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Keywords: lightning; thunderstorms; hail; climatology

Article

Analysis of Lightning Climatology for Central Europe

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Abstract: A lightning climatology covering 16 years based on ground measurements is presented and discussed. Instead of the lightning density, the focus lies on the analysis and interpretation of mean Amperages per thunderstorm. This enables to identify regions with a particularly high risk of strong thunderstorms. In autumn the Nort-Sea and the Po valley is characterized by few but very strong thunderstorms. During the convective the number density of thunderstorms increases significantly over land. The Alpine region is by far most affected by strong thunderstorms, whereby the severity of the thunderstorms is on average much higher in the southern (Po Valley) than in the northern foothils. Also some regions along the western and eastern border of Germany are on average affected by very strong thunderstorms. The patterns form some sort of a U-shape, which results from the lifting of incoming moist air from the west or east by the orography. The analysis reveals that the mean amperage could be a good candidate for the estimation of risks induced by strong hail events.

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1. Introduction

Thunderstorms endanger life and infrastructure. They occur very frequently during summertime in Central Europe. Information of the lightning density and strength is important in order to estimate possible risks and the costs for insurances and to support protections measures, either personally or for structures (e.g., [1]). Therefore, lightning data is used in many application ranging from thunderstorm nowcasting to the generation of climatologies for climate monitoring, which is for example useful to calculate the needed cover of insurances. Below are some examples of lightning applications in nowcasting and climatology to highlight the importance of the data.

The NowcastSatAviation (NCS-A) method [2] uses the GLD360 lightning data [3–7] from VAISALA for the nowcasting of severe convection. The use of lightning data for this method was a customer requirement e.g., "Lufthansa System". Using only satellite or NWP information would lead to a much higher False Alarm Ratio (FAR) in combination with a lower probability of detection. The product is used by several key customers and the lightning data is an important building block of this success Also the Convective Diagnosis Oceanic (CDO) products [8] are based on lightning data. Here, data from EarthNetworks ground based global network [9] are used, in addition to Cloud Top Height (CTH) and OT information from geostationary satellites [10]. The respective algorithm is used to detect the area of thunderstorms that are most hazardous for aviation. Climatologies of lightning data are of high value for all kinds of risk assessments. They can also be used to improve the thunderstorm forecast unsing bias correction based on artificial intelligence. Climatologies are also of high relevance for the monitoring and analysis of the climate change. However, for this purpose at least several decades of a homogeneous data set would be necessary. Finally, the analysis of lightning is essential for the general understanding of thunderstorms. The applications for lightning climatologies are manifold. In this paper a lightning climatology for Central Europe based on LINET [11,12] data is presented and analysed in the following sections. This region is well covered by the regional LINET data, which offers a high detection efficiency for lightning data. Lightning measurements in the

VLF/LF wavelength region provide a higher number of flashes and are therefore well suited for high resolution climatologies.

LINET data has been already used to analyse thunderstorms in Central Europa by [13]. She found that the highest number of lightning strokes occurs in the pre-alpine region of southern Germany and some local maxima in low mountain ranges. In contrast, the lowest number of lightning strokes was found in areas of the North and Baltic Sea. The maximum of thunderstorms occurs in the sommer season (June to August), whereby the diurnal cycle shows a maximum in the afternoon. Further she found that the time of daily maximum occurs later in the afternoon in summer compared to spring and autumn. However, the analysed data set covered only 6 years. Therefore in our study a longer time series is generated and discussed. In this paper we cover 16 years from 2007-2023. Also several other authors have analysed thunderstorms in Europe. In this context, a brief overview of key works dealing with lightning climatologies is given as a basis for the discussion of our results.

A regional lightning climatology of the UK and Ireland was presented and discussed in [14] The climatology covers a 12-year period from 2008 and 2019 and they compared the lightning fingerprints for different regions in order to gather additional insights for the temporal distributions of lightning. They found that different regions exhibit contrasting summer thunderstorm seasons and that diurnal lightning distributions have also a significant regional dependency with stronger afternoon peaks over-land. Further regions more prone to winter thunderstorms were identified as having northwest facing coastlines [14].

Kahraman et al. [15] addressed the poor representation of thunderstorms in conventional climate models, which results in high uncertainty in predicted future changes up to conflicting results. Beside simulations they use ATDNet observations [16] in order to discuss this issue and to improve the modelling of thunderstorms and thus of lightning. A prolonged series of ATDNet observations were also analysed by [17]. They found that the annual flash density was highest in Northeast Italy. In line with other studies in Europe they observed the highest lightning frequency during the afternoon hours and the lowest frequency at night. They also provided the lightning density, but unfortunately the lightning density depends largely on the lightning networks (see Section 2) and are thus only rudimentary comparable with results from other lightning networks. Further, a 10 year climatology is rather short for the analysis of thunderstorm patterns.

Morgenstern et al. [18] used EUCLID (European Cooperation for Lightning Detection) lightning data together with ERA5 reanalysis in order to analyse meteorological environments favourable for thunderstorms. They found two major thunderstorm environments: Wind-field thunderstorms, characterised by increased wind speeds but relative low CAPE values and mass-field thunderstorms, characterised by large CAPE values, high dew point temperatures, and elevated isotherm heights. They found that wind-field thunderstorms occur mainly in winter and more over the seas, while mass-field thunderstorms occur more frequently in summer and over the European mainland.

