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Number of Single Stroke Flashes in the Alpine Region of Austria

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***Abstract*—The present analysis shows data of measurements of natural cloud-to-ground lightning performed during warm season thunderstorms in the Alpine region of Austria. These measurements were performed during six years from 2009 to 2018 to generate a ground truth dataset of atmospheric discharges. The used measurement system consists of a high speed video and an electric field recording system (VFRS), to observe the optical properties of lightning discharges and to record the transient electric field. Measurements have been conducted at 33 different measurement locations and 735 negative cloud-to-ground flashes have been recorded during 61 days spread over the whole measurement period. Data of the Austrian Lightning Location System (LLS), ALDIS (Austrian Lightning Detection and Information System), is correlated with the VFRS ground truth data to complete the dataset. These datasets are used to analyze possible reasons for the detected variation of single stroke flashes in the Alpine region of Austria. The calculated values for single stroke flashes of the present analysis are also compared to previously published values (12 – 24 %) from different countries. Additionally radar data and wind measurements have been analyzed to classify thunderstorm types in order to investigate the effect of thunderstorm organization on their lightning characteristics. Compared to values from the literature the percentage of negative single stroke flashes in this study is higher (27 %). Results of this report shall contribute to a better understanding of atmospheric discharges in general and their behavior in the Alpine region in particular.**

Keywords—Cloud-to-Ground Lightning; LiOn; Single Stroke Flash; Ground Truth Data; Alpine Region; Lightning Location System;

I. INTRODUCTION

Single stroke flashes are cloud-to-ground (CG) lightning flashes that consist of one stroke only. The percentage of single stroke flashes influences the multiplicity statistics, which describes the number of strokes per flash. The multiplicity is one of the main characteristics of lightning flashes and is for example relevant for the protection principles of transmission lines [1]. Due to the analysis of ground truth lightning observation data from the alpine region (on-sight VFRS measurements), we can unambiguously assign every stroke to a flash. In the present study, we therefore analyze the occurrence of single stroke flashes.

Additionally we investigate a possible relation between thunderstorm types (single cells, multicells, supercells or lines) and its lightning characteristics. Thunderstorm organization into characteristic types is mainly driven by the amount of vertical wind shear (change of the wind vector, both in speed and in direction) with height (see [8, 9]). We classify the thunderstorm of each measurement day in two alternative ways: a manual classification according to radar characteristics and a classification based on the strength of vertical wind shear.

Our dataset consists of a combination of ALDIS LLS data and information derived from the VFRS data. This makes a comparison of parameters, such as multiplicity and the percentage of single stroke flashes, for data of both systems possible. Reasons for misclassification of single stroke flashes by the LLS can be analyzed too. The recorded ground truth data was also used to evaluate other parameters of CG flashes for the Alpine region and the performance of the Austrian LLS (see [2 – 6]). The presented dataset shows measurements of six years, from 2009 to 2018. Previous analyses for some of the recorded flashes can be found in [7]. Datasets of 2017 and 2018 are analyzed for the first time regarding single stroke flashes.

Previously published results are based on numerous studies and international publications, conducted in various regions all over the world during the last decades. The 45 % of single stroke flashes, described by Anderson and Eriksson in [1], still exceeds our highest value and is today seen as overestimation by factor two (see [10]). Zhu et al. published the lowest value in the literature (12 %; [11]). They used data of electric field measurements from Florida for their analyses. For the records in New Mexico by Kitagawa et al., electric field and moving-film camera records were correlated [12]. These measurements showed a single stroke flash percentage of 13 % [12]. Measurements in Malaysia, analyzed by Baharudin et al., showed a percentage of 16 % for electric field measurements [13]. The analyses of Rakov and Uman [14] in Florida showed a percentage of 17 % same as analyses of Balarotti et al. in Brazil [15]. The measurement data of Rakov and Uman is based on electric field records and a multiple-station TV system [14]; measurements of Balarotti et al. have been conducted with high speed video cameras in correlation with LLS data [15]. For the records in Sweden, done by Cooray and Pérez [16], which showed a single stroke flash percentage of 18 %, broadband electric field records were used. The analysis of measurements from Arizona described by Saraiva et al. [17] showed a percentage of 19 % (high speed video observations). 21 % have been reported for analyses in Belgium (Poelman et al. [18]) and Sri Lanka (Cooray and Jayaratne [19]). For analyses in Belgium [18] a VFRS dataset and LLS data was used and for measurements in Sri Lanka [19] electric field measurements have been analyzed. The result of 24 % of Antunes et al. in Brazil has been conducted with high speed video cameras in correlation with LLS data [20].

