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Key Points:
- Global model captures diurnal phase of lightning
- Spatial and seasonal distributions of lightning compare favorably to two observed data sets
- The global model has excessive lightning over the tropical oceans

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Simulated Lightning in a Convection Permitting Global Model

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Abstract High-resolution (grid spacing 10 km in midlatitudes) model simulations using explicitly resolved convection in the Met Office Unified Model, as part of the Horizon 2020 PRIMAVERA project, are used to provide a global lightning climatology. The results show for the first time that global simulations can capture the strong diurnal flash rate variation as well as the seasonal variation. The lightning parametrization uses information about the graupel and ice water path to estimate a total lightning flash rate. Comparisons are made with the World Lightning Location Network (that mainly detects cloud to ground lightning) and combined Lightning Imaging Sensor and Optical Transients Detector data set (that provides an estimate of total flash rate). The model results generally capture the temporal behavior and spatial distribution of the lightning over land. Over the ocean, the lightning in the Intertropical Convergence Zone appears excessive.

Plain Language Summary We use a high-resolution global model that explicitly resolves convection to predict lightning flash rate. The representation of lightning in the model depends upon the upward flux of ice and the amounts of graupel present in the cloud. The model is able to capture the strong diurnal behavior of the lightning activity with the greatest flash rates in the local afternoon. The spatial and seasonal patterns of lightning agree well with two independent observational data sets.

1. Introduction

Electrical storms (and often the associated hail precipitation) can be life threatening and cause costly damage. Having the capability to accurately simulate and forecast lightning would be useful to provide warnings and products for users such as the aviation industry. This work presents the first simulations of global lightning that capture the strong diurnal flash rate variation as well as the seasonal variation.

The simplest approach to estimating lightning flash rates in models empirically links gross properties of convective storms, such as the cloud top height, to flash rates as suggested by Price and Rind (1992). More physically based approaches have been constructed on the assumption that the ice-ice collision noninductive charging mechanism was the dominant route to cloud electrification (Deierling et al., 2005; Latham et al., 2007). This led to a range of parametrizations that link upward ice mass flux and graupel amounts to lightning flash rates (e.g., McCaul et al., 2009). Still more complex approaches have been proposed that simulate the evolving electric field in a storm and subsequent discharge to represent lightning (e.g., Barthe et al., 2012; Fierro et al., 2013). These approaches still have to parametrize the magnitude and sign of charging due to microphysical process rates and temperature based on empirical evidence.

In terms of previous global lightning simulation, Finney et al. (2018) make use of an approach derived from the mass flux diagnosed in the convection schemes. While this is more physically linked to the fundamentals of the electrification process than methods based on cloud top height, it suffers from the shortcoming that in global models, the diurnal peak in convection is around local noon (Birch et al., 2015), whereas lightning over major continental regions is observed to peak in the afternoon (e.g., Cecil et al., 2014; Virts et al., 2013). In this study, by carrying out the convection explicitly, we avoid this problem. However, switching off the convective parametrization relies on the model explicitly simulating the key convective processes accurately, which in reality happen at very small scales (meters to kilometer scales). At currently affordable global resolutions (down to 10 km midlatitude resolution), such processes are likely to be poorly represented (e.g., reduced magnitude of vertical velocities) but can still give insight into the impact of a radically different representation of convection on the global-scale model simulation.

