Characteristics of North European winter lightning related to a high positive mode of the North Atlantic Oscillation

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Abstract

The North Atlantic Oscillation (NAO) is a large-scale alternation of atmospheric masses between the Icelandic Low and Azores High pressure systems. It has a strong effect on European winter climate especially in its positive mode, which manifests itself by above-average precipitation and severe winter storms in the North Atlantic region. In this study, we use the World Wide Lightning Location Network data and investigate properties of lightning which occurred in Northern Europe during a severe winter 2014/2015, when NAO was in its strongest positive mode over the last two decades. We found that the diurnal distribution of winter lightning was nearly random, nevertheless superbolts with energies above one megajoule surprisingly appeared at night and in the morning hours. They were concentrated above the ocean close to the western coastal areas. We show for the first time that winter lightning in the North Atlantic, including superbolts, were predominantly single stroke flashes.

Plain language summary

One hundred years ago, unexpected occurrence of winter lightning above the British Islands and Northern Europe attracted attention of the British Meteorological Office, asking readers of the Nature journal to assist in investigation of winter thunderstorms by sending postcards with reports of observed lightning flashes. Today, we still do not fully understand these spectacular and potentially dangerous natural phenomena but have new possibilities to detect them. Lightning strokes excite electromagnetic pulses, which are now routinely used to localize lightning by triangulation techniques based on networks of radio receivers. In this study, we use the World Wide Lightning Location Network data and investigate properties of lightning which occurred in the north European region during a severe winter 2014/2015. Here we show that the

diurnal distribution of winter lightning was nearly random, nevertheless superbolts with energies above one megajoule surprisingly appeared at night and in the morning hours. They were concentrated above the ocean close to the western coastal areas. We show for the first time that winter lightning in the North Atlantic, including superbolts, were predominantly single stroke flashes.

Key words

Winter lightning, North Atlantic Oscillation, superbolts

Key points:

- North Atlantic winter superbolts appeared mostly at night and in the morning hours.
- They were concentrated above the ocean close to the western coastal areas.
- Detected winter lightning were predominantly single stroke flashes.

1. Introduction

Thunderstorms, which occur during winter months, are often accompanied by very strong gusty winds, heavy precipitation in a form of snow, rain or hail, and occasionally by very energetic lightning (Schultz & Vavrek, 2009). Damaging forces of medieval winter thunderstorms have already been reported in very old written historical records. One of the oldest entries describes a thunderstorm occurring in central Bohemia in February 1395 (Munzar & Franc, 2003). Numerous disastrous fires caused by winter lightning were reported from several European countries in 1555–1556 (Munzar & Franc, 2003).

At the beginning of the twentieth century, unexpected occurrence of winter lightning above the British Islands and Northern Europe attracted attention of the British Meteorological Office, asking readers of the Nature journal to assist in investigation of winter thunderstorms by sending postcards with reports of the time, position and number of observed lightning flashes (Cave, 1916; 1923). As a result, monthly amounts of flashes eyewitnessed by the Nature readers living in different parts of the British Islands were published (Bower, 1926; 1927).

Approximately at the same time when these postcards were inspected, the British climatologist Sir Gilbert Walker introduced a term North Atlantic Oscillation (NAO) for a large scale alternation of atmospheric masses between the Icelandic Low and Azores High pressure (Walker, 1925). NAO controls the variability of the winter climate in the North Atlantic region, being responsible for approximately 40% of the winter fluctuations of the tropospheric pressure fields (Pinto & Raible, 2012). The strength of NAO is described by the monthly NAO index. Its calculation is based on the difference between normalized mean sea-level pressure strengths of the Azores High and the Icelandic Low. A positive NAO phase is characterized by an intensified Azores High and deeper Iceland Low. This situation leads to a stronger meridional pressure gradient over the North Atlantic region. Unusually high positive values of the NAO index were observed to manifest themselves by above-average precipitation and severe winter storms over British Isles and other parts of northwestern and northern Europe including occurrence of extreme cyclones (Pinto et al., 2009).

