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Lightning-caused fires in the Alps: Identifying the igniting strokes

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ABSTRACT

Lightning is the most important natural wildfire ignition source worldwide. However, identifying the specific lightning causing a forest fire is a challenging task. The goal of this study is to understand how different methodological approaches affect the association between igniting lightning and natural fires. To this purpose, we combined data on 267 lightning-caused forest fires from Switzerland with data on cloud-to-ground lightning strokes for the period 2000–2018. We searched for the most probable igniting lightning (candidate) among all lightning that occur during the days (up to two weeks) before fire detection in the vicinity (< 10 km) of the ignition point. We tested the suitability of 14 methods that combine different spatio-temporal approaches and selection criteria. Our results show that each method selected different candidate lightning for a subset of the fires, while for other fires identical candidate lightning were selected by different methods. Methods using criteria that combine simultaneously space and time, such as the index A, selected candidate lightning with short distances from the ignition points and short holdover times (i.e., the time between ignition and fire detection). On the contrary, methods that minimize the holdover time selected a great proportion of candidate lightning located at long distances. The majority of the candidate lighting were recorded within 1 km from the fire starting point and in less than 24 h before fire detection. The proportion of positive strokes was significantly higher among candidate lightning than in the rest of lightning, which supports the hypothesis that positive lightning are more likely to ignite a forest fire than negative ones. This study highlights the importance of the methodological choice when searching for the candidate igniting lightning of a wildfire.

1. Introduction

Lightning is the most important natural wildfire ignition source worldwide (Pyne et al., 1996; Scott et al., 2014). In boreal forests of North America, lightning accounts for the majority of fire ignitions and burned area (Hanes et al., 2019; Kasischke et al., 2002; Veraverbeke et al., 2017). In Europe, due to the stronger human influence, the proportion of lightning-caused fires has been historically less important. In boreal forests of Fennoscandia, lightning caused 13% of the fires in Finland (Larjavaara et al., 2005a) and 8% in Sweden (Granström 1993). In highly fire-prone Mediterranean areas, the relevance of lightning-induced fires is even lower (i.e., ca. 5%; Ganteaume et al., 2013; Martínez et al., 2009; Vázquez and Moreno, 1998).

In the Alps, lightning fires account for a third of the forest fires and burned area during the summer months (Cesti et al., 2005; Conedera et al., 2006; Müller et al., 2013; Vacchiano et al., 2018). There, lightning fires differ substantially from anthropogenic ones. Lightning fires occur usually from May to September, mainly at higher elevation, in coniferous stands, and on steeper slopes (Conedera et al., 2006; Müller and Vacik, 2017; Pezzatti et al., 2009). In addition, an increase in lightning fire activity in this area is expected due to climate (i.e., more frequent and severe summer droughts; CH2018, 2018) and land use change (i.e., increase in forest area and fuel buildup; Conedera et al., 2006; Pezzatti et al., 2016).

Lightning fires are associated with lightning strokes occurring during summer thunderstorms in dry, hot periods (Cesti et al., 2005; Reineking et al., 2010; Wotton and Martell, 2005), and may have a prolonged latent phase between ignition and fire detection, the so-called holdover time (Wotton and Martell, 2005). In fact, lightning-caused fires tend to start smoldering in the organic matter surrounding the base of the tree hit by the lightning (Cesti et al., 2005; Ogilvie, 1989; Pineda and Rigo, 2017). This smoldering phase mostly

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lasts one to three days before the fire translates to flaming combustion (Anderson, 2002; Nash and Johnson, 1996; Pineda and Rigo, 2017; Schultz et al., 2019). Extreme cases of holdover fires up to few weeks are however reported (Dowdy and Mills, 2012a; Duncan et al., 2010; Wotton and Martell, 2005).

The holdover time phenomenon complicates the precise identification of the igniting lightning (Dowdy and Mills, 2012a; Flannigan and Wotton, 1991; Schultz et al., 2019), which is a prerequisite for studying lightning-caused fires in more detail (e.g., Chen et al., 2015; Dowdy and Mills, 2012a; Pineda et al., 2014). Besides, other factors such as the detection efficiency (DE) and location accuracy (LA) of the lightning location system (LLS; Diendorfer, 2007; Nag et al., 2015), as well as misclassifications of the ignition cause and spatio-temporal accuracy of fire databases (Müller et al., 2013) may affect the likelihood of correctly assigning a wildfire to the specific igniting lightning.

A reliable lightning-wildfire association can help to describe the natural fire regime, for example by estimating the holdover duration (Pineda and Rigo, 2017; Schultz et al., 2019), clarifying the cause of fires (Müller et al., 2013), understanding the characteristics of igniting lightning (Müller and Vacik, 2017; Pineda et al., 2014) and modeling lightning fire occurrence (Chen et al., 2015; Wotton and Martell, 2005). Unfortunately, there are no datasets that unambiguously relate igniting lightning to the corresponding wildfires. Identifying with absolute certainty the igniting lightning of a forest fire by simply searching within the lightning dataset remains thus a challenge. However, continuous improvements of LLSs and fire databases (e.g., Pezzatti et al., 2019; Schulz et al., 2016) facilitate the identification of possible igniting lightning and numerous methodologies have been developed to match wildfires and related lightning (Table 1).

The overall goal of this study is to understand how different methodologies affect the association between igniting lightning and natural fires in Switzerland. To this purpose, we combined two independent datasets (lightning-caused forest fires and lightning) for the period 2000–2018 and tested different methods to assign a candidate lightning to each single fire. Additional specific aims of this study are (i) to describe the temporal lag (i.e., holdover time) and spatial distance between lightning stroke and wildfire detection, and (ii) to explore the possible influence of specific lightning attributes (i.e., polarity, peak current, and multiplicity) on fire ignition.

2. Data and methods

2.1. Study area

The study area covers the whole of Switzerland and extends over 41,285 km^2 (Fig. 1). The Swiss territory ranges from 193 to 4634 m a.s.l. across the Alps, which cover 62% of the country (Gonseth et al., 2001). Dominant tree species in the Alpine area, where most of the lightning fires take place (Conedera et al., 2006), are *Picea abies, Fagus sylvatica, Abies alba, Larix decidua* and *Pinus sylvestris*. More than 80% of lightning occur during summer thunderstorms from June to August with a peak in July. In Switzerland, in the period 2000–2018 lightning caused, on average, 14.6 fires and 13.7 burned ha per year. Lightning fires occur more frequently in years with severe summer drought (e.g., 2003, 2015 and 2018) and rarely exceed 1 ha (Pezzatti et al., 2019).