A Pan-Alpine Climatology of Lightning and Convective Initiation was generated and analysed by [19]. The Alpine region is a hot-spot for lightning activity in Europe. Again data from EUCLID (2005-2019) is used for the study. They found a maximum activity for Cloud to Ground (CG) flashes from mid-May to mid-September, with a peak at the end of July and overall a afternoon peak in the diurnal cycle occuring in the afternoon. They argued that since many thunderstorms follow the prevailing mid-latitude westerly flow, a peak of CG flashes extends from the mountains into the plains and coastal areas of northeastern Italy and Slovenia. Finally, they found that CG flashes over the sea/coast occur less frequently than in plains and mountains. Probably as a consequence of the lower diurnal cycle in the surface temperature they observed a weaker diurnal cycle for ocean thunderstorms. Further, the seasonal maximum of thunderstorms is in autumn instead of summer.

Spatiotemporal variability of lightning activity in Europe and the relation to the North Atlantic Oscillation teleconnection pattern is discussed in [20], based on lightning data from a SIEMENS network covering 15 years. [20]. Their results emphasis the crucial role of large-scale flow in steering the spatial and temporal patterns of convective activity.

Probably one of the longest observations analysed so far is presented in the work of [21]. This study uses the PERUN lightning detection network managed by IMGW-PIB (Institute of Meteorology and Water Management – National Research Institute) during period 2002 to 2020. They found that the highest electrical activity occurs in central Poland (Mazovian Lowland) and the lowest in the Pomeranian Lake District. However, during 18 years the network have changed, e.g., by addition of stations (Legnica, Chojnice and Kozienice,) which affects the lightning tendency and thus the trends. Thus, more studies in order to investigate trends in thunderstorms and to analyse the reasons are needed.

Studies that covers a longer time period are using usually additional data sources beside measurements, e.g., [22]. The analysed data set covers a period from 1979-2017, but in addition to measurements also NWP reanalysis data (ERA4) were used. They found annual peak thunderstorm activity in July and August over northern, eastern, and central Europe, contrasting with peaks in May and June over western and southeastern Europe. They argue that the thunderstorms in the Mediterranean are driven by the warm waters and thus have has predominant activity in the fall (western part) and winter (eastern part) while the nearby Iberian Peninsula and eastern Turkey have peaks in April and May. They also investigated trends in thunderstorms. Their analysis of thunderstorm days indicates an increase over the Alps and central, southeastern, and eastern Europe with a decrease over the southwest. However, they used NWP data in there study which induces the risk of artificial trends. For more reliable trend analysis a longer time series of observations is needed.

In contrast to the studies above we focus for the analysis of the thunderstorms on the average Amperage. We believe that this quantity is less sensitive to changes in the network and thus better suited for the analysis of ligthning climatologies (see Section 2). In addition, many small thunderstorms produce likely less damage than a few large storms. Within this context it has also to be considered that as a result of the high number of thunderstorms protective measures might be only possible and reasonable for the "most" severe storms. Thus, we believe that our approach enables a better analysis of the regional patterns and a better assessment of the risks for damages induced by thunderstorms. More over, our approach might be more stable for climate trend analysis as it appears to be more robust with regard to the combination of time series from different lightning networks. In addition, to the knowledge of the authors this manuscript presents an analysis of the the longest LINET climatology discussed so far. As far as the authors know, this study is the first time where the benefit of lightning climatologies for AI based thunderstorm forecasts are discussed.

2. Materials and Methods

The climatological data discussed in this study is based on LINET lightning data [11] from the Nowcasting AG. The LINET network consists of several lightning sensors in Europe equipped with a field antenna, a GPS receiver and a field processor to analyse the information of the signal in the VLF/LF wavelength region, thus, in radio bands.

The Very Low Frequency range (VLF; 500 Hz– 50 kHz), allows a larger distance between the stations, but on cost of a lower detection efficiency. Networks operating in this spectral range have usually a lower detection efficiency concerning cloud to cloud (CC) lightning and measure dominantly cloud to ground lightning flashes. This leads to lower number of lightning flashes per thunderstorm, in particular in the low amperage range. This is illustrated in Figure 1 and is one motivation to focus on the analysis of mean amperage per thunderstorm in this study. The VLF frequency corresponds to wavelength from 10–100 km.

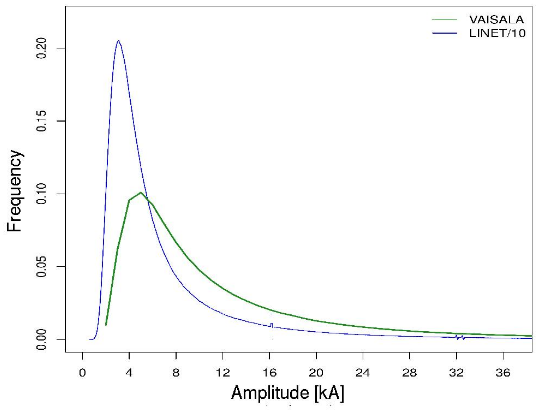

Figure 1. Illustration of differences in the frequency of detected lightning flashes. LINET detects much more flashes for weak thunderstorms with low absolute Amperage. With increasing Amperage the differences balances out. Example for June/September 2017.

