

A New Lightning Climatology for Cape Canaveral Air Force Station and NASA Kennedy Space Center

William P. Roeder
45th Weather Squadron
Patrick AFB, FL

1. Introduction

The 45th Weather Squadron (45 WS) is the U.S. Air Force unit that provides weather support to America's space program at Cape Canaveral Air Force Station (CCAFS) and National Aeronautics and Space Administration (NASA) Kennedy Space Center (KSC). The weather requirements of the space program are very stringent (Harms et al., 1999). In addition, the weather in east central Florida is very complex. This is especially true of summer thunderstorms and associated hazards. Central Florida is 'Lightning Alley', the area of highest lightning activity in the U.S. (Holle et al., 2016). The 45 WS uses a dense network of various weather sensors to meet the operational requirements in this environment (Roeder et al., 2003).

A new lightning climatology was developed for CCAFS/KSC. The purpose is to update the previous lightning climatology to improve lightning risk assessment. In particular, a method was developed to infer a new parameter, the density of lightning ground contact points, which is more useful than other parameters in risk assessment. These climatologies were built by the 14th Weather Squadron, the Air Force climatology center at the request of 45 WS.

Mention of any commercial product or vendor does not represent endorsement by the government.

2. The New Lightning Climatology for CCAFS/KSC

The new lightning climatology for CCAFS/KSC are a set of six maps: 1) cloud-to-ground (CG) flash density, 2) CG stroke density, 3) CG ground contact density, 4) CG multiplicity, 5) CG mean peak current, 6) CG frequency negative polarity, 7) CG frequency positive polarity, and 8) total lightning flash

density (both lightning aloft and CG lightning). These maps are in Figure-1 through Figure-8, respectively.

The CG lightning climatology is useful for risk assessment of personnel safety and key facilities such as launch pads. The data source was the National Lightning Detection Network (NLDN) (Cummins and Murphy, 2009) (Cummins et al., 1998). The period of record was 17-years (1997-2013). This period was chosen to provide a large enough sample size for reliable results and since the performance of NLDN has been relatively stable after a major upgrade in 1996 (Cummins et al., 2006). There were also continual incremental improvements from 1997 onward. Another large improvement to NLDN was completed in 2013 (Nag et al., 2016) but that would have provided only three years of observations, which would be inadequate for a lightning climatology. Including the data from 2014 and 2015 was desired but excluded since the lightning flash data at 14th Weather Squadron for those years were contaminated with stroke data.

The total lightning climatology is useful for assessing the risk of lightning affecting ground operations at CCAFS/KSC since the 45 WS lightning warnings are issued for any lightning including lightning aloft. The total lightning climatology is also useful for risk assessment to aviation and space launch, although the risk of rocket triggered lightning is not included, which can be more frequent than the risk of natural lightning (McNamara et al., 2010). The data source was the Earth Networks Total Lightning Network (ENTLN) (Heckman, 2013). The period of record was 6-years (2000-2015). A longer period is desired for a climatology, but this is all the ENTLN data available at 14th Weather Squadron since the Air Force only began use of ENTLN data in 2010.

All the lightning climatologies are displayed on maps with 1 km x 1 km squares within about 30 nmi of CCAFS/KSC. This area was chosen to provide at least 5 nmi coverage around all key facilities supported or used by 45 WS: to the north this is the northern edge of KSC property, to the east--the point of Cape Canaveral, to the south--the southern edge of Patrick AFB, and to the west--the Weather Surveillance Radar owned by the 45th Space Wing. The eastern edge was extended farther east to place CCAFS/KSC, the main area of interest, in the center of the map. The lat/lon of the upper left and lower right corners are (29.07° N, 81.25° W) and (28.05° N, 80.20° W), respectively.

3. Discussion

There are several operational, scientific, and procedural items in these climatologies that need to be discussed.

3.1 Local Maximum of Flash Density Higher Than Previous Climatologies

Many previous lightning climatologies had CG lightning flash densities of about 14 flashes/km²yr for the local maximum in east central Florida near Orlando (Holle et al., 2016). However, this climatology shows a flash density of about 20 flashes/km²yr in that location (Figure-1), more than 40% higher than in the previous climatologies. This is an artifact of the much finer horizontal resolution used in this local lightning climatology.

This climatology uses 1 km x 1 km squares, while the other climatologies used squares of about 20 km x 20 km or more (Holle et al., 2016). The larger squares dilute local maxima with surrounding lower flash densities resulting in lower peak values for the maxima, especially in areas of large gradients of local flash density. Likewise, smaller squares could cause local minima to be higher than shown in climatologies with larger squares. Vaisala, Inc. did some analysis suggesting that the differing resolutions was the cause of the discrepancies in the local maxima (Brooks, 2016).

The 45 WS then asked the 14th Weather Squadron to confirm this by repeating the flash density analysis with the same data but varying square size. These varied climatologies are shown in Figure-9. The flash densities were 20 flashes/km²yr for 1 x 1 km squares, 17 flashes/km²yr for 5 x 5 km squares, and 15 flashes/km²yr for 10 x 10 km squares. These values are plotted in Figure-10. Note that the flash density is converging toward the flash density observed in earlier climatologies with larger squares.