2.2. Lightning data

We acquired cloud-to-ground (CG) lightning data for the whole of Switzerland for the period 2000–2018 from the European Cooperation for Lightning Detection (EUCLID; http://www.euclid.org) network. Each stroke record included id number, coordinates, date and exact time, type of lightning (only CG strokes were considered in this study), flash id, number of CG strokes per flash (i.e., multiplicity), peak current and polarity, and length of the semi-major axis of the confidence ellipse at 50% probability. Single CG strokes were grouped into CG flashes based on a spatio-temporal clustering that assigns individual strokes to a particular flash when they occur within 10 km and within a second from the first stroke of the flash and 500 ms from the previous stroke of the flash (Diendorfer, 2007; Poelman et al., 2016). Lightning detection efficiency of the EUCLID network is estimated to be > 90% (> 95% in recent years) for flashes, and > 80% for strokes (Diendorfer, 2007; Romero et al., 2011; Schulz et al., 2016). Following previous studies in central Europe (Müller and Vacik, 2017; Müller et al., 2013), we excluded positive CG strokes with peak current under 10 kA from the analyses because of the probability of misclassification (i.e., classified as small-current positive CG strokes instead of intra-cloud (IC) discharges; Biagi et al., 2007; Manoochehrnia et al., 2007; Schulz et al., 2005). In terms of location accuracy, the size of the confidence ellipse (i.e., the area around the reported location within which there is a 50% probability that the CG stroke occurred; Diendorfer et al., 2014; Hunt et al., 2014) decreased over time (Diendorfer et al., 2014; Schulz et al., 2016). In the study area, the median value of the length of the semi-major axis of the 50% confidence ellipse decreased from 400 m in the period 2000–2006 to < 100 m after 2015.

2.3. Forest fire data

We extracted all the fire records classified as lightning-caused between 2000 and 2018 from the forest fire database of Switzerland "Swissfire" (https://www.wsl.ch/swissfire; Pezzatti et al., 2019). Each record included fire id, coordinates of the fire ignition point, spatial

Table 1
Studies combining and matching wildfire and lightning data.

Publication	Study area	Period	Number fires	Lightning data level	Lightning location error[1]	Buffer radius	Temporal window	Selection criteria
Nash and Johnson, 1996	Alberta and Sask. (Canada)	1988–1993	2551	Flash	5–10 km	5 km	14 days	Minimum holdover
Wotton and Martell, 2005	Ontario (Canada)	1992–2001	5169	Flash	1–2 km	10 km	none	Minimum holdover
Larjavaara et al., 2005b	Finland	1998–2002	522	Stroke	1 km	10 km	2 days (50 h)	Index A
Duncan et al., 2010	Florida (USA)	1986–2003	230	Flash	350 m	2 km	none	Minimum holdover
Dowdy and Mills, 2012a	Victoria (Australia)	2000–2009	1797	Stroke	Not described	5 km	none	Minimum holdover
Müller et al., 2013	Austria	1993–2010	573	Flash	< 400 m	10 km	10 days	Decision tree and matrices
Pineda et al., 2014	Catalonia (Spain)	2004–2009	548	Stroke	Not described	10 km	3 days	Maximum index A
Chen et al., 2015	Daxing'anling (China)	2005–2010	627	Flash	Not described	10 km	none	Minimum holdover
Schultz et al., 2019	USA	2012–2015	905	Flash	< 500 m	10 km (variable)	14 days	Daily minimum distance
This study	Switzerland	2000–2018	267	Stroke	< 400 m	5–10 km (variable)	7–14 days	Several

[1] In most of the studies, the Location Accuracy of the Lightning Location System is not unambiguously described.

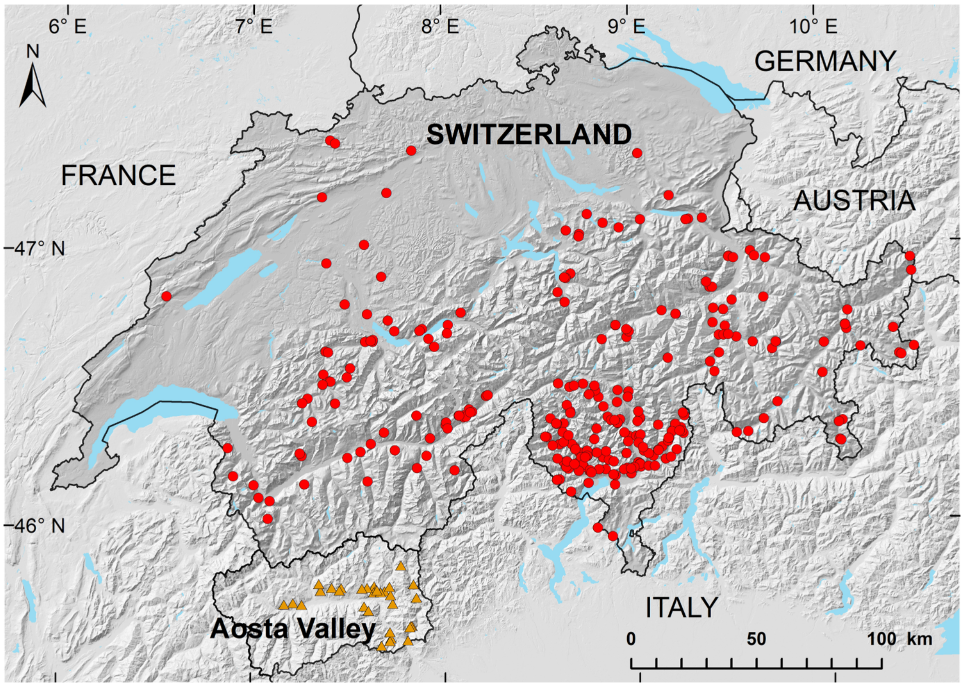

Fig. 1. Location of 267 lightning-caused wildfires (circles) in Switzerland between 2000 and 2018 and 32 lightning-caused fires (triangles) in Aosta Valley (Italy) between 2012 and 2018.

accuracy (four classes: < 50, 50–500, 500–1000, > 1000 m), date and detection time (when the fire was discovered), level of temporal accuracy (minute, hour, day), and fire cause reliability (sure or supposed). The resulting 278 records were then checked for data completeness and reliability. We assigned 24:00 h (local time) of the same day as detection time for 14 fires missing the precise time of detection. That is, the minimal temporal accuracy for a lightning fire to be included in the analyses was "day". For 247 fires, the date, hour and minute of fire detection were recorded, whereas for six fires the exact minute was unknown. For other 10 fire events, the missing information could not be retrieved (in six cases the localization of the ignition point was missing, whereas in four other cases the precise detection date was unknown) and the corresponding records were discarded from the dataset. We also removed an additional wildfire that resulted to be a restart of a previous one. The final dataset consisted of 267 lightning fires (Fig. 1).

