Global Lightning Derived from Satellite-Based Lightning Climatology and CMIP5 Climate Model Output

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1. Background and Motivation

Lightning is widely associated with severe weather, but it also plays other roles in the Earth system. Lightning is energetic enough to break the chemical bonds of molecular nitrogen and oxygen, and is important to atmospheric chemistry through the nitrogen biogeochemical cycle (e.g. Levy et al. 1996; Price et al. 1997). Lightning also acts as essentially the only natural ignition source for fires (Flannigan et al. 2009; Pechony and Shindell 2009; Price and Rind 1994), which are a component of the Earth's carbon cycle.

While lightning is an important phenomenon in the Earth system, global climate models do not directly simulate the process of lightning initiation and discharge. Atmospheric chemistry models, which are critical components of global climate models (e.g. Fiore et al. 2012), require lightning to simulate the natural formation of nitrogen oxides (Price et al. 1997) and rely on climatologies of lightning from satellite-based data sets of lightning or empirically-derived lightning parameterizations (Allen and Pickering 2002). Global fire models rely almost entirely on monthly climatologies of lightning from satellite-based data sets (Kloster et al. 2010; Li et al. 2012; Pechony and Shindell 2009). **Diverse communities of researchers, such as those in atmospheric chemistry, global fire modeling, and even paleoclimatology would benefit from methods to estimate past and future spatiotemporal patterns of lightning.**

Global climate models simulate many parameters related to convection, including total precipitation rate (**Figure 1**), convective precipitation rate, and convective mass flux. Theoretical, field, and higher resolution modeling studies of thunderstorm dynamics have found that the product of the upward and downward mass flux of ice in the presence of supercooled water is related to lightning flash rate (Blyth et al. 2001; Deierling et al. 2008). Thus, there is a physical basis for exploring relationships among **simulated convective parameters and observed lightning**.

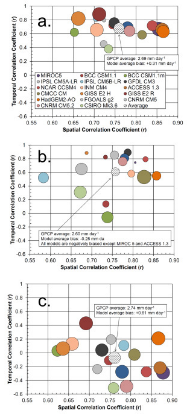

Figure 1. Comparisons of observed precipitation rates from GPCP and simulated by CMIP5 climate models used in this study for (a) all grid cells, (b) land grid cells, and (c) ocean grid cells. The filled, colored circles each represent the absolute value of the difference between mean annual precipitation (MAP) rate from one of the climate models and GPCP. The larger the circle, the larger the difference from GPCP. The average difference is shown with a patterned fill, and the size of this circle is quantified in the inset. The spatial correlation is calculated from a comparison of the MAP from GPCP and from each climate model. The temporal correlation is calculated as a comparison of the mean monthly precipitation from GPCP and from each climate model. A near-perfect match to GPCP would have a very small circle diameter, and the circle would be located in the upper right quadrant.

2. Satellite and Model Datasets

Lightning: Global flash rates are from the Optical Transient Detector (OTD) (Christian et al. 2003) and the Lightning Imaging Sensor (LIS) (Boccippio et al. 2002), the latter of which is on the NASA Tropical Rainfall Measurement Mission (TRMM) (Kummerow et al. 2000) satellite. This study uses the mean monthly climatology dataset (LISOTD_HRMC_V2.3, 0.5° x 0.5° spatial resolution) available at http://thunder.nsstc.nasa.gov/, which is a combination of OTD data (available globally from 1995-2000) and LIS data (available between 38°S and 38°N latitude from 1998-present) (Cecil et al. 2012).

Precipitation: Observations are from the monthly Global Precipitation Climatology Project (GPCP) version 2.2 (Adler et al. 2003; Huffman et al. 2009), which merges data from multiple satellite-based sensors and sounders with ground-based rain gauge data. The merged data product is available at 2.5° x 2.5° spatial resolution from http://precip.gsfc.nasa.gov/. In this study, GPCP is used to evaluate whether climate models are capturing the spatiotemporal patterns in total precipitation (**Figure 1**).

