Eleven Years of Total Lightning Insights From Belgium's Ground-Based Lightning Location System BELLS

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Abstract

Presented here is a 11-year lightning climatology spanning the years 2013 to 2023, as recorded by the ground-based Belgian Lightning Location System (BELLS). This study delves into not only the spatial and temporal attributes of cloud-to-ground (CG) lightning flashes but also places specific emphasis on assessing the impact of changes in sensor technology on the system's ability to detect intracloud (IC) lightning. Additionally, the findings are compared with data collected by a comparable network covering Austria and Germany. In Belgium, the mean CG flash densities vary between 0.1 flashes km^{-2} yr^{-1} and 1.3 flashes km^{-2} yr^{-1}, with an average flash density of 0.59 flashes km^{-2} yr^{-1}. The change of sensor configuration in Belgium, specifically by reducing the distances between sensors, has notably enhanced the detection of cloud pulses. From 2016 onward, there has been a consistent rise in the proportion of cloud discharges, reaching around 95%. In terms of flashes, the IC:CG ratio can reach values as high as 7-8, which is a factor of 2 greater than what is observed in Austria and Germany. Between 2013 and 2020, there was a downward trend in the average negative CG multiplicity, which decreased from 2.2 to a low of 1.25. After 2020, it began to steadily increase again. This trend is similar to what is observed in Austria and Germany. Finally, the study reviews the estimated peak currents for negative first and subsequent CG strokes.

1 Introduction

Through automated lightning observations, significant advancements have been achieved in our understanding of the spatial and temporal patterns of lightning. This exploration has spanned various spatial scales, such as local, regional, continental, and global, with varying levels of granularity depending on the observation techniques and their associated frequency domains.

At one end of the spectrum, very high-frequency (VHF) lightning mapping arrays (LMAs) excel at detailing the path of charged particles on a relatively small spatial scale. At the opposite end, very low-frequency (VLF) networks provide a comprehensive view of electrical activity across the majority of the globe at any given time. In between, numerous ground-based networks operate at lower frequencies (LF). Additionally, space-based lightning observations in the optical spectrum have opened up new avenues for gaining insights into this captivating natural phenomenon.

The main objective of this paper is to document the changes in the configuration of the Belgian Lightning Location System (BELLS), a ground-based system, over the past decade. As we will demonstrate, these changes have significantly impacted the detection of cloud discharges in the LF domain. The paper will also present spatial and temporal statistics of lightning occurrences, along with an analysis of peak current.

2 Lightning Location System

2.1 Belgian Lightning Location System

The Royal Meteorological Institute of Belgium (RMIB) started in 1992 with automated lightning observations, with the primary focus to provide high quality total lightning observations over Belgium. At that time, this was made possible employing the so-called Surveillance et Alerte Foudre par Interférométrie Radioélectrique (SAFIR) sensors. The SAFIR sensors combined a localization antenna operating at VHF (110─118 MHz) and a discrimination antenna at LF frequencies (300 Hz─3 MHz). Hence, based on an interferometric technique the network was able to detect cloud-to-ground (CG) as well as intracloud (IC) lightning events. The network consisted by then out of three SAFIR sensors, and a fourth one was installed in 1996. The locations of the SAFIR sensors are plotted in Figure 1 in red. This network configuration was stable until the switch was made in 2010 to a new total lightning processor (TLP) of Vaisala. This marks the start of modernizing the network into what is known today as the Belgian Lightning Location System (BELLS). Not only was there a change in the software, but also and above all at the level of hardware. In 2011, one LS7001 was put in operation in the middle of Belgium, i.e., at Ernage, and participated hand-in-hand with the SAFIR sensors. In 2013 raw data was received from six additional LS7001 sensors located in France, two in Germany and one in the Netherlands. This was made possible by the cooperation of neighboring partners such as Météorage and Siemens, which remains standing