2.4. Independent evaluation data

As an evaluation dataset, we used data from Aosta Valley, an Italian region located within the Alps that shares similar environmental conditions, such as weather, climate, forest types, topography, and natural fire regime with most of the Swiss Alps. The dataset consisted of 32 lightning-caused forest fires that occurred between 2012 and 2018 (Fig. 1), for which experts from the Forest Center of the Forest Service of Aosta Valley identified possible igniting CG flashes from those listed in the EUCLID database based on firefighting experience as well as criteria such as distance and holdover time. We acquired lightning data covering Aosta Valley for the study period and applied the same methods described in Section 2.5. to the independent set of 32 lightning fires. We then compared our results with the identification proposed by the local Forest Service to verify the agreement between the methods tested and expert knowledge.

2.5. Linking lightning strokes with forest fires

Existing approaches for detecting igniting lightning select a buffer area centered at the fire ignition point to account for location errors of fire and lightning data, and define a temporal window backward of several days to account for the holdover time. These parameters differ between study areas and may depend on the accuracy of the available data (buffer area) and the specific environmental conditions (holdover time; Table 1).

Selection criteria to find the most likely igniting lightning consider a single parameter (e.g., holdover time) or a combination of parameters by applying a decision tree or index (Table 1). In this context, Larjavaara et al. (2005b) proposed the index A, a spatio-temporal proximity index calculated for each single CG stroke that takes into consideration holdover time (T) and spatial distance (S) to the fire as follows:

$$A = \left(1 - \frac{T}{Tmax}\right) * \left(1 - \frac{S}{Smax}\right)$$

where Tmax defines the longest considered holdover time and Smax the maximum buffer radius around the ignition point. Index A is positive when both holdover time and spatial distance are lower than Tmax and Smax respectively. The closer in time and space is the lightning to the fire, the closer to one is the index A.

In this study, we considered two different values for both maximum buffer distance (i.e., 5 and 10 km) and maximum holdover time (i.e., 7 and 14 days). Schultz et al. (2019) recommended a maximum buffer distance of 5 km, whereas 10 km is a common maximum distance used in the literature that accounts for possible large location errors (Table 1). In the Alps, most of the natural fires are detected during the first week (Conedera et al., 2006), but holdover times of two weeks are also reported (Cesti et al., 2005; Müller et al., 2013).

In order to identify a likely igniting stroke (hereafter, candidate lightning) among all lightning strokes within the maximum buffer distance and the longest holdover time (hereafter, potential candidate lightning) for each lightning-caused fire, we combined two approaches (i.e., fixed and individual buffer radius) with four different selection criteria: maximum index A, minimum holdover time, minimum distance, and daily minimum distance (Table 2). The "maximum index A" criterion selects the CG stroke with the maximum index A value, as proposed by Pineda et al. (2014), by setting 168 h (7 days) or 336 h (14

Table 2
Methods applied to select candidate lightning.

Approach	Selection criterion		Max A		Min time		Min dist		Min dist day	
Fixed radius	Maximum distance		5 km	10 km	5 km	10 km	5 km	10 km	5 km	10 km
	Maximum time	7 d	●	●	–	–	–	●	–	–
		14 d	●	●	●	●	–	●	●	●
Individual radius	Maximum distance		Indiv		Indiv		Indiv		Indiv	
	Maximum time	7 d	–		–		–		–	
		14 d	●		●		●		●	

Max A = maximum index A; Min time = minimum holdover time; Min dist = minimum distance; Min dist day = daily minimum distance; Indiv = individual radius; d = day.
● = method applied; – = method not applied.

days) and 5 km or 10 km as Tmax and Smax respectively. The "minimum holdover time" criterion selects the CG stroke with the minimum holdover time among all potential candidates, while the "minimum distance" criterion selects the closest CG stroke to the ignition point within the considered holdover time. The "daily minimum distance" criterion, as proposed by Schultz et al. (2019), searches for the CG stroke with the minimum distance within the date of fire detection. If no CG strokes are found on that date, the search continues on the previous day, and this process continues backward until a CG stroke is found.

The difference between the fixed and individual radius approaches consists in the procedure used to search for potential candidate lightning in space. In the fixed radius approach, the potential candidate lightning are searched by applying a maximum buffer radius (5 or 10 km) around the fire ignition point and a maximum holdover time of 7 or 14 days. In a second step, the four selection criteria described above were applied to all potential candidate CG strokes to find the candidate lightning. On the contrary, in the individual radius approach the search for potential candidate lightning is based on the spatial location accuracy of both lightning fires and CG strokes. We considered as potential candidate lightning the CG strokes whose 99.9% confidence circle intersects the accuracy area of the fire ignition point (i.e., a circle with a radius of 50, 500, 1000 or 2000 m according to the location accuracy reported in the Swissfire database). We first calculated the semi-major axis of the 99.9% confidence ellipse of CG strokes by applying a scaling factor of 3.157 to the 50% confidence ellipse (Diendorfer et al., 2014; Grant et al., 2011). We then built a circle with the semi-major axis as radius instead of an ellipse to (1) simplify the analysis by avoiding ellipse eccentricity and (2) to guarantee that more CG strokes are included as potential candidates (Fig. 2). Like in the fixed radius approach, the four selection criteria were then applied to all potential candidate CG strokes. In summary, we tested 14 combinations of parameters, selection criteria and approaches (hereafter referred to as methods) and discarded some methods to limit redundancy and to simplify the presentation of results (Table 2).

2.6. Characteristics of candidate lightning strokes

We investigated the characteristics of the selected candidate lightning at two levels. First, we tested differences between the 14 methods by confronting the sets of candidate lightning selected by each method. Second, we chose one of the methods and looked for differences in electrical characteristics in comparison with lightning that did not cause any fire.