The low frequency is defined in the range of 30–300 kHz and has a wavelength range from 1–10 km. Hence for this range a denser network of receiving stations are needed. Thus, this range is usually used for regional data and is not well suite for a global lightning network.

LINET exploits the LF spectral range that allows a better identification of Cloud to Cloud discharges, and hence detects a larger number of flashes. They use baselines of ca. 200 km for an adequate coverage in Central Europe. In many areas at the border of the LINET coverage with the inclusion of the Mediterranean Sea, the distances between the stations are on average larger than in central europe; consequently, the detection efficiency is lower in these regions. During the last 15 years the LINET measurement network was modified, e.g., by adding stations and updates of the retrieval software. Although this improves the detection of weak lightninh flasshes in particular at the borders of the network, it probably also leads to inhomogeneities in the time series. Thus, this study focus on Central Europe where the density of station was high from the beginning (see [11]) and hence a more homogeneous data set can be assumed. Further, for the analysis we focus therefore on spatial patterns of absolute Amperage values. Please note, that in the original data the Amperage can be positive or negative. Figure 2 illustrates a typical distribution for summer time.

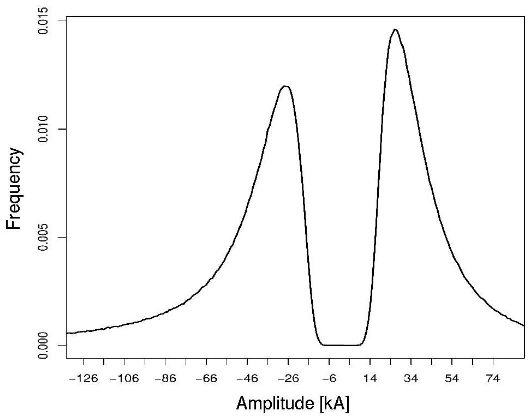

Figure 2. Illustration of differences in the frequency of lightning flashes with negative and positive charges. Example for June/September 2017.

The programming language Julia [23] has been used to calculate the Monthly mean kAmp devided by number of thunderstorms and the number of thunderstorm flashes per month. Further Julia has been used to transfer the data to a regular grid with a resolution of 0.05 degrees. The Climate Date

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Operators (CDO) [24] are used to estimate monthly long term means of the data. Beside an analysis of the LINET climatology we focus on the relation of weather and lightning distribution and discuss possible implications for climate change. Thus, in the next section basic driver for thunderstorms are briefly discussed and used to analyse and understand the patterns of the lightning climatology presented in Section 3.

2.1. Basic Drivers for Thunderstorms

Moisture, instability of the atmosphere and an updraft lifting are the main driver for thunderstorms. Strong wind shear is an indicator for severe thunderstorms. For surface dewpoints less than 13 degrees Celsius the conditions are not favourable for the occurrence of thunderstorms because they are often associated with stable atmospheres, which depresses vertical movement. However, lower dewpoints could also lead to thunderstorms in the case of forced lift of air induced by e.g., mountains or fronts.

Stable atmospheres depresses the updraft of air parcels and hence deep convection and with that the development of thunderstorms. Therefore, instability of the atmosphere is an important pre-requisite for the development of thunderstorms. CAPE is often used to indicate the instability in terms of thunderstorm likelyhood. Very often, instability occurs in the middle and upper levels of the troposphere but not in the lower troposphere. Low level stability is often referred to as convective inhibition. In case of convective inhibition a forced lift of air is needed to overcome the thermal barrier in the lower troposphere. Therefore, forced lift of air is also a key trigger mechanism for thunderstorms.

There are many different lift mechanisms. In the following the main mechanisms for Central Europe are discussed. Fronts bring cold air which lifts the warm air. Because of this thunderstorms induced by fronts are a very common in Central Europe. Another reason are mesoscale convergence boundaries such as sea land breezes, mountain valley winds and forced updraft by orography.

We assume that the value of Amperage correlates with the severity of the thunderstorms. This is a reasonable assumption, cause the higher the updraft the higher the friction between the particles and the higher the electric charging. This is simple physics. However, it is important to note that the same thunderstorm would lead to different Amperage values for different measurement networks as a consequence of different measurement techniques, see Figure 1.

3. Results

3.1. The Spatial Patterns

For the sake of clarity the dicussion of the results is separated in cold season covering October to March and the convective season, covering April to September.

Cold season

Figure 3 shows the results for the cold season which is on average characterizzed by stable atmospheric conditions.. Overall the thunderstorm activity is much lower in the cold season than in the convective season. The atmosphere is on average characterized by stable atmospheric conditaions which suppresses the development of thunderstorms. Further cold air can absorb less water vapour and is thus less moist. However, in contrast to the convective season high Amperage patterns are apparent over the North-Sea in the autumn months September, October and November, and too a much lesser extend in December.

