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Global patterns of lightning properties derived by OTD and LIS

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Abstract. The satellite instruments Optical Transient Detector (OTD) and Lightning Imaging Sensor (LIS) provide unique empirical data about the frequency of lightning flashes around the globe (OTD), and the tropics (LIS), which has been used before to compile a well received global climatology of flash rate densities.

Here we present a statistical analysis of various additional lightning properties derived from OTD/LIS, i.e. the number of so-called "events" and "groups" per flash, as well as the mean flash duration, footprint and radiance. These normalized quantities, which can be associated with the flash "strength", show consistent spatial patterns; most strikingly, oceanic flashes show higher values than continental flashes for all properties. Over land, regions with high (Eastern US) and low (India) flash strength can be clearly identified. We discuss possible causes and implications of the observed regional differences. Although a direct quantitative interpretation of the investigated flash properties is difficult, the observed spatial patterns provide valuable information for the interpretation and application of climatological flash rates. Due to the systematic regional variations of physical flash characteristics, viewing conditions, and/or measurement sensitivities, parametrisations of lightning NO_x based on total flash rate densities alone are probably affected by regional biases.

1 Introduction

Lightning is an important natural phenomenon that is studied in various scientific disciplines, e.g. high-energy physics, risk assessment, meteorology, hydrology, climate, and atmospheric chemistry. However, the quantitative understanding of the factors determining the occurrence and intensity of lightning, and thus its spatio-temporal patterns, is still rather poor.

The Optical Transient Detector (OTD) (Boccippio et al., 2000b; Christian et al., 2003) and its successor, the Lightning Imaging Sensor (LIS) (Christian et al., 2000), provide for the first time a global, empirical time series of flash observations from space. OTD was delivered on a Pegasus rocket (Microlab-1) at $\approx$ 710 km altitude, and was operated from April 1995 until March 2000. Its field-of-view covered a 1300 km $\times$ 1300 km region of the Earth with a spatial resolution of 10 km and a temporal resolution of 2 ms. LIS, part of the Tropical Rainfall Measuring Mission (TRMM) was launched in November 1997 and is still presently in operation. In contrast to OTD, LIS observations are restricted to the tropics ($\pm 38°$) due to the lower altitude (350 km until August 2001, 400 km thereafter) and inclination of the TRMM orbit. The LIS field-of-view covers 600 km $\times$ 600 km with a nadir spatial resolution of about 4 km.

The lightning climatology derived from OTD/LIS (Cecil et al., 2012) provides a unique observational basis for the global flash distribution. This enables quantitative analyses of various quantities related to lightning. For instance, OTD/LIS flash rate densities, i.e. the number of flashes per time and area, can serve as validation reference for parametrised flash rate densities. Such parameterisations are required in global chemistry models to account for the production of nitrogen oxides (NO_x=NO+NO_2) by lightning, which has high impact on tropospheric chemistry as it enables catalytic production of tropospheric ozone. Several flash parameterisation schemes exist which are based on various input parameters, e.g. cloud top height, updraft velocity, or convective precipitation. Tost et al. (2007) compared several up-to-date flash parameterisations and showed that they differ substantially from each other, and none is capable of reproducing the OTD/LIS flash rate climatology satisfactorily.

OTD/LIS flash rates are also directly used to up-scale various per-flash parameterisations. For instance, Nesbitt et al.

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(2000) and Murray et al. (2012) estimate the global lightning NO_x (LNO_x) production by scaling the climatological flash rate densities by a per-flash LNO_x production factor, which is, however, rather uncertain as well (Schumann and Huntrieser, 2007), and the assumption of one globally valid number of the LNO_x production per flash is a coarse simplification.

Similarly, precipitation parameters, e.g. the rain-yield (Takayabu, 2006) or ice precipitation (Blyth et al., 2001) can be up-scaled globally from a flash climatology.

Most of such studies involving the OTD/LIS climatology employ the provided flash rate densities. These are derived from the number of detected flashes, without any differentiation of flash characteristics. However, flash properties, like Intra-Cloud (IC) vs. Cloud-to-Ground (CG) flashes, channel length, channel current, multiplicity, or energy, are highly variable. Consequently, empirical relations of various quantities to flash counts show very high scatter (see e.g. the correlations of flash rates with cloud heights shown in Ushio et al. (2001)).

In addition to statistical fluctuations, flash characteristics (particularly channel length) vary systematically on regional and temporal (seasonal) scales as a consequence of differences in cloud depth and thundercloud charge extent; see for example the comparison of summertime storms in New Mexico with wintertime storms in Japan shown in Krehbiel et al. (1983).