Differences between the 14 implemented methods were analyzed in terms of the following variables: distance to the ignition point, holdover time, multiplicity (number of CG strokes in the flash), peak current, and polarity (positive or negative) of the candidate lightning. We calculated the mean and median of all considered variables for all 14 methods. For the dichotomous variable polarity, we calculated the percentage of positive CG strokes, whereas for peak current absolute values were retained after computing positive and negative CG strokes separately. We then used (1) effect size (i.e., the raw difference between two means or two medians), (2) 95% confidence interval of the mean and median using the bias-corrected-and-accelerated (BCa) bootstrap method with 5000 resamples (Kirby and Gerlanc, 2013), and (3) histograms of distance and holdover time to highlight differences between methods.

In order to explore the potential role of electrical characteristics in igniting forest fires, we confronted multiplicity, peak current and polarity of (1) the candidate strokes selected by one of the most suitable methods, with (2) all potential candidate strokes within 10 km and 14 days, as well as (3) all registered strokes in Switzerland during the study period (i.e., lightning climatology). We calculated mean multiplicity, mean peak current and percentage of positive strokes for each of the three lightning datasets. In addition to effect sizes and 95% confidence intervals of the means, we run Wilcoxon rank sum tests to confirm whether multiplicity and peak current distributions are similar between the three lightning datasets, and Z-tests of equal proportions to confirm whether the proportion of positive strokes are the same. Given the large differences in size between the three lightning datasets (Table 6), we took 1000 samples of $n = 259$ without replacement from each of the two datasets gathering potential candidate strokes and all strokes of Switzerland. We run the tests 1000 times (one for each sample) and rejected the null hypothesis when the p-value < 0.05 (Riley et al., 2013). All the analyses were performed within the R statistical framework (R Core Team, 2018).

3. Results

3.1. Differences between methods

Each method selected a different set of candidate lightning. Table 3 shows the percentage of identical candidate lightning assigned by the different methods. In general, the percentage of agreement between two methods exceeded 50%, reaching values above 80% between methods that apply the maximum index A value in the fixed radius approach. All methods, apart from the ones using the minimum holdover time criterion, selected the exact same candidate lightning for 45% of the wildfires (i.e., 121 out of 267). The greatest discrepancies in the selection of candidate lightning were found when applying methods with the minimum holdover time, in which the match was inferior to 40% with the rest of methods.

The number of fires without a candidate lightning increased when maximum distance and/or maximum holdover time were reduced (Table 4). Similarly, the individual radius approach also increased the number of fires without any candidate lightning. On the other side, when using the evaluation dataset from Aosta Valley, we found that the highest agreement in candidate lightning was equal to 62.5% of the wildfires (i.e., 20 out of 32; Table 4). This may partly be due to the greater tendency of the Forest Service to select positive lightning. On

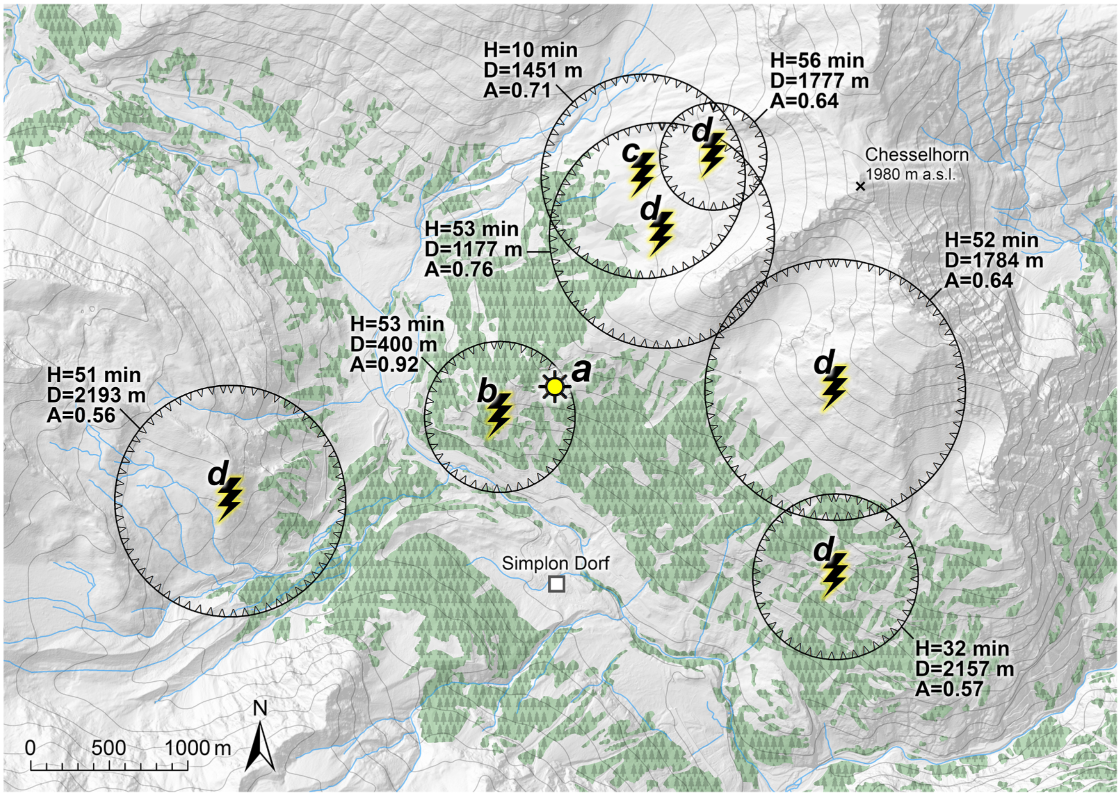

Fig. 2. Example of how candidate lightning are assigned to a lightning-caused fire (a) in the center of the figure. The closest CG stroke (b) is selected as candidate in most of the methods studied here. However, the minimum holdover time criterion selects a different CG stroke (c). Other recorded CG strokes (d) are not selected as candidates. Circles represent 99.9% confidence areas. A single potential candidate CG stroke exists (b) when the individual radius approach is applied. H = holdover time; D = distance; A = index A.

average, in Aosta Valley the 14 methods selected 27% of positive candidate lightning, while the Forest Service selected 40%. Methods based on the minimum holdover time as selection criterion produced the lowest agreement, matching at most 25% of the candidate lightning selected manually by the local Forest Service.