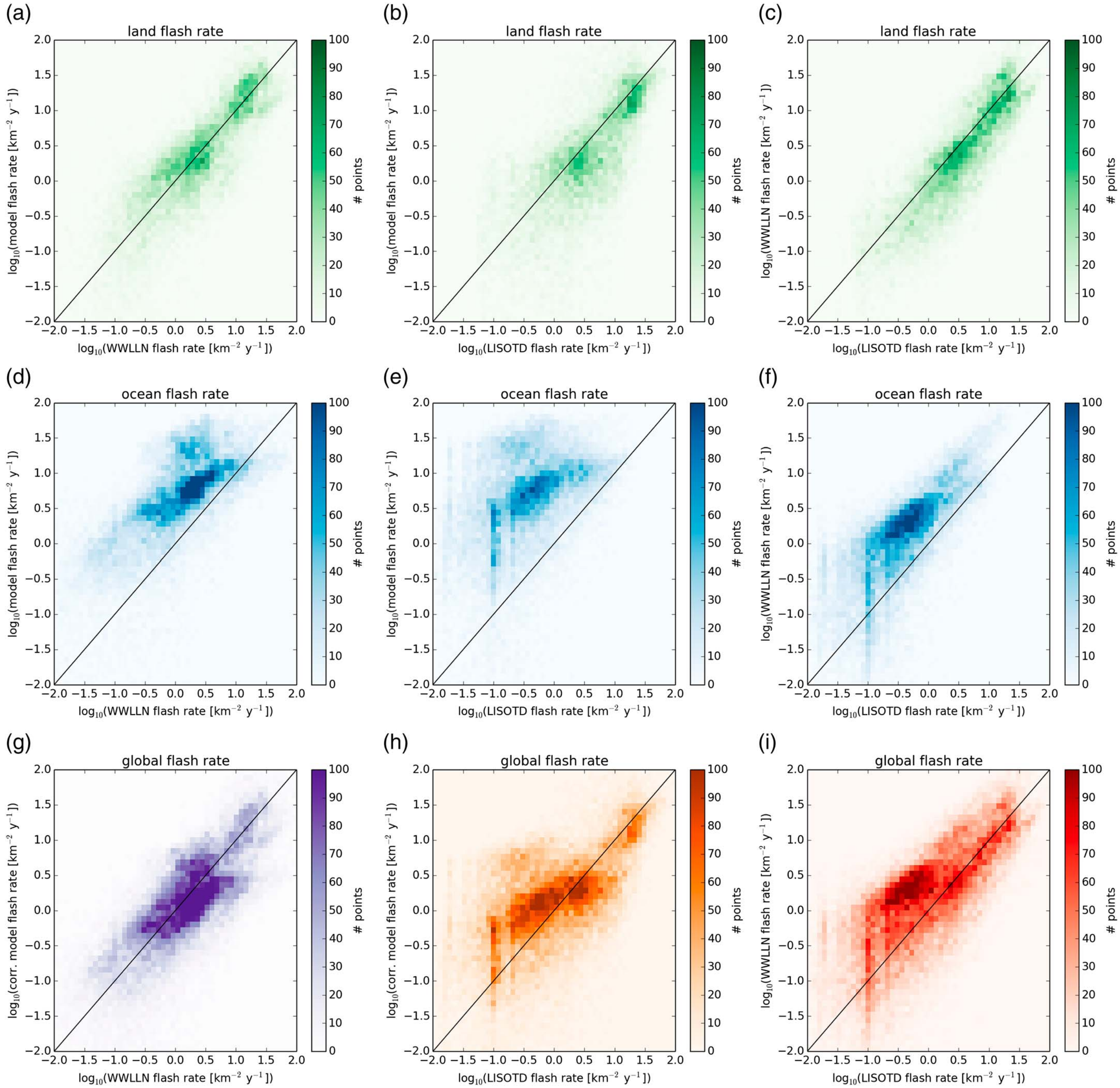

Figure 1. Two-dimensional histograms of lightning flash rate. (a) WWLLN versus model, land. (b) LISOTD versus model,land. (c) LISOTD versus WWLLN, land. (d) WWLLN versus model, ocean. (e) LISOTD versus model, ocean. (f) LISOTD versus WWLLN, ocean. (g) WWLLN versus corrected model for all points (ocean points reduced by factor of 5), (h) LISOTD versus corrected model for all points. (i) WWLLN versus LISOTD for all points. The 1:1 line is shown in black. LISOTD = Lightning Imaging Sensor Optical Transients Detector; WWLLN = World Wide Lightning Location Network.

This study reports on the climatology of lightning produced from a convection-permitting global simulation and compares the results to observed climatologies obtained using two different methods.

2. Model Description

2.1. Global Model Configuration

The configuration of the model is based on the HadGEM3 GA7.1 model (Walters et al., 2017). The explicit convection configuration takes this standard setup, removes the convection parametrization, adds a Smagorinsky