Climate model fields: Simulated total precipitation (P), convective precipitation (C), and convective mass flux (M) are from climate models that contributed to the Coupled Model Intercomparison Project Phase 5 (CMIP5, http://cmip-pcmdi.llnl.gov/cmip5/) data archive. CMIP5 (Taylor et al. 2012) is a coordinated effort among international climate modeling groups to simulate past, present, and future climate to better understand the response of the climate system to human and natural perturbations to energy balance. CMIP5 model output forms the basis for the Intergovernmental Panel on Climate Change Fifth Assessment Report (IPCC 2013) working group reports. P, C, and M are investigated for ocean and land-based grid cells separately.

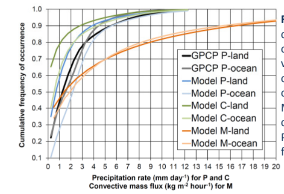

Figure 2. Average cumulative frequency of occurrence for values of P-land, P-ocean, C-land, C-ocean, M-land, and M-ocean from the climate models, and P-land and P-ocean from GPCP.

Initial comparisons: Re-grid all datasets to a 2.0 x 2.5 degree latitude x longitude grid. Then evaluate the data over land and ocean grid cells, with variables labeled accordingly.

What are the most common values? **Figure 2** shows the distribution of total precipitation (P-land, P-ocean), convective precipitation (C-land, C-ocean), and convective mass flux (M-land, M-ocean). P and C tend to depend on land or ocean, while M from models does not. This distribution is useful when assessing uncertainty.

Which convective parameters are related to lightning? Statistical comparisons of lightning (L-land, L-ocean) from OTD/LIS are shown in **Figure 3**. Lightning is much more closely related to land-based parameters, and most directly with M-land. At least, in the linear model.

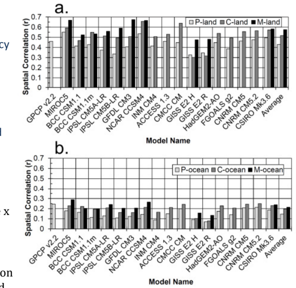

Figure 3. Spatial correlation coefficient between observed lightning flash rate density from OTD/LIS, observed precipitation from GPCP, and precipitation, convective precipitation, and convective mass fluxes simulated by CMIP5 climate models used in this study. Comparisons are presented for (a) land and (b) ocean grid cells. High spatial correlation coefficients indicate that the location of lightning and the corresponding comparison fields are similar.

3. Research Objective

Based on the **Background** and initial analysis of the **Datasets**, this study combines satellite observations of lightning and CMIP5 climate model simulations to derive an empirical non-linear parameterization of lightning in terms of simulated convective parameters. The spatial scale is 2.0 x 2.5 degrees. The temporal scale is monthly.

4. Methods

To address the objective, begin by breaking the problem into land and ocean since convective regimes are expected to be distinct (Williams and Stanfill, 2002), and corresponding OTD/LIS lightning data corroborates this (Cecil et al., 2012). Evaluate how lightning over land and ocean (**L-land and L-ocean**) are related to total precipitation over land and ocean (**P-land, P-ocean**), convective precipitation over land and ocean (**C-land, C-ocean**), and convective mass flux over land and ocean (**M-land, M-ocean**). Bin the data into evenly-distributed bins and evaluate.

Calculate the mean and various percentiles for the values of each model in each bin for all convective parameters (**Figure 4**). From these binned values, calculate the multi-model median (**black line in Figure 4**). The relationship of L-land and P-land for both models and GPCP are very similar, lending weight to the ability of models to capture precipitation over land (**Figure 1**). Although not shown, other percentiles in the bins are similar but displaced. Ocean comparisons are not shown, but summary evaluations are shown in **Table 1**.

The multi-model median of the mean (**Figure 4**) and percentiles are shown in **Figure 5**, along with GPCP in the case of P-land. The spread in statistical values is similar to uncertainty, but this must be judged relative to **Figure 2**.