Huntrieser et al. (2008) report on regional differences of the per-flash LNO_x production. High NO_x per flash has been observed over Florida, while tropical LNO_x production over Brasil was found to be lower. As possible explanation, Huntrieser et al. (2008) proposed that subtropical flashes have, on average, longer stroke lengths as a consequence of higher vertical wind shear compared to tropical flashes. Beirle et al. (2010) analysed satellite observations of NO_2 after lightning events, and found regional differences as well: enhanced NO_2, if any, was observed primarily over the South-Eastern US, the Mediterranean, or Eastern China, while almost no NO_2 enhancement was observed in the tropics. However, many studies based on flash counts (or flash rate densities) simply ignore such regional variations of flash properties for lack of empirical data. This potentially has large impact for conclusions based on lightning climatologies.

In this study, we investigate to what extent the OTD/LIS measurements themselves provide additional information on regionally varying flash properties. A "flash" identified by OTD or LIS is the result of a multi-step clustering algorithm. The detected number of "events" and "groups" per flash (see Sect. 2), as well as information on total flash radiance, duration, and spatial extent, are provided for each individual flash. We investigate the spatial patterns of these flash properties. The resulting means (Sect. 3) reveal clear and consistent spatial patterns, showing regions with "strong" versus "weak" flashes.

Below, we thus simply use the term "strength" to summarize the level of the average flash properties. Though a direct physical interpretation is difficult (Sect. 4), such semi-quantitative information of regionally varying flash strength is still of high importance for the interpretation of lightning climatologies (see Conclusions).

2 Methods

In this study we investigate mean global patterns of various flash properties, based on the OTD and LIS time-series. LIS provides better statistics due to the longer measurement period. OTD, however, allows us to investigate the extra-tropics as well.

OTD and LIS flash detection is based on radiance measurements at 777.4 nm, a prominent atomic oxygen line in lightning spectra. Flashes are detected in a multiple step procedure, as explained in detail in Christian et al. (2000) and Mach et al. (2007):

- An *Event* is the basic unit, defined as a single CCD detector pixel exceeding the intensity background threshold.
- A *Group* is defined as one or more simultaneous events, i.e. events that occur in adjacent detector pixels within the same integration time frame ($\approx$2 ms).
- Finally, all groups occurring within 330 ms of a previous group and within 16.5/5.5 km (OTD/LIS) are clustered into a *Flash*.

The clustering of simultaneous (within 2 ms) neighbouring events into a group accounts for the spatial smearing of the optical pulse by clouds. The subsequent clustering of groups into a flash accounts for potential flash multiplicity and merges multiple strokes, which are typically separated in time by some 10 ms.

The orbital OTD/LIS datasets are provided in hdf format by NASA. For each individual flash, information on place and time, number of events and groups, flash duration, radiance, and footprint (i.e. the spatial extent, LIS only) is given. Table 1 lists the investigated quantities and the respective hdf field names in the OTD and LIS datasets. Note that the applied quality criteria basically removes measurements affected by the South Atlantic Anomaly (SAA). LIS is less affected by the SAA than OTD due to the lower orbit.

All quantities are averaged by summing them up over the complete time series (OTD: 1995-2000; LIS: 1998-2012) on a global $1^\circ \times 1^\circ$ grid, and setting them in relation to the absolute number of flashes subsequently. Grid pixels are removed completely from the further analysis if more than 50% of total flashes are flagged. By this conservative masking, potential artefacts are avoided. Nevertheless, similar investigations might be possible for a less restrictive flagging, if potential biasses are carefully excluded.

Table 1. Investigated flash properties and the respective filed names in the hdf data files provided by NASA

Property	Description	Unit	OTD variable name	LIS variable name
groups	Number of groups contributing to the flash		children	child_count
events	Number of events contributing to the flash		events	grandchild_count
radiance	Integrated radiance of all events	$\frac{\mathrm{J}}{\mathrm{m^2\ sr\ \mu m}}$	rad	radiance
duration	Flash duration	s	delta	delta_time
footprint	Spatial extent of the flash	km^2	-	footprint
quality	Selection of trustable observations		QA (skip if QA(3)>250)	alert_flag (skip all alerts except platform anomaly)

Table 2. Mean OTD flash properties 1995-2000 for different regions, time of day, and seasons. Global values are given in absolute numbers (first row). The other lines are given relative to the global value for better comparison to LIS (Table 3). Hemispheric summer and winter means are calculated for latitudes of 30° polewards.