The North Sea is still relative warm during these months and the evaporation is therefore still relatively high. Thus, the North Sea acts as a source for relative warm and moist air. Cold fronts induced by autumn storms can lead to a crash of cold air with this warm and moist air. In addition the associated fronts form a vertical wetch that leads to forcing and thus are favoring the development of thunderstorms. Therefore, the patterns are probably induced by frontal autumn storms.

With regard to the classification of Morgenstern [18] these storms are wind-field thunderstorms, characterised by increased wind speeds but relative low CAPE values. A comparison with the lightning densities (Figures in Appendix B, A1 and A2) reveals that these hot spots are a result of relative few, but very strong thunderstorms. It is therefore evident that the overall stable conditions during the cold season (low CAPE) lead to very low frequency of thunderstorms but these thunderstorms are on average characterised by relative high Amperage and hence a very severe nature. As the Baltic sea has in average lower wind velocities and fewer heavy storms, there are no respective patterns apparent over the Baltic sea.

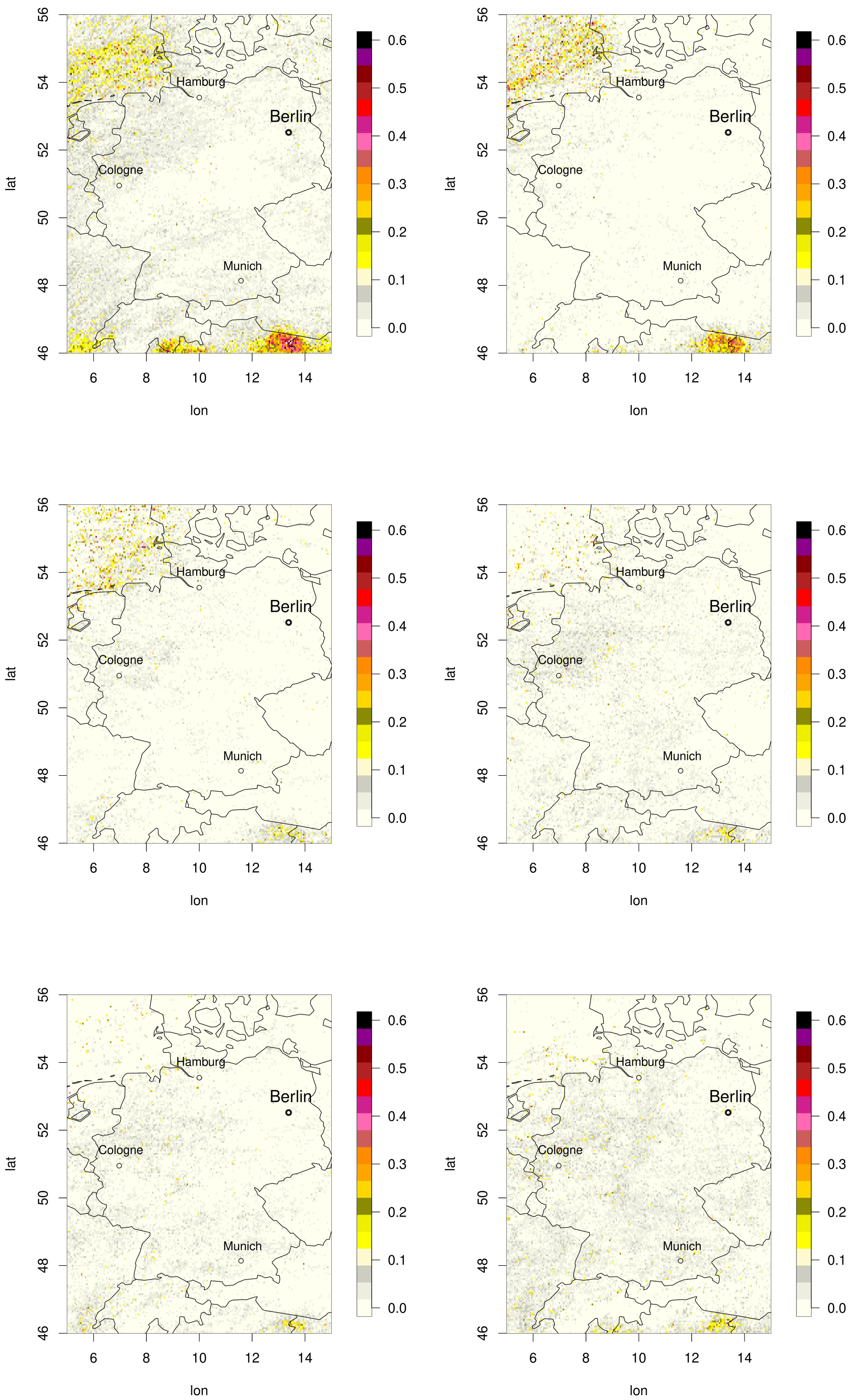

Figure 3. Monthly mean kAmp devided by number of thunderstorms for months October to March, starting in the upper left.