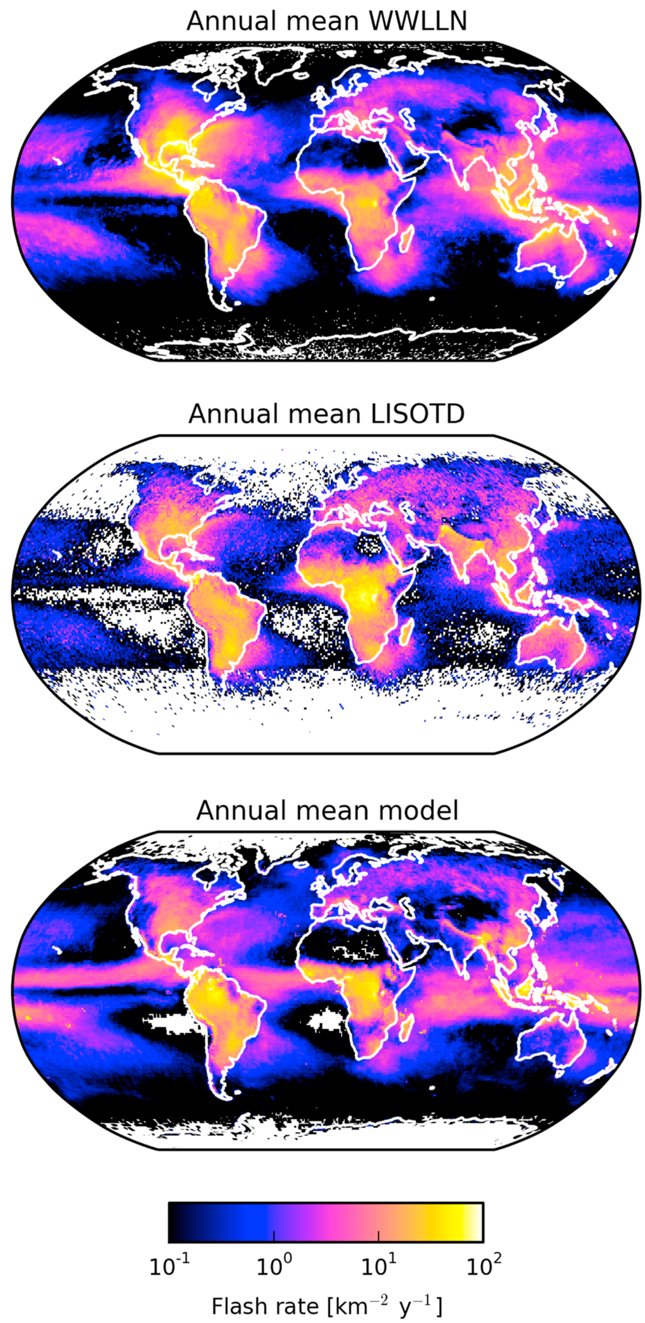

Figure 2. Annual mean flash rate of (top) WWLLN observations, (middle) LISOTD observations, and (bottom) corrected model. LISOTD = Lightning Imaging Sensor Optical Transients Detector; WWLLN = World Wide Lightning Location Network.

subgridscale mixing scheme, prognostic graupel, and hence allows electrification to be included, based on McCaul et al. (2009). Both stochastic schemes are switched off (Stochastic Kinetic Energy Backscatter 2 and Stochastic Perturbed Tendencies), since they use components from the convective parametrization. Several different forcings are used (compared to the standard GA7.1 setup). The ozone, greenhouse gas, sea surface temperature, and sea-ice forcings follow the Coupled Model Intercomparison Project Phase 6 High Resolution Model Intercomparison Project protocol (Haarsma et al., 2016); in particular, the sea surface temperature and sea ice are based on the daily, 0.25-degree HadISST2.2.0 data set (Kennedy et al., 2017). However, unlike standard High Resolution Model Intercomparison Project, the prognostic aerosol scheme remains on in this configuration. The N1280 resolution (10km grid spacing at 50degrees latitude) global model was run for 5 years (2005–2009).

