

Global patterns of lightning properties derived by OTD and LIS by S. Beirle et al.

Reply to anonymous referee #2

Green: Reviewer comment.

Black: Authors' reply.

We thank Reviewer #2 for the constructive comments and suggestions. Below we reply to them one-by-one.

Reviewer comment: 1. No reference is made to the special properties that lightning in coastal regions have, and the analysis is divided strictly according to land/ocean areas. Many research papers have been published which account for the special properties of lightning flashes occurring within several ~ 10 s of km from the land-sea border. These flashes exhibit properties which differ from marine and oceanic flashes, as well as from those that occur inland. For example: (Seity et al., JGR, 2001; Petrova et al., Atmos Res. 2014;). The $1^\circ \times 1^\circ$ grid resolution is probably too coarse to achieve this distinction and so important details differentiating between lightning characteristics are lost.

Authors' reply: We thank the reviewer for this suggestion, and we have re-analysed the data accordingly. In order to classify coastal flashes appropriately, we now first sort the flashes to separate land/ocean/coast bins on a finer resolution of 0.1° . For the display of global maps, we keep the 1° resolution to have sufficient statistics.

This re-analysis has the following outcomes:

1. Due to the better resolution of the surface classification, the separation of land/ocean is more appropriate now. Several flashes, which have been classified as continental based on our simple 1° mask in the discussion paper, are now identified as coastal or oceanic. Consequently, the mean flash properties over land are now even lower (Fig. 3), and the separation of flash "strength" is even clearer between land and ocean. The y-axis of Fig. 3 has been adopted accordingly.
2. Coastal flash properties generally fall in-between those of land and ocean:

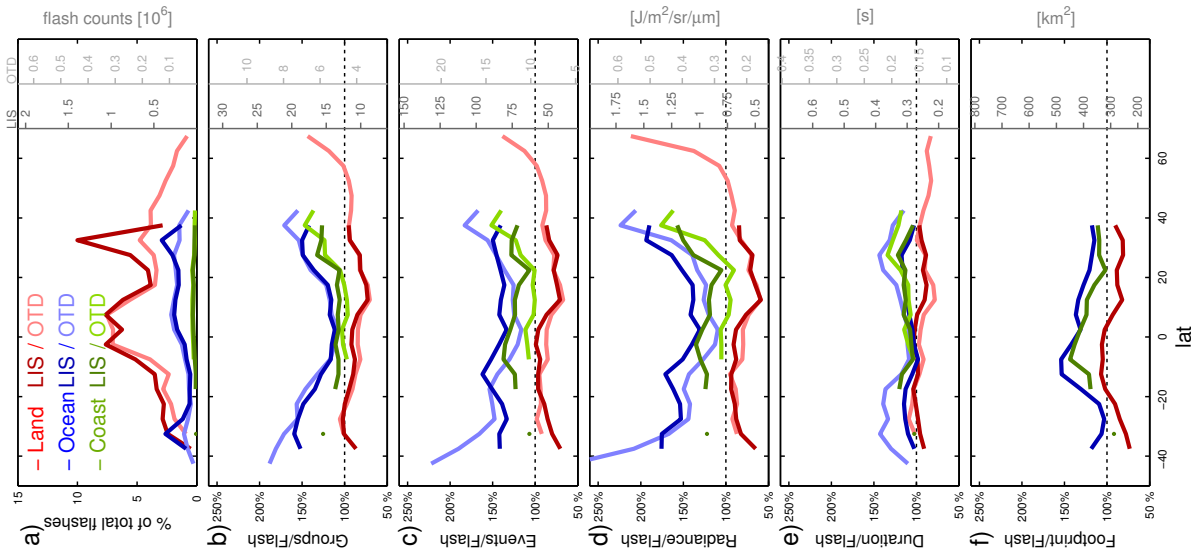


Fig. R1: Latitudinal dependency of mean flash properties separately for land (red), ocean (blue), and coastal regions (green). Error bars ($\approx 10\%$) are omitted to keep the plot clear.

However, in the revised manuscript, we do not include the coastal flashes in Fig. 3 in order to not distract from the key message, i.e. that there is a significant difference between mean flash properties for ocean and land, but none between (normalized) OTD and LIS. But we now include the mean statistics of coastal flashes to tables 2 and 3, and provide Fig. R1 in the supplementary material as well. However, as we do not observe coastal flashes to be “special”, we keep the respective discussion in the manuscript quite short.