A winter-time meteorological scenario which can lead to an ascent of the air warmer than its surroundings - a condition necessary for generation of thunderclouds - is the spread of a cold air over a warmer lake, ocean or sea water (Williams, 2018). Therefore, there are only three regions at the northern hemisphere where the winter storms regularly produce numerous lightning flashes: Japan, Mediterranean and the USA (Montanyà et al., 2016). Thundersnow events were searched in the World Wide Lightning Location Network (WWLLN) (Rodger et al., 2004) data from 2010-2015 in regions with low surface temperatures (Adhikari & Liu, 2019). The majority of snow lightning events were found to occur over high mountainous regions. Low-elevation events were observed exclusively in continental and coastal areas with slightly higher occurrence during evening and pre-midnight hours. The WWLLN data from 2010 to 2018 were also examined (Holzworth et al., 2019) with a focus on superbolts with stroke energies above 1 MJ, it means with energies by three orders of magnitude larger than the mean energy of all lightning strokes detected by WWLLN. The distribution of superbolts globally peaked in the Northern Hemisphere winter from November to February in the European North Atlantic region and in the Mediterranean, and appeared only over water. Lightning data from the Optical Transient Detector from 1995 to 2000 for the North Atlantic Ocean and western Europe were analyzed (de Pablo & Soriano, 2007) with respect to the NAO. The authors found a correlation between positive NAO indexes and increases of lightning rates at latitudes above 50°N.

The number of strokes per flash (flash multiplicity) is an interesting quantity which is thought to reflect variations in climate and terrain(Schulz et al., 2005). The flash multiplicity is unfortunately very sensitive to both the detection efficiency of a given lightning location system and the algorithm used for grouping the strokes into a multi-stroke flash. Parameters, which determine inclusion of individual strokes into a flash are the maximum inter-stroke distance, the maximum inter-stroke time interval and/or the maximum total duration of a flash. Different combinations of parameters were used in different studies (Schulz et al., 2005; Pédeboy, 2012; Rakov & Huffines, 2003) where a typical maximum inter-stroke distance was 10 - 20 km, a typical maximum inter-stroke interval was 0.5 s - 1s, and typical maximum flash duration was 1-

2 s. A study of cold season lightning flashes (Adhikari & Liu, 2019) shows that 55 % of flashes contain only one stroke, 20 % had a multiplicity of 2, and remaining 25 % of flashes were composed of more than 2 strokes. About 16% of flashes were positive, with a larger fraction of single stroke flashes. In another study conducted in Austria (Schulz et al., 2005), a multiplicity of negative lightning flashes was ~ 2.5 in contrast with a multiplicity of ~ 1.2-1.3 of positive lightning flashes.

In the present paper we report results of our analysis of lightning detected by WWLLN in the north European region during the winter 2014/2015, which exhibited the largest positive NAO index in the last two decades. We investigate the temporal and spatial distribution of lightning flashes with respect to their energies and multiplicity. We especially focus on superbolts with energies above 1 MJ.

2. Data set

The variation of NAO monthly indexes during last two decades provided by the Climate Prediction Center of the Weather National Service NOAA is plotted in Fig. 1a by a black line. The median values for winter seasons (October – March) vary from -1.2 to 1.4 and are represented by blue rectangles in Fig. 1a. The winter season 2014/2015 exhibited the highest positive value of the NAO (highlighted by a red oval in Fig. 1a), when the NAO indexes reached even 1.9 in December 2014 and 1.8 in January 2015. During this winter, newspapers in the UK, Germany, Poland, and Scandinavia reported extremely strong storms, which caused huge power outages, damages of buildings, and collapses of traffic paralyzing the daily life. The strongest storms got their names “Dagmar“, “Elon“, “Felix“, “Egon“, “Rachel“ (Fig. 1b), or “Hermann“ by different news reports in countries affected by storms (“Snow and ice bring severe weather alert,” 2015; “Storm Rachel brings a month’s rain in one day Scot Region.,” 2015; “Stormen

Dagmar har ramt Jylland," 2015). The occurrence of strong lightning was also manifested by formation of a particular type of dispersed radio signals– so called daytime tweek atmospherics, which were found to originate in the north European lightning strokes. These usual night time signals were untypically observed during the day. After propagating in the sub-ionospheric waveguide, they were recorded at a low-noise observing site in the South of France and reported (Santolík & Kolmašová, 2017) for the first time in Europe.

We used the WWLLN data and investigated properties of lightning, which were detected in the north European region from October 2014 to March 2015. We analyzed spatial and temporal distribution of lightning strokes, their energies and multiplicity, while focusing on extremely dangerous superbolts with sub-megajoule energies. We limited the area of our interest by 50°N, 20°W and by 60°E. Our dataset consists of more than 90 thousand localized lightning detections. For the majority of strokes, WWLLN also delivered estimates of their energy and errors in the energy calculations. The information about the number of the WWLLN stations entering the algorithms for localization and energy estimation of individual strokes is also available. To create a subset of strokes with reliable energy estimates we excluded all cases with relative experimental errors greater than 70%, and with energy estimates based on less than 3 stations. Applying these criteria for the reliability of energy estimates (Roger et al., 2017) we reduced the original dataset by 17 %. The stroke energies ranged across five orders of magnitude from tens of J up to units of MJ, with a heavy-tail distribution (see Supporting Fig. 1). The mean stroke energy was 0.1 ± 0.3 MJ; the median stroke energy was 1.3 kJ. The strokes occurring in colder months of December, January and February were ten times stronger (mean energy of 0.2 ± 0.5 MJ, median energy of 6 kJ, Supporting Fig. 2) than strokes hitting the North Atlantic in

October, November and March (mean energy of 0.02 ± 0.1 MJ, median energy of 600 J, Supporting Fig. 3).