3.2 Inference of Stroke Density

The stroke density could not be calculated directly since the stroke data from NLDN was not available at 14th Weather Squadron, the Air Force climate center that developed these lightning climatologies for 45 WS. Therefore, the stroke data was inferred by multiplying each flash by its multiplicity (number of strokes in the flash) and assuming all the strokes will occur in the same 1 km x 1 km square as the flash. This assumption often fails since about half of flashes have strokes with multiple ground contact points and the typical distance between those strokes is about 3 km (Valine and Krider, 2002). However, if there is no systematic pattern in the multiplicity across the area, then for a large sample this issue should be resolved in the averaging process. As shown in Figure-4, the mean multiplicity appears to be fairly random across the land of east central Florida. Therefore, the process used to infer the annual mean stroke density is reasonable.

3.3 Multiplicity Over Water Vs. Over Land

While the mean multiplicity appears random over the land the east central Florida, there is definitely a difference between the mean multiplicity over land and over water (Figure-4). The over water mean multiplicity is 3.16 strokes per flash while the mean multiplicity over land is slightly lower with 2.75 strokes per flash. These multiplicities are statistically significant with a p-value of 0.015. The mean multiplicity over water appears to be randomly distributed, as it is over land, though with a higher overall mean than over

land. A higher multiplicity over water has been widely observed elsewhere (Schulz, 2016) (Sugita and Matsui, 2016).

3.4 Ground Contact Density—A Better Way to Access Lightning Risk to Facilities

The annual mean ground contact density is a better approach to CG lightning risk assessment than flash density or even stroke density. While this approach has been discussed by others (Cummins, 2014) (Stall et al., 2009), it has not been widely applied. Many CG flashes have multiple return strokes and often those return strokes have multiple ground contact points separated by kilometers (Saba et al., 2006) (Valine and Krider, 2002). Flashes rarely have three or more ground contact points. Therefore, the most frequently used flash density will likely underestimate the risk from CG lightning. However, a stroke density can overestimate the risk. Consider a CG flash with five strokes where the first strokes hit the ground at point-A and the third through fifth strokes strike the ground at point-B a few km from point-A. There is one flash, five strokes, and two ground contact points. Even though point-A is struck twice, the risk to personnel or property is not double that of one stroke since the large majority of risk of injury/death/damage is covered by the first stroke. Likewise, the risk at point-B is not triple that of one stroke. Therefore, of the three metrics, the number of ground contact points is best estimate of risk. This holds up for other scenarios. For example, if all five strokes struck point-A, there would be one flash, one ground contact point, and five strokes. Again, the number of ground contact points is the best metric of risk (although in this case the number of flashes has the same value). Therefore, a climatology of CG lightning ground contact points would be a better tool for risk assessment to personnel and property.

Unfortunately, a method to infer ground strikes from flash data has not been readily available. Comparing stroke location error ellipse data can be done (Cummins, 2014) but is computationally inconvenient and has not been widely applied. For this climatology,

a new method to infer the number of ground contact points was developed. While not as accurate as the location error ellipse approach, it is much simpler. The probability of a second ground contact point is adapted from da Silva Ferro et al. (2012). Assuming these results observed in Brazil apply elsewhere and assuming that flashes with three or more ground contact points are rare, then Table-1 provides the expected number of ground strikes as a function of flash multiplicity. While fractional ground strike points are unrealistic, over a large sample, the results should average to a reasonable result. These results are plotted in Figure-8.

Table-1

A new algorithm to convert cloud-to-ground flash multiplicity into expected number of ground strikes. Adapted from da Silva Ferro et al. (2012).

Multiplicity	Expected Number of Ground Strikes
1	1.000
2	1.485
3	1.731
4	1.882
5	1.961
6	1.991
7	1.996
8	1.999
≥ 9	2.000

3.5 Peak Current Over Water Vs. Over Land

These lightning climatologies show a systematic increase of peak current over water as compared to land (Figure-5). The mean peak current over water is 25.2 KA, while the mean over land is 19.5 KA. These peak currents are statistically significant with a p-value of < 0.0001.

This increase of peak current over water has been widely observed (Schulz, 2016) (Sugita and Matsui, 2016). The enhancement of peak current extends a small distance inland, which is consistent with another recent

report of the effect (Nag and Cummins, 2016). This undermines suggested mechanisms for the enhanced peak current based on surface properties and gives credence to explanations based on aerosol difference over water vs over land.

3.5 Polarity Distribution

The CG lightning in this data set had a raw negative polarity in 89% of the flashes, or a raw positive polarity of 11%. This is a lower/higher frequency of negative/positive polarity than is usually reported. However, these data are not corrected for weak current positive flashes that are lightning aloft flashes misidentified as CG flashes.

4. Future Work

The most important future work for this local lightning climatology is to verify that the assumption of no more than two ground contact points per cloud-to-ground flash is reasonable. Or if that assumption is not reasonable, update the multiplicity to expected ground contact points in Table-1 and recalculate the ground contact density map.

The period of record for these CG lightning climatologies is 17 years (1997-2013). Unfortunately, the data from 2014 had to be excluded since the NLDN flash data at 14th Weather Squadron were contaminated with some stroke data. That led to 2015 also being excluded due to the difficulty of using noncontiguous years in the analysis. Finally, 2016 was not used since this analysis was begun near the start of that year. Therefore, these climatologies should be redone after the stroke contamination in 2014 is corrected and 2019 has ended since a good rule of thumb is to update statistical analyses when the sample size has increased by 40% or more. In this case, that would be after another 6 or more years have occurred beyond the current 1997-2013 period.