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High mean amperages are also apparent south of the Alps with peaks in September and October. Here, still relatively warm and moist air from the Po valley and lifting by the mountains in case of southern winds are the main driver for the relative high mean Amperages. During this period strong southern winds are very frequent according to the Memsglobal model of Meteoblue, e.g., [25]. Beside the above mentioned regions the Amperage is low over the Alps and the northern foothills of the Alps. In this region usually cold air from the Alps meets relative cold air from the low lands. If the synoptic weather situation leads to warm air in the lower lands, there is no significant lifting by the mountains, as the wind comes very seldom from the North. Finally, storms are on average much weaker there than over Northern Germany. Hence, their are no significant triggers for ligting of air. The winter months January and February, but also March show overall a very low thunderstorm activity.

Figure 4. Orography map for Europe . Copyright San Jose, CC BY-SA 3.0, via Wikimedia Commons.

Convective or Warm Season

Overall the thunderstorm activity is much higher in the convective season, so that the scale for the Amperage has to be adjusted to higher values from May onwards, see Figure 5 From May onwards the mean Amperage and the number of lightning increase and the highest thunderstorm activity can be observed in June and July. Central Europe is driven by westerly winds. The mountains act as natural barrier and as a strong lift for warm and moist air. It is therefore not surprising that the foothills of the Alps shows by far the highest thunderstorm activity in line with the finding of other authors. However, the comparison of the flash density with the mean Amperage per thunderstorm reveals an interesting feature. The number of flashes is higher in the northern side of the foothills in June and July, but the mean Amperage is highest in the southern side of the foothills. This means that the thunderstorms are on average much stronger on the southern side. On both sides the Alps act as lifting depending on the wind direction, but there is a greater difference in the height between the foothills and the Alps and the air on the southern side is on average warmer and contains on average more moisture. Thus the Mountain valley winds are mucht stronger and on average the difference in moisture is much greater. Favorable synaptic winds from the southern direction add an additional lifting force and thus the conditions for very severy storms are well given leading on average to more severe thunderstorms. Hence it is not surprising that according to Eumetsat the Po valley suffers the gretest losses induced by hail events. They also argue that the night-time hailstorm of Sunday, 4 August 2002, is a good example for a synoptic disturbance combined with the polar jet stream triggering the formation of deep convective storms in northern Italy.

Also in other Alpine regions the effect of the topography on the strength of the thunderstorms is very well apparent. Also on the west side of the Alps the pattern of the mean Amperage correlates well with the patterns of the orography (see Figure 4, [26]) in comparison to Figure 5), which is expressed as patterns of high mean amperages along the slightly curved Alpine topography. Here winds from the westerly direction leads to a strong lifting induced by the oroggraphy of the Alps. Also in this

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region the cmoparison of the mean Ampereage with the lightning number density reveals interesting features. In June and July high Ampereage west of the rhine valley (Bodensee) are apparent whereas the lightning number density is much higher father east along the Alps. This means that this regions is charactereized by very strong thunderstorms.

The comparison of the number density and the mean amperage reveals another important feature. As mentioned the dominant wind direction are western winds at the surface, but there is also a relative high share of eastern winds. Moist air transported from either the western or the eastern direction is lifted by the orography on the western and eastern borders of Germany, see Figure 4. The additional lifting of the low mountain ranges either on the west or the east increases the force of the updraft and hence the strength of the thunderstorms. After the additional lifting vanishes the force of the thunderstorms decreases on average as well. In this manner the middle of Germany is protected from severe thunderstorms by the orography, resulting on some sort of U-ring shape. Exception is the North-West region close to the sea, but this is the region with pre-dominantly heavy frontal storms and hence the role of the orographic lifting is partially replaced by lifting forced by strong winds.

The thunderstorm activity decreases significantly in September, but the Southern Alpine regions holds still large hotspots.

