Cloud-to-Ground Lightning Estimates Derived From SSM/I Microwave Remote Sensing and NLDN

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1. Abstract

A physically based correlation exists between passive microwave brightness temperatures and lightning flash rates (Liu et al. 2011). Current lightning observations are made on land (NALDN, **Figure 1a,b**, Orville et al. 2011) and from space (TRMM LIS, **Figure 2**, Cecil et al. 2012). Each lightning detection system has fundamental limitations. TRMM satellite coverage is limited to the tropics and subtropics between 38°N and 38°S, so lightning at the higher latitudes of the northern and southern hemispheres is not observed. The detection efficiency of NLDN sensors is at least 90%, but the sensors are only located in the USA (Orville et al. 2011). Even if data from other ground-based lightning sensors (World Wide Lightning Location Network, the European Cooperation for Lightning Detection, and Canadian Lightning Detection Network) were combined with TRMM and NLDN, there would be enormous spatial gaps in present-day coverage of lightning. In addition, a globally-complete time history of observed lightning activity is currently not available either, with network coverage and detection efficiencies varying through the years. This study focuses on using DMSP SSM/I microwave brightness temperature data to estimate cloud-to-ground (CG) lightning with NLDN as ground verification. The potential exists for a complete global CG lightning climatology using decades of DMSP data.