In general, we should keep in mind that analyses based on electric field records are mostly based on all flashes recorded up to a certain distance around the measurement location. If measurements are conducted with a camera system, the recorded data is limited to the field of view of the camera. Therefore, the recorded data shows for some cases maybe just a sample of the complete lightning activity, which occurred during the observed thunderstorm.

II. INSTRUMENTATION

A. Video and Field Recording System (VFRS)

The VFRS was build up to record ground truth data of atmospheric discharges in the Alpine region of Austria. With this system on-site observations at pre-selected places (see Fig. 1), where thunderstorms are predicted for a certain time, are possible. For naturally occurring CG flashes, electric field and video data can be recorded in the observed area (see [3, 4, 7, 21). The system consists of two main components: a high speed camera and an electric field measurement system. The synchronization of the components to GPS time provides the proper conjunction and comparability of the data of each atmospheric discharge.

The electric field measurements are used to determine waveform characteristics of each stroke. The general setup of this system is described in [2]. During measurements of 2009, 2010 and 2012 videos have been recorded with a monochrome camera with a frame rate of 200 frames per second, 8-bit image depth and VGA resolution (640 x 480 pixels). From 2015 on, a newer type of camera is in use. This camera allows recording monochrome videos with a frame rate of 2000 frames per second, 14-bit image depth and a resolution of 1248 x 400 pixels (see [3, 4]).

B. Lightning Location System ALDIS

ALDIS operates a sensor network of eight lightning detection sensors in Austria (see Fig. 1). Additionally, ALDIS became one of the processing centers of EUCLID in 2001. They are therefore processing the data of currently 166 sensors of the EUCLID network distributed all over Europe. The ongoing comparison of detected strokes with ground truth data (VFRS data or direct current measurements at the Gaisberg tower) helps to determine the performance of the system regarding main detection parameters (e.g. location accuracy, detection efficiency and peak current distribution). Due to continuous adaptation and improvement of the system, the median location accuracy is in the range of 100 m (for more detailed information see [5], [21] and [23]).

III. DATA

Table 1 shows the analyzed dataset for negative CG flashes for VFRS measurements from 2009 to 2018. The entire dataset contains 735 negative CG flashes with 196 single stroke flashes, recorded at 33 different measurement locations on 61 different days. Fig. 1 shows all analyzed negative CG flashes and single stroke flashes (merged data from 2009 to 2018), the VFRS measurement locations and the ALDIS sensor locations.

Table 1: Analyzed thunderstorms, total flashes and single stroke flashes for VFRS data for 2009 and 2018

Year	Thunder-storms	Total Flashes	Single Stroke Flashes
2009	2	45	9
2010	13	109	33
2012	8	117	30
2015	15	153	37
2017	10	94	25
2018	13	217	62

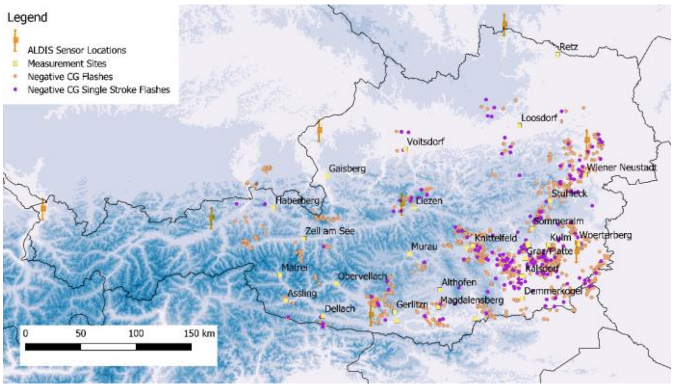

Figure 1: Recorded data for negative CG flashes (multi and single stroke flashes) merged for 2009 until 2018, VFRS measurement locations and ALDIS sensor locations