3. The re-analysis also brought a bug to light: While optimizing the threshold for the SAA masking at an early stage of the analysis, the complete LIS dataset has been accidentally appended to the total counts instead of overwriting them. Thus, the total number of LIS flashes in the discussion paper is too high by a factor of 2. Fortunately, this bug has no effect on the per-flash results, as just every quantity was doubled, while the ratios remain unchanged (and this is also the reason, why this bug was not directly noticed, as all maps of per-flash quantities are unaffected). In the revised manuscript, this bug is fixed, and the total flashes (Fig. 2a, Fig. 3a (absolute y-axis for LIS), table 3) are correct now. The threshold of minimum counts applied in Figs. 1 and 2 has been adopted accordingly (from 100 to 50). The resulting OTD maps thus now include more unmasked pixels.

Reviewer comment: 2. What is urgently missed from the analysis presented in section 3 is a depiction of lightning activity as a function of time, namely an hourly diurnal cycle. While the authors use the day/night division in tables 2 and 3, the type of hourly lightning number (perhaps shown by grouping flashes in different continents or latitude strips) is of unique importance to the study of the Global Electrical Circuit as exemplified by the Carnegie Curve (see for example reviews by Rycroft et al., SSR, 2008; JASTP, 2012). The authors should add this extra analysis to this section, and compare it with the daily curves of the ionospheric potential gradient (Harrison, 2013).

Authors’ reply: The diurnal cycle of lightning activity and its link to the Global Electric Circuit (GEC) is indeed an exciting and important aspect, which has been studied for OTD and LIS flashes in great detail recently:

Mach, D. M., Blakeslee, R. J. and Bateman, M. G.: Global electric circuit implications of combined aircraft storm electric current measurements and satellite-based diurnal lightning statistics, *J. Geophys. Res.*, 116(D5), D05201, doi:10.1029/2010JD014462, 2011.

Blakeslee, R. J., Mach, D. M., Bateman, M. G. and Bailey, J. C.: Seasonal variations in the lightning diurnal cycle and implications for the global electric circuit, *Atmospheric Research*, 135136, 228243, doi:10.1016/j.atmosres.2012.09.023, 2014.

In our study, we focus on mean per-flash quantities. For this approach, we consider the original OTD/LIS flash counts without any correction for viewing time or detection efficiency (DE). The diurnal cycle of mean flash properties thus has to be interpreted with caution:

1. The OTD/LIS DE has a diurnal cycle; during daytime, background radiances are far higher than during night, such that DE is decreased during daytime (see Boccippio et al., 2002, and Christian et al., 2003 (Fig. 3 therein)).

2. Due to the conservative masking of the area affected by the SAA, flashes over South America are almost completely skipped in our analysis.

Nevertheless, we have investigated the diurnal patterns of mean flash statistics (Fig. R2).

Flash counts as function of LT (Fig. R2 a), left) generally show the diurnal pattern reported before (e.g., Figure 14 in Mach et al., 2011), i.e. a late afternoon maximum over land, and a weak variability over ocean. The diurnal patterns of flash counts look slightly different for OTD and LIS, which is probably due to the different diurnal cycles of the respective DE.

Flash counts as function of UT (Fig. R2 a), right) show a peak at about 14-16 UTC, which look different from previous studies (e.g., Figure 4 in Mach et al., 2011, with a maximum at about 20 UTC). This discrepancy is caused by the conservative masking of the SAA, which essentially skips the South American continent completely from our analysis.