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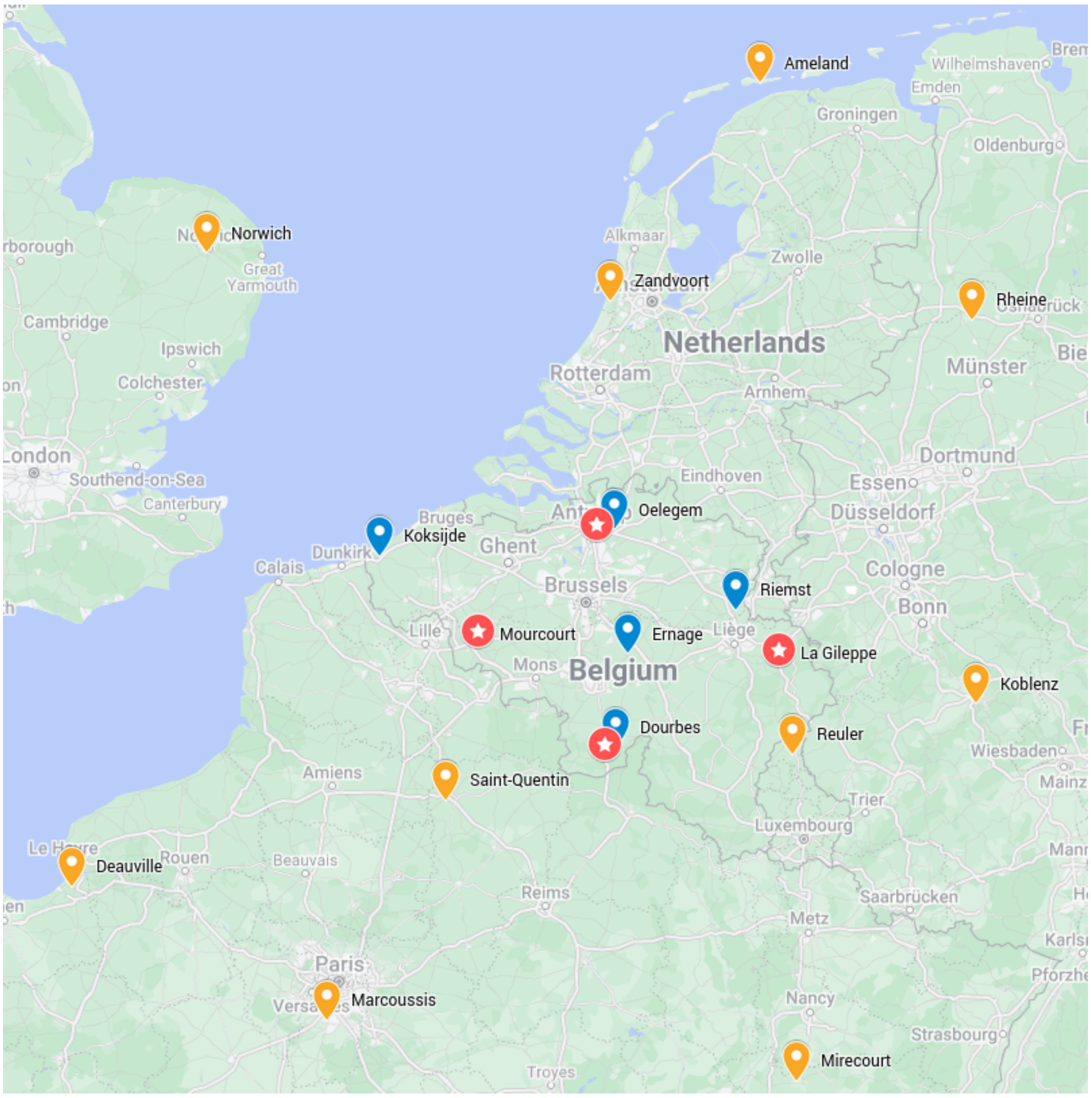

Figure 1 Locations of the sensors in BELLS. In red the SAFIR sensors, in blue the RMIB-owned LS7002 sensors and in yellow LS7002 sensors owned by either Météorage, OVE-ALDIS, or MeteoLux. [Map data ©2024 Google, GeoBasis-DE/BKG (©2009)]

today. Together with the LS7001 in Belgium, the combined LF sensors at that time were performant enough to detect CG discharges over Belgium. A big change came in 2015 and 2017, when the number of LS sensors increased in Belgium by one and three, respectively, bringing the total number of LF sensors in Belgium to five. On top of that, all sensors changed from LS7001 to LS7002 from 2016 onward. Some other changes occurred, whereby for instance some sensors in France were dismantled and other sensors came in place. Finally, in 2018 one extra LS7002 sensor was added to the network, located in Luxembourg.