Tables 5 and S1 (Supplementary material) report effect sizes and 95% confidence intervals of distance and holdover time of the candidate lightning strokes. We observed some patterns. (1) As a rule, increasing the maximum distance resulted in candidate lightning with higher distances and lower holdover times, while increasing the maximum holdover time resulted in lower distances and higher holdover times. The magnitudes of these changes were variable and depended on the selection criteria. (2) The minimum distance and the minimum holdover time selection criteria generated extremes values of holdover time and distance respectively, whereas the maximum index A and the daily minimum distance criteria generated intermediate values (Fig. 3). (3) Effect sizes between methods using the fixed and individual radius approaches were not large and confidence intervals often overlapped (Table 5; Fig. 3), even though 87.4% of the potential candidates found by the fixed radius approach were discarded by the individual radius approach.

In most of the methods, distributions of distance and holdover time resemble an exponential decay, where the majority of the candidate lighting were recorded within 1 km from the fire starting point and in

Table 3
Percentages of identical candidate lightning selected by the different methods.

Method	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1. Max A 5 km 7d	–	**86.7**	**89.7**	**93.9**	*22.1*	*6.1*	**82.9**	67.7	**82.9**	77.2	74.1	*19.0*	57.8	65.4
2. Max A 5 km 14d	**86.7**	–	**82.9**	**89.4**	*18.6*	*4.6*	**85.6**	77.6	79.1	72.2	72.6	*16.7*	64.6	63.5
3. Max A 10 km 7d	**89.7**	**82.9**	–	**91.6**	*23.2*	*9.5*	**83.3**	65.8	**84.0**	**84.0**	71.5	*20.5*	55.5	66.5
4. Max A 10 km 14d	**93.9**	**89.4**	**91.6**	–	*22.8*	*6.8*	**85.6**	70.7	**84.4**	79.5	76.0	*19.4*	59.3	66.2
5. Min time 5 km 14d	*22.1*	*18.6*	*23.2*	*22.8*	–	*25.5*	*17.1*	*14.1*	*31.9*	*25.9*	*16.3*	*28.9*	*10.3*	*18.6*
6. Min time 10 km 14d	*6.1*	*4.6*	*9.5*	*6.8*	*25.5*	–	*8.0*	*4.2*	*8.7*	*16.7*	*5.7*	*22.4*	*3.4*	*8.4*
7. Min dist 10 km 7d	**82.9**	**85.6**	**83.3**	**85.6**	*17.1*	*8.0*	–	77.9	73.8	72.6	68.8	*17.5*	64.3	60.5
8. Min dist 10 km 14d	67.7	77.6	65.8	70.7	*14.1*	*4.2*	77.9	–	62.7	57.4	62.0	*13.7*	**82.9**	52.5
9. Min dist day 5 km 14d	**82.9**	79.1	**84.0**	**84.4**	*31.9*	*8.7*	73.8	62.7	–	**87.8**	67.3	*21.3*	52.9	69.2
10. Min dist day 10 km 14d	77.2	72.2	**84.0**	79.5	*25.9*	*16.7*	72.6	57.4	**87.8**	–	62.4	*21.3*	48.3	67.3
11. Max A Indiv 14d	74.1	72.6	71.5	76.0	*16.3*	*5.7*	68.8	62.0	67.3	62.4	–	*27.0*	71.1	**81.0**
12. Min time Indiv 14d	*19.0*	*16.7*	*20.5*	*19.4*	*28.9*	*22.4*	*17.5*	*13.7*	*21.3*	*21.3*	*27.0*	–	*18.3*	*38.4*
13. Min dist Indiv 14d	57.8	64.6	55.5	59.3	*10.3*	*3.4*	64.3	**82.9**	52.9	48.3	71.1	*18.3*	–	60.5
14. Min dist day Indiv 14d	65.4	63.5	66.5	66.2	*18.6*	*8.4*	60.5	52.5	69.2	67.3	**81.0**	*38.4*	60.5	–

Max A = maximum index A; Min time = minimum holdover time; Min dist = minimum distance; Min dist day = daily minimum distance; Indiv = individual radius; d = day.
In bold percentages > 80%; in italics percentages < 40%.

Table 4
Percentages of fires in Switzerland without candidate lightning and agreement with the candidate lightning selected in Aosta Valley.

Method	[1]Uncoupled fires in Switzerland (%)	[2]Agreement with Aosta Forest Service (%)
1. Max A 5 km 7d	6.7	62.5
2. Max A 5 km 14d	3.0	59.4
3. Max A 10 km 7d	1.9	62.5
4. Max A 10 km 14d	1.5	62.5
5. Min time 5 km 14d	3.0	25.0
6. Min time 10 km 14d	1.5	12.5
7. Min dist 10 km 7d	1.9	62.5
8. Min dist 10 km 14d	1.5	50.0
9. Min dist day 5 km 14d	3.0	62.5
10. Min dist day 10 km 14d	1.5	62.5
11. Max A Indiv 14d	4.9	56.3
12. Min time Indiv 14d	4.9	18.8
13. Min dist Indiv 14d	4.9	43.8
14. Min dist day Indiv 14d	4.9	56.3

Max A = maximum index A; Min time = minimum holdover time; Min dist = minimum distance; Min dist day = daily minimum distance; Indiv = individual radius; d = day.

[1] Percentage of fires in Switzerland for which the methods did not find any candidate lightning.

[2] Percentage of fires in the Aosta Valley dataset for which the methods selected the same candidate lightning chosen by the local Forest Service.

less than 24 h before fire detection (Fig. 4). Tables S2 and S3 report cumulative values of distance and holdover distributions respectively for each of the methods. Surprisingly, minimum holdover methods produced a different distance distribution, where the number of candidate lightning did not decrease with increasing distance to the wildfire. On the other side, more than 20% of the candidate lightning from minimum distance methods displayed a holdover time longer than seven days.

3.2. Electrical characteristics

We did not find relevant differences in the studied electrical characteristics (i.e., multiplicity, peak current, and polarity) of the candidate lightning among the different methods (Table S4). To describe then the electrical characteristics of candidate lighting, we chose the method that selects strokes with the maximum A value within 10-km radius and 14-day holdover time. This is one of the best methods in terms of uncoupled fires and agreement in the evaluation dataset (Table 4), and produces relatively low values of both distance and holdover time (Fig. 3). Differences between candidate lightning, potential candidate lightning, and lightning climatology become evident concerning polarity (Table 6). In particular, the proportion of positive strokes was more than twice higher among candidate lightning than in the potential candidate lightning dataset. While positive strokes were also more frequent among candidate lightning than in the Swiss lightning dataset, only 38.0% of the tests confirmed that this difference in polarity was statistically significant at $\alpha = 5\%$. On the other hand, the multiplicity of candidate and potential candidate lightning was nearly equal, although the multiplicity of all Swiss CG strokes was significantly lower. This difference is mainly due to that 60.6% of all Swiss CG flashes are composed of a single stroke, while less than half of candidate (46.3%) and potential candidate strokes (47.6%) belonged to mono-stroke flashes. Moreover, confidence intervals around the means and statistical tests did not show any significant difference in peak current between candidates and the rest of lightning. As expected, peak currents were higher in positive (mean = +29.2 kA) than in negative candidate strokes (mean = −14.1 kA).