Region	Flashes	Groups per flash	Events per flash	Radiance per flash	Duration per flash
Global unit	4.39 $\times 10^6$	4.7	9.5	0.265 $\frac{\mathrm{J}}{\mathrm{m^2\ sr\ \mu m}}$	0.15 sec
Land	84.0%	91%	90%	88%	95%
Day	51.5%	87%	85%	88%	90%
Night	32.5%	99%	99%	89%	104%
Summer	17.6%	93%	87%	92%	88%
Winter	0.5%	203%	233%	322%	132%
Ocean	16.0%	146%	151%	162%	124%
Day	7.9%	149%	155%	179%	125%
Night	8.1%	142%	148%	145%	124%
Summer	1.5%	159%	154%	171%	133%
Winter	1.2%	177%	205%	283%	100%
US East	3.8%	115%	111%	103%	124%
US West	1.5%	82%	76%	74%	84%
Congo	13.0%	80%	80%	72%	93%
India	3.7%	68%	61%	52%	73%
Indonesia	5.7%	99%	107%	102%	107%

To investigate possible diurnal or seasonal variations, we perform the analysis also for day versus night, and winter versus summer, separately.

3 Results

Mean flash properties have been calculated on a 1°× 1°grid. Here we present the results for total flash counts (a) and the investigated flash properties, i.e. groups per flash (b), events per flash (c), flash radiance (d), duration (e), and footprint (f) (LIS only), in three ways: (A) as global maps (Figures 1 and 2), (B) as tables of mean properties for land and ocean (including day/night and summer/winter differences), and some dedicated regions (Tables 2 and 3), and (C) as zonal means, separately for land and ocean (Fig. 3).

Note that the absolute numbers of all properties are different for OTD and LIS due to different instrumental and orbital properties. Nevertheless, the *relative* patterns for OTD and LIS are very similar. For better comparability, we adjust the scales for both instruments according to the respective global mean value as given in the first rows in tables 2 and 3.

Table 3. As table 2, but for LIS 1998-2012.

Region	Flashes	Groups per flash	Events per flash	Radiance per flash	Duration per flash	Footprint per flash
Global unit	27.11 $\times 10^6$	12.3	58.7	0.760 $\frac{\mathrm{J}}{\mathrm{m^2\ sr\ \mu m}}$	0.27 sec	313 km^2
Land	82.9%	92%	91%	86%	98%	95%
Day	30.5%	86%	76%	86%	100%	88%
Night	52.4%	95%	99%	87%	97%	100%
Summer	8.7%	87%	77%	73%	93%	82%
Winter	0.8%	145%	142%	209%	103%	110%
Ocean	17.1%	141%	145%	166%	108%	123%
Day	5.2%	142%	133%	184%	111%	115%
Night	11.9%	140%	150%	158%	107%	126%
Summer	1.5%	144%	146%	158%	117%	123%
Winter	1.9%	153%	144%	223%	93%	108%
US East	4.7%	120%	111%	113%	114%	100%
US West	1.7%	93%	81%	77%	95%	83%
Congo	12.3%	87%	91%	80%	103%	97%
India	7.3%	67%	57%	49%	76%	68%
Indonesia	4.6%	106%	126%	124%	106%	130%

Figures 1a and 2a display the total flash counts for OTD and LIS, respectively. Note that the conversion of these flash counts into a flash rate density, i.e. flashes per time and area, as provided in OTD/LIS climatologies, requires additional information on detection efficiency and view time. In particular, the latitudes close to the orbital turning points are better covered than the low latitudes (compare the maxima of LIS flash counts at 30-35°, which are not visible in the OTD data, see Fig. 3a). The appropriate correction of these effects is done elsewhere (e.g. Cecil et al. (2012)), while in this study, the actual number of detected flashes is needed for the calculation of the mean flash properties. But still, the simple flash counts clearly indicate the regions with strong lightning activity in central Africa, the South-Eastern US, or Northern India. Parts of South America, where lightning activity is high as well, are masked by the applied quality flag as a consequence of the SAA. Flash counts over oceans are generally far lower than over continents.