With the gradual introduction of the newer and performant LS7001/2 sensors in the network, the manner by which to observe total lighting therefore switched from an VHF interferometric technique to a combination of time-of-arrival (TOA) and direction finding (DF) method at lower frequencies. Since 2011, the SAFIR sensors provided only signal and timing information to locate CG events. By the end of 2016 the SAFIR sensors no longer participated in CG detections and were only allowed to aid in the detection of cloud pulses. A few years later however, in 2020, it was decided to switch off entirely the SAFIR sensors from the network.

Figure 1 depicts the current state of the sensor configuration of BELLS. It consists of 15 LS7002 sensors (in orange and blue), of which five are owned by RMIB and located in Belgium (Dourbes, Ernage, Koksijde, Oelegem, Riemst), five are owned by OVE-ALDIS and located in Germany (Koblenz, Rheine), the Netherlands

(Ameland, Zandvoort) and the United Kingdom (Norwich), four are owned by Météorage and located in France (Deauville, Marcoussis, Mirecourt, Saint-Quentin) and one is owned by MeteoLux, the Air Navigation Authority of Luxembourg (Reuler). With baselines down to 60-70 km in Belgium and up to 150-200 km at the edge of the network, it makes BELLS the network with the shortest baselines in the world operating at low frequencies, to the best knowledge of the author.

2.2 European Lightning Location System EUCLID

The European Cooperation for Lightning Detection (EUCLID) consists of more than 150 sensors spread across Europe. This Lightning Location System (LLS) is one of the best documented networks in Europe, hence the interested reader is referred to [1], [2], [3] for more in-depth information about the network. In short we can state that the location accuracy (LA) is of the order of 100 m, while the detection efficiency (DE) for negative strokes and flashes reaches 70-84% and 96-98%, respectively. The latter range of DEs stems from the applied ground-truth method; whether based on instrumented tower data on one hand or video and electric field records on the other hand.

Note that the majority of the sensors within BELLS are currently integrated in EUCLID. Hence, applying similar sensor technology and central processor, it is safe to assume that the DE and LA values quoted for EUCLID are applicable for BELLS as well.

3 Results

In this section the lightning observations between 2013 and 2023 as observed by BELLS are presented. To enable the comparison to the observations of EUCLID in nearby countries such as Austria and Germany, only data from the LF LS700x sensors have been reprocessed, thereby eliminating SAFIR participation entirely.

3.1 Temporal statistics

Figure 2a presents the yearly total number of events detected, i.e., the sum of CG strokes and IC pulses, within the Belgian border. A sudden increase in the total number of events is evident from 2016 onward. This marks also the time when all the LS7001 sensors changed to LS7002, leading to a rapid rise in the proportion of cloud pulses. The solid black line in the Fig. 2a indicates the percentage of cloud pulses relative to the total number of events. It is seen that in between 2013 and 2015 this value is just above the 50% marker, followed by a sudden increase to about 80% in 2016 This value continued to rise in the subsequent years, reaching a peak of just over 95% in 2021. Figure 2b zooms in on the CG part only. It displays the temporal distribution of CG strokes and associated flashes. There is an annual variability, with the maximum observed in 2018, with the lowest level of CG stroke (/flash) activity occurring in 2022 (/2023). Such a variability is in line with previous findings in which the temporal variation of CG flashes over the period 2004-2013 based on EUCLID observations is investigated [4].