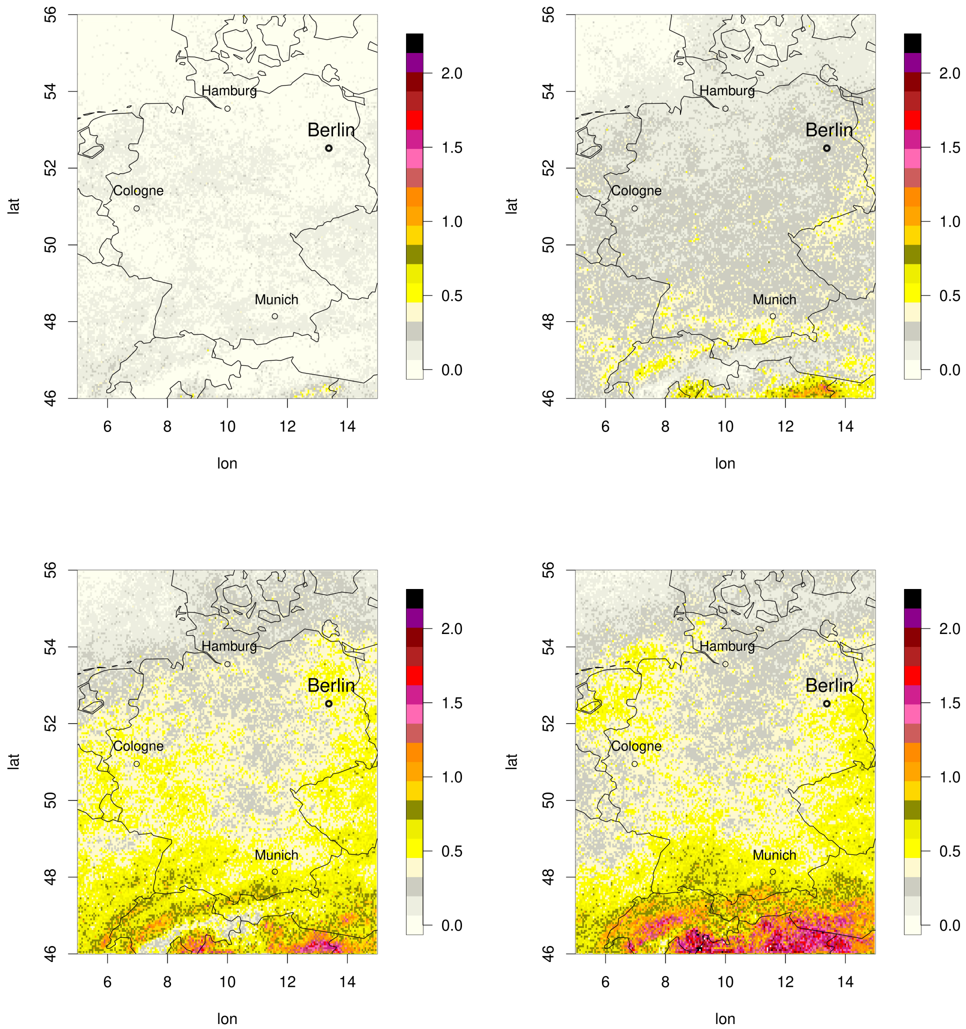

Figure 5. *Cont.*

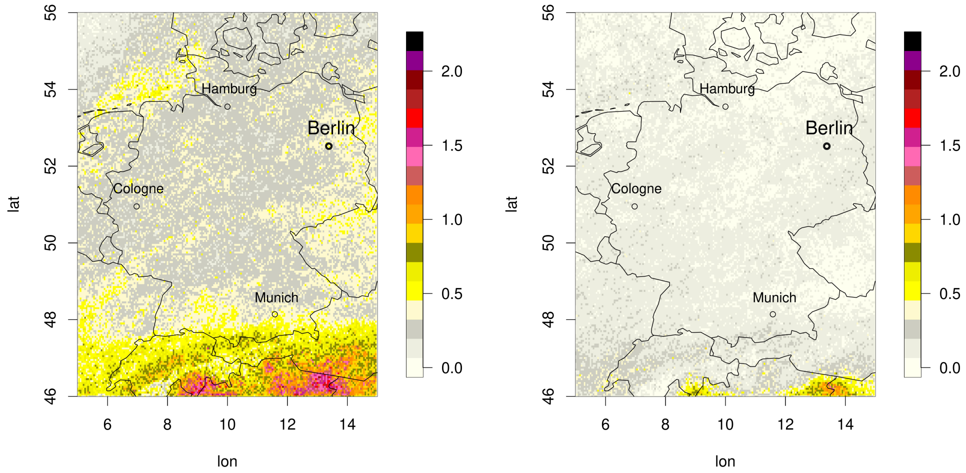

Figure 5. Monthly mean kAmp devided by number of thunderstorms for months April to September starting upper left.

4. Discussion

The results presented in the previous section emphasis the role of large-scale flows and lifting by orography in steering the spatial patterns of convective activity. Wapler [13] found in accordance with other authors that the highest number of lightning strokes occurs in the pre-alpine region of southern Germany but that also some local maxima in low mountain ranges are noticeable. This finding is confirmed in this paper based on a longer time series. Hoever, the mean Amperage per lightnig event shows not only some further hotspots but also modifies the picture of particularly vulnerable regions. Becasue, the patterns of the mean Amperages does likely provide a better information about the probabiliy of extreme thunderstorms and hail events than the number of flashes. First visual comparisons with hail climatologies e.g., [27] supports this hypothesis. The match of the patterns is much better for mean Amperages per thunderstorm than for number densities. This is supported by physics because on average a higher severity of a thunderstorm means higher updraft forces and hence a higher trigger for the formation of hail. This demonstrates the importance of this quantity, which has so far been treated neglectfully as other studies usually focussed pre-dominantly on lightning density. Also for trend analysis this quantity might be more robuts concerning addition or change of measurement stations than the number of flashes.

Author Contributions: Sophie Döpp performed the analysis of different lightning networks (Fig 1 and Fig 2) and supported the writing of the manuscript. Richard Mueller performed the generation and analysis of the lightning climatology and is the principal author of the manuscript.

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Data Availability Statement: The data used for the figures of the climatology as available under DWD open data policy at https://go.dwd-nextcloud.de/index.php/s/9GJnJwfsJGPcMXT and https://go.dwd-nextcloud.de/index.php/s/m8LG3K3mZDZED2X.

