Weather Station (KXMR). Records from KXMR were recorded from 1953 through 1978; records from KTTS were recorded from Mar 1979 through current. A thunderstorm-day is defined as occurring when thunder is heard and recorded by the observer, regardless of its proximity to the observation site. The cloud producing thunder could be several miles distant. Indeed, thunder can usually be heard up to 16 km from the thunderstorm, covering an area nearly four times as large as the 5nm (9.26km) warning area. One example of distant thunder in the CCAFS/KSC area is early morning storms that are semi-stationary more than 5nm (9.26km) off the coast. Thunderstorm-day climatology provides extreme over-estimate of lightning impact and work-time lost. Not only can thunderstorms outside of 5nm (9.26km) be erroneously counted, but a single lightning flash counts as an entire thunderstorm day. The chance of lightning occurring through the entire 24-hour period is exceedingly remote. Another source of over-estimation by thunderstorm-day climatology is poor horizontal resolution. Thunder from local lightning “hot spots” can be heard by observers outside local areas of concern. The CCAFS/KSC area has significant local structure in lightning activity, as shown in Section 3.3.

3.2 *Lightning Advisories*

A more accurate approach for estimating lightning impacts is the average number of days lightning actually occurred within 5nm (9.26km) of the location versus the average thunderstorm-day climatology (Table 1). Table 1 shows the distinct difference in the average number of days thunder was recorded at KTTS and KXMR versus the number of days lightning occurred within 5nm (9.26km) of Complex 40/41. Over the past few years, a more realistic estimate given to the requestor has been the number of hours during which the location was covered by a lightning advisory. Though better than thunderstorm-day climatology, this approach is still an overestimate of lightning impact because of false alarms and the inability to accurately predict when the threat ends.

TABLE 1. AVERAGE DAYS WITH LIGHTNING

Month	TTS	XMR	Obsvd w/i 5nm (9.26km) of CX 40/41 (94-98)
Jan	1	1	1
Feb	2	1	1
Mar	3	3	3
Apr	4	3	2
May	7	8	3
Jun	14	13	8
Jul	17	16	9
Aug	16	15	8
Sep	10	10	9
Oct	4	4	1
Nov	2	1	1
Dec	1	1	1
Ann	**81**	**76**	**47**

A two-tiered approach to lightning advisories and warnings supporting Kennedy Space Center was implemented in 1990 (Wicklund and Youngren, 1993) and followed by implementation for operations on Cape Canaveral Air Force Station in 1995. The Range Weather Forecaster issues the initial Phase-I lightning watch with a desired lead-time of 30 minutes when potential for lightning is expected to move into, or develop within 5nm (9.26km) of specified work areas. This advisory is upgraded to a Phase-II lightning warning when lightning is considered imminent or actually occurring within the aforementioned 5nm (9.26km) work area. The advisory is for all types of lightning. In 1997, the Air Force Weather Agency implemented a two-tiered lightning watch/warning process throughout the USAF, based on the 45 WS system.

Ground operations are typically curtailed when a Phase-1 watch is issued. General guidelines used by the Safety Office in the Titan Integrate, Transfer, and Launch (ITL) area follow: (1) work in progress can continue when a Phase-1 watch is issued, (2) work must be stopped and crews go to shelter when a Phase-2 lightning warning is issued, and (3) no new task(s) can be started while a Phase-I watch is in effect. Table 2 represents the average number of hours Phase-1 and Phase-2 lightning watches and warnings were in effect for Complex 40/41 during the period 1995 through 1999.

Historically, there have been costly delays due to lightning induced damage. Using CGLSS data, the strike point, time, azimuth, range, and normalized peak strength of strikes within 5nm (9.26km) of Launch complex 40/41 are provided daily to systems personnel to assist in assessment of potential damage to critical spacecraft and booster components. The extent of the system search for possible damage is a function of distance and peak current. These searches may or may not result in discovery of damage. The most conservative criterion used to identify potential damage is any lightning strike detected within 1.25nm (2.32km), regardless of observed peak current. From Jan 90 – Oct 95, forty-eight (6%) of the total CG strikes detected within 5nm (9.26km) of Complex 40/41 met this criterion for potentially damaging lightning (Chai, et al., 1996). Improvements in system accuracy and detection efficiency have potential for large cost savings and have been the primary reason for CGLSS upgrades.