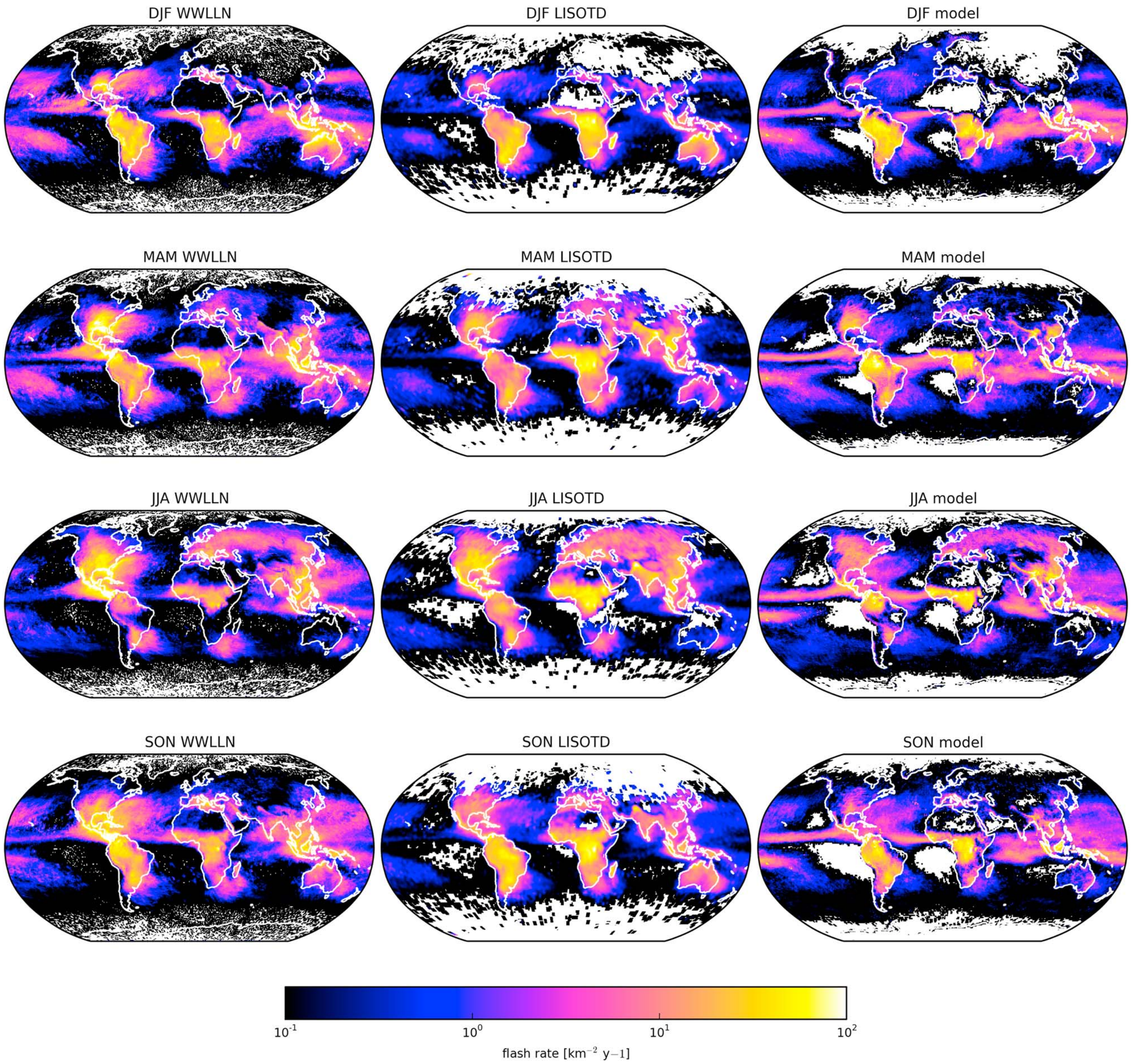

Figure 3. Seasonal mean flash rates from the WWLLN observations (left column), LISOTD (center column), and corrected model output (right column). LISOTD = Lightning Imaging Sensor Optical Transients Detector; WWLLN = World Wide Lightning Location Network; DJF = December-January-February; MAM = March-April-May; JJA = June-July-August; SON = September-October-November.

2.2. Parametrized Lightning

Explicit lightning forecasts are made using the McCaul et al. (2009) scheme coupled to the Unified Model microphysics. This does not directly compute charging and discharging but instead uses a combination of two indices to statistically predict the lightning flash rate based upon empirical results; these are the upward flux of graupel mass at the −15 °C level and the total ice water path (including all ice species and graupel) in the column. This parametrization was derived from a model-observation comparison of severe thunderstorms in the United States. The coupling to the Unified Model is exactly as described in Appendix A of Wilkinson (2017). For this analysis, the global model flash rates were aggregated to 1° resolution.