4. Discussion

4.1. Methods to assign igniting lightning

Our results highlight how critical the methodological choice (i.e., the approach, selection criterion and parameters to be applied) is when searching for the igniting stroke of a lightning-caused fire. The individual radius approach is conceptually more appropriate and flexible because it allows choosing the error distribution (Hunt et al., 2018), probability level (Grant et al., 2011) and shape of the confidence area around each stroke (Diendorfer et al., 2014). In addition, individualizing the confidence area reduces drastically the number of potential candidates with respect to the fixed radius approach. In our case, we utilized a Gaussian error distribution, a 99.9% probability level and a circle instead of an ellipse to build the confidence area around each CG stroke. However, the individual radius approach

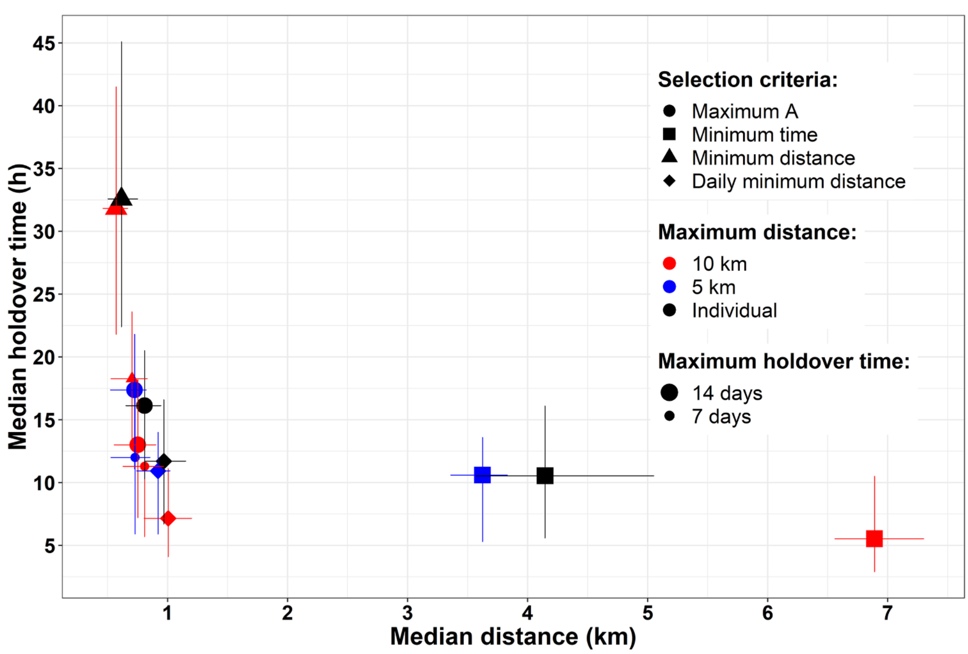

Fig. 3. Median distance and holdover time of candidate lightning selected by the different methods. Error bars represent 95% confidence intervals.

Table 5
Median distance and holdover time in each method.

Method	Distance			Holdover time		
	Median (m)	[1]ES median (m)	[2]Overlap CI medians	Median (h)	[1]ES median (h)	[2]Overlap CI medians
1. Max A 5 km 7d	730	–	–	12.0	–	–
2. Max A 5 km 14d	725	−5	Yes	17.4	5.4	Yes
3. Max A 10 km 7d	809	79	Yes	11.3	−0.7	Yes
4. Max A 10 km 14d	753	23	Yes	13.0	1.0	Yes
5. Min time 5 km 14d	**3624**	**2894**	**No**	10.6	−1.4	Yes
6. Min time 10 km 14d	**6890**	**6160**	**No**	5.5	−6.5	Yes
7. Min dist 10 km 7d	704	−27	Yes	18.3	6.3	Yes
8. Min dist 10 km 14d	572	−158	Yes	**31.8**	**19.8**	**No**
9. Min dist day 5 km 14d	921	191	Yes	10.9	−1.1	Yes
10. Min dist day 10 km 14d	1006	276	Yes	7.2	−4.8	Yes
11. Max A Indiv 14d	809	79	Yes	16.1	4.1	Yes
12. Min time Indiv 14d	**4146**	**3416**	**No**	10.5	−1.5	Yes
13. Min dist Indiv 14d	616	−115	Yes	**32.6**	**20.6**	**No**
14. Min dist day Indiv 14d	969	239	Yes	11.7	−0.3	Yes

Max A = maximum index A; Min time = minimum holdover time; Min dist = minimum distance; Min dist day = daily minimum distance; Indiv = individual radius; d = day.
In bold values corresponding to large effect sizes.
[1] Effect Size: difference between medians. All the effect sizes were calculated using the first method as reference.
[2] Overlap between 95% BCa bootstrap Confidence Intervals of medians. All the overlaps were calculated using the first method as reference.

produced a higher number of fires without a candidate lightning, a lower agreement in the evaluation dataset from Aosta Valley, and slightly higher distance and holdover time compared to methods applying the fixed radius approach.

Regarding the selection criteria, the minimum holdover time criterion selected candidate strokes at any distance within the considered radius. This may result in a great proportion of possibly wrong candidates, as suggested by the low match with the rest of candidate lightning selected by the other methods tested, as well as the poor agreement in the Aosta Valley dataset. Similarly, the minimum distance criterion selected a higher proportion of candidate lightning with long holdover times, which is unlikely for the Alps (Conedera et al., 2006).

Selection criteria combining space and time (i.e., maximum index A and daily minimum distance), on the contrary, produced low values of both distance and holdover time, and a high match between candidate lightning irrespectively of changes in the parameters (i.e., maximum distance and holdover time). This is relevant because close distances and short holdover times increase the confidence that the correct set of igniting lightning are identified (Schultz et al., 2019). Moreover, both criteria yielded the highest agreement in Aosta Valley.

There is in any case a trade-off regarding the search parameters. Increasing the maximum distance and holdover time guarantees a higher number of fires paired with a candidate lightning, but it may rise the distance and/or holdover time of some candidates as well. Nonetheless, for methods that apply the maximum index A and daily minimum distance criteria, despite changing the values of the parameters, the confidence intervals of the medians overlapped, the distributions of distance and holdover time remained similar, and the level of agreement in the Aosta Valley dataset was not affected.