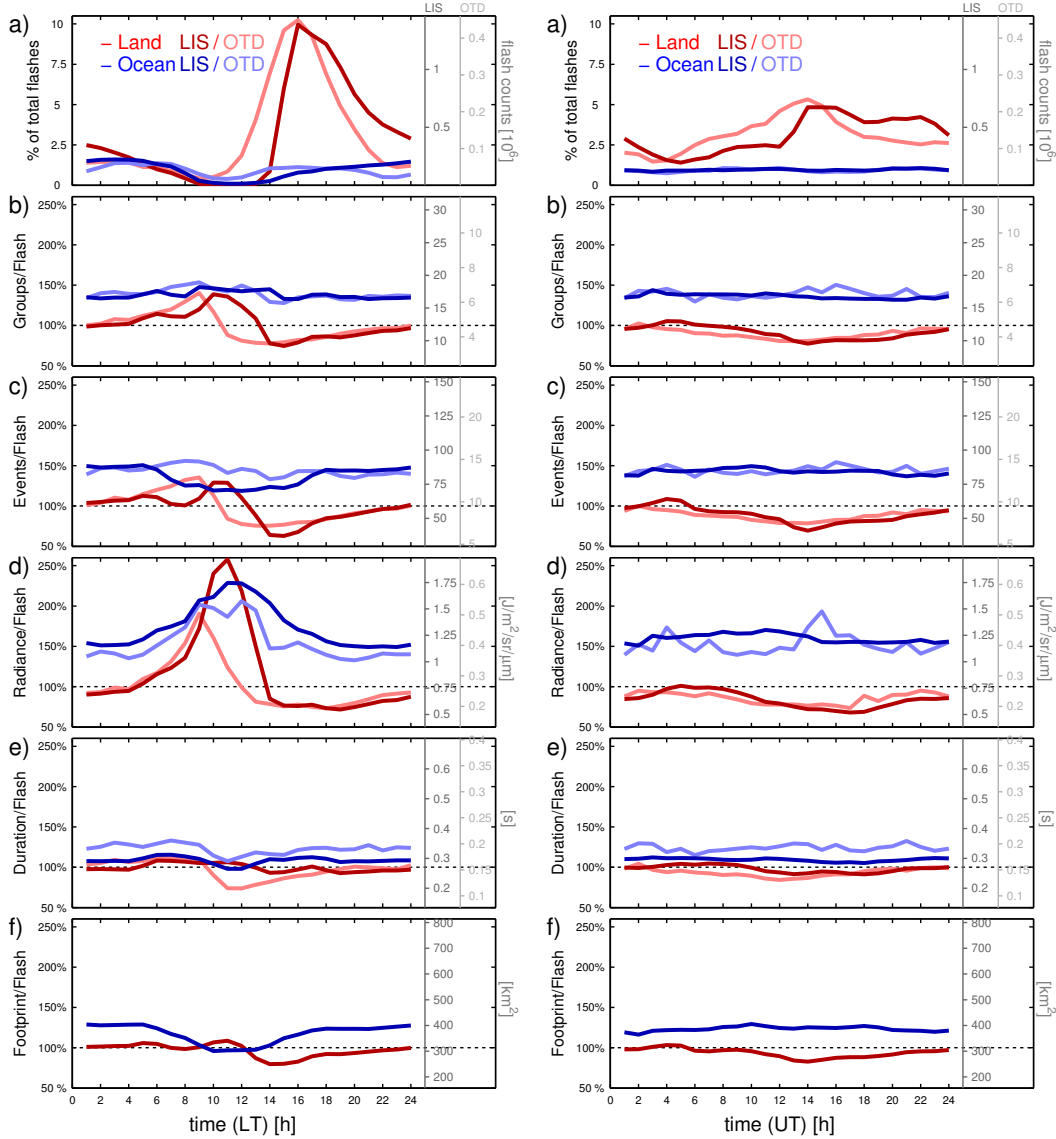


Fig. R2: Dependency of mean flash properties on time of day in LT(left) and UT(right), separately for land (red) and ocean (blue).

The investigated per-flash radiance (d) reveals a strong dependency on LT, with a noon maximum, where flash counts are minimum. This can probably be mostly explained by DE: due to the high background under daylight conditions, the weaker flashes are missing in the statistics, and mean flash properties are thus biased by bright events. The number of groups and events per flash is enhanced at noon as well (over continents), but far less than radiance per flash. In the afternoon, groups and events per flash show a minimum over continents, whereas for oceanic flashes, dependencies on LT are quite weak (except for radiance).

The dependency of per-flash quantities on UT is generally weak, but one important systematic pattern can be observed, i.e. a minimum of most quantities over land at about 14:00 UT. This is caused by the fact that at that time, lightning is most active in Africa, a region with rather moderate mean flash properties.

As the aspect of diurnal patterns is indeed important, but quite difficult to interpret for our approach, we deal with this topic in the supplementary material. In the manuscript, we add a short discussion to recent studies and our results in the supplements. The most relevant outcome from our analysis with respect to the GEC is that flashes in Central Africa are frequent, but probably rather weak. Thus, studies on the diurnal cycle (UT) of flash counts or flash rate densities might overestimate the contribution from African flashes to the global

pattern at about 14:00 UT (compare Fig. 11 in Harrison, “The Carnegie Curve”, 2012).

Reviewer comment: 3. The authors correctly point out that the IC/CG ratio is latitude dependent and that one cannot use a single “US type” value (if such a value even exists). The topic should be expanded in view of earlier work, such as Price and Rind (GRL, 1993), Soriano et al. (JGR, 2007) and Mackerras et al. (JGR, 2006). It is always better to relate these differences to thermodynamics and cloud physics considerations, as exemplified by Mushtak et al. (Latitudinal variation of cloud-base height and lightning parameters in the tropics; Atmos. Res., 222- 230, 2005) than to just leave them as a statement.