The period of record for the lightning aloft climatology is only 6 years (2010-2015). This is due to Air Force Weather only beginning to use the ENTLN total lightning in 2010 and it becoming available for archiving at 14th

Weather Squadron beginning that year. This climatology should be updated after 2018 has ended since enough new sample size would have accumulated by then.

The polarity distribution should be improved by filtering out lightning aloft misidentified as CG flashes. This is usually done by excluding positive strokes with small peak currents, e.g. $\leq +3$ KA (Zhu et al., 2016).

5. Summary

A new lightning climatology for CCAFS/KSC and the surrounding area was created. This new climatology consists of six maps: 1) cloud-to-ground (CG) flash density, 2) CG stroke density, 3) CG ground contact density, 4) CG multiplicity, 5) CG mean peak current, and 6) total lightning flash density (both lightning aloft and CG lightning). These maps are in Figure-1 through Figure-6, respectively. A new approach to infer ground strike density was developed. Ground strike density is preferred to the more common ground-to-ground flash density, or even stroke density, for risk assessment to ground facilities. The total lightning climatology is useful for assessing the operational impact of 45 WS lightning warnings, since they are based on both cloud-to-ground lightning and lightning aloft. The total lightning climatology is also useful for assessing the lightning risk to aviation and space launch, although this does not include the risk of rocket triggered lightning, which can be more frequent than the risk of natural lightning.

5. Acknowledgements

The 45 WS is extremely grateful for the continual outstanding support from the 14th Weather Squadron, the U.S. Air Force climatology center, in developing these lightning climatologies and in every one of the many climatology projects they have provided over many years. This paper was reviewed by the following 45 WS personnel: Col Shannon, Commander; and Maj Josephson, Chief of Systems.

6. References

- Brooks, W. A., 2016: personal communication, Vaisala, Inc., 9 May 16
- Cummins K. L., and M. J. Murphy, 2009: An overview of lightning locating systems: History, techniques, and data uses, with an in-depth look at the US NLDN, *IEEE Transactions on Electromagnetic Compatibility*, **Vol. 51**, No. 3, 499-518
- Cummins, K. L. J. A. Cramer, C. J. Biagi, E. P. Krider, J. Jerauld, M. A. Uman, and V. A. Rakov, 2006: The U.S. National Lightning Detection Network: Post-upgrade status, *2nd Meteorological Applications of Lightning Data*, 9 pp.
- 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
- da Silva Ferro, M. A., M. M. F. Saba, and O. Pinto, 2012: Time-intervals between negative lightning strokes and the creation of new ground terminations, *Atmospheric Research*, **116**, 130-133 (www.elsevier.com/locate/atmos)
- Harms, D. E., A. A. Guiffrida, B. F. Boyd, L. H. Gross, G. D. Stroh, R. M. Lucci, J. W. Weems, E. D. Priselac, K. Lammers, H. C. Herring and F. J. Merceret, 1999: The many lives of a meteorologist in support of space launch, *8th Conference on Aviation, Range, and Aerospace Meteorology*, 10-15 Jan 99, 5-9
- Heckman, S., 2013: Earth Networks Total Lightning Network overview, *6th Conference on Meteorological Applications of Lightning Data*, 5-10 Jan 13
- Holle, R. L., K. L. Cummins, and W. A. Brooks, 2016: Seasonal, monthly, and weekly distributions of NLDN and GLD360 cloud-to-ground lightning, *Monthly Weather Review*, **Vol. 144**, DOI: 10.1175/MWR-D-16-0051.1, Aug 16, 2855-2870
- McNamara, T. M., W. P. Roeder, and F. J. Merceret, 2010: The 2009 update to the lightning launch commit criteria, *14th Conference on Aviation, Range, and Aerospace Meteorology*, Paper 469, 14-18 Jan 2010, 16 pp.
- Nag, A., and K. L. Cummins, 2016: Characteristics of negative cloud-to-ground lightning over land and ocean, *33rd International Conference on Lightning Protection*, Oct 16,
- Nag, A., M. J. Murphy, and J. A. Cramer, 2016: Update to the U.S. National Lightning Detection Network, *24th International Lightning Detection Conference & 6th International Lightning Meteorology Conference*, 18-21 Apr 16, 7 pp.
- Roeder, W. P., D. L. Hajek, F. C. Flinn, G. A. Maul, and M. E. Fitzpatrick, 2003: Meteorological and oceanic instrumentation at Spaceport Florida – Opportunities for coastal research, *5th Conference on Coastal Atmospheric and Oceanic Prediction and Processes*, 6-8 Aug 03, 132-137
- Saba M. M. F., M. G. Ballarotti, and O. Pinto, 2006: Negative cloud-to-ground lightning properties from high-speed video observations, *Journal of Geophysical Research*, **Vol. 111**, D03101, 9 pp.
- Schulz, W., 2016: The European Lightning Location System EUCLID: Performance validation and observations, *24th International Lightning Detection Conference & 6th International Lightning Meteorology Conference*, 18-21 Apr 16, 7 pp.
- Stall C. A., K. L. Cummins, E. P. Krider, and J. A. Cramer, 2009: Detecting Multiple Ground Contacts in Cloud-to-Ground Lightning Flashes, *Journal of Atmospheric and Oceanic Technology*, **Vol. 26**, No. 11, DOI: 10.1175/2009JTECHA1278.1, Nov 09, 2392-2402
- Sugita, A., and M. Matsui, 2016: Lightning occurrence characteristics in 2015 in Japan as observed by the JLDN, *24th International Lightning Detection Conference & 6th International Lightning Meteorology Conference*, 18-21 Apr 16, 7 pp.
- Valine, W., and E. P. Krider, 2002: Statistics and characteristics of cloud-to-ground lightning with multiple ground contacts, *Journal of Geophysical Research*, **107** (D20), 4441, doi:10.1029/2001JD001360
- Zhu Y., V. A. Rakov, M. D. Tran, and A. Nag, 2016: A study of NLDN responses to cloud discharge activity based on ground-truth data acquired at the LOG, *24th International Lightning Detection Conference & 6th International Lightning Meteorology Conference*, 18-21 Apr 16, 7 pp.