Figure 1a. NALDN Sensor Locations and Type

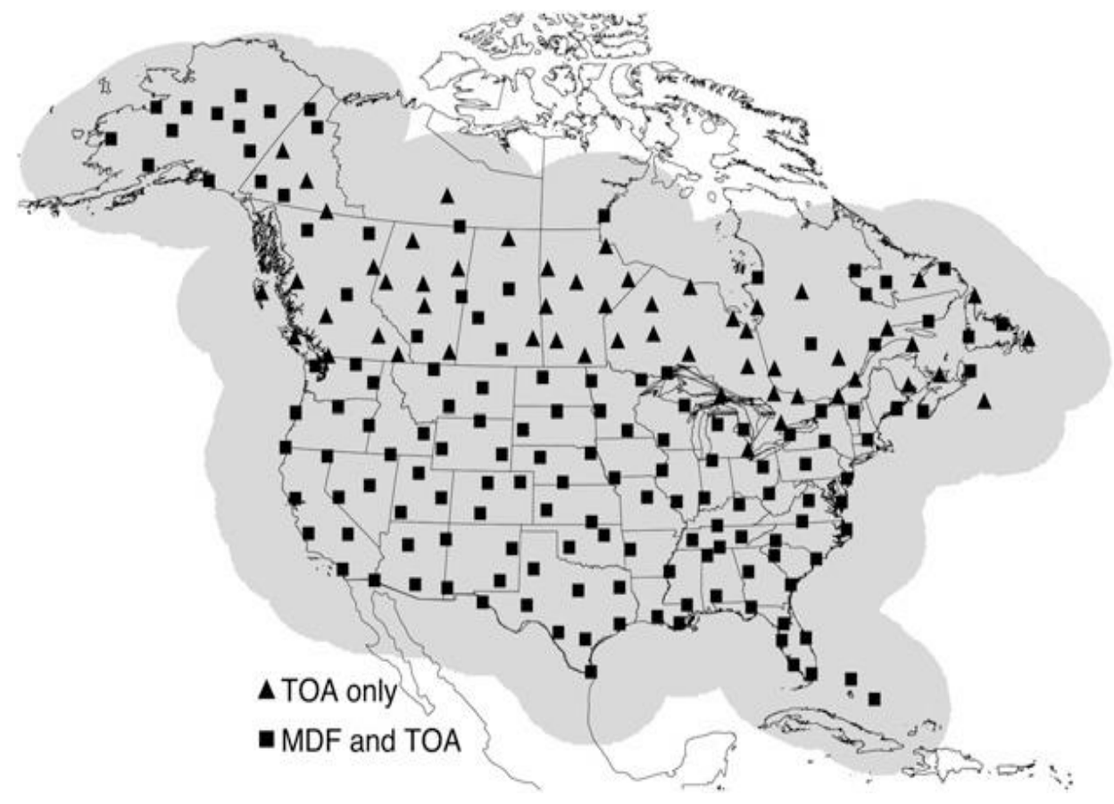


Figure 1b. NALDN Annual Flash Density

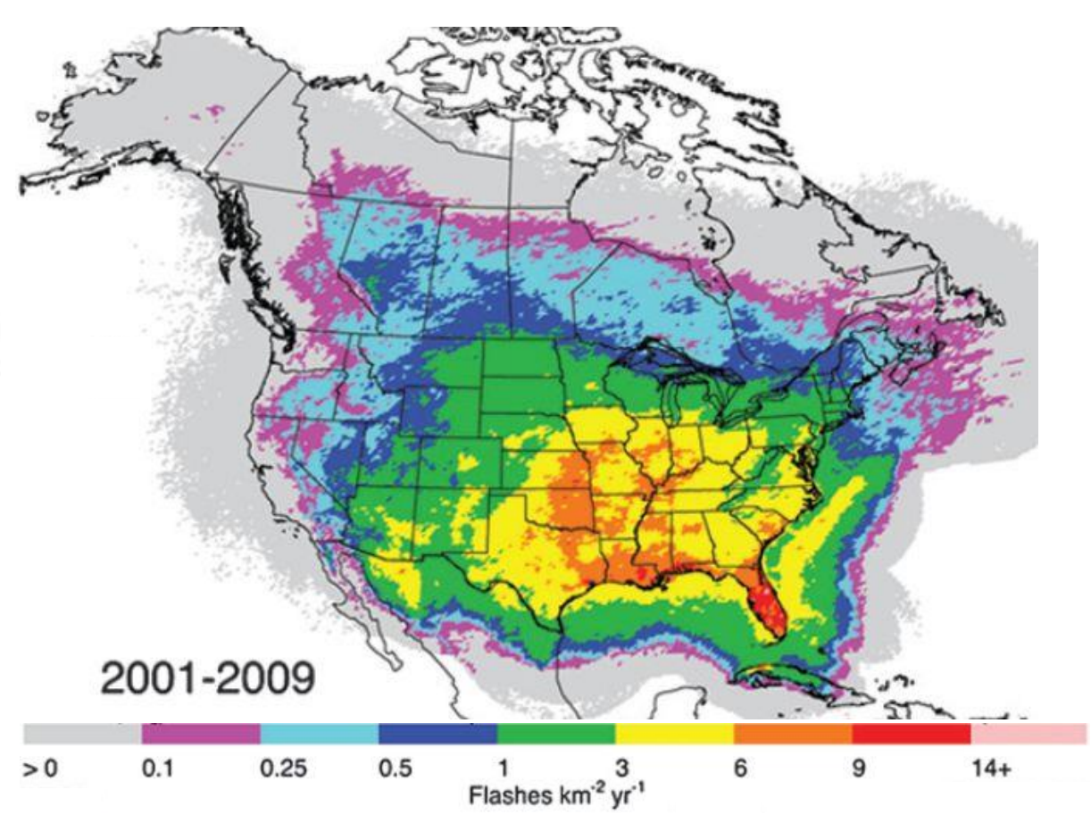
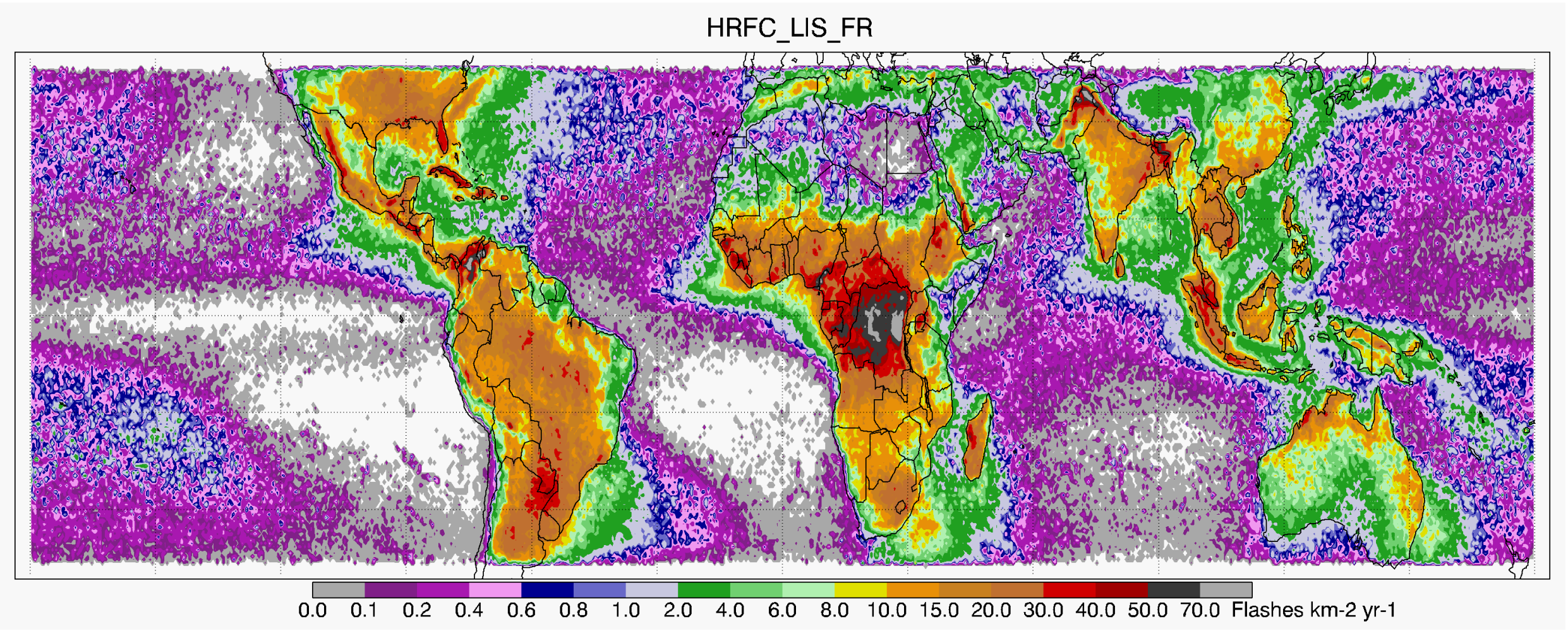


Figure 2. TRMM LIS Average Annual Flash Density



2. Introduction

Lightning observations are collected using ground-based and satellite-based sensors. The National Lightning Detection Network (NLDN) in the United States uses multiple ground sensors to triangulate the electromagnetic signals created when lightning strikes the Earth's surface (Orville et al. 2011). Satellite-based lightning observations have been made from 1998 to present using the Lightning Imaging Sensor (LIS) on the NASA Tropical Rainfall Measuring Mission (TRMM) satellite, and from 1995 to 2000 using the Optical Transient Detector (OTD) on the Microlab-1 satellite (Kummerow et al. 1998 and Liu et al. 2011). Both LIS and OTD are staring imagers that detect lightning as momentary changes in an optical scene. Passive microwave remote sensing (85 and 37 GHz brightness temperatures) from the TRMM Microwave Imager (TMI) has also been used to quantify characteristics of thunderstorms related to lightning (Liu et al. 2011 and Cecil et al. 2012).

Previous research by Liu et al. (2011) using the TRMM LIS and Microwave Imager (TMI) showed that there is a statistically significant correlation between lightning flash rates and passive microwave brightness temperatures. The physical basis for this correlation emerges because lightning in a thunderstorm occurs where ice is first present in the cloud and electric charge separation occurs. These ice particles efficiently scatter the microwave radiation at the 85 and 37 GHz frequencies, thus leading to large brightness temperature depressions. Lightning flash rate is related to the total amount of ice passing through the convective updraft regions of thunderstorms. Confirmation of this relationship using LIS and TMI data, however, remains constrained to TRMM observational limits of the tropics and subtropics.