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Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

CAPE	Convective Available Potential Energy
DWD	Deutscher Wetterdienst

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DOAJ	Directory of open access journals
LINET	Lightning Network
kA	Kilo Ampere
MDPI	Multidisciplinary Digital Publishing Institute
TS	Thunderstorms
VLF	Very Low Frequency
LF	Low Frequency

Appendix A

Appendix A.1

The figures of the flash densities (number of flashes per month) are presented in the appendix, Figures A1 and A2).

Appendix B

Below the figures for the ligthning density.

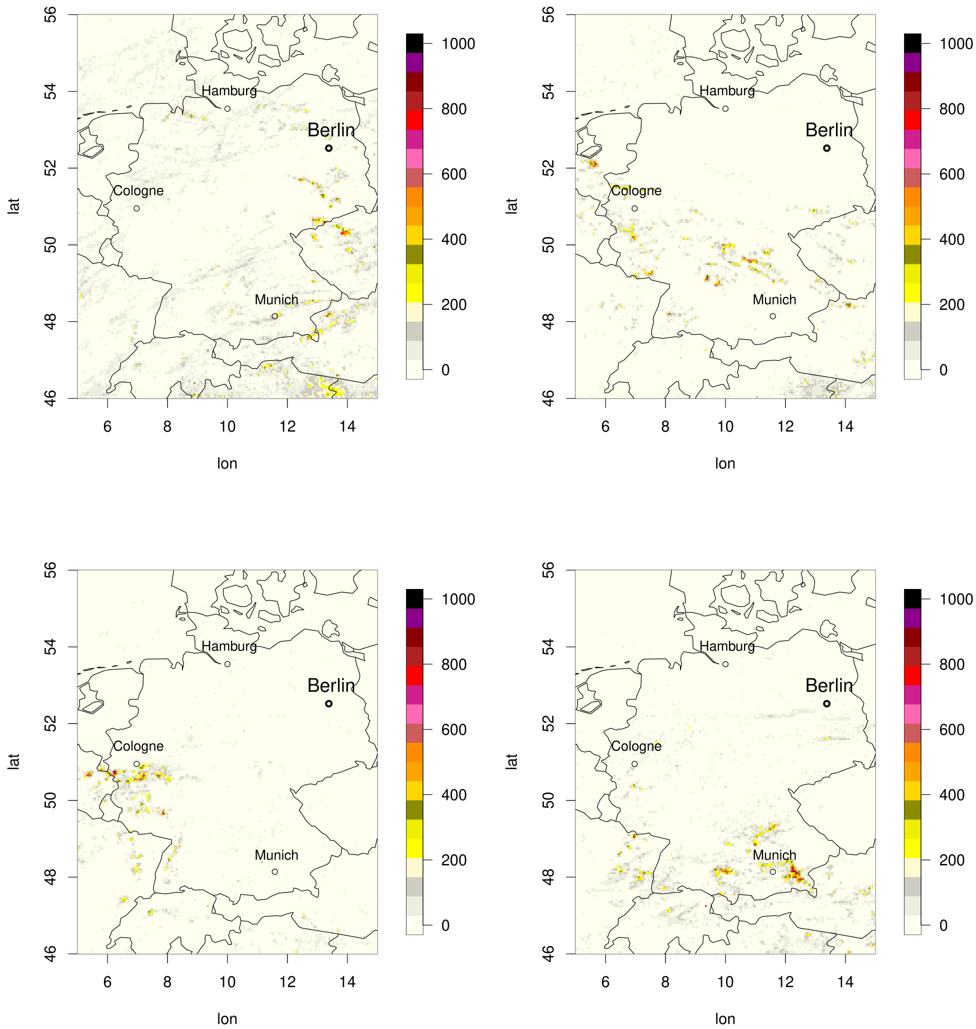

Figure A1. *Cont.*

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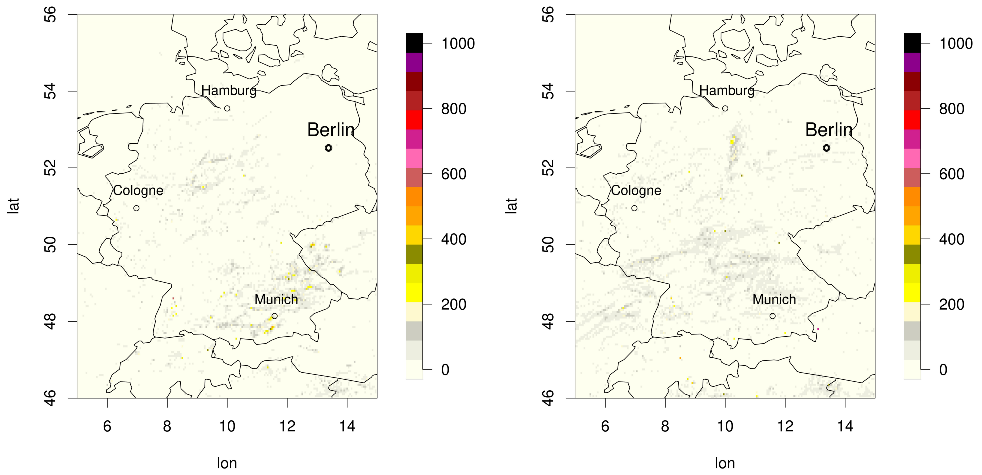

Figure A1. Number of lightning flashes per month.