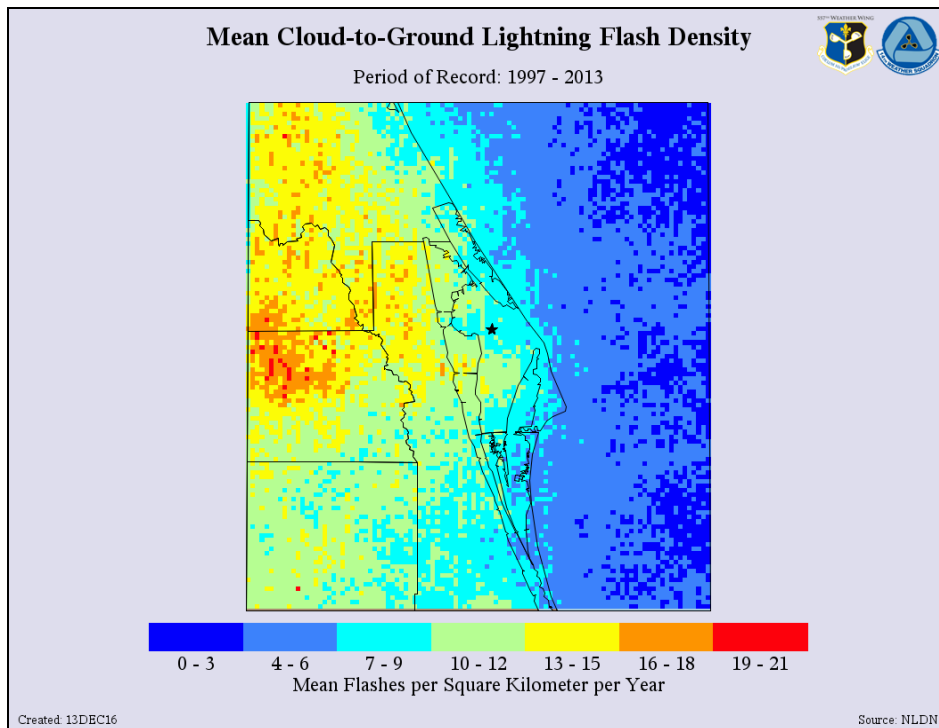


Figure-1. Average annual CG lightning flash density for the CCAFS/KSC area. The data are from NLDN (1997-2013).

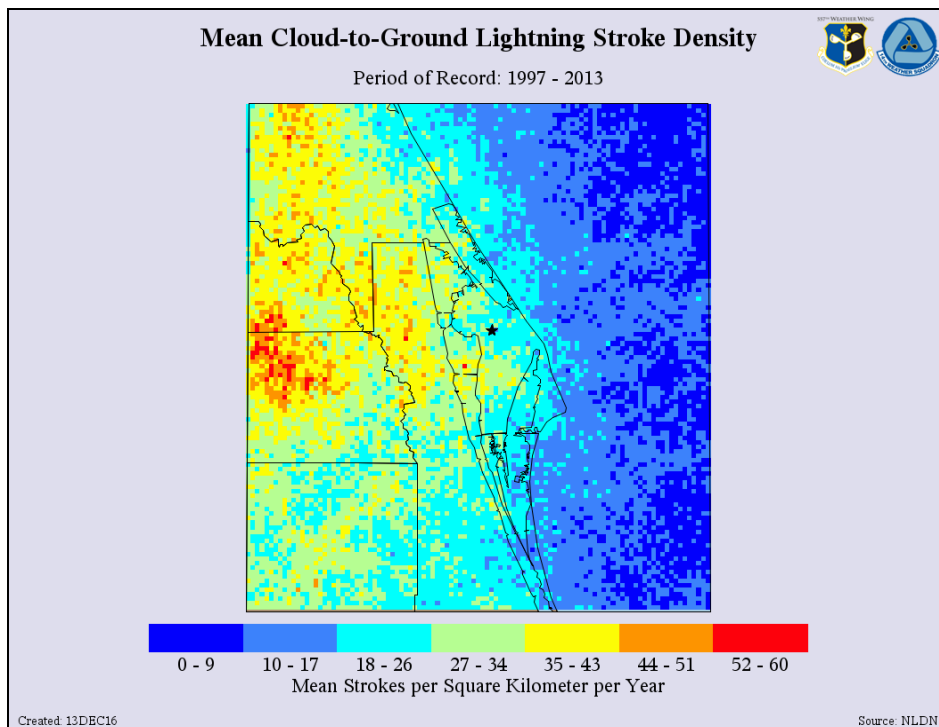


Figure-2. Average annual lightning ground stroke density for the CCAFS/KSC area. The data are from NLDN (1997-2013). The stroke density was inferred the multiplicity for each flash.