Wilkinson (2017) examined the performance of the lightning parametrization using all of the operational lightning forecasts generated from the Met Office UK variable resolution model during the month of June 2016. He found that the model performed well in terms of lightning location, with forecasts displaced from the observations by an average of 73.2 km and with 81.3% of lightning forecasts being displaced less than 100 km from

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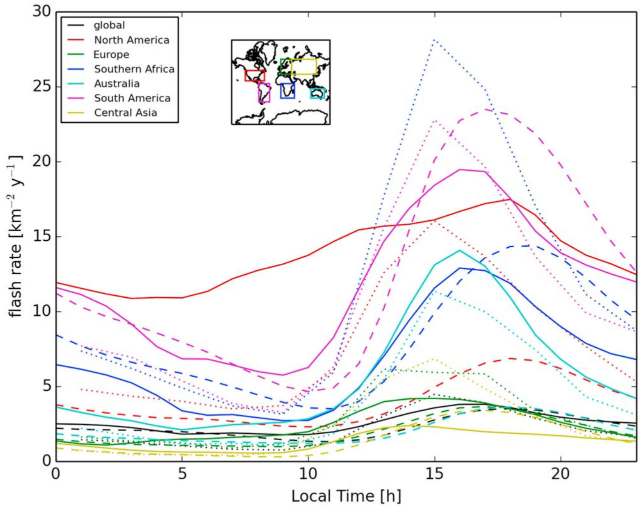

Figure 4. Annual diurnal (solar local time) mean flash rates for different regions. Solid lines are the World Wide Lightning Location Network observations, dotted lines are from the Lightning Imaging Sensor Optical Transients Detector observations, and dashed lines are from the corrected model values.

the observations. The coverage of the model compared favorably with forecast storms being of similar size to those observed, but the model over-forecasts the number of predicted lightning flashes by at least a factor of six in a high-resolution regional setting.

3. Observed Lightning

We use lightning climatologies based on the World Wide Lightning Location Network (WWLLN; Virts et al., 2013) that typically detects cloud to ground lightning (corrected for detection efficiency, Hutchins et al., 2012) and the combined Lightning Imaging Sensor Optical Transients Detector (LISOTD) data based on satellite-borne sensing of optical flashes. The WWLLN climatology extends the Virts et al. (2013) data range from 15 April 2009 to 14 April 2016 (pers comm Virts). The lightning location is obtained from a global network of sensors that detect very low frequency radio waves and use time of group arrival analysis to estimate a location. Accuracy of the location for the network coverage in 2011 was better than 5 km for 61% of the observations. The absolute detection efficiency of cloud to ground lightning flashes is thought to be around 11% from comparisons over the United States (Dixon et al., 2016). Bürgesser (2017). Thompson et al. (2014) performed detailed comparisons of the LIS and WWLLN data and found that while the WWLLN had a low detection efficiency over land (1% to 10%), it was better over oceans (>16–20%). The climatology for WWLLN presented here has been corrected using a single-assumed detection efficiency of 10%. Global maps of flash rate at 1° resolution were provided for annual, seasonal, and annual hourly resolved means.

The LISOTD-combined climatology is derived from optical flash sensors on satellites in low earth orbit: one sensor is on board a satellite in an equatorial orbit (LIS), while the other sensor (OTD) is on a polar-orbiting satellite. The gridded climatologies are described in Cecil et al. (2014) and have been corrected for detection efficiency that ranges from 49% to 88% based on sensor, time of day, and geographical location. This method is capable of detecting both cloud to ground and cloud to cloud lightning. Global maps at 0.5° and 2.5° resolution derived from data obtained from 1995 to 2015 have been regridded onto 1° resolution to allow comparison between data sets. No attempt has been made to harmonize the WWLLN and LISOTD data sets apart from the gross correction of the WWLLN data set assuming a 10% detection efficiency and any differences serve as a measure of uncertainty.