Satellites from the Defense Meteorology Satellite Program (DMSP) have **global coverage** and are equipped with a passive microwave imager called the Special Sensor Microwave Imager (SSM/I). Like TMI, SSM/I also observes brightness temperatures at 85 and 37 GHz. Unlike the TRMM satellite, however, DMSP satellites do not have a lightning sensor, and SSM/I has never been used to derive global lightning.

3. Research Objective

We investigate how microwave brightness temperatures from DMSP SSM/I and ground-based cloud-to-ground (CG) lightning data from NLDN are related. Our goal is to derive a spatially-complete time history of CG lightning for the USA.

4. Methods

The strongest thunderstorms generally have minimum 85 GHz Polarized Corrected brightness Temperatures (PCT) less than 150 K (Liu et al. 2011). 8 complete years of DMSP data was used from 2005 to 2013 from the F13, F14 and F15 DMSP satellites, as this is when the most complete NLDN data is available due to network upgrades and expansion (Rudlosky and Fuelberg 2010). Archived radar data was used to resolve the spatial extent of a subset of individual storms (**Figures 3, 4**). NLDN data for each storm's respective spatial extent defined by radar data was used to calculate the CG flash rate density for the storm. The CG flash rate densities were then compared to the area of 85 GHz PCT below 150 K. A linear model is used to capture the relationship between storm-specific CG flash rates and area of 85 GHz PCT below 150 K (**Figure 5**).

Figure 3. Archived radar data of thunderstorms on 24 May 2008

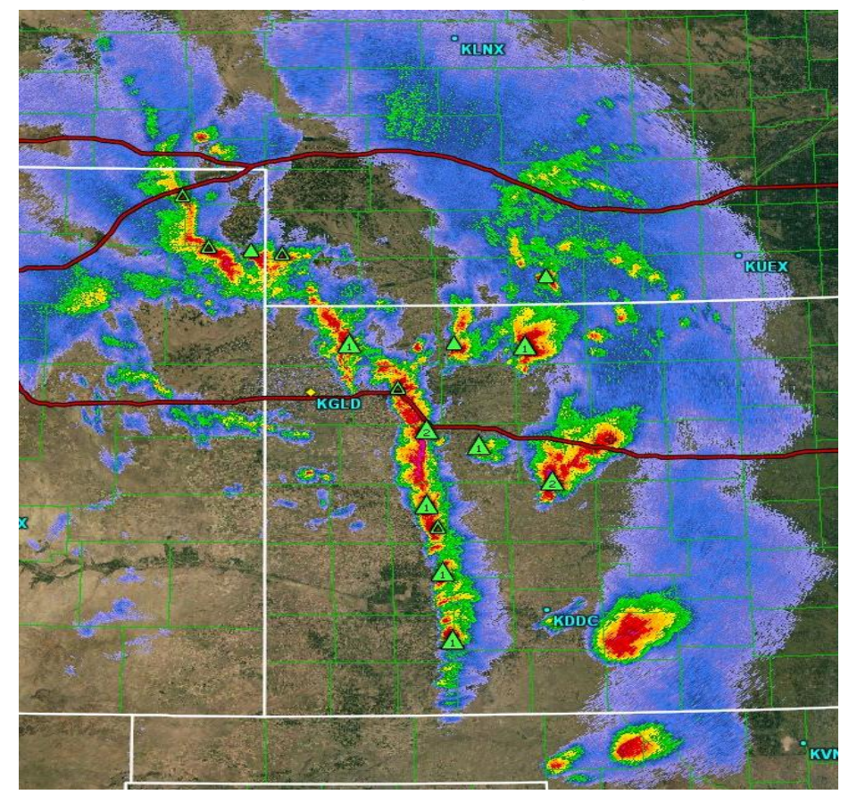


Figure 4. As per Figure 3, but showing the DMSP SSM/I view of the thunderstorms in terms of its 85 GHz brightness temperature. Cold brightness temperatures indicate high ice volumes.