The global maps of the various flash properties (b to f)

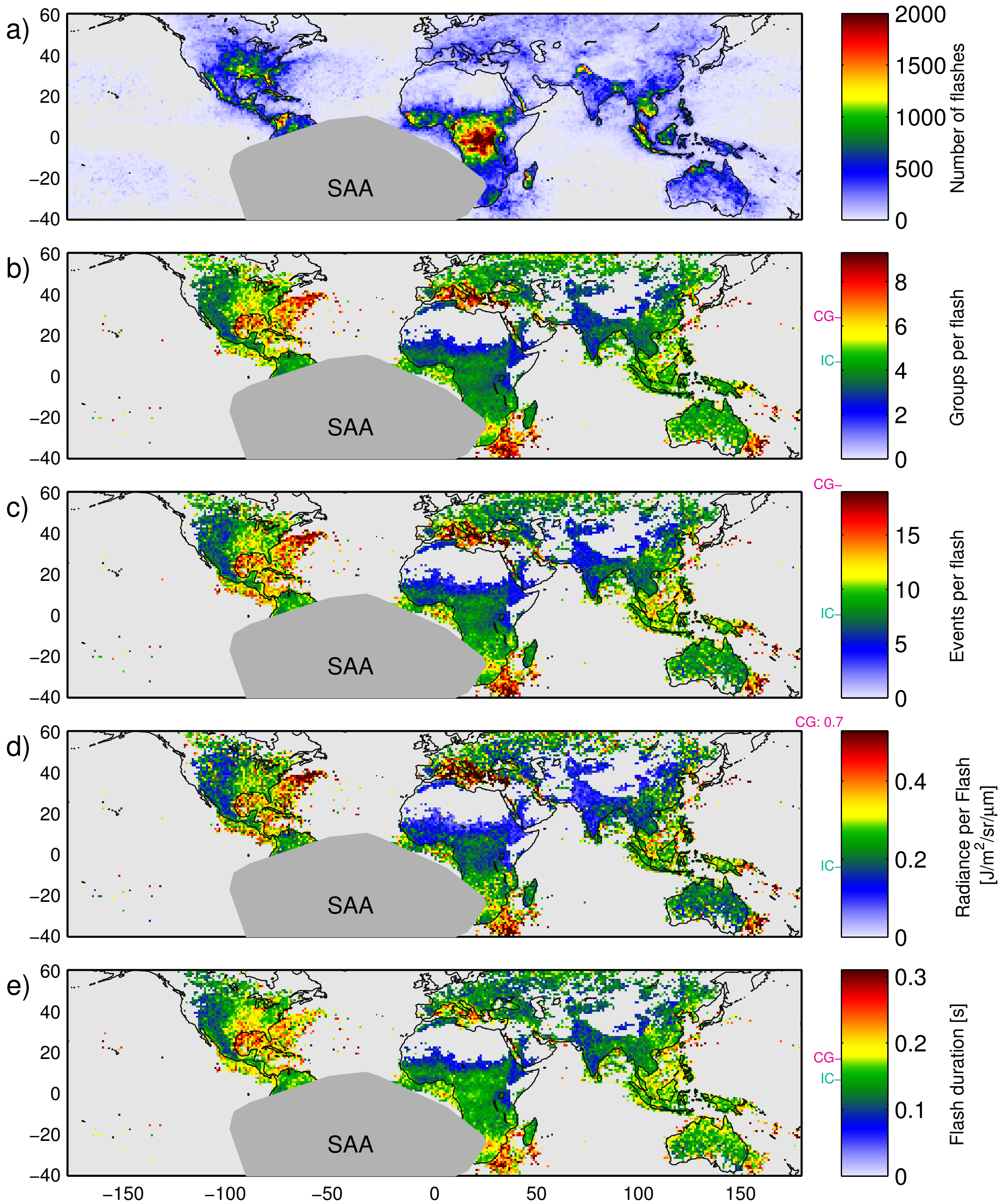

Fig. 1. (a) Total number of flashes derived from OTD (1995-2000) on 1° × 1° grid. Parts of South America are masked out by the applied quality flags as a consequence of the SAA.
(b)-(e) Global mean flash properties, i.e. groups (b), events (c), radiance (d), and duration (e) per flash. Grid pixels with less than 100 flashes and the area affected by the SAA are discarded (light/dark grey, respectively). The color scale of panels (b) to (e) ranges from 0 to twice the respective global mean value (see first row in table 2). The IC/CG marks in cyan/magenta at the colorbar indicate the mean properties of IC/CG flashes in the U.S. as derived by Koshak (2010) (see Sect. 4.3 for details).