Authors’ reply: There seems to be a misunderstanding: We are not proposing to use a single “US type” value of the IC/CG ratio. Instead, we discuss how far the observed regional patterns of mean flash statistics can be related to the (poorly known) regional variations of the IC/CG ratio, and if the latter might even be deduced from OTD/LIS statistics. Koshak (2010) has shown that the number of groups per flash, events per flash, etc. is, on average, different for IC and CG flashes, based on direct comparisons of OTD with coincident NLDN measurements. These values of the “US type” mean number of groups per flash etc. for IC and for CG flashes are marked in the colorbars of Fig. 1. But the regional patterns of flash statistics often exceed the interval spanned by the US-type IC and CG values, as there are several factors affecting the statistics of OTD/LIS flash properties besides the IC/CG ratio. However, estimates of the IC/CG ratio can be deduced from OTD/LIS measurements of the maximum group area in a flash (Koshak, 2011; Koshak and Solakiewicz, 2011; Koshak and Solakiewicz, 2014¹).

In the revised manuscript, we have extended the respective paragraph, including additional references, and clarified the line of argument.

Reviewer comment: 4. The discussion of the origin of the land-ocean differences in lightning properties seems incomplete without focusing on the properties of thunderclouds over the different surfaces. See for example the paper by Williams and Stanfill (The physical origin of the land-ocean contrast in lightning activity; C. R. Physique 3, 1277-292, 2002). The authors need to enlarge this part of the manuscript.

Authors’ reply: We have added a new sub-section on the land-ocean contrast to the discussion, and refer to Williams and Stanfill. However, the reasons for oceanic flashes being “stronger” than continental flashes remain unclear and require further investigations.

Reviewer comment: 5. The discussion of the possibility to compare flash multiplicity derived from NLDN and other like systems and the LIS/OTD statistics is interesting and offers intriguing possibilities. I expect the authors to review the topic more thoroughly and to suggest a practical way of doing this. The multiplicity of strokes is a common and well-used parameter in lightning climatology, with special importance to the detection efficiency of lightning detection system. It is latitude/season dependent and has been thoroughly studied by many groups (see Pinto et al., 1999; Schulz and Diendorfer, 2006). It would be interesting to compare this space-based flash duration vs. multiplicity values to the video- based studies conducted by Fleenor et al. (AR, 2009), Saba et al. (JGR, 2010) and Ballarotti et al. (JGR, 2012).

Authors’ reply: We agree that it would be great if OTD/LIS flash duration could be used to deduce the flash multiplicity. However, we do not think that this is easily possible, as “in general, the larger the number of component strokes, the longer is the duration of the flash, but there is no definite relationship between the number of strokes and the duration” (Malan et al., 1956).

The comparison of mean flash duration to local multiplicity values provided in literature as referred to by the reviewer is difficult, as these studies are quite local, and especially because they only analyse CG flashes, while in our statistical analysis, the means are probably dominated by IC flashes.

Thus, this interesting topic needs further investigation which has to be based on detailed comparisons of flash durations to multiplicity for flashes coincidentally detected by OTD/LIS and ground-based sensors, ideally in different regions of the world. Such an analysis is beyond the scope of this study.

¹Koshak, W. J., and R. J. Solakiewicz, 2014: A method for retrieving the ground flash fraction and flash type from satellite lightning mapper observations, J. Atmos. Oceanic Technol., in review.

Reviewer comment: 6. The issue of positive ground flashes is not well covered and is discussed only in passing, and in my mind is the weakest point in the paper. The reference to the classic Kitagawa and Michimoto (1994) paper misses many new findings concerning winter thunderstorms and I urge the authors to update their section 4.6 to reflect this (the Rakov and Uman 2003 book is a good place to start). Also, it should be noted that the high percentage of +CG does not occur only in winter thunderstorms but also in MCSs at different stages of evolution (Stolzenburg et al. MWR, 1994) and as shown by Lyons et al. (Science, 1998) may reflect ingestion of smoke aerosol particles into the clouds that alters their charge structure and increase the fraction of +CGs.

Authors' reply: We agree that this point was only touched in the discussion paper.

Initial point of this line of thought was the observation of the increase of per-flash groups/events/radiance with latitude (Fig. 3), which is essentially caused by wintertime flashes (old Tables 2+3, new Figures in supplement). In the revised manuscript, we have thus extended the analysis of the seasonal dependency, and added global maps for LIS and latitudinal dependencies, analogue to Figs. 2 and 3, for each season to the supplementary material. These plots illustrate more clearly that the increase of events/flash and especially radiance/flash with latitude is particularly strong in the respective hemispheric winter. Highest values are observed over Japan in winter, where mean radiance/flash is increased by a factor of 5 for LIS and even 8 for OTD (new tables 2+3). We have extended the respective result section, and added a new section about Japan winter lightning to the discussions, replacing the section on CG+ flashes in the discussion paper. We still mention CG+ as a possible reason for the high flash strength in winter. But we do not extend the discussion of CG+ flashes and their possible link to mean flash properties, as this would be pure speculation at this point; e.g. possible effects of CG+ in MCSs on the observed flash properties are hard to evaluate without additional, regionally resolved information on the fraction of CG+ flashes.