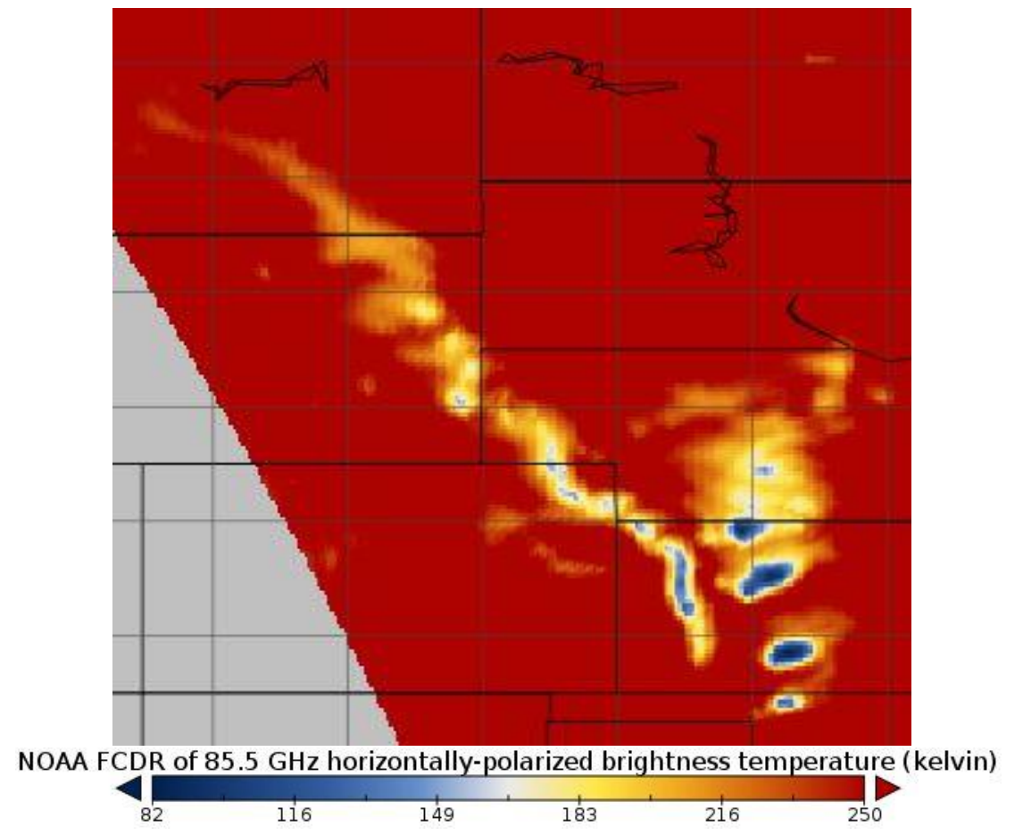
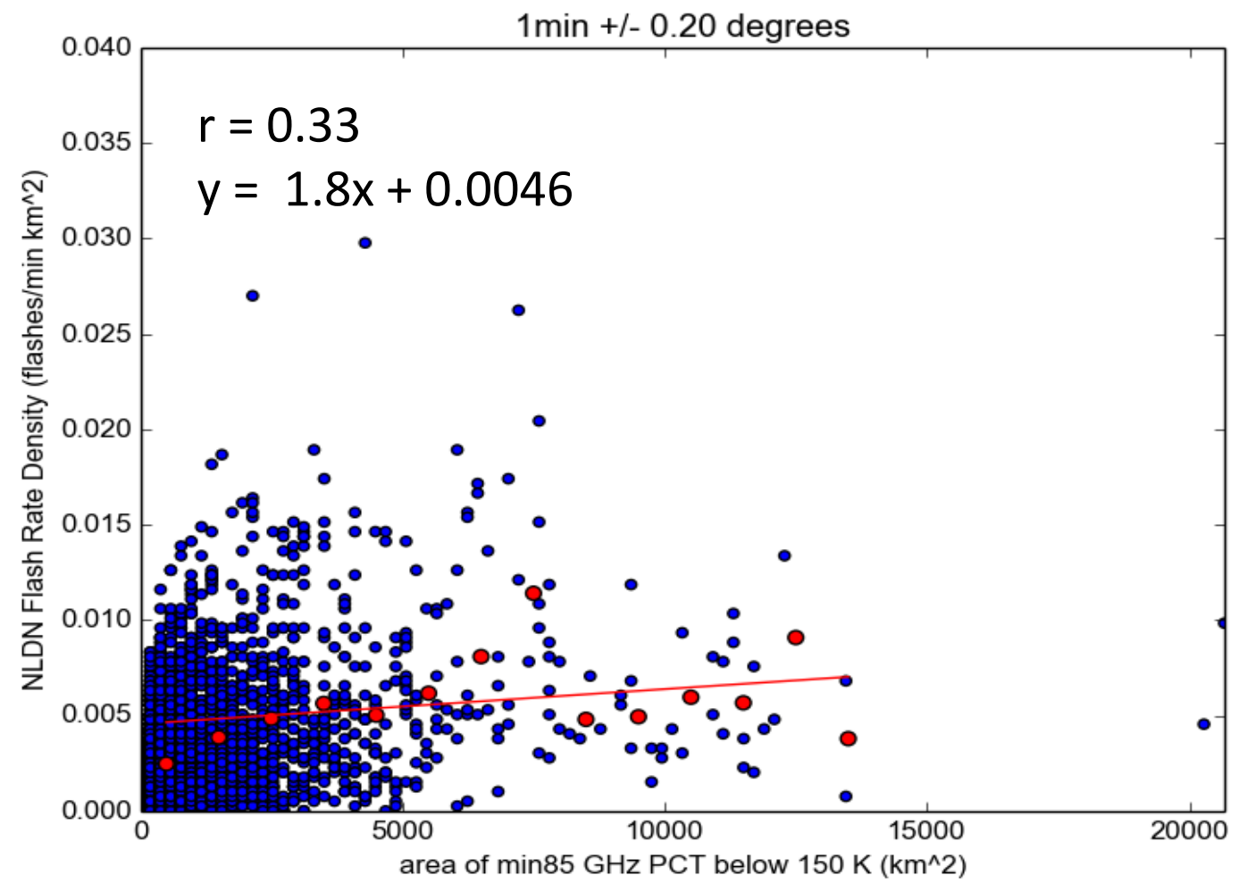
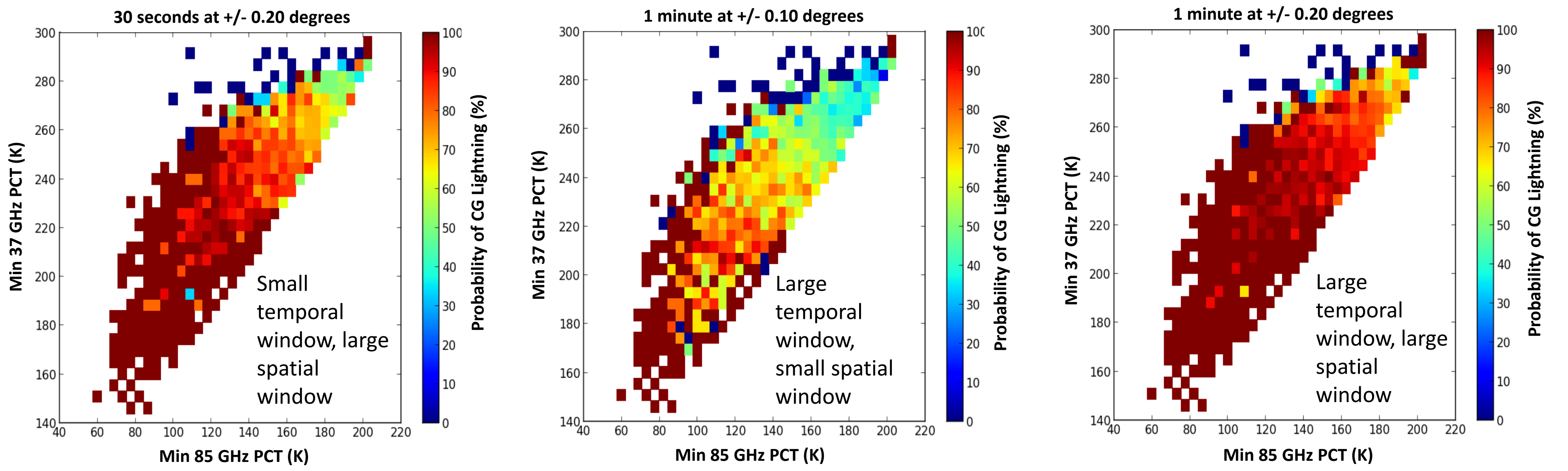