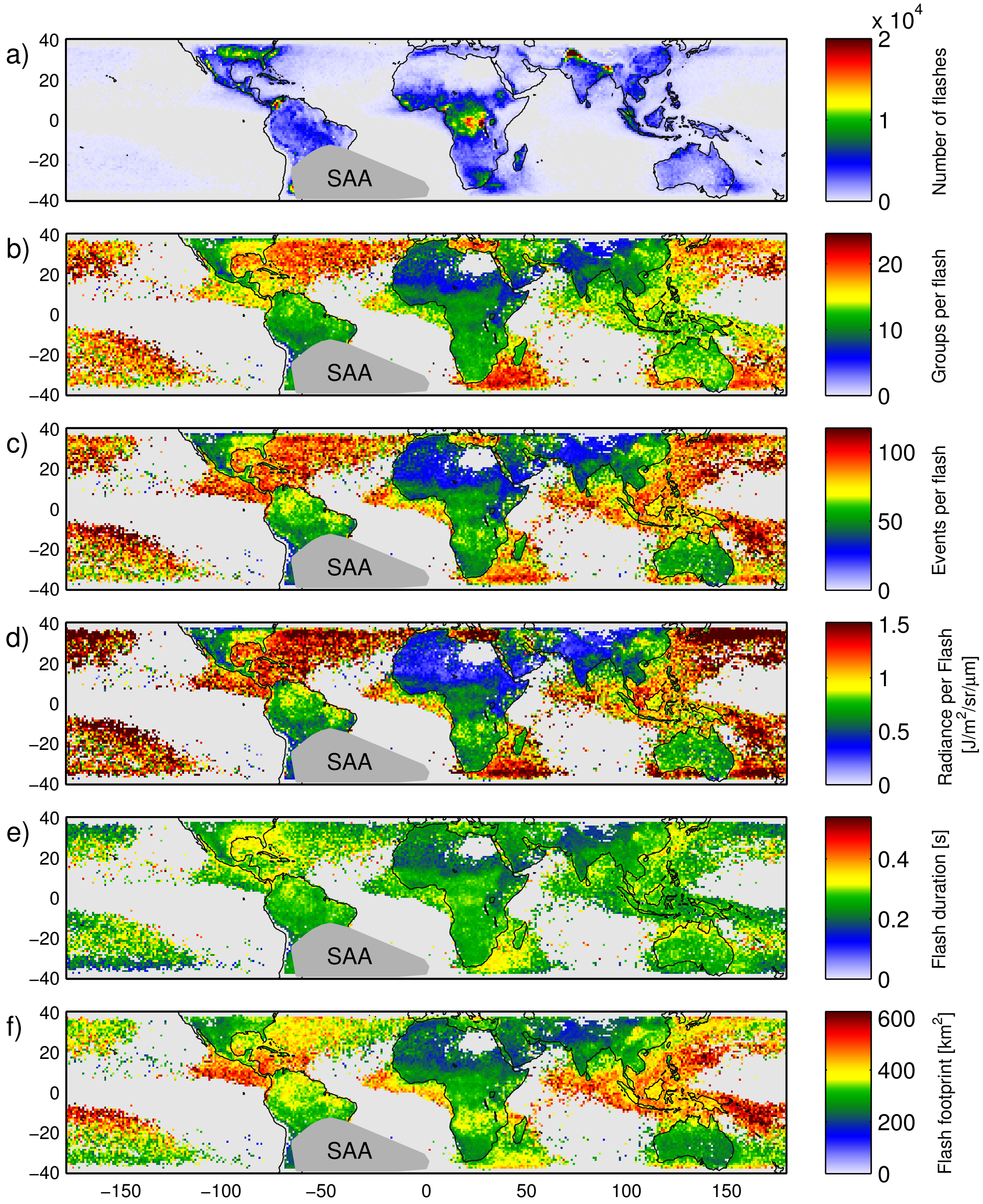

Fig. 2. (a) Total number of flashes derived from LIS (1998-2012) on 1° × 1° grid. Parts of South America are masked out by the applied quality flags as a consequence of the SAA.
(b)-(f) Global mean flash properties, i.e. groups (b), events (c), radiance (d), duration (e), and footprint (f) per flash. Grid pixels with less than 100 flashes and the area affected by the SAA are discarded (light/dark grey, respectively). The color scale of panels (b) to (f) ranges from 0 to twice the respective global mean value (see first row in table 3).