4. Results

Figure 1 shows comparisons between observed flash rate from the WWLLN and LISOTD data sets and the model predicted values. Over land (Figures 1a–1c), comparison between the model and observations as well as between the two observation data sets indicates that the majority of points lie within half an order of magnitude of the 1:1 line. Linear regression (in logspace) parameters indicate that intercepts are between −0.2 and 0. Correlation coefficients are 0.80, 0.65, and 0.85 for WWLLN versus model, LISOTD versus model, and WWLLN versus LISOTD, respectively. In contrast, the comparison over the ocean (Figures 1d–1f) indicates that the model is overestimating lightning flash rate relative to the climatologies by a factor of 4–6.5 based on linear regression (in logspace). We note that Finney et al. (2014) found that lightning over ocean required a lower value of the constant relating upward ice flux to flash rate when comparing reanalysis and LIS data and consequently used different values in their lightning parametrization over land and ocean. In these simulations, a single value was used everywhere, but we can represent the effect of choosing a lower value over ocean by dividing by a factor of 5.0 based on the difference between the WWLLN, LISOTD, and model. It can also be seen that WWLLN lightning flash rates are consistently a factor of ~2 larger than the LISOTD flash rates over the ocean (Figure 1f). Using the calibrated model flash rate (factor of 5 reduction over ocean), the comparison with the observations over land and ocean together (Figures 1g and 1h) indicates correlation coefficients from linear regression in logspace of 0.76 and 0.54 for the WWLLN versus model and LISOTD versus model, respectively. The comparison of the two observational data sets (Figure 1i) has more spread due to the

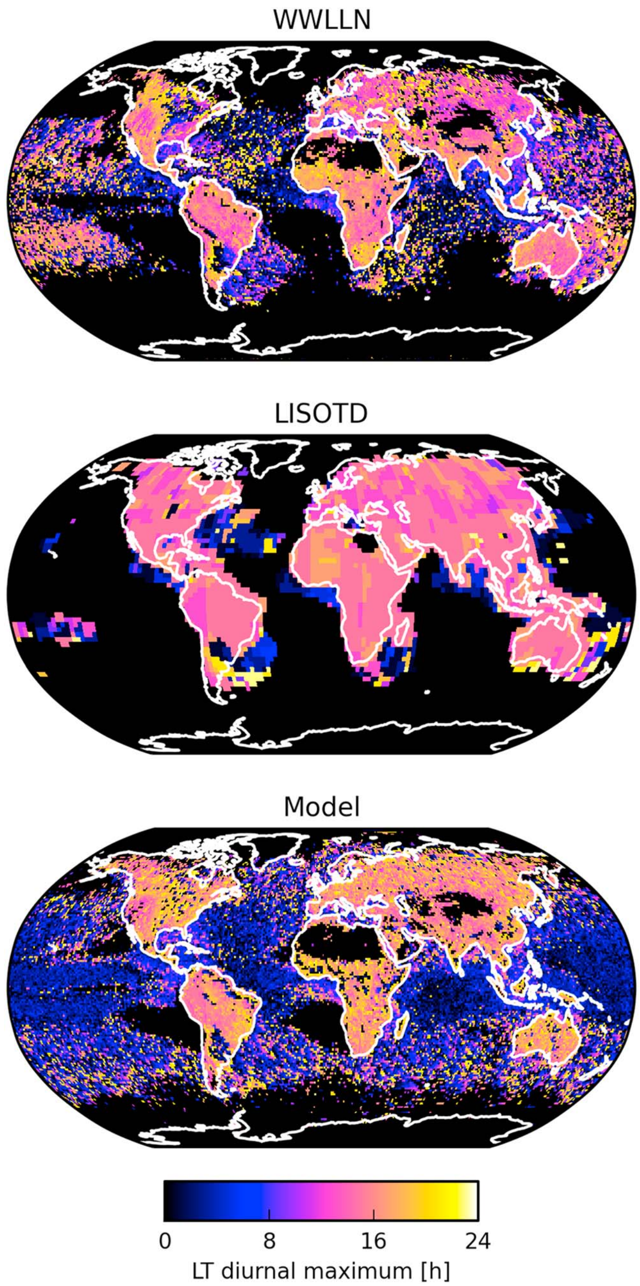

Figure 5. Global map of the solar local time of maximum flash rate from WWLLN (top), LISOTD (middle), and model (bottom). LISOTD = Lightning Imaging Sensor Optical Transients Detector; LT = local time; WWLLN = World Wide Lightning Location Network.

disagreement over ocean and a correlation coefficent of 0.73. For the remaining figures, the corrected model data will be used.

Annual mean flash rates (Figure 2) indicate that much of the spatial distribution of lightning is captured. For example, the maxima in the maritime continent, equatorial Africa, and South America (e.g., Venezualan hotspot) are reproduced. In more detail, regions such as the edge of the Himalayan plateau and the Andes are highlighted. More subtly, the arc of less intense flash rates spanning from Europe through central northen Asia toward China is evident, as well as the Rockies/plains split over North America. Spanning the land and into the oceans, there are regions of moderate flash rates extending from the eastern coasts of Argentina, South Africa, and Australia. Over the equatorial ocean regions, it is clear that the model appears to be predicting excessive activity in the Intertropical Convergence Zone.