Figure 5. Linear Model for area of 85 GHz PCT below 150 K and NLDN Flash Rate Density



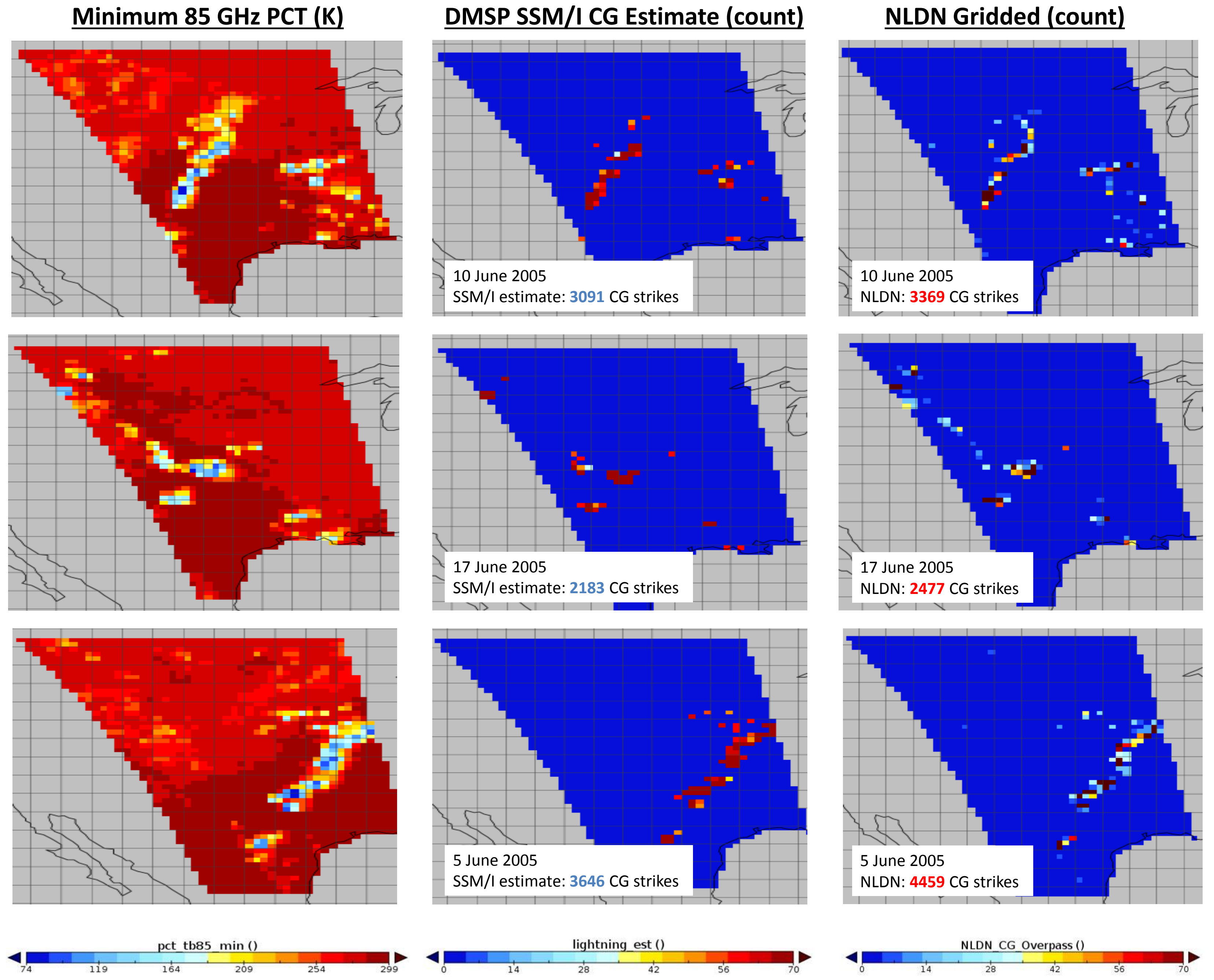
To extend the results to weaker storms, the probability of CG lightning (instead of the flash rate) was calculated for all storms from the 8 years of DMSP data (**Figure 6**). NLDN data was used to determine if a CG strike occurred for a storm based on different temporal and spatial criteria. The probability of CG lightning was plotted as a function of minimum 85 GHz PCT and minimum 37 GHz PCT following Liu et al. (2011). These probabilities were used in conjunction with the linear model from **Figure 5** to estimate the CG flash rate for weaker storms with minimum 85 GHz PCTs greater than 150 K.

Figure 6. 2-D Histograms for the probability of at least 1 Cloud-to-Ground lightning strike occurring within the given temporal and spatial criteria for any given minimum 85 and 37 GHz PCT



Three individual DMSP overpasses over the contiguous United States were used to test the derived relationships at the 1min +/- 0.20 degree criteria (**Figure 7**). The linear model was applied to pixels with a minimum 85 GHz PCT below 150 K and the probability of lightning was applied to pixels with a minimum 85 GHz PCT warmer than 150 K and less than 200 K. NLDN was used to count the number of CG strikes across the overpass area during the overpass time in order to verify the DMSP SSM/I CG estimates on a scene-by-scene basis.