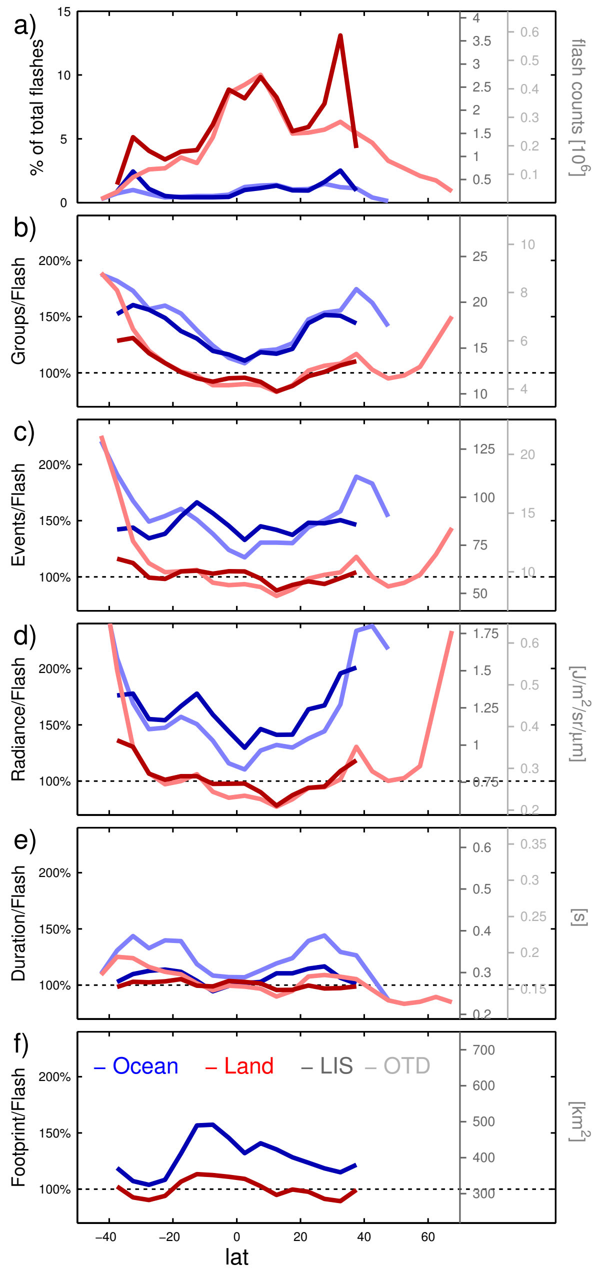

Fig. 3. Latitudinal dependency of the mean flash properties for OTD (light) and LIS (dark), separately for land (red) and ocean (blue). All quantities are integrated in latitudinal bands of 5° width and normalized to the respective global sum of flash counts (a) or the global mean (b to f), respectively (see first rows in tables 2 and 3), to make OTD and LIS comparable. The original scales for both OTD and LIS are shown on additional axes at the right. Means with less than 5000 flashes in a latitudinal band are skipped. Footprint is not available for OTD.

reveal clear spatial patterns, which are widely consistent among the different flash properties, as well as between OTD and LIS (note that 1. light/dark grey pixels represent missing values due to low statistics/the SAA, respectively, and 2. OTD means are generally noisier due to the shorter time series). Most pronounced is, again, a strong land/ocean contrast; but while the total number of flashes (a) is larger over continents, all investigated per-flash quantities (b to f) show enhanced values over oceans. For instance, the flash radiance over ocean is, on average, almost twice as high as over land. The number of groups and events per flash, as well as the flash footprint, are up to 50% higher over ocean, while the flash duration is on average only 10% longer over ocean (see tables 2 and 3). Particularly high values over ocean are found at the Eastern coasts of the U.S., Australia, and South Africa, as well as over the Mediterranean Sea.

Beyond the land-ocean contrast, additional regional differences over continents can be observed: for all properties, the lowest values are found over North Africa, India, and Western China, while high values are observed for the Eastern US, Eastern China, and Indonesia. In central Africa, where calibrated OTD/LIS flash rate densities are highest (Cecil et al., 2012), flash properties are slightly below average (compare tables 2 and 3).

The numbers of groups (b) and events (c) per flash are strongly correlated. The radiance per flash (d) is very similar to the number of events (c) per flash, but with higher amplitude of regional variation. The flash duration (e) shows rather weak, but nevertheless significant regional variability. The mean footprint (f) shows regional variations similar to (b) or (c) over land, but a different latitudinal dependency over ocean compared to (b) (compare Fig. 3).