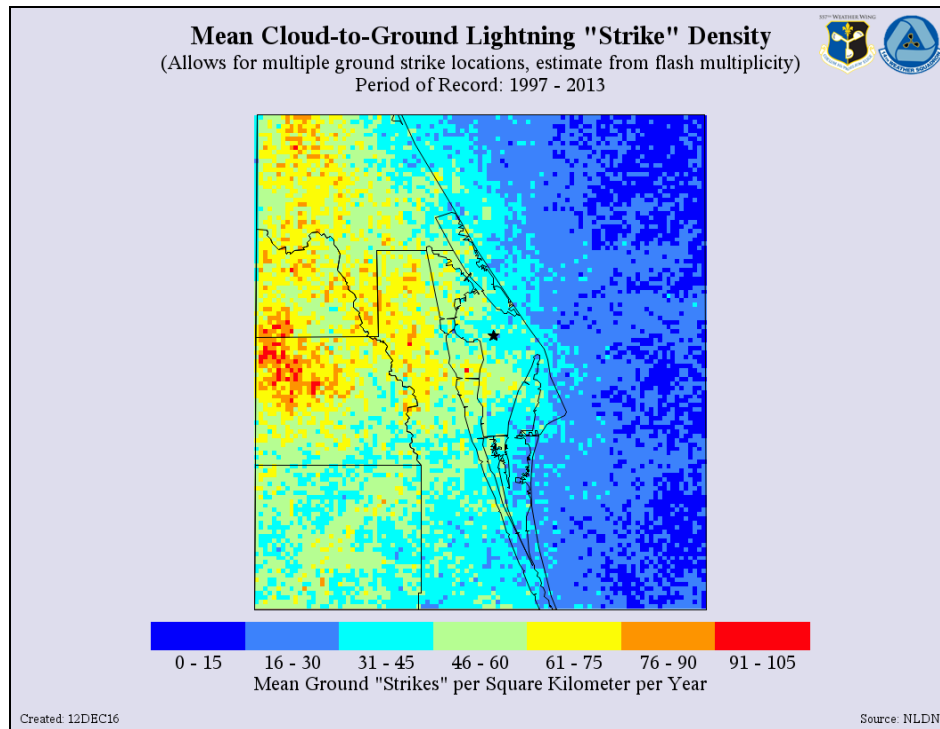


Figure-3. Average annual CG lightning ground strike density for the CCAFS/KSC area. The ground strike density was inferred from the probability of multiple ground strikes as a function of multiplicity applied to each CG flash. The data are from NLDN (1997-2013).

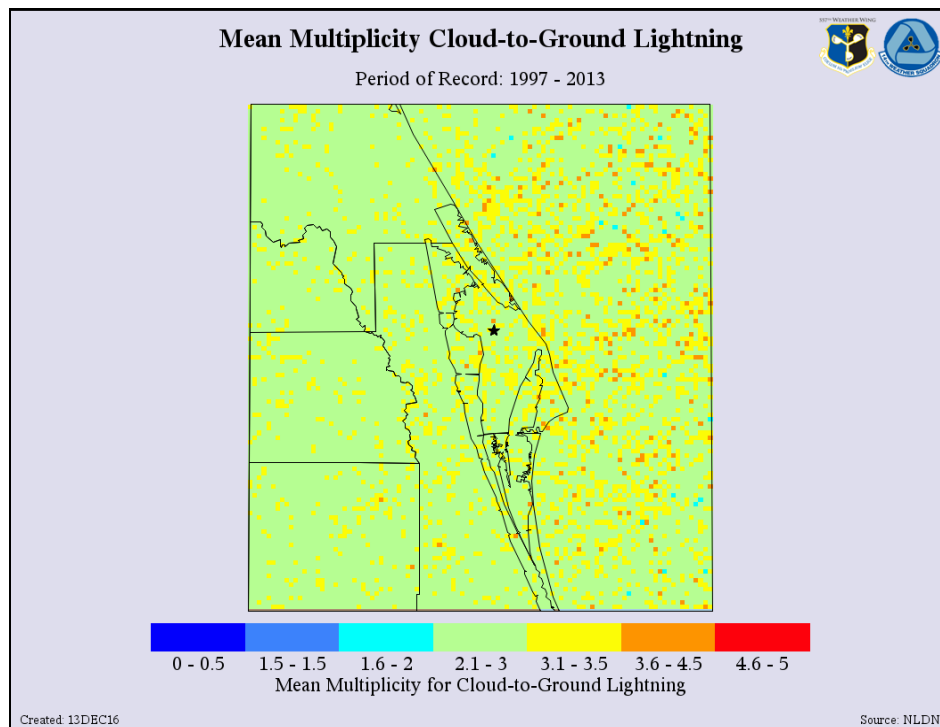


Figure-4. Average multiplicity of cloud-to-ground flashes for the CCAFS/KSC area. The data are from NLDN (1997-2013).