If forecasters could predict CG lightning perfectly, the work hours lost due to needless advisories would be significantly reduced. Analysis of CG lightning strikes within 5nm (9.26km) of Complex 40/41 indicates potential for up to a 75% reduction in lost time. Further analysis of advisories shows the largest problem resides in termination of advisories. Knowing when the lightning advisories may be safely cancelled is one of the greatest challenges facing the 45 WS. With current skill, the forecasters must necessarily be conservative in canceling advisories, in the interest of personnel safety. Residual charge in thunderstorm debris clouds makes it difficult to disregard concern for CG strokes. Lightning strikes, well over 1 hour after the previous strike, have been observed. The common occurrence of CG strikes from debris clouds trends toward conservatism. Long distance lightning from anvil clouds is another forecast challenge. CG strikes have occurred in the local area initiated from cumulonimbus clouds tens of kilometers distant traveling through inter-connected highly charged anvil clouds. Single strike events, usually strong amplitude positive polarity, with more than thirty minutes between strikes, are common during the end of storm period. Intra-Cloud (IC) lightning is usually a pre-cursor for the initial CG stroke, thus Phase 2 will be issued prior to the first CG strike. False alarms (issuance of an advisory when the phenomena did not occur) are of a lesser problem. Table 3 indicates duration of CG strike events within 5nm (9.26km) of CX 40/41 as detected by CGLSS from 1993 through 1998. An event is defined as a time period when CG lightning occurs within 5nm (9.26km) of Complex 40/41 with less than 30 minutes between strikes.

TABLE 2. AVERAGE TIME PHASE I/ PHASEII WATCH/WARNINGS IN EFFECT FOR CX 40/41 (POR: 95 – 99)

Mon	Phase 1 (Hrs:Min)	Phase 2 (Hrs:Min)	Duration of CG Events 1995-98
Jan	13:12	3:19	00:35
Feb	16:43	5:34	01:43
Mar	22:47	9:29	02:21
Apr	13:19	4:03	00:37
May	34:50	13:13	01:50
Jun	57:01	23:28	06:46
Jul	67:00	21:52	05:35
Aug	76:29	25:59	07:17
Sep	59:04	17:11	06:30
Oct	17:11	3:44	00:25
Nov	6:14	1:14	00:08
Dec	12:44	2:04	00:05
Ann	400:52	131:15	33:56

TABLE 3. DURATION OF CG-STRIKE EVENTS

Year	≤30 Minutes	31 – 60 Minutes	>1 Hour	Single Strike Event
1993	36	11	7	22
1994	58	18	9	26
1995	48	17	8	22
1996	38	14	15	17
1997	56	19	9	30
1998	43	15	9	20
Total	279	94	57	137
%	64.9%	21.9%	13.3%	31.9%

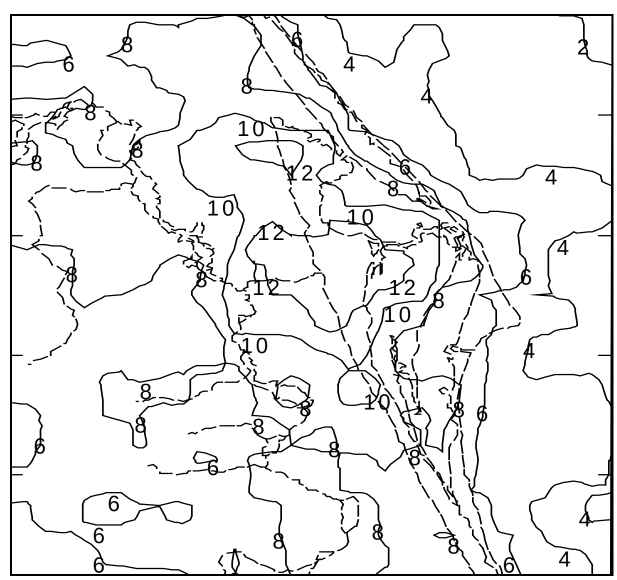

Figure 3. Mean Annual Number of Cloud to Ground Strikes per km^2 (1990-1994)

3.3 Lightning Flash Density

The number of cloud-to-ground strikes per year shows a wide variation within the CCAFS/KSC complex. For the five-year period 1990-1994, the annual average ranged from 5 to 13 flashes per km^2 as recorded by the CGLSS (Figure 3).