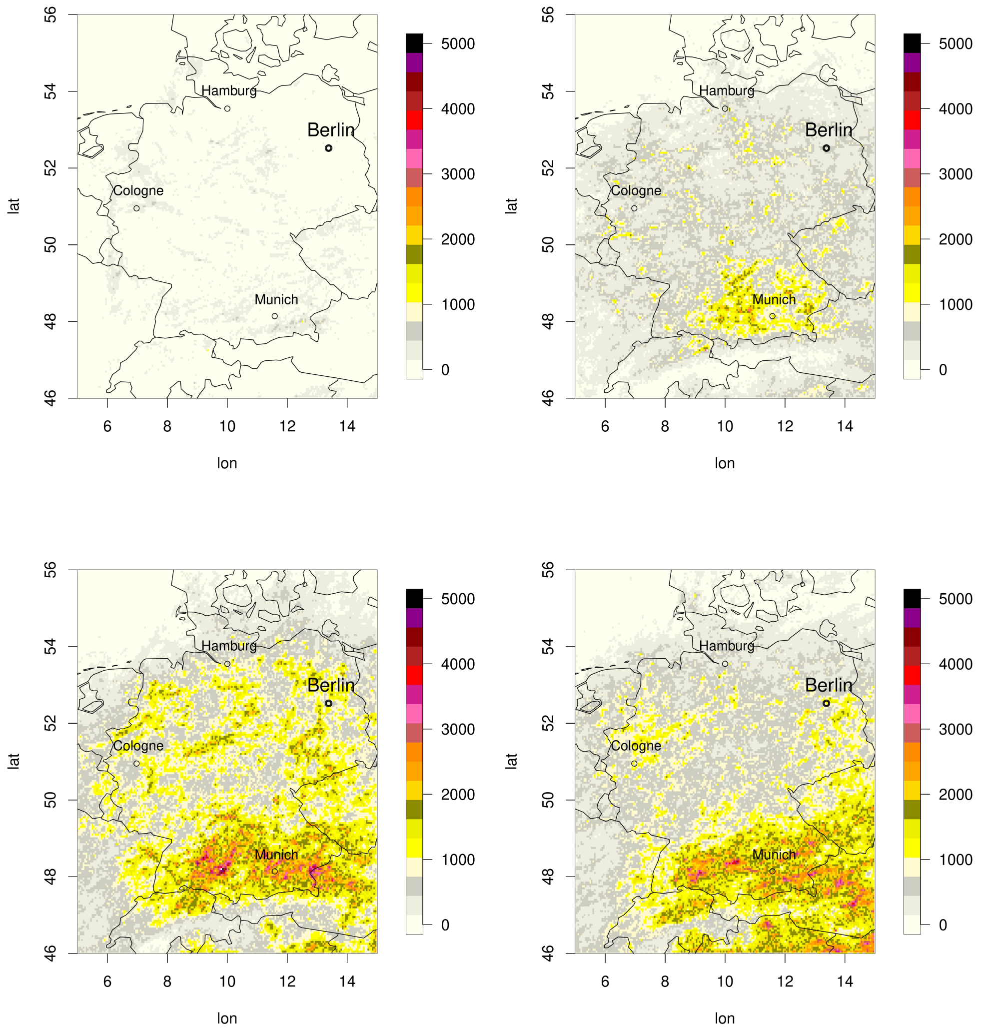

Figure A2. *Cont.*

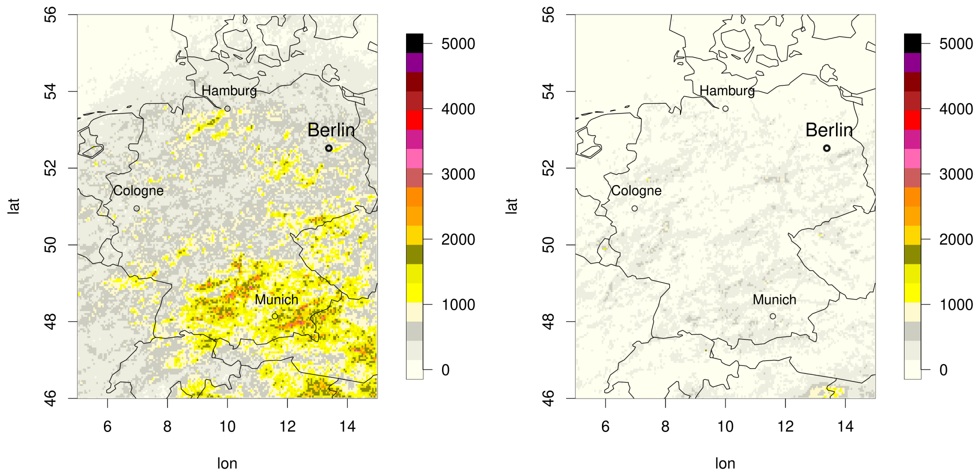

Figure A2. Number of lightning flashes per month.

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