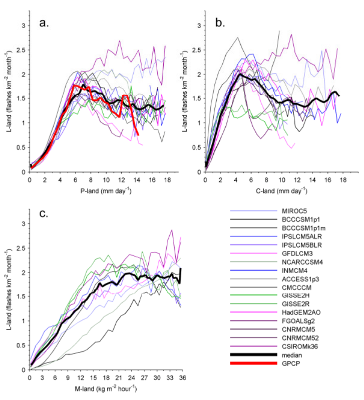

Figure 4. The **mean** relationship between mean monthly L-land (flashes km^{-2} month^{-1}) and binned precipitation for (a) P-land (mm day^{-1}), (b) C-land (mm day^{-1}), and (c) M-land (kg m^{-2} hour^{-1}). The multi-model median line (thick line black) is based on the values from the individual climate models listed in the legend. The mean value of from the GPCP observationally-based P-land dataset (thick red line) is also shown.

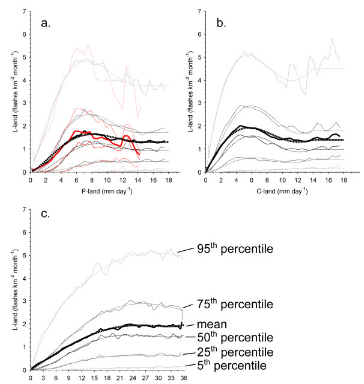

Figure 5. The **mean** and statistical percentiles of the range of values of L-land (flashes km^{-2} month^{-1}) for each value of (a) P-land (mm day^{-1}), (b) C-land (mm day^{-1}), and (c) M-land (kg m^{-2} hour^{-1}). The multi-model median is shown in shades of black, GPCP is the dark grey solid line near the mean values curve in (a). The polynomial parameterizations (e.g. **Equation and Table 1**) for each percentile are overlaid as a dashed lines.

Following previous studies about lightning parameterization (Allen and Pickering, 2002), a 5th degree polynomial is fit to the multi-model median values in **Figure 4** (black line)

$$L = a_1X + a_2X^2 + a_3X^3 + a_4X^4 + a_5X^5$$

where L is the monthly lightning flash rate density (flashes km^{-2} month^{-1}) and X is one of either P (mm day^{-1}), C (mm day^{-1}), or M (kg m^{-2} hour^{-1}) for land or ocean grid cells, and a_1 through a_5 are the fit coefficients (**Table 1**). P and C are the **monthly averaged values**, while M is the monthly value through the 0.44 hybrid-sigma pressure level in the various models. This value of M serves as an indicator of deep convection, and corresponds to ~427 hPa.

input variable	a_1	a_2	a_3	a_4	a_5
P-land (mm day^{-1})	1.43E-01	8.01E-02	-1.52E-02	9.11E-04	-1.82E-05
C-land (mm day^{-1})	6.54E-01	-2.86E-02	-9.63E-03	1.01E-03	-2.69E-05
M-land (kg m^{-2} hour^{-1})	1.31E-01	-1.93E-03	8.87E-05	-6.84E-06	1.17E-07
P-ocean (mm day^{-1})	3.26E-02	-7.16E-03	1.02E-03	-7.31E-05	1.93E-06
C-ocean (mm day^{-1})	5.11E-02	-1.04E-02	1.09E-03	-5.66E-05	1.17E-06
M-ocean (kg m^{-2} hour^{-1})	1.06E-02	6.71E-04	-8.58E-05	2.41E-06	-1.97E-08

Table 1. Fit coefficients for the empirical model for mean lightning flash rate density that occurs as a function of total precipitation (P), convective precipitation (C), or convective mass flux (M) over land (P-land, C-land, M-land) and ocean (P-ocean, C-ocean, M-ocean). The output is monthly lightning flash rate density (flashes km^{-2} month^{-1}).

5. Results

Convective mass flux best captures the spatiotemporal distribution of observed lightning (**Figure 6**). Derived lightning seasonality is captured with 95% confidence over 69% of land, but only 30% of ocean. Spatially, the correlation of derived lightning and observed lightning is 0.74. Overall, global observations suggest lightning occurs at an annual rate of 47 flashes s^{-1}, while lightning from the parameterization occurs at 44 flashes s^{-1}. The parameterization works considerably better over land. Also, as would be expected from a parameterization developed from average lightning, the parameterization tends to underpredict lightning over regions with the highest flash rates and overpredicting lightning for regions with the lowest flash rates.