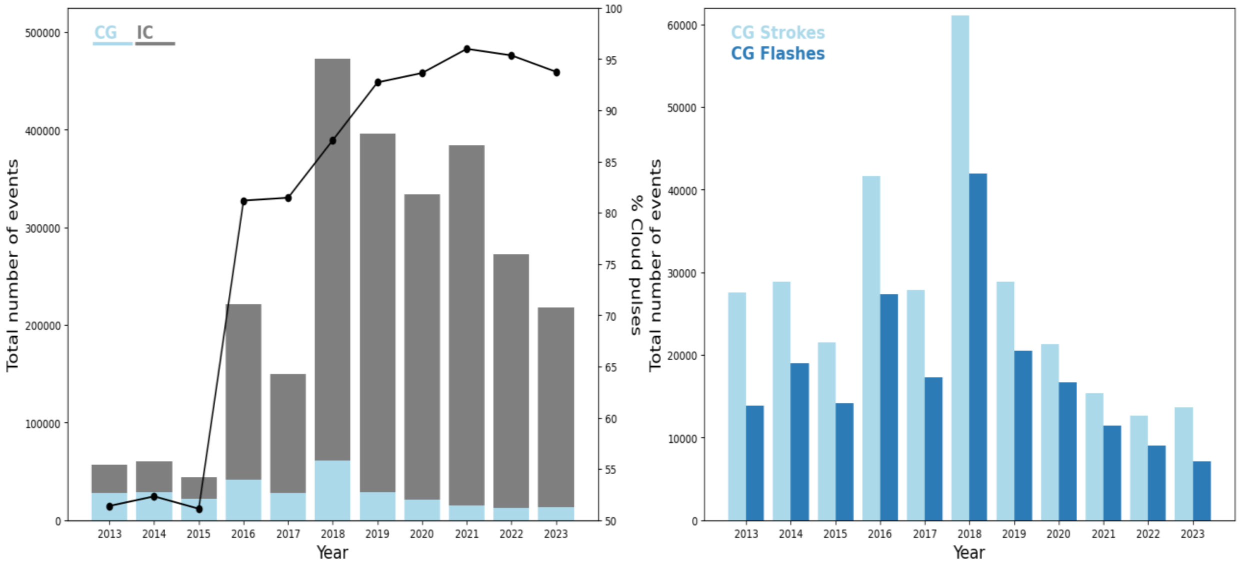

Figure 2 (a) Annual total, i.e., IC + CG, event counts, and (b) CG strokes and flashes based on 2013-2023 BELLS data.

In Fig. 3, the IC:CG ratio of flashes in Belgium (BEL) observed by BELLS is compared to what is found in Austria (AUT) and Germany (DEU) as observed by EUCLID. The peak observed in 2016 in case of AUT and DEU is a consequence of the flash grouping algorithm at that time. Only CG strokes could be grouped within a flash if spatial and temporal criteria were met, whereas in case of IC pulses, each IC pulses created a single IC flash resulting in an overestimation of the number of IC flashes. A new grouping algorithm was introduced in 2017 which allowed the grouping of multiple IC pulses in a single IC flash or in a hybrid CG flash. When reprocessing the BELLS data, the new grouping algorithm has been applied over the full time period under investigation. As a result, this peak in 2016 is not present in case of BEL. While in BEL the IC:CG flash ratio is about 1 in 2013-2015, it gradually increases up to a value of 6-8 during the last three years. In case of AUT and DEU, this value is a factor of about two lower. From this, it can be inferred that smaller baselines in Belgium permits to detect more IC flashes, compared to regions with larger baselines such as in AUT and DEU.

3.2 Spatial statistics

The total amount of CG flashes recorded within Belgium over the eleven-year period under investigation is approximately 198,000. Hence, it follows that the average flash density N_g is 0.59 fl km^{-2} yr^{-1}, assuming the surface area of Belgium is 30,688 km^2. This value is about 15% lower than the 0.7 fl km^{-2} yr^{-1}, found by EUCLID over the period 2004-2013 [4].