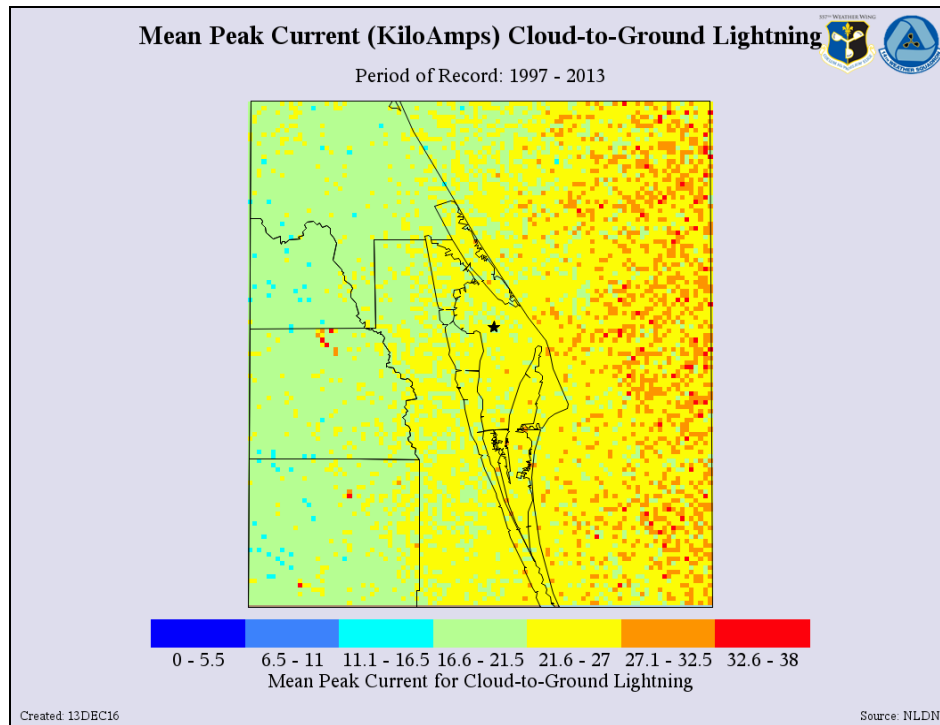


Figure-5. Average peak current of cloud-to-ground flashes for the CCAFS/KSC area. The data are from NLDN (1997-2013).

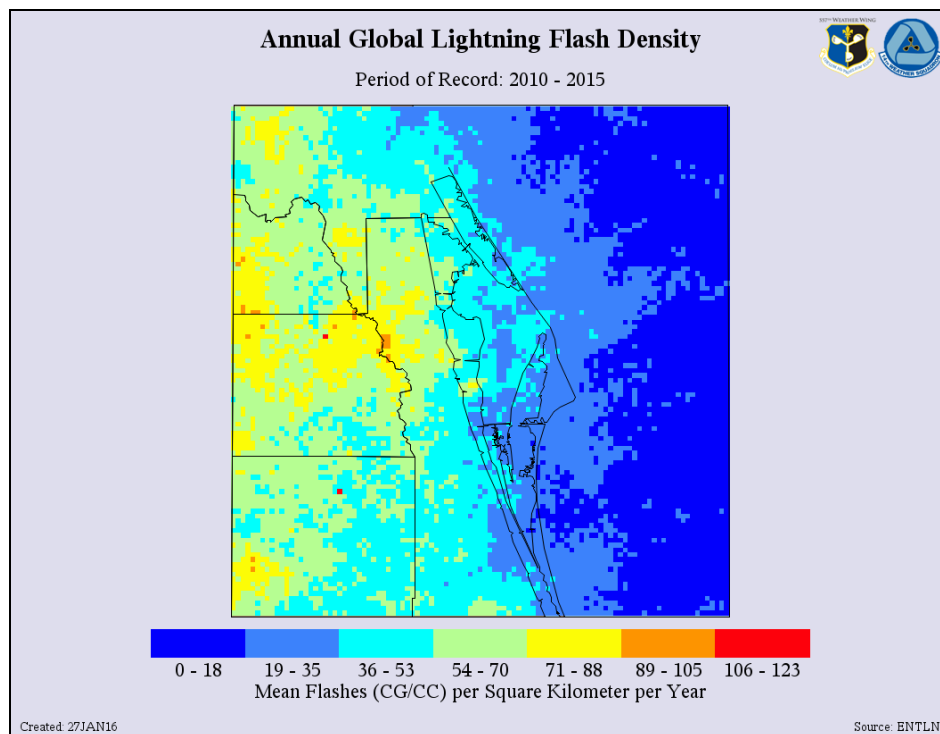


Figure-6. Total lightning flash density for the CCAFS/KSC area, both lightning aloft and cloud-to-ground lightning. The data are from ENTLN (2010-2015), an admittedly short period for a lightning.