Comparisons with a previous parameterization (**Figure 7**) suggest that the new parameterization against convective parameters such as C and M from CMIP5 models are a significant improvement, both in magnitude and seasonality.

A robust feature of the relationship between lightning and climate model convective parameters is that lightning flash rate increases linearly (**Figures 4-5**) with increases in C and M for a significant subset of the total range (**Figure 2**) of those convective parameters. Namely, this linear proportionality is evident when C < 4-5 mm day^{-1} and M < 15-16 kg m^{-2} hour^{-1}, which account for about 90% of the values simulated by the climate models.

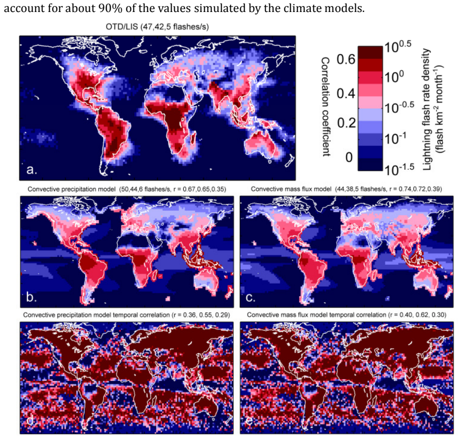

Figure 6. Maps of mean annual lightning flash density (flashes km^{-2} month^{-1}) from (a) OTD/LIS, (b) the parameterization based on C-land and C-ocean, and (c) the parameterization based on M-land and M-ocean. Also shown are maps of seasonal correlation coefficients between OTD/LIS mean monthly lightning and (d) parameterized lightning based on C-land and C-ocean and (e) parameterized lightning based on M-land and M-ocean. Statistics at the top of the lightning maps (a, b, c) are the mean annual flash rates for the globe, land, and ocean (flashes s^{-1}), and the spatial correlation coefficient for globe, land, and ocean between OTD/LIS and the derived lightning maps in b and c. The statistics at the top of d and e are the spatially-averaged mean seasonal correlation coefficients for the globe, land, and ocean.

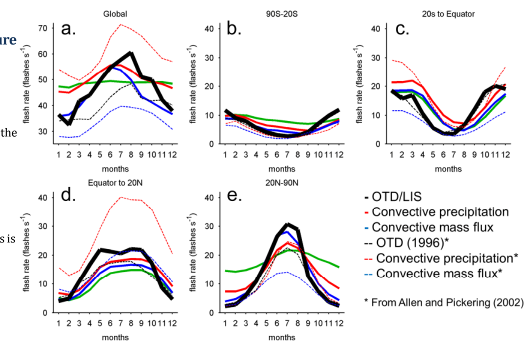

Figure 7. Mean monthly total (land and ocean) lightning flash rates (flashes s^{-1}) from OTD/LIS (black line), the lightning parameterizations using C-land and C-ocean (red solid line) and M-land and M-ocean (blue solid line), and lightning parameterizations from Allen and Pickering (2002) using convective precipitation (red dashed line) and convective mass flux (blue dashed line). Also shown are the 1996 OTD lightning averages from Allen and Pickering (2002). The averages are shown for regions of interest.

6. Conclusions

This presentation focuses on the methods, findings, and ways that satellite data and CMIP5 model output could further be used to understand past, present, and future spatiotemporal distributions of global lightning. The parameterization is immediately relevant to communities of global climate modelers. Paleo, historical, and projection studies using climate models can all take advantage of the results to create simulated lightning maps for studies of the time history of lightning distributions and at least relative changes in magnitude. The linearity found in this study suggests that any changes in convective precipitation and convective mass flux in the future would result in lightning flash rates that change proportionally. This linearity could be a valuable way to assess future lightning distributions suggested by climate model projections of convective parameters such as convective mass flux.

7. References/Acknowledgments

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