Figure 4 plots the spatial distribution of the mean annual flash density from 2013-2023. Values range between 0.1 and 1.3 fl km^{-2} yr^{-1}. The area with the lowest density is located in the west, towards the coast. On the other hand, hotspots with elevated flash densities are spread out over the country. The spatial pattern as found in [4], i.e., higher densities observed toward the east and south-east of Belgium which overlaps with regions of higher elevation (the Ardennes), is not reproduced with the data of the last eleven years.

3.3 Flash multiplicity

The multiplicity of a flash indicates the number of strokes associated to the flash. Since strokes are artificially grouped together, based on specific-chosen spatial and temporal criteria, the algorithm applied to make flashes will influence the multiplicity in the end. In our case, the temporal and spatial criteria used are 1.5s and 10 km, respectively. In addition, an interstroke time interval of 0.5 s is allowed. Beside the flash grouping algorithm, the LLS' stroke detection efficiency (DE) obviously affects the outcome as well. The EUCLID stroke DE has been assessed in Belgium in 2011 and was determined to be 84% [5]. This is in line with the overall values quoted in Sect. II.B. Note that at that time only the LS7001 sensor at Ernage was operational in Belgium. With the addition of LS700x sensors in Belgium after 2011, it can be assumed that the stroke DE of 84% in Belgium is a lower limit of the value of most recent years for both BELLS and EUCLID.

Figure 5a plots the annual mean multiplicity in negative CG flashes. It follows that the annual mean multiplicity is not a static value, but changes from year to year ranging between 1.25 to 2.2. Averaged over the full period, a mean multiplicity of 1.52 is found for negative CG flashes in Belgium. This is clearly an underestimation when compared to what is retrieved from high speed video recordings. [6] found a value of 3.67, based on video recordings of 1174 negative downward lightning flashes taken in different regions, including Austria, Brazil, South Africa, and the USA. The multiplicities found

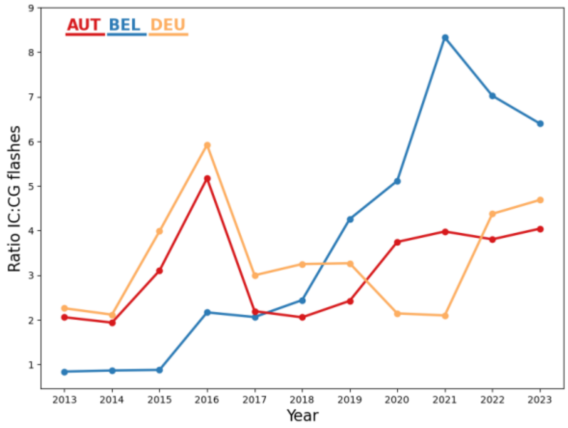

Figure 3 Distribution of the IC:CG flash ratio in Belgium (BEL) based on BELLS and in Austria (AUT) and Germany (DEU) based on EUCLID data over the 2013-2023 period.

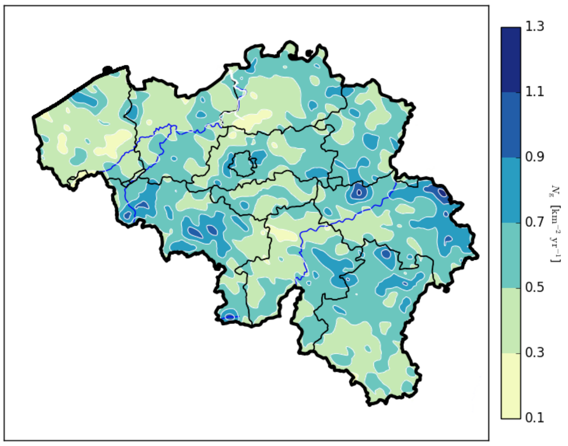

Figure 4 Spatial distribution of the mean annual flash density N_g [km^{-2} yr^{-1}] based on 2013-2023 BELLS data.