In summary, the method of the maximum index A within10 km and 14 days provides reasonable candidates among the methods analyzed. The maximum index A criterion produces low median values of both distance and holdover time, a fixed radius of 10 km increases the number of fires with a candidate lightning and the level of agreement in the Aosta Valley evaluation dataset, and a maximum holdover of 14 days is compatible with previous knowledge and has no relevant influence in the distribution of holdover time.

4.2. Holdover duration

Holdover duration represents a key challenge when attempting to identify igniting lightning. Our results show that the distribution of holdover duration in Switzerland is skewed to the right and follows the shape of an exponential distribution, which agrees with other studies in Canada (Kourtz, 1967; Nash and Johnson, 1996; Wotton and Martell, 2005) and the USA (Schultz et al., 2019). However, according to our results, the most recent stroke is not necessarily the one igniting the fire. The most recent strokes produce a rather uniform or left-skewed distance distribution, in which the candidates are much farther from the wildfire start locations in comparison with the other methods. In our study, more than 60% of the natural fires were detected in less than one day, and more than 80% within the first three days. Holdover durations were estimated to be longer in boreal forests of Canada (Nash and Johnson, 1996; Wotton and Martell, 2005), and shorter in Mediterranean ecosystems (Pineda and Rigo, 2017; Pineda et al., 2014).

Drivers of holdover duration are not well understood. Fuel (e.g., litter depth, moisture and flammability) and thunderstorm characteristics (e.g., timing and velocity) may influence holdover duration (Anderson, 2002; Cesti et al., 2005; Larjavaara et al., 2005b). For instance, morning and afternoon ignitions may be detected sooner than evening and night ignitions, that tend to smolder overnight until burning conditions become more favorable the day after when solar heating raises temperature and diminishes relative humidity (Pineda and Rigo, 2017). Igniting strokes are commonly associated with less rainfall (Dowdy and Mills, 2012b; Müller and Vacik, 2017; Pineda and Rigo, 2017). However, the precise role of thunderstorm-related precipitation in the holdover duration remains unclear (Pineda and Rigo, 2017). Holdover time may also be driven by non-environmental factors. In remote boreal areas, more time is required to detect a wildfire in comparison with central and southern Europe (Conedera et al., 2006; Flannigan and Wotton, 1991).

4.3. Influence of lightning attributes on fire ignition

There is a broad consensus that “dry lightning” (i.e., lightning that occur without significant rainfall) have a greater change of igniting a fire (Abatzoglou et al., 2016; Dowdy and Mills, 2012b; Pineda and Rigo, 2017). Nevertheless, the influence of specific attributes such as polarity, multiplicity, and presence of long continuing current (LCC) on the ignition potential of a lightning is still debated (Hall and Brown, 2006; Pineda et al., 2014). For example, some studies found that positive strokes are more likely to start forest fires (e.g., McGuiney et al.,

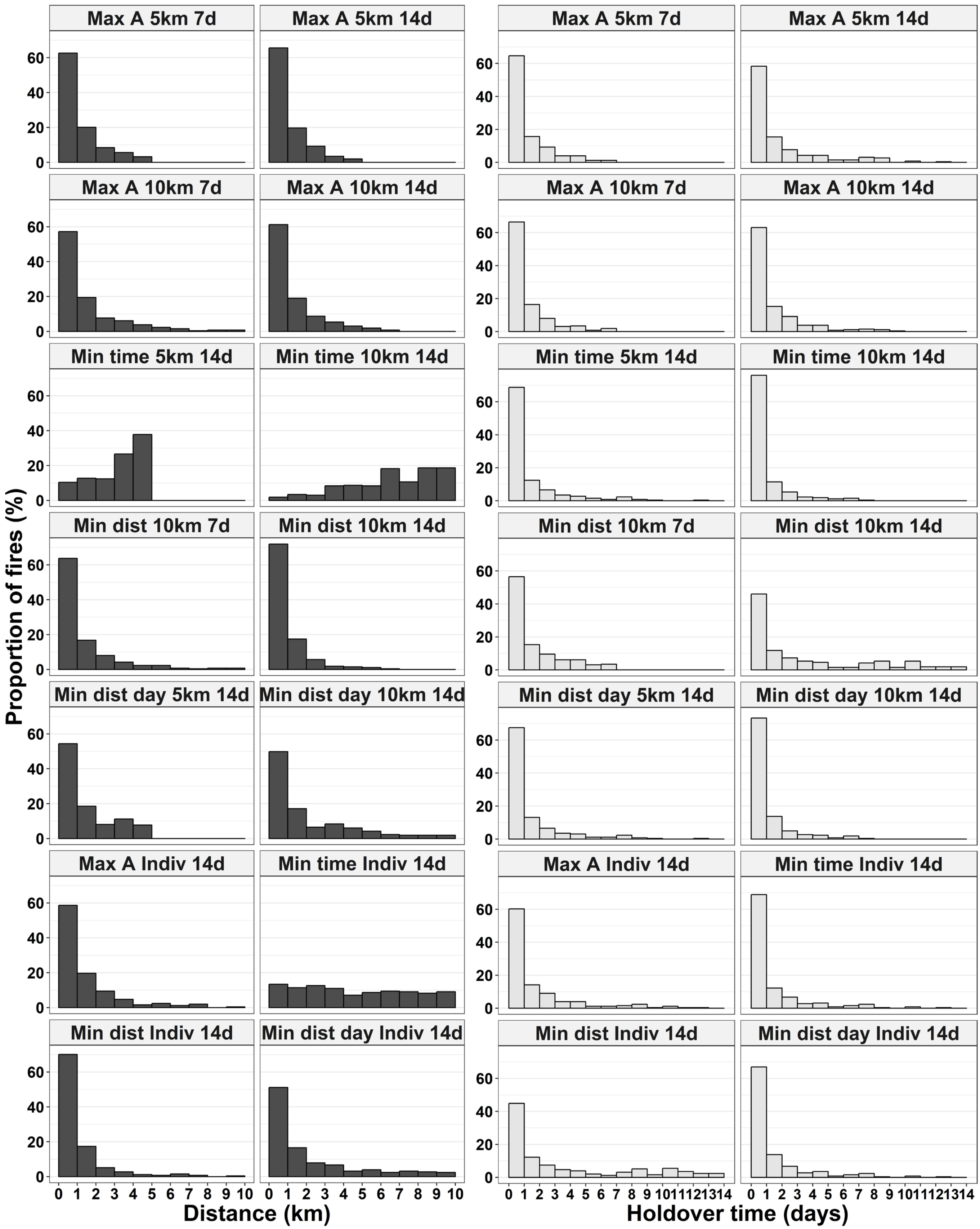

Fig. 4. Distribution of distance and holdover time in each method. Distance refers to the distance between the reported location of the candidate lightning and the wildfire ignition point. Holdover time refers to the time elapsed since the candidate lightning occurred until the wildfire was detected. Max A = maximum index A; Min time = minimum holdover time; Min dist = minimum distance; Min dist day = daily minimum distance; Indiv = individual radius; d = day.