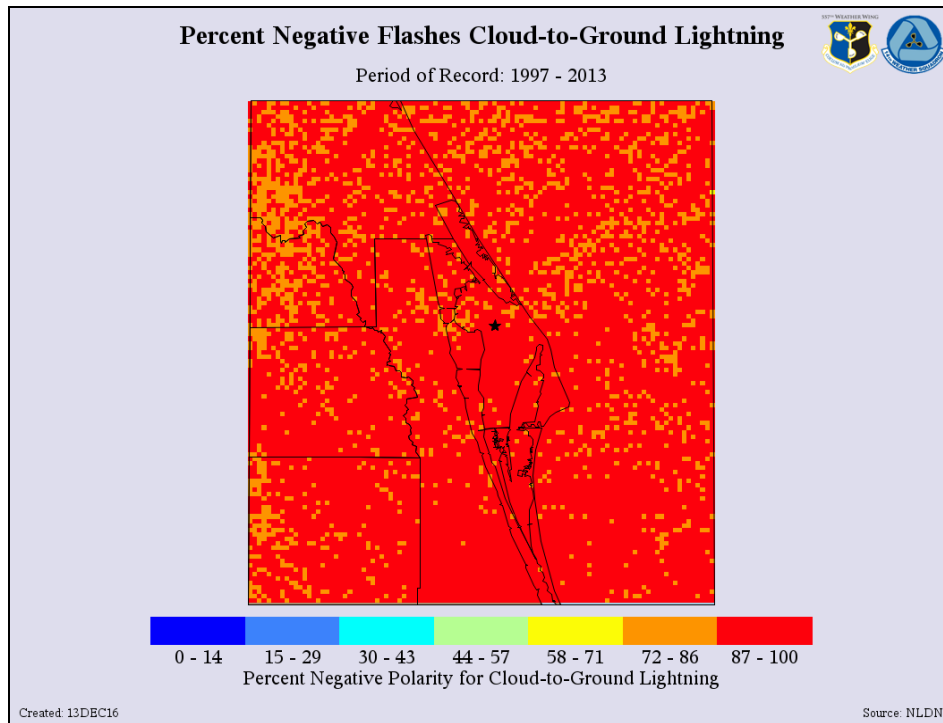


Figure-7. Frequency of negative polarity of cloud-to-ground flashes for the CCAFS/KSC area (not corrected for lightning aloft misidentified as CG flashes). The data are from NLDN (1997-2013).

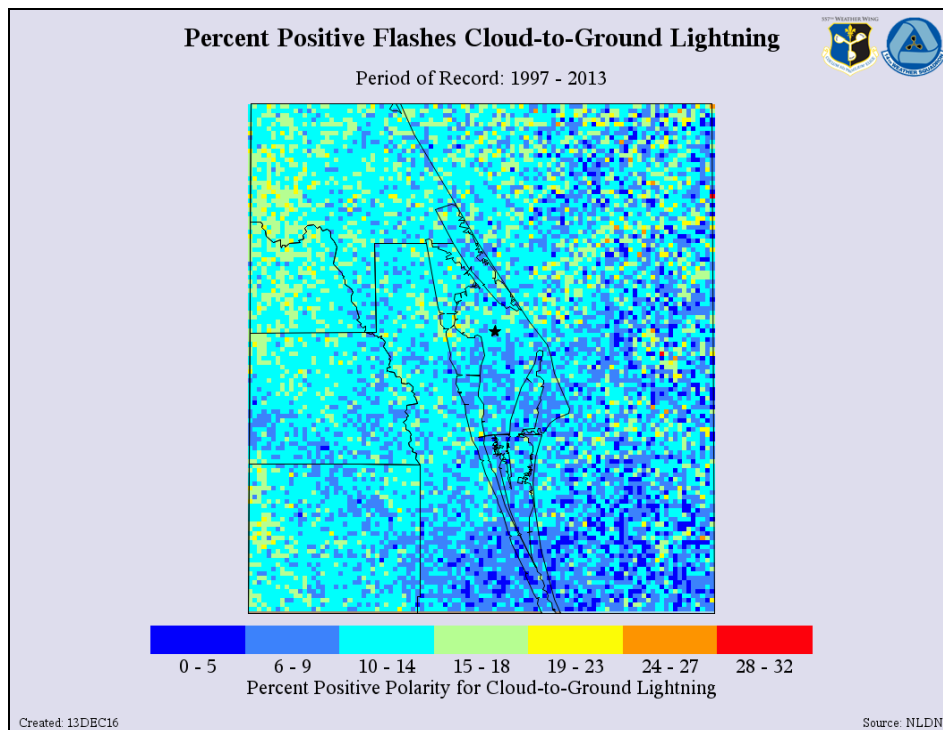
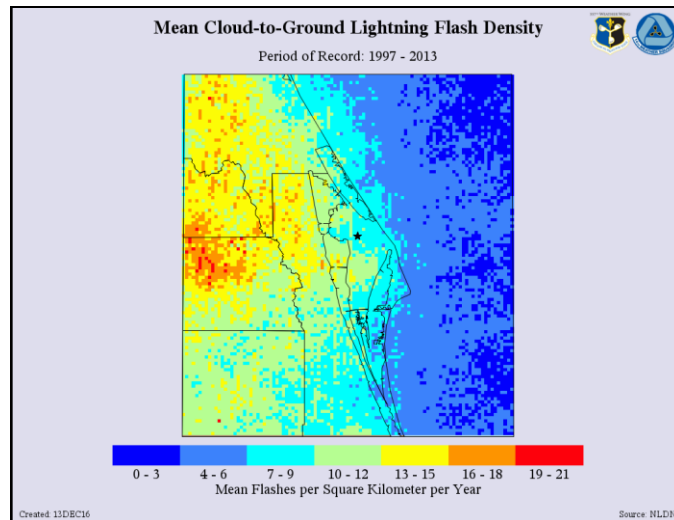
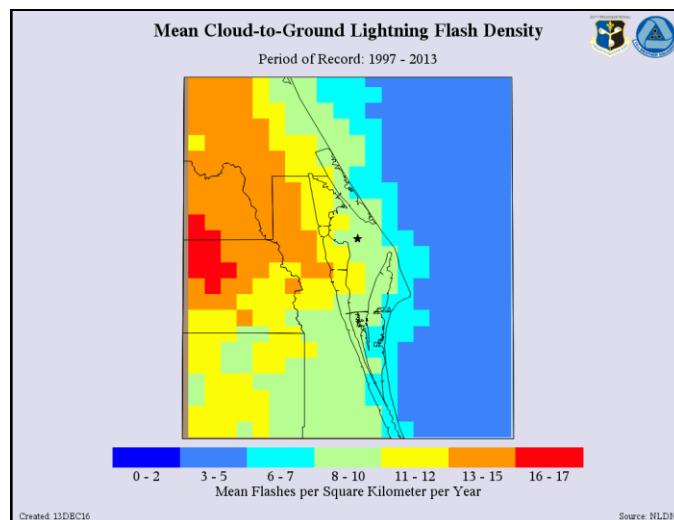