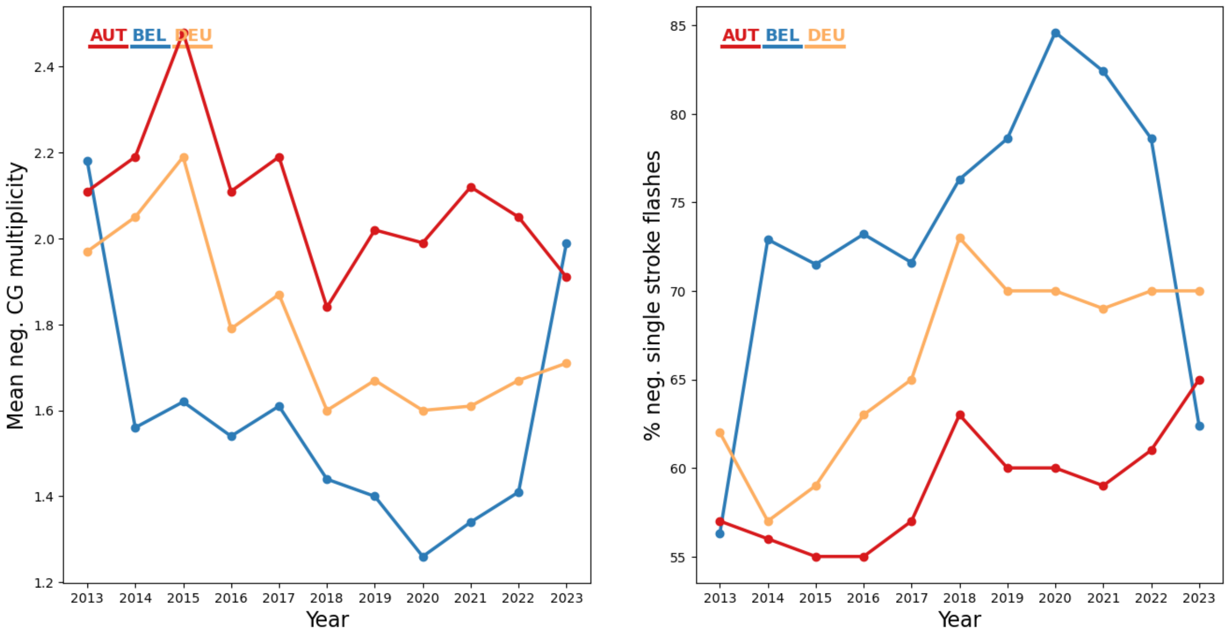

Figure 5 Annual distribution of (a) the mean multiplicity in negative flashes and (b) percentage of single stroke flashes in Austria (AUT), Belgium (BEL) and Germany (DEU).

in AUT and DEU, based on EUCLID observations, are higher compared to what is found in Belgium. However, overall a similar decreasing trend is found in between 2013-2020, followed by an increase thereafter. The difference in multiplicity between AUT, BEL and DEU has been described already before in [2]. In their Fig. 5b the spatial distribution of the mean multiplicity within the EUCLID domain is plotted. It revealed that the mean flash multiplicity varies from one region to another in line with Fig. 5a of this study.

Figure 5b depicts the distribution of the percentage of single-stroke flashes. Of course, this behavior goes hand in hand with what has been shown in Fig. 5a. On average, the percentage of single-stroke flashes in Belgium is 74%. This is again higher than what is observed in AUT and DEU. Likewise, this high percentage of single-stroke flashes is an overestimation with respect to ground truth observations which puts it more in the range of 30% [6]. The overestimation could partly be explained by the fact that, on average, first strokes exhibit a higher absolute peak current compared to subsequent strokes and are hence more easily detected by ground-based LLSs. On the other hand, misclassification of cloud pulses contributes as well to a higher percentage of single-stroke flashes. In their 2016 study, Zhu et al. [7] focused on evaluating the classification accuracy (CA) of CG and IC events, utilizing data from the U.S. National Lightning Detection Network (NLDN) and comparing it with optical and electrical field observations from the Lightning Observatory in Gainesville (LOG), Florida. It was found that the NLDN achieved an IC CA of 86%. The evaluation of CA for the NLDN is relevant to EUCLID and BELLS, as those networks employ comparable technology in terms of hardware and software. Since 14% of IC events contaminate CG observations, this could account for the observed high percentage of single-stroke flashes in Belgium and its nearby regions, which warrants further investigation.