To conduct the classification of thunderstorms, radar data and data of ambient wind conditions have been used. The Aeronautical Meteorological Service (Austrocontrol GmbH) operates the Austrian radar network. They merge data of five radar stations into a composite, which provides a three-dimensional picture of precipitation intensity at a spatial resolution of one kilometer and a temporal resolution of five minutes. Different thunderstorm types can be identified by their characteristic behavior in radar data. An alternative classification is based on measured winds at an altitude of 6 km and at the surface in the closest possible distance from the thunderstorm sites. The wind vector at an altitude of 6 km is measured twice a day from rising radiosondes at selected weather stations (Vienna, Udine and Munich in vicinity of our study area). The surface wind vector is extracted from the closest automatic station operated by the Zentralanstalt für Meteorologie und Geodynamik (ZAMG), whose data are available at ten-minute intervals. This network consists of almost 300 stations, hence the closest station is usually less than 10 km away from a given thunderstorm.

IV. METHODOLOGY

The VFRS data are first correlated with the ALDIS LLS data by using GPS time. The video and electric field data are then analyzed and documented. This process allows determining all relevant parameters for CG flashes (e.g. multiplicity and percentage of single stroke flashes; see [22]).

For the present analysis, the occurrence of single stroke flashes in the Alpine region are analyzed in more detail. The detections of single stroke flashes by the VFRS and the LLS are compared for each year and over the entire measurement period. The differences of the percentage of single stroke flashes over individual measurement days or measurement locations and years are analyzed as well. The calculated values for the percentage of single stroke flashes of the VFRS measurements are compared additionally with values from previous international studies.

We also address possible influences of meteorological conditions and resulting thunderstorm types on lightning characteristics. The best discriminator between “disorganized” (short-lived and mostly weak) and “organized” (long-lived and often severe) thunderstorms is the amount of vertical wind shear, i.e. the change of wind direction and speed with height [8, 9]. The most commonly used measure is the vector difference between the wind vectors at the surface and at an altitude of 6 km, which is called “0-6 km shear” or “deep-layer shear” (DLS).

Under weak vertical wind shear, a thundercloud is almost vertical (Fig. 2 top left). This simplest, shortest-lived form of a thunderstorm is called single cell. It is built by an updraft of warm and moist air, which is quenched by a rain-cooled downdraft as soon as the cloud starts producing precipitation. Stronger vertical wind shear acts to tilt the entire thundercloud and thereby “organizes” it into a precipitation-free updraft side and a precipitation-bearing downdraft side. Rising bubbles of warm and moist air on the updraft side then sustain the thunderstorm. Under moderate vertical wind shear, this regeneration occurs periodically, and the resulting thunderstorm is called a multicell (Fig. 2 top right). Under strong vertical wind shear, the regeneration occurs more or less continuously, and the thunderstorm is called a supercell (Fig. 2 bottom left). Note that the distinctive fuzzy ice shield (“anvil”) which forms the cloud top is symmetric in case of a single cell, whereas it becomes more and more asymmetric as the vertical wind shear and the thunderstorm organization increase.

In addition to these three characteristic discrete types, thunderstorms may also organize into a line. This is favored when a cold front or another “linear” mechanism triggers thunderstorms, and when vertical wind shear is strong (Fig. 2 bottom right) [9].

In radar data, single cells are round and move with the background wind, whereas higher-organized thunderstorms exhibit V-shapes and deviant motions – periodically in case of multicells, continuously in case of supercells. This distinction is used for our first classification scheme. By analyzing radar data, the actual storm properties can most directly be related to the detected lightning characteristics, although there may be hybrid forms that may not be uniquely classified.