Seasonal results (Figure 3) indicate that the model captures the annual migration of the maxima over land with the greatest values occurring during the summer season in each hemisphere. However, North America does not appear active enough in the model throughout the year, and flash rates in the Indian Ocean appear overdone.

To examine the diurnal behavior of the lightning in the model, Figures 4 and 5 show daily flash rates for specific regions and maps of the local time of occurrence of the maximum for each grid box, respectively. Hourly resolved annual mean flash rates indicate for the regions chosen that the maximum appear to occur from 13 to 18 local solar time for both the model and observations. The magnitude of the diurnal variation agrees to within factor of three for the calibrated model and observed flash rate. The regions with the worst agreement in terms of magnitude are North America and Australia. Comparing the time of maximum flash rate in a global sense clearly indicates (Figure 5) that the land regions are dominated by maxima in the midafternoon (15 local time [LT]) to evening (20LT), while over the ocean, more early morning values (2–5 LT) are prevalent. Spatial patterns across continents also seem to be reproduced to some extent: for instance, the contrast between the North American Rockies and plains to the east and the region of morning minima seen over Paraguay and Argentine in South America. Less well done is the variation across Africa and Australia.

5. Discussion

The variable detection efficiency of WWLN relative to the LISOTD over land and ocean has been explored by Bürgesser (2017) and Thompson et al. (2014). This variability explains why a single global detection efficiency correction applied to the WWLLN data leads to differences between the LISOTD and WWLLN data over ocean. Reasons given for WWLLN detection efficiency being better over ocean include improved radio propagation efficiency, increased energy involved in lightning, and differences in the character of the lightning over ocean. While no firm conclusions can be drawn, the fact that the modeled lightning rates need to be reduced over ocean relative to the land suggests that the simple link to ice/graupel amounts and upward flux of ice is not sufficient to capture this variability. Another possibility is that the model is overpredicting graupel over ocean that may be linked to the use of atmosphere-only simulations where the sea surface temperature does not have a diurnal behavior. However, it is unclear if this would lead to artificially high graupel and hence lightning rates. It will be interesting to see if the more complex prognostic charge approaches to predicting lightning can do better at representing this ocean-land split in the behavior of the lightning or alternative diagnostic lightning representations (e.g., Lopez, 2016; Petersen et al., 2005).

The good correlation between the flash rates over land predicted by the model and from the observations ($r = 0.65, 0.80$) is a useful result, but the welcome lack of bias between the observations and model is likely to be coincidental. The same lightning parametrization in the same model but at higher resolution was seen by Wilkinson (2017) to overpredict the lightning flash rates by a factor of ~6. For these simulations, the coarser grid resolution leads to smaller-resolved vertical velocities which in turn will reduce column integrated amounts of ice and graupel used in the parametrization to predict lightning. Thus, the dampening of the lightning flash rates is likely to become stronger with increased model grid length. We note that the McCaul et al. (2009) lighting parametrization was calibrated against severe thunderstorms over the continental United States, and therefore, any model employing a lightning parametrization derived from high-resolution observations for regional scale modeling will have to be recalibrated for deployment in a global setting.

The strong diurnal modulation in flash rate with a peak in the local late afternoon in agreement with observations is a strong feature of this climatology. Because of the intimate link between lightning and convection, the ability to explicitly do convection even if it is not accurately represented at this resolution captures the important physics for this process. This result suggests that it would be possible to use this approach to produce global lightning forecasts that could be used by the aviation industry, for example.

Besides the need to increase the model resolution to capture the evolution and character of the convective clouds better, there is also a need to refine and improve the microphysical process rates and particle size distributions that control the evolution of the parameters used to predict lightning flash rates.

6. Conclusions

Five years of data from a high-resolution (~10 km) global convection-permitting model have been used to form a global climatology of lightning flash rates. This model climatology was compared to observed climatologies created using radio and optical techniques. The results indicate that the model is able to capture the diurnal behavior of lightning with peak activity occurring in the late afternoon and early evening over land. Seasonal and annual distributions of lightning capture the observed distributions over land. The model overestimates the lightning flash rate over the oceanic equatorial regions.

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