The number of groups per flash shows a clear minimum in the tropics, most pronounced over ocean, but also evident over land (Fig. 3). Latitudinal dependencies of events per flash and mean radiance are similar. The flash footprint, however, shows a clear maximum at ≈ 10° S, both over land and ocean. At high latitudes, OTD properties show very high values for groups and events per flash, and in particular for the mean radiance radiance, both over land and ocean. The winter/summer comparison (table 2) reveals that these high values occur only in the respective hemispheric winter, when radiances are tripled over land, while summer values are close to average. Note that the effect is also observed for LIS (table 3), but less pronounced, as high latitudes are not covered.

The separate analysis of daytime vs. nighttime flashes reveals only small differences, which are partly opposing for OTD and LIS (e.g. the number of events per flash over ocean, which are higher at daytime for OTD, but higher at nighttime for LIS). Most pronounced is the change in mean radiance, which is higher during daytime over ocean, while no effect is visible over land. However, these findings might be affected by the detection efficiency, which is generally higher during nighttime.

4 Discussion

The systematic analysis of various OTD/LIS flash properties reveals consistent spatial patterns. Obviously, lightning properties differ regionally. However, our results can not easily be interpreted quantitatively. Here we discuss possible causes for, and impacts of, regional differences of the quantities measured by OTD/LIS, and to what extent they are related to physical lightning properties like flash energy, altitude, multiplicity (i.e., the number of strokes per flash), or the fraction of cloud-to-ground (CG) and intra-cloud (IC) flashes.

4.1 The OTD/LIS clustering algorithm

The OTD/LIS flash clustering algorithm is carefully elaborated (Christian et al., 2000) and validated (Boccippio et al., 2000b), while variations of the applied thresholds have only small impact on the resulting flash counts (Mach et al., 2007). However, due to the need for an algorithm working on global scale, the clustering algorithm has to be optimized for a wide range of conditions, and thus might be performing less accurate for specific regions with extreme conditions. Validation so far is limited to some comparisons to ground-based lightning-detection networks, mostly over the US (using the National Lightning Detection Network™, NLDN). Over remote regions like Central Africa, and particularly over Oceans, validation of OTD/LIS flash counts is quite difficult.

For example, over Northern India, a region with a significantly high number of flash counts, all investigated quantities are minimum. Thus, the flash counts might be overestimated by the clustering algorithm due to extraordinary regional conditions. Validation of the OTD/LIS measurements with ground-based lightning location networks in different parts of the world would thus be highly desirable.

4.2 Cloud effects

Variations in the meteorological regimes and cloud microphysical properties drive varied electrification processes and thundercloud charge distributions which directly affect the characteristics (like energy, current, or channel length) of the resulting lightning discharges.

In addition, clouds have a strong impact on the propagation of the optical pulse. Essentially, they cause a spatial smearing of the optical pulse, and the effect is more pronounced for flashes embedded more deeply below cloud top (Thomason and Krider, 1982; Koshak et al., 1994).

A comprehensive explanation of the regional variations in the observed OTD/LIS flash properties therefore requires indepth examination of both the lightning source and the cloud multiple scattering medium. Note, however, that cloud effects alone cannot explain the consistent patterns of Figs. 1 and 2. Spatial smearing by clouds might result in a larger footprints as well as higher number of groups and events per flash, but not in enhanced radiances, which are integrated per flash.

Thus, the observed regional variations in the OTD/LIS parameters probably indicate, to a significant extent, physical differences of the *flash* characteristics rather than cloud conditions.

4.3 Cloud-to-ground vs. intra-cloud flashes

One important specification of flashes is the differentiation into CG and IC flashes. IC flashes are more frequent, while the LNO_x production per flash was considered to be higher for CG flashes. However, different studies reveal high variability, and a few studies even suggest that the LNO_x production per flash is about equal for both IC and CG flashes (see the discussion and references given in Schumann and Huntrieser (2007)).

Boccippio et al. (2001) compiled maps of the IC/CG ratio over the US by comparing flash rates from OTD (IC+CG) to ground-based measurements from NLDN (CG only). Koshak (2010) has investigated the statistics of OTD flash radiance, area, duration, number of events and number of groups separately for CG and IC flashes (again identified by coincident NLDN measurements). A high variability of all these quantities was found, but there was a clear separation of the *means* for sufficiently large sample size, with generally higher means for CG compared to IC flashes. Based on these findings, the fraction of CG flashes might in principle be deduced from the flash statistics observed from space (Koshak, 2011; Koshak and Solakewicz, 2011). Generally, high values of the investigated flash properties probably indicate a high fraction of CG flashes. However, it is not possible to assign the observed regional patterns of lightning characteristics to changes of the CG fraction alone: in some parts of the world, the mean values derived from OTD are out of the interval spanned by the mean values for IC and CG flashes as reported by Koshak (2010) for the US. For illustration, the respective mean values of CG and IC flashes from Koshak (2010) (table 2 therein) are indicated in the colorbar of Fig. 1. In other words, the observed mean radiance per flash (or any other quantity) can not be described globally by a simple linear combination of “US type” CG and IC flashes.