We therefore corroborate our results by using an alternative classification based on DLS, which relies on expected rather than actually observed thunderstorm behavior, but can be automatized and can therefore rule out any subjectivity. We compute DLS from the 6 km wind measured by the 12 UTC radiosonde at the closest site (either Vienna, Udine or Munich, depending on the thunderstorm site) and the surface wind measured by the closest automatic station immediately before the onset of the thunderstorm. This is characterized by starting precipitation, a drop of temperature, a wind shift and/or wind gusts. Weak, moderate and strong DLS are defined with values below 10 m/s, between 10 m/s and 20 m/s, and above 20 m/s, respectively [9].

Figure 2: Examples for single cell, multicell, supercell and line thunderstorms from top left to bottom right; © Georg Pistotnik

V. RESULTS

A. *Single Stroke Flashes Detected by VFRS and LLS*

Fig. 3 shows the percentage of single stroke flashes for specific measurement days of 2017 and 2018 for ten or more recorded flashes, as example for detection differences between VFRS and LLS data. The single stroke flash percentage shows a considerable variability for the individual thunderstorm days.

Lowest values for the data of 2017 and 2018 are in the range of 5 to 10 %, highest values show a percentage of over 40 % both for VFRS an LLS data (see Fig. 3). Similar analyses for our measurements of 2009 to 2015 can be found in [7].

Over the course of an entire season, the day-to-day variability of the percentage of single stroke flashes largely levels out to values between 20 % and 30 % per VFRS data and between 22 % and 30 % per LLS data (Table 2). Again, VFRS data and LLS data differ from each other. The described overestimation of single stroke flashes of LLS data in [21] does not occur and is not expected for this analysis, because of the comparison with ground truth data (i.e. misclassified inter/intra-cloud flashes are not included).

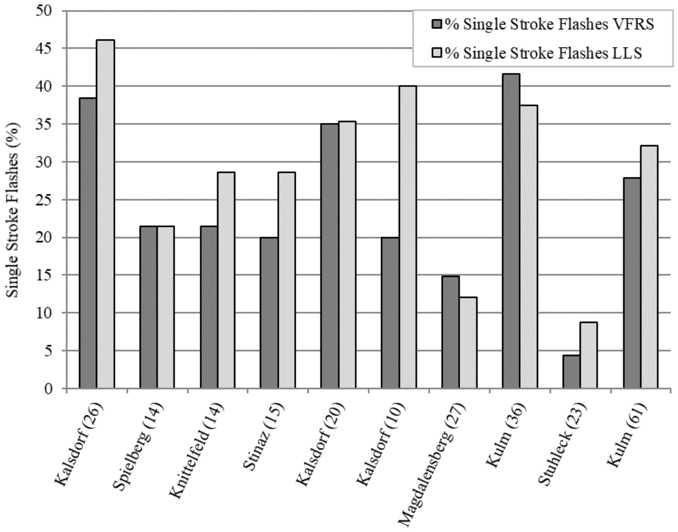

Figure 3: Percentage of single stroke flashes of VFRS and LLS data for measurement locations of 2017 and 2018; number of recorded flashes in brackets

The mean value of the percentage of single stroke flashes for the whole measurement period is 27 % for VFRS measurements (total 735 flashes) and 26 % for LLS data (total 711 flashes).

Table 2: Single stroke flash percentage for VFRS and LLS data from 2009 to 2018

Measurement Period	Single Stroke Flashes for VFRS Data	Single Stroke Flashes for LLS Data
2009	20 %	25 %
2010	30 %	24 %
2012	26 %	25 %
2015	24 %	22 %
2017	27 %	30 %
2018	29 %	30 %

B. *Comparison to Single Stroke Flash Data from Literature*

Table 3 shows a summary of results for the percentage of single stroke flashes of the present and previous analyses. As described in the introduction, these percentage values were calculated by using datasets generated from different recording systems. For the records in Florida [11], Malaysia [13], Sweden [15] and Sri Lanka [19] electric field records have been analyzed. For the analyses of New Mexico [12], electric field and moving-film camera records were correlated. The analyses of Rakov and Uman [14] in Florida were based on electric field records and a multiple-station TV system. Analyses for Brazil [15, 20], Belgium [18] and Arizona [17] have been conducted as high speed video observations or VFRS.