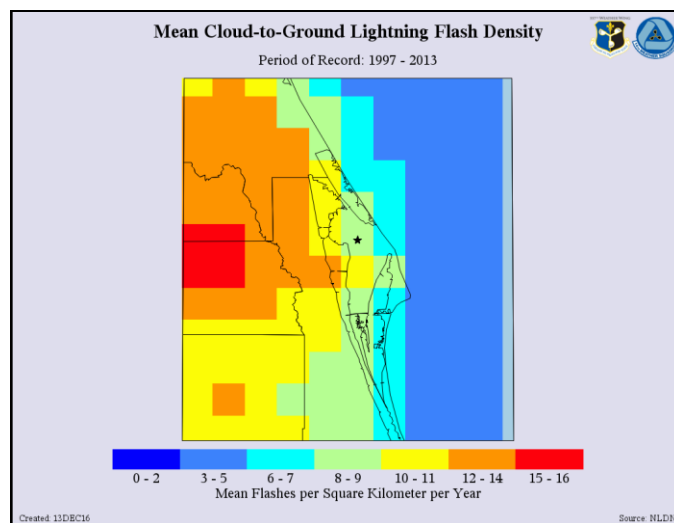
Figure-8. Frequency of positive polarity of cloud-to-ground flashes for the CCAFS/KSC area (not corrected for lightning aloft misidentified as CG flashes). The data are from NLDN (1997-2013).



a) 1 x 1 km squares. Local maximum flash density ~20 Flashes/km²Yr.



b) 5 x 5 km squares. Local maximum flash density ~17 Flashes/km²Yr.



c) 10 x 10 km squares. Local maximum flash density ~15 Flashes/km²Yr.

Figure-9. The cloud-to-ground lightning flash density for the CCAFS/KSC area, analyzed with three different sized squares: a) 1 x 1 km, 2) 5 x 5 km, and 3) 10 x 10 km. All three analyses used the same data. The data are from NLDN (1997-2013).

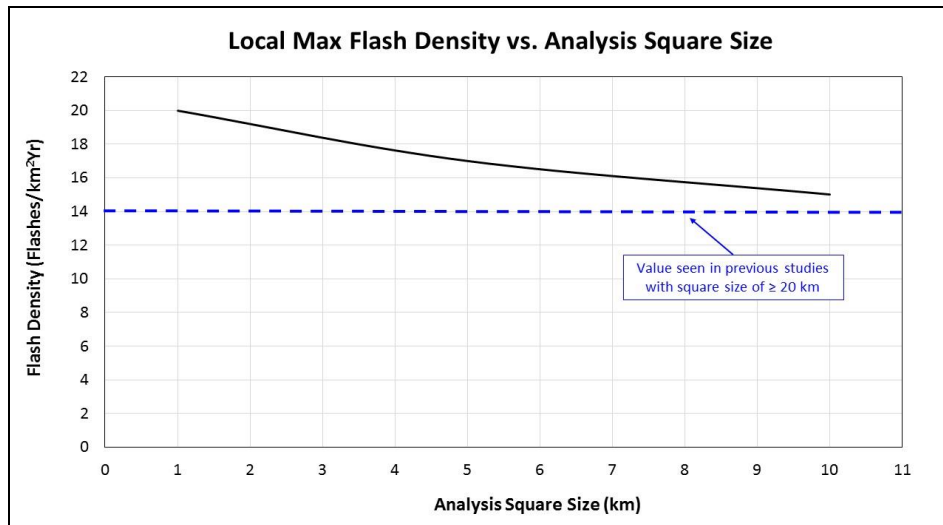


Figure-10. Flash density of local maximum in CG lightning near Orlando, FL as a function of analysis square size. Due to the small scale of lightning climatology in Florida, the local maximum decreases as the size of the analysis square increases as the local maximum is diluted with surrounding data with lower annual average flash density. The local maximum converges to the value of about 14 flashes/km²yr seen in previous CONUS and Florida flash densities.