4. FORECAST IMPROVEMENT EFFORTS

Changes in instrumentation or implementation of new equipment and/or procedures over the past 12 years had significant impact on the 45 WS lightning advisory program. In 1989, a trained individual dedicated for radar and lightning support was assigned. The individual only advised the Duty Forecaster who issued the advisory. The Phase-1/Phase2 lightning watch and warning program was implemented for the KSC in 1991. CGLSS was upgraded in the early 90's, eliminating numerous false strike errors. In 1993, the individual dedicated to radar and lightning support was assigned the responsibility for issuance of watches, warnings, and advisories. He worked 5 days/week during the convective season from 1000L through the end of convection. The Lightning Detection and Range (LDAR) as described by Harms et al., (1998) was installed in the Range Weather Operations in 1996. CGLSS was upgraded again in 1998, with the addition of a sixth sensor, which greatly improved accuracy and detection efficiency.

The dedication of an individual solely for radar and lightning duties, known as the Thunderstorm Coordinator, and implementation of the Lightning Detection and Range (LDAR) system probably had the greatest effects on issuance of lightning advisories and warnings. The Lightning Detection and Ranging (LDAR) system consists of a network of seven receiver sites. It detects all types of lightning, including inter-cloud, intra-cloud, cloud-to-air, and cloud-to-ground lightning. LDAR was developed, and is operated and maintained, by KSC. The ability to detect and graphically display in-cloud lightning affected both issuance and termination of advisories – the forecaster could see the in-cloud lightning before a CG strike and the lingering electrical activity in the debris after the decay of the active storm. Studies indicate an average of a 4-minute delay between lightning aloft and the initial occurrence of CG lightning. But 28% of time, there is less than one minute between lightning aloft and the initial CG stroke, the reporting time interval of LDAR. See Table 4 for comparison of the CGLSS and LDAR capabilities and characteristics.

Even with the large suite of lightning detection systems, the foremost lightning forecast tool at 45 WS is radar. The 45 WS uses two weather radars: a 5-cm modified WSR-74C, with an Integrated Radar Information System (IRIS) volumetric-scan post-processor; and a 10-cm WSR-88D located at NWS/Melbourne (Boyd, et al., 1999). The WSR-74C/IRIS has been modified to provide volume scans every 2.5-min, and can be configured to provide customized 'user configured' products such as VIL-Above-0°C (Roeder and Pinder, 1998). Follow-on operational research indicates that two simultaneous thresholds of layered VIL between –10°C to –15°C and –15°C to –20°C should provide even better skill forecasting the onset of lightning (D'Arcangelo, 2000).

The Thunderstorm Coordinator developed a set of rules for forecasting the initiation and ending of lightning based on radar reflectivity intensity and depth versus key temperature levels. These became known as the "Pinder Principles" (Roeder and Pinder, 1998). These rules have been refined and made available for use by all 45 WS forecasters.

The latest upgrade of the CGLSS in 1998, addition of a sixth sensor and implementation of TOA algorithms, resulted in improvement of detection efficiency to 98% and location accuracy to 250m versus the previous cited 92% and 500m (Roeder, et al, 2000).