The analyzed ground truth VFRS data, merged from 2009 to 2018, show a higher percentage of single stroke flashes than previous studies in other parts of the world (see Table 3). Just for 2009 and 2015, values in the range of the 12 to 24 % of previous studies have been found (see Table 2). The sample sizes of our measurements are in the range of the ones stated in the literature for each individual year (see Table 1).

Table 3: Summary of results for the percentage of single stroke flashes of the present (merged data from 2009 to 2018) and previous analyses by various authors

Location	Measurement System	Sample Size	Single Stroke Flashes
Florida [11]	Electric Field	478	12 %
New Mexico [12]	Video	83	13 %
Malaysia [13]	Electric Field	100	16 %
Florida [14]	Video	76	17 %
Brazil [15]	Video	883	17 %
Sweden [16]	Electric Field	137	18 %
Arizona [17]	Video	209	19 %
Belgium [18]	Video	57	21 %
Sri Lanka [19]	Electric Field	81	21 %
Brazil [20]	Video	357	24 %
Present analysis	Video	735	27 %

C. *Single Stroke Flash Data by Thunderstorm Type*

Table 4 shows the percentage of negative single stroke flashes with respect to our manual thunderstorm classification considering radar data. This classification reveals very similar percentages of negative single stroke flashes in single cells (26 %), multicells (27 %), supercells (28 %) and thunderstorm lines (26 %). To avoid issues related to too small sample sizes, the somewhat more sparsely populated classes of multicells, supercells and lines have been merged into a joint category of organized thunderstorms, which yields a value of 27 % as well.

Table 4: Percentage of single stroke flashes calculated by thunderstorm type

Number of Thunderstorms	Thunderstorm Type	Flashes	Single Stroke Flashes
21	Single Cell	234	26 %
29	Multicell	378	27 %
3	Supercell	43	28 %
8	Line	78	26 %
32	Multi-, Supercell	421	27 %
40	Multi-, Supercell and Line	499	27 %

The objective classification according to vertical wind shear (DLS) confirms these results (Table 5). It yields a single stroke flash percentage of 27 % for DLS below 10 m/s, when single cells are most common, 27 % for DLS between 10 and 20 m/s when multicells are the most likely mode, and 32 % for DLS above 20 m/s, when supercells or lines are common. Again merging all cases with DLS > 10 m/s into a joint category of enhanced vertical wind shear, the resulting single stroke flash percentage value is 27 %. The higher percentage of single stroke flashes in the class of strong DLS (> 20 m/s) therefore entirely appears to be an artifact of the small sample size.

Table 5: Percentage of single stroke flashes for a categorization by vertical wind shear between 0 to 6 km wind shear (DLS)

Number of Thunderstorms	Vertical Wind Shear (DLS)	Flashes	Single Stroke Flashes
24	0 to 10 m/s	273	27 %
32	11 to 20 m/s	422	26 %
5	> 20 m/s	38	32 %
37	> 10 m/s	460	27 %

VI. DISCUSSION

Ground truth measurements in the Alpine region of Austria show the highest amount of single stroke flashes (27 %) compared to values of other international publications (12 - 24 %, [10, 11]). This amount influences the multiplicity statistics (i.e. the number of strokes per flash). The multiplicity is one of the main characteristics of atmospheric discharges and is linked to the protection principles of transmission lines for example [1]. Due to the analysis of ground truth data of on-site VFRS measurements, we can correctly assign every stroke to a flash and get insights in real flash distributions.

The percentages of single stroke flashes show a considerable deviation for the individual thunderstorm days. A deviation of 4 to 42 % for VFRS measurements and 9 to 46 % for LLS measurements have been determined for thunderstorm days of 2017 and 2018 (see Fig. 3). The observation of this deviation is comparable with the analysis of Diendorfer et al. [24].