Table 6
Electrical characteristics of candidates, potential candidates, and all lightning.

Electrical characteristics		[5]CG strokes		
		Candidate	Potential	Switzerland
Number		259	38,537	1698,861
Multiplicity	Mean	2.5	2.4	**2.0**
	[1]ES mean	–	−0.1	**−0.5**
	[2]Overlap CI means	–	Yes	**No**
	[3]Tests rejected (%)	–	3.7	**99.1**
[4]Peak current (kA)	Mean	16.7	15.0	15.8
	[1]ES mean	–	−1.8	−0.9
	[2]Overlap CI means	–	Yes	Yes
	[3]Tests rejected (%)	–	26.6	20.3
Polarity	% positive	17.4	**7.7**	**10.7**
	[1]ES% positive	–	**−9.7**	**−6.6**
	[2]Overlap CI% positive	–	**No**	**No**
	[3]Tests rejected (%)	–	**90.7**	38.0

In bold values corresponding to large effect sizes.
[1] Effect Size: difference between means or proportions. All the effect sizes were calculated using the "candidate" dataset as reference.
[2] Overlap between 95% BCa bootstrap Confidence Intervals of means or proportions. All the overlaps were calculated using the "candidate" dataset as reference.
[3] Percentage of times that the null hypothesis of the Wilcoxon rank sum test and Z-test of equal proportions was rejected (i.e., p-value < 0.05). All the tests were performed using the "candidate" dataset as reference.
[4] In absolute values. Peak current was also analyzed separately for positive and negative CG strokes.
[5] Three datasets: candidate strokes selected by the maximum index A within 10 km and 14 days method; potential candidate strokes within 10 km and 14 days of each lightning-caused fire; all strokes from Switzerland 2000–2018.

2005; Müller and Vacik, 2017; Wotton and Martell, 2005), whereas others did not (e.g., Hall and Brown, 2006; Larjavaara et al., 2005b; Nauslar, 2014; Pineda et al., 2014).

It is generally accepted that lightning with LCC (i.e., a continuing current that lasts for at least 40 ms; Brook et al., 1962; Kitagawa et al., 1962) heat the fuel for longer and have consequently a higher capacity to ignite a fire (Fuquay et al., 1967, 1972; Grahan et al., 1997; Latham and Schlieter, 1989; Latham and Williams, 2001; Rakov and Uman, 2003). Since LCC is more frequent in positive lightning than in negative ones (Anderson, 2002; Grahan et al., 1997; Saba et al., 2010), positive lightning should have a greater ignition capacity. Therefore, it is not polarity itself but its association with another lightning phenomenon such as continuing current (which is not measured by the LLS) that might influence fire ignition (Larjavaara et al., 2005b).

Our results are consistent with the hypothesis that positive lightning are more likely to ignite a forest fire than negative ones. Although negative lightning are responsible for the majority of the natural fires in Switzerland, we found a significantly higher proportion of positive strokes among candidate lightning than in the rest lightning. Since most of the CG strokes are negative, but the LCC phenomenon is more frequent in positive strokes, the LCC hypothesis could explain our findings. On the contrary, multiplicity and peak current of igniting lightning are not substantially different from the rest of lightning, as highlighted in other studies (Müller and Vacik, 2017; Pineda et al., 2014; Schultz et al., 2019).

4.4. Lack of candidate lightning

Similarly to other studies (e.g., Pineda et al., 2014; Schultz et al., 2019), we did not find any igniting lightning for some wildfires. In three cases, we assumed a misclassification of the ignition source (Müller et al., 2013) since these fires occurred in October and even one in November. For another fire, it is possible that no candidate lightning was found because of its location near the Swiss border and we lacked lightning data outside Switzerland.

In other cases, the lack of candidate lightning is mostly due to methodological constraints. In total, we identified 25 wildfires (i.e., 9.4% of the wildfires studied) without a candidate lightning for at least one of the 14 methods. For some wildfires, this is the consequence of applying more restrictive methods, such as a 5-km search radius or the individual radius approach. Although some CG strokes may not be detected by the LLS, this does not necessarily imply a lack of candidate lightning since thunderstorm activity is frequently associated with a high number of CG strokes in summer months (Larjavaara et al., 2005b; Manoochehrnia et al., 2007; Müller et al., 2013).

Finally, in some cases, the effective holdover time may exceed the limits set by our methods. Holdover times overrunning two weeks are reported for Canada (Wotton and Martell, 2005), the USA (Duncan et al., 2010) and Australia (Dowdy and Mills, 2012a), while in central Europe we are only aware of maximum holdover durations of 15 days (Cesti et al., 2005; Müller et al., 2013). Therefore, it seems plausible that some lightning fires smolder for more than 7 days in the Alps, but we assume that the proportion of holdover fires exceeding 14 days must be very low in Switzerland.

5. Conclusions

There is an increasing interest in lightning-caused fires, especially in how climate change may affect the natural fire regime. This study demonstrates that the methodology to link lightning and fires must be considered carefully. According to our results, in the Alps selection criteria that combine space and time, such as maximum index A and daily minimum distance, are more appropriate than those maximizing either only distance or holdover time. The individual radius approach may be conceptually more recommendable, but also presented certain practical disadvantages. Accordingly, a fixed maximum radius of 10 km and a maximum holdover time of 14 days seem to be reasonable parameters for the Alpine conditions. The study also shows that positive lightning may be more likely to ignite a fire. Besides, holdover fires in the Alps are not so rare considering that approximately 20% of the fires smolder for more than two days. In conclusion, identifying single igniting lightning is not a trivial task but is a necessary step to advance the knowledge on lightning-caused fires, in particular to predict natural fire ignition probability and assess daily fire danger.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.agrformet.2020.107990.

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