TABLE 4. COMPARISON OF CGLSS AND LDAR

	LDAR	**CGLSS**
Sensor Type	VHF/TOA	MDF/TOA
Number Of Sensors	7	6
Sensor Spacing	6 - 10 km	20 km
Effective Range	100 km	100 km
Lightning Detected	All	Cloud-to-ground
Flash Detection Efficiency	≈ 100%	98%
Lightning Process Located	VHF radiation	Return stroke, ground strike point
Locating Accuracy	100 m	0.25 km
Locations Per Flash	10 – 1000	1-5
Peak Location Rate	10,000 s^{-1}	74 min^{-1}
Display	Stand-alone	Stand-alone & MIDDS
Source	NASA developed	Commercial product

5. SUMMARY

Lightning is one of the most important environmental considerations for planning space launch operations as well as posing a threat to life and property. Data from an extensive lightning detection equipment network is used to aid forecasting and to provide a baseline for assessing lightning induced damage. Three methods to evaluate lightning impacts were presented, which are, in order of increasing quality: thunderstorm-day climatology, lightning advisory duration, and lightning detection. Results vary considerably between these methods. Changes in forecast procedures, either through new or upgraded lightning sensors or new procedures, have improved 45 WS lightning forecast performance over the past several years. Continued improvements in lightning forecasting are still needed. Analyses of lightning advisories show that improved forecasting of lightning cessation would be especially beneficial.

6. REFERENCES

Boyd, B. F., D. E. Harms, M. S. Gremillion, and M. E. Fitzpatrick, 1999: Weather Radar Improvements For Space Launch Support *Preprints, 29th International Conference On Radar Meteorology*, 12-16 Jul 99, Montreal, Quebec, Canada, 856-859.

Chai, J. C., J. I. Montegut, and S. Derusssy, 1996: Survey of 1990-95 CGLSS Data and the Retest Criteria, Proc. of IEEE 1997 International Symp. on Electromagnetic Compatibility (Austin, TX, Aug. 18-22, 1997), 391-396.

Cox, C. C., 1999: A Comparison Of Horizontal Cloud-To-Ground Lightning Flash Distance Using Weather Surveillance Radar And The Distance Between Successive Flash Method, M.S. thesis, Air Force Institute of Technology, AFIT/GM/ENP/99M-03, pp 130.

Cummins, K. L., M. J. Murphy, E. A. Bardo, W. L. Hiscox, R. B. Pyle, and A. E. Pifer, 1998: A Combined TOA/MDF Technology Upgrade Of The U.S. National Lightning Detection Network, *Journal Of Geophysical Research*, 103, 9035-9044.

D'Arcangelo, D. L., 2000: Forecasting The Onset of Cloud-Ground Lightning Using Layered Vertically Integrated Liquid Water, M.S. thesis, Pennsylvania State University, Aug 00, pp 60.

Harms, D. E., B. F. Boyd, R. M. Lucci, and M. W. Maier, 1998: Weather Systems Modernization To Support The Space Launch Program At The Eastern Range And Kennedy Space Center. *Preprints 10th Symposium On Meteorological Observations And Instrumentation*, Phoenix, AZ, 11-16 Jan 98, 317-322.

Harms, D. E., B. F. Boyd, R. M. Lucci, M. S. Hinson, and M. W. Maier, 1997: Systems used to evaluate the natural and triggered lightning threat to the Eastern Range and Kennedy Space Center, *Preprints 28th Conference On Radar Meteorology*, Austin, TX, 7-12 Sep 97, Amer. Meteor. Soc., 240-241.

Roeder, W. P., J. T. Madura, and D. E. Harms, 2000: Lightning Safety For Personnel At Cape Canaveral Air Force Station And Kennedy Space Center, *Joint Army Navy NASA Air Force/Safety & Environmental Protection Symposium*,8-12 May 00, Cocoa Beach, FL, CPIA Pub 698, 59-70.

Roeder, W. P. and C. S. Pinder, 1998: Lightning Forecasting Techniques for Central Florida in Support of America's Space Program, *Preprints 16th Conference On WeatherAnalysis And Forecasting*, Phoenix, AZ, 475-477.

Roeder, W. P., 1995: Bullet Background Paper On Lightning Hazards Within 5 NM, 45 WS internal document, 26 Sep 95, pp 2.

Wicklund, G. and G. Youngern, 1993: Operational Impact and Economic Savings of a Two-Phase Lightning Warning System for the John F. Kennedy Space Center and Cape Canaveral Air Station, *Preprints 13th Conference On Weather Analysis And Forecasting Including Symposium On Flash Floods*, Vienna, VA, 2-6 Aug 93, 92-95.