For the performed measurements, varying percentages of single stroke flashes for different years are shown for both, LLS and VFRS data (see Table 2). The variance could be caused by the different spectrum of thunderstorm characteristics for individual years. In addition, the different number of measurements over the years could influence each result. The sample sizes of our measurements by year are in the range of the ones stated in the literature (see Table 1 and 3). The described overestimation of single stroke flashes of LLS data in [21] does not occur and is not expected for analyses correlated with VFRS measurements, because of the comparison with ground truth data (i.e. misclassified inter/intra-cloud flashes not included).

Results of almost all previous studies regarding single stroke flashes show data of one particular area in each country. For such analyses, variances of the single stroke flash occurrence among the country cannot be detected or excluded.

The different results for Florida could be caused by the use of two different measurement techniques. Zhu et al. (12 % single stroke flashes; [11]) used electric field measurements for their analysis, whereas the records of Rakov and Uman (17 % single stroke flashes [14]) are based on electric field records in correlation with a multiple-station TV system. The number of total analyzed flashes could also be a cause for this deviation (478 flashes [11] versus 76 flashes [14]). As already mentioned for measurements with a camera system or a VFRS, the recorded data is limited to the field of view of the camera. In contrast, every occurring CG flash around the recording system can be detected by using electric field records. Therefore, the recorded video data shows for some cases maybe just a sample of the complete lightning activity, which occurs during the observed thunderstorm. This could be a possible reason for the variation of the results (see Table 2) too.

Results of 24 % for five thunderstorm days of Antunes et al. [20] and 17 % for 109 storms of Ballarotti et al. [15] represent again data of the same area. The records of both studies have been conducted with high speed video cameras in correlation with LLS data (see [15, 20]). However, the larger percentage of single stroke flashes reported by Antunes et al. in [20] could be related to the limited number thunderstorm days (random measurement of storms with a higher amount of single stroke flashes) but also by the yearly different spectrum of thunderstorm characteristics in general. Antunes et al. [20] also found different lightning characteristics with different thunderstorm types, but could not find a direct relation between lightning frequency and thunderstorm type.

Our analysis showed similar percentages of single stroke flashes for different thunderstorm types same as for categorizations by different values of vertical wind shear between 0 and 6 km height. The objective classification according to vertical wind shear confirms the results of the manual classification of thunderstorms by using radar data (see Table 4 and 5). For the calculated single stroke flash percentage of 32 % for a deep-layer shear in excess of 20 m/s, it has to be kept in mind that these events are less common (five analyzed thunderstorms; see Table 5). After the combination of all storms with wind shear regimes favoring higher storm organization (DLS > 10 m/s) into one category, the percentage of single stroke flashes is again similar to the category under weak vertical wind shear (27 %; see Table 5).

We pointed out two possible hypotheses for the distribution of single stroke flashes for different thunderstorms in [7]. First, organized storms could indeed be more common in the Alpine region than in many other parts of the world. Second, we cannot discount the possibility that our measurements are subject to a sampling bias for the short-lived nature of single cells.

Both hypotheses cannot be confirmed for the present analysis. First, the analyzed dataset shows a uniform distribution between the number of analyzed single cells (i.e. DLS < 10 m/s) and organized storms (i.e. DLS > 10 m/s), even if the short-lived nature of single cells makes them often elusive for measurements with a mobile system. The longer lifetime of better-organized thunderstorms of course enhances the planning and preparation time and makes them more attractive for atmospheric discharge recordings with a mobile system, but this fact is not reasonable for our measurements over six years (24 thunderstorms at a DLS < 10 m/s versus 37 thunderstorms at a DLS > 10 m/s; see Table 5). Second, the percentages of negative single stroke flashes for classified single cells, or alternatively for thunderstorms under weak vertical wind shear (DLS < 10m/s) show no significant differences to the merged category of multi-, supercells and lines same as to storms with enhanced vertical wind shear (DLS > 10 m/s; see again Table 5).

The higher percentage of negative single stroke flashes might therefore (at least partly) be caused by meteorological aspects in the Alpine region of Austria (e.g. total thunderstorm height and charge distributions in the clouds).

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