3.4 Peak Current

It is common to assign the peak current of the first stroke in a flash as the peak current of the flash. As a result, it is found that the mean (median) estimated peak currents in negative and positive flashes in Belgium is -10.0 (-6.0) kA and +34.3 (+17.0) kA, respectively. As expected, positive flashes exhibit in general a higher absolute peak current compared to what is estimated for negative flashes.

Figure 6 plots the annual distribution of mean absolute peak current in negative CG flashes only. It is observed that the median absolute peak current of subsequent strokes (orange) is larger than of the first stroke in all flashes (red). This is somewhat against the expectations, as in general the opposite is found. To understand this alleged discrepancy, the peak currents are further subdivided into the peak current of 1st strokes in multiple stroke flashes (light blue) and in single stroke flashes (blue). From this, it is inferred that the absolute mean (median) peak current of 1st strokes in multiple stroke flashes is +17.2 (+11.0) kA; a factor of two larger than what is found for the absolute peak current in single stroke flashes. Due to the fact that the percentage of flashes with one stroke in Belgium is high, this lowers the absolute

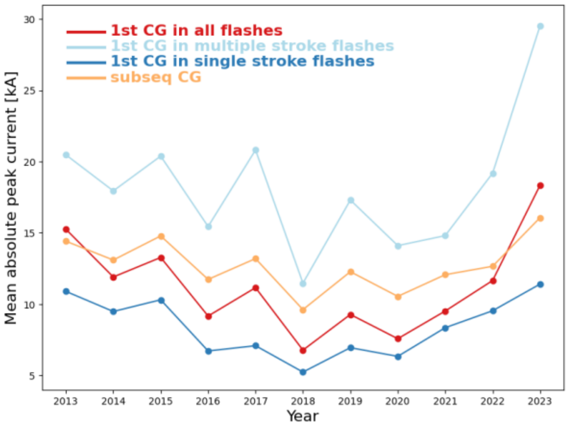

Figure 6 Annual distribution of the mean absolute peak current in Belgium.

peak current of the first strokes when all flashes are considered below the value found for subsequent strokes. Note that a similar behavior as in Belgium is found in Germany based on EUCLID data, but not in Austria.

4 Discussion

The detection of lightning discharges seems straightforward employing present-day technology. Yet, no two networks observe exactly the same. This is precisely reflected in this particular study. Both BELLS and EUCLID use similar sensor and central processor technology of the same provider, i.e., Vaisala. Without regard to the fact that in this work different areas are compared, in general similar trends are visible in the annual distributions in Belgium, Austria and Germany. Yet, looking more closely, subtle differences do exist. For instance, in Fig. 5b one notices that the distributions by EUCLID for AUT and DEU peak at 2018, followed by a decline afterward. Such a behavior is also found in BEL, albeit two years later in 2020. The reason for this is the introduction of a new classification scheme in the central processor at different times. This in turn reduced the misclassification of cloud discharges as isolated CGs; affecting the percentage of single stroke flashes.

Sensor configuration impacts the measurements as well. Short baselines in BELLS facilitate the detection of cloud discharges, as evidenced from the high IC:CG flash ratio in Belgium. On the other hand, the sensitivity of the network to detect lightning events, together with a certain percentage of misclassification, leads to a higher proportion of cloud discharges which are being classified as isolated single stroke flashes. As a consequence, the average CG flash multiplicity is skewed toward lower values, when compared to high-speed camera observations. Yet another element that points to the effect of misclassification is the difference in absolute peak currents. A factor of about three lower absolute peak current for single stroke flashes compared to the peak current of first strokes in multiple stroke flashes suggests that misclassification plays a factor in this as well.

5 Acknowledgment

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