Figure 7. 85 GHz Polarization-Corrected Brightness Temperature (left), DMSP SSM/I Cloud-to-Ground (CG) Estimate (center), and Gridded NLDN CG counts (right) for 3 DMSP SSM/I overpasses of the USA during summer months.



10 June 2005
SSM/I estimate: 3091 CG strikes

10 June 2005
NLDN: 3369 CG strikes

17 June 2005
SSM/I estimate: 2183 CG strikes

17 June 2005
NLDN: 2477 CG strikes

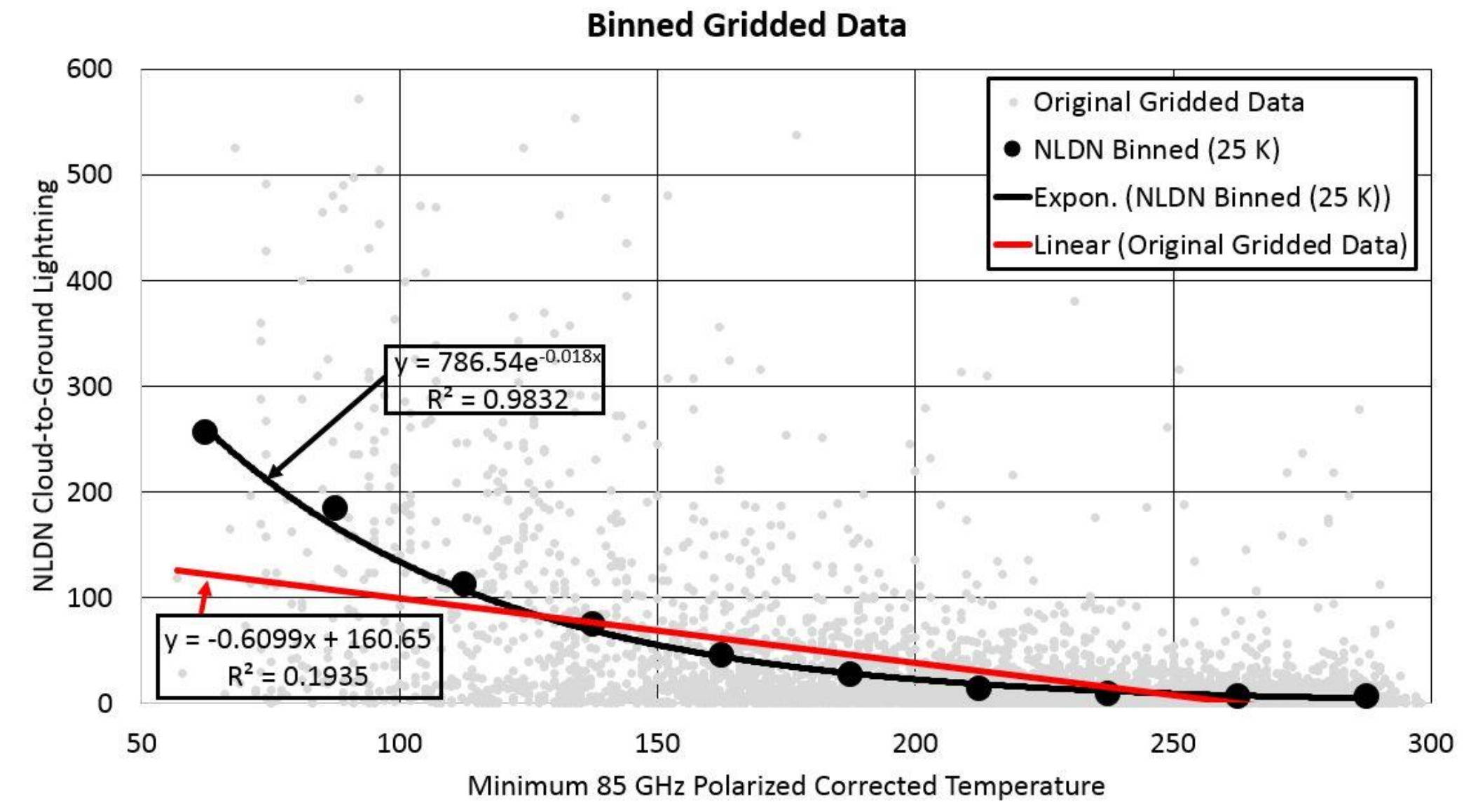
5 June 2005
SSM/I estimate: 3646 CG strikes

5 June 2005
NLDN: 4459 CG strikes

5. Results

To better understand the full dependence of lightning on 85 GHz brightness temperatures, NLDN and SSM/I were identically geolocated on a rectangular latitude-longitude grid (0.5 degree by 0.5 degree). NLDN data was extracted during the ~7 minute temporal window of the SSM/I overpass time from southern to northern USA in order to obtain a more accurate comparison between the brightness temperatures and ground verification on a grid-by-grid basis. The gridded analysis revealed that the CG maximum is not always geographically co-located with the lowest brightness temperatures, therefore the NLDN CG strikes were binned and averaged in increments of 25 K from 50 – 300 K (**Figure 8**).

Figure 8. Binned NLDN (lightning counts) versus SSM/I Brightness Temperatures from values aggregated to identical 0.5 x 0.5 degree grid



An exponential fit to the binned data (**Figure 8**) was used in conjunction with the histograms (**Figure 6**) to re-estimate the CG lightning in a method similar to the first three cases. Scene-by-scene comparisons in **Figure 9** are from 90 separate DMSP overpasses of the USA. The original estimation method used for the first three cases (**Figure 7**) is in blue, the exponential estimate using the binned data is in black, the linear estimation obtained from the minimum 85 GHz PCT and NLDN CG count on a grid-by-grid basis is in red, and the ideal 1:1 is in green. The models perform well for the scenes with lower amounts of CG lightning, but are underestimating the extreme cases. **Figure 10** shows the same models but fit only to scenes with less than 3000 NLDN CG strikes. This is done to focus the analysis on the bulk of the lightning events and highlight how the extremes affect the comparison of total scene CG lightning from SSM/I versus NLDN.