4.4 Flash multiplicity

A flash typically consists of several successive strokes. As the total flash duration is generally longer for a larger number of strokes (Malan, 1956), the global distribution of flash duration from OTD and LIS might be interpreted as proxy of the flash multiplicity. This interpretation is in accordance to the findings of Rakov and Huffines (2003), who report on a low fraction of single-stroke flashes (i.e., a high fraction of multiple stroke flashes) in the South-Eastern US, which is the continental region with longest flash duration. Note, however, that the range of variation of the other investigated quantities is much larger. That is, the flash multiplicity can explain part of, but not completely, the observed regional differences in flash strength.

4.5 Peak current

The global pattern of peak currents in negative CG flashes has been investigated recently by Said et al. (2013), based on observations of the global lightning network GLD360. Peak currents reveal a strong and sharp land-sea contrast, with much higher values over sea (consistent with our observations), which can not be explained by DE alone. The physical reason for this land-sea difference remains unclear and requires further investigations.

Over land, the peak current reveals some similarities to our spatial patterns as well; a significant number of negative events with peak currents above 150 kA is observed over the South-Eastern U.S. and over China, but only very few of such high-current flashes are found in Central Africa or Northern India (compare Said et al. (2013), Fig. 6 therein).

4.6 Positive CG flashes

Flash properties, in particular radiances, are extraordinary high in winter (Tables 2 and 3). This is probably related to the special characteristics of wintertime lightning, which reveals a high fraction of CG flashes with positive currents ("+CG") and high charge transfer (Kitagawa and Michimoto, 1994).

4.7 Implications for lightning NO_x

The flash energy is directly related to the NO_x production by lightning (Wang et al., 1998). Thus, from the regional differences of the mean radiance per flash, one would expect particularly high LNO_x production per flash e.g. over the Mediterranean, the Pacific downwind (east) from Australia, or the Eastern US, whereas it should be low for e.g. Central Africa. These regional differences are consistent with the findings of Huntrieser et al. (2008), who observed the highest LNO_x production per flash in Florida, and with Beirle et al. (2010), where enhanced NO_2 due to lightning, if any, was observed over the respective regions with high radiance per flash.

5 Conclusions

The satellite instruments OTD and LIS provide multi-annual time series of global lightning, establishing an ample dataset sufficient for the investigation of robust mean flash characteristics, despite the high variability of individual flashes. The flash rate density climatologies based on OTD/LIS (Cecil et al., 2012) are a unique dataset and are widely used in lightning research and related topics.

We have analysed additional OTD/LIS information to investigate regional variations in flash characteristics. All investigated quantities, i.e. the number of groups and events per flash, as well as the mean flash radiance, duration, or footprint, reveal clear and mostly consistent spatial patterns.

Generally, oceanic flashes – by far less frequent than continental flashes – show higher per-flash values: mean radiances are twice as high for oceanic flashes compared to land. Over continents, regions with strong (especially the Eastern USA) and weak (e.g. India, with only half as many events per flash) flash characteristics can be identified.

The observed regional differences are driven by many factors (e.g., differences in cloud scattering properties, the relative number of CGs and ICs, flash multiplicity, fraction of positive polarity CGs, cloud charge extent and magnitude). Further investigations are needed to identify the most important drivers, which requires additional information, e.g. from local and global ground-based lightning networks. However, the observed extreme values over ocean or remote regions like Central Africa will probably remain challenging to evaluate further due to the lack of regional data.

Due to the complex interaction of different effects, a simple inversion of the investigated flash properties, for retrieving flash quantities like the CG/IC ratio, is quite difficult. Nevertheless, the regional variations of flash characteristics found in this study provide added knowledge, with direct implications for applications of OTD/LIS climatologies. In particular, the results of this study will help to improve the parameterisation of the LNO_x production within global chemistry/climate models.

The high values of mean flash properties observed in the Eastern US needs to be recognised by the scientific community since a significant fraction of lightning field studies and aircraft campaigns are conducted in this region. That is, LNO_x estimates derived from this region are likely not applicable to the global scale.

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