Figure 9. Model comparisons against NLDN for DMSP scenes

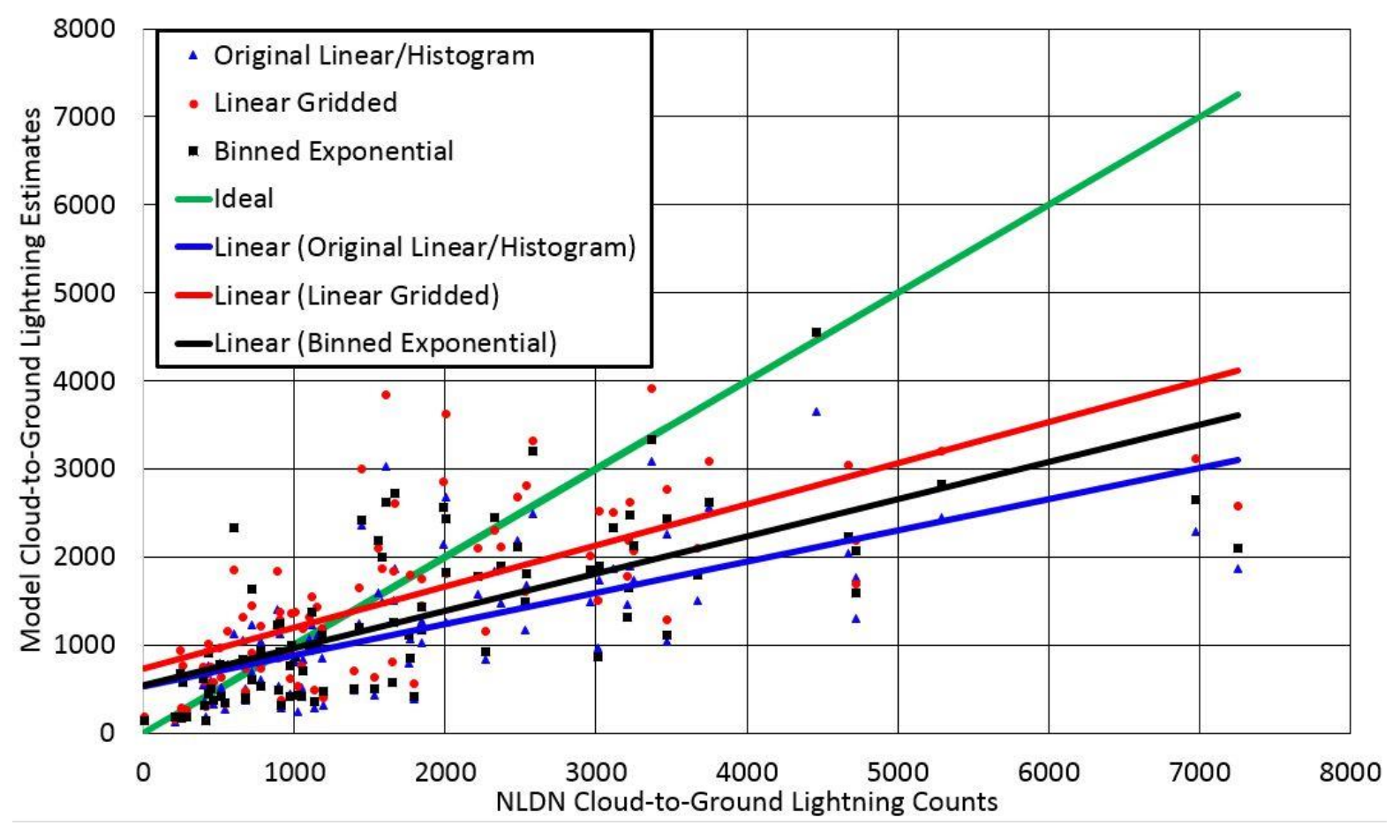
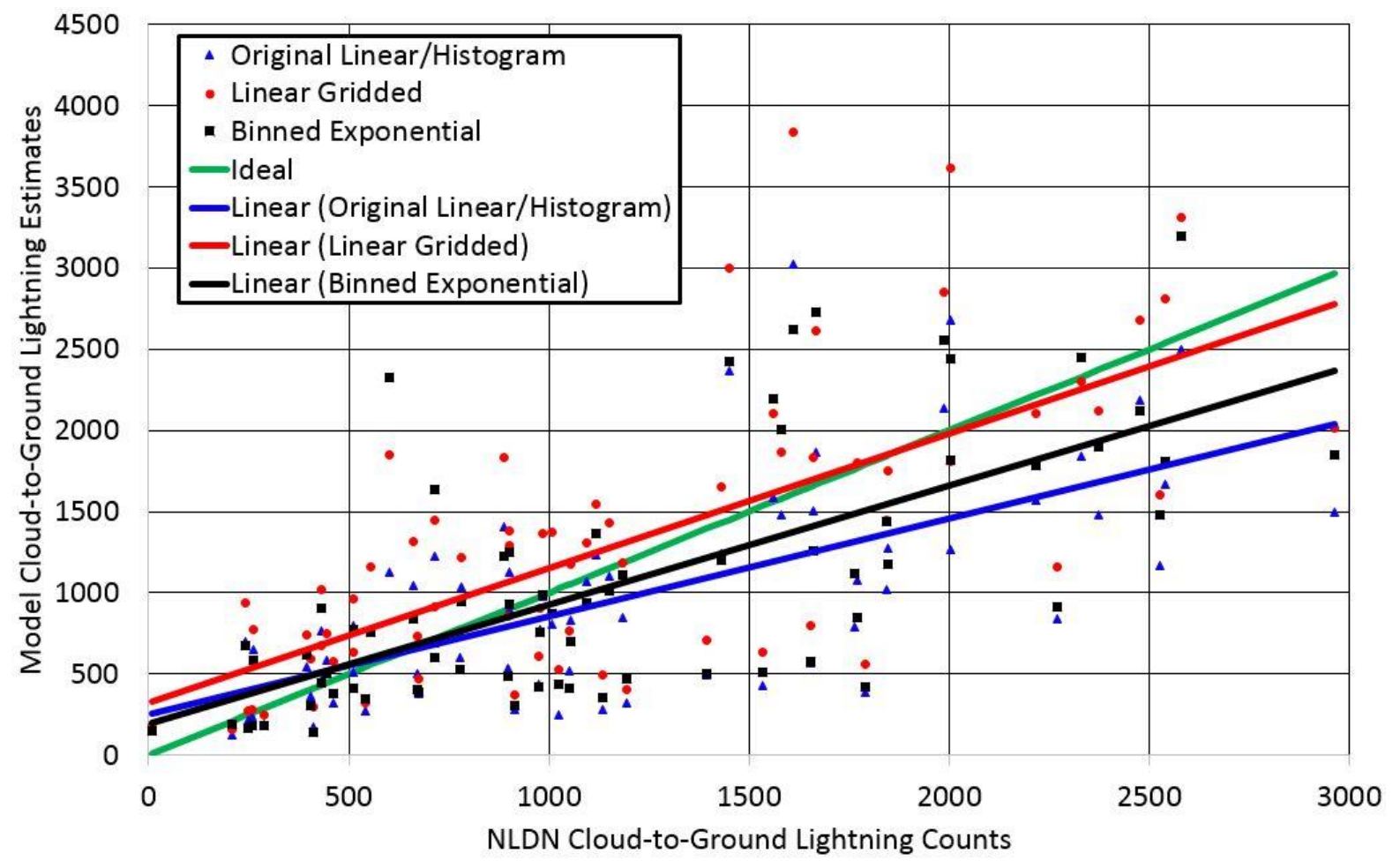


Figure 10. Model Comparisons against NLDN for DMSP Scenes With less than 3000 Cloud-to-Ground Lightning Counts



6. Conclusions and Future Work

Global maps of lightning are only beginning to be collected using ground-based networks of sensors (WWLDN, GLD360, for example Rudlosky and Fuelberg 2010; Orville et al. 2011; Lay et al. 2004) and these will contribute to ~15 years of data from TRMM LIS for the tropics and subtropics, as well as ~4 years of data from OTD (Cecil et al. 2012), and the detailed data in North America (NALDN, Orville et al. 2011) and Europe (Pohjola et al. 2013). Our research shows that by considering the relationship of lightning to thunderstorm ice volume via microwave remote sensing data, maps of cloud-to-ground (CG) lightning can be derived.

DMSP SSM/I microwave remote sensing data have been collected from a network of satellites starting in 1992 and currently continue collect data. We used SSM/I data from the DMSP F13 (1995-2009), F14 (1997-2008), and F15 (2000-Present) satellites and NLDN data to test whether brightness temperature values could be used to derive CG lightning. Our results show great promise for the majority of lightning features (**Figure 10**), although underestimates for extreme lightning events are a problem (**Figure 9**).

The methods in this research (**Figures 6-8**) have been derived using specific thunderstorm cases, but could be applied to all DMSP SSM/I data for the USA, creating a history of lightning strikes similar to that of TRMM LIS (except only for CG) and comparable to NLDN. Furthermore, the methods could be extended to the global scenes captured by DMSP SSM/I. Global verification will be more challenging since ground-based networks are most established in the USA (Orville et al. 2011), but initial estimates could be compared against TRMM LIS for the subtropics and tropics after making assumptions about the latitude-dependent ratio of CG to intracloud lightning (e.g. Prentice et al. 1977).

The most innovative potential in this research is that SSM/I could provide a global time history of CG lightning derived from microwave remote sensing. This time history would be coincident with the period associated with the on-going climate change (e.g. Hartmann et al. 2013), could be used to test recent claims about increasing lightning rates as a function of temperature (Romps et al. 2014), and would also cover parts of the world (ie. the northern hemisphere boreal shield and Arctic) that are experiencing rapid observed climate change.

7. References and Acknowledgments

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Cecil, D.J., et al.., 2012: Gridded lightning climatology from TRMM-LIS and OTD: Dataset description. *Atmos. Res.*; **Hartmann**, D. L., et al. (2013), Observations: Atmosphere and Surface, in *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*; **Kummerow**, C., et al., 1998: The Tropical Rainfall Measuring Mission (TRMM) Sensor Package. *J. Atmos. Oceanic Technol.*; **Lay**, E. H. (2004), WWLL global lightning detection system: Regional validation study in Brazil, *Geophysical Research Letters*; **Liu**, C., et al.2011: Relationships between lightning flash rates and passive microwave brightness PCTs at 85 and 37 GHz over the tropics and subtropics. *J. Geophys. Res.*; **Orville**, et al., 2011: The North American Lightning Detection Network (NALDN)-Analysis of Flash Data: 2001-09. *Mon. Wea. Rev.*,; **Pohjola**, H. (2013), The comparison of GLD360 and EUCLID lightning location systems in Europe, *Atmospheric Research*; **Prentice, S. A.**, (1977), The Ratio of Cloud to Cloud-Ground Lightning Flashes in Thunderstorms, *Journal of Applied Meteorology*; **Romps**, et al. (2014), Projected increase in lightning strikes in the United States due to global warming, *Science*; **Rudlosky**, **S. D.**, et al.., 2010: Pre- and postupgrade distributions of NLDN reported cloud-to-ground lightning characteristics in the contiguous United States. *Monthly Weather Review*; Figures produced using GR2Analyst, Python, and Panoply. Panoply is a NASA product available to the public at http://www.giss.nasa.gov/tools/panoply/