3. Spatial and temporal distribution of lightning strokes

The map on Fig. 2a shows the distribution of all detected lightning strokes plotted in 0.5° x 0.5° bins. They occurred predominantly above the ocean but with a higher concentration close to the western coastal areas, which were hit by up to 430 strokes per bin during the analyzed period of 6 months, i.e., one stroke per 3.3 km^2. There was nearly no lightning activity detected above the continent. The temporal distribution of lightning strokes with reliable energy estimates plotted as a function of the local time is represented in Fig. 2b by a gray line. The lightning discharges occurred nearly randomly during the day and night and their distribution did not exhibit a typical afternoon peak. Nevertheless, if we calculated the median energy in 1-hour local time bins (shown by a black line in Fig. 2b), a surprising peak arose around the local midnight. The strokes detected during the night had median energy values of about 3 kJ, three times higher than during the day. This effect is possibly even underestimated as the signals generated by daytime lightning are more attenuated when propagating in the Earth-ionosphere waveguide and we can thus expect a lower number of reliably detected weak strokes during the day which would shift the median daytime energies to higher values.

4. Spatial and temporal distribution of superbolts

Now we limit our dataset to extraordinary strong lightning and selected only superbolts – lightning strokes with energies above 1 MJ. Superbolts represented only 2.6 % of detected strokes with reliable energy estimates. Similarly as in (Holzworth et al., 2019) we analyzed separately superbolts with energies between 1 and 2 MJ and superbolts with energies above 2 MJ, which are respectively represented in the map in Fig. 3a by blue and red dots. The superbolts appeared exclusively above the seawater with higher occurrence rates close to the western coastline of British Islands, Norway and Denmark. A few superbolts were detected even at high latitudes above 65°N. Temporal distributions of superbolts in Fig. 3b clearly show that superbolts only rarely struck in the afternoon and that the most energetic strokes with energies above 2 MJ preferred to appear in the night and morning hours. The majority of superbolts occurred during the three coldest months in the middle of the winter season (see Supporting Figures 4 and 5).

5. Flash multiplicity

To investigate the multiplicity of flashes detected by WWLLN, we analyzed the whole dataset to find multi-stroke flashes consisting of strokes with striking points closer than 10 km, the inter-stroke intervals below 500 ms, and occurring within 1 s. This grouping procedure resulted in 83 % of single-stroke flashes and 17 % of multi-stroke flashes. The number of strokes in individual multi-stroke flashes varied from two to twelve. The multiplicity from the whole dataset is illustrated in Fig. 4a by gray columns. In the reduced dataset with reliable energies, the energy ratio of the second stroke and the first stroke E2/E1 in all multiple flashes varied over eight orders of magnitude (Fig. 4b, solid line) with a median value of 0.16. The energy ratio of the third stroke and the first stroke E3/E1 shows similar properties as E2/E1, just for a smaller number of cases, with the median value reaching 0.11.

When we limited our dataset only to energies above 1 MJ (yellow columns in Fig. 4a), we found a similar percentage of subsequent strokes but only very exceptionally with multiplicities larger than 3. We also found that the superbolts struck just once: inthe rare cases when subsequent strokes occurred, they never reached the superbolt energies above 1 MJ. Median energy ratios E2/E1 and E3/E1 in multiple flashes with superbolts are therefore extremely low, respectively reaching only 4.10^{-4} and 3.10^{-4}. This means that they are by nearly three orders of magnitude weaker than subsequent strokes collected from the entire data set.

6. Discussion and summary

An extreme North Atlantic Oscillation observed in winter 2014/2015 shifted tracks of numerous severe storms and deep depressions across the North Atlantic Ocean into Northern Europe. Our analysis of more than ninety thousand lightning strokes detected by WWLLN showed that lightning predominantly occurred above the ocean and along the western coastal areas. This is consistent with the results of the global superbolt study (Holzworth et al., 2019), but we also show the same effect for weaker lightning. Our results are very different from the distribution of snow lightning (Adhikari & Liu, 2019), indicating that lightning strokes considered in our study were detected mainly during rainstorms. As the surface seawater was warmer due to the NAO positive phase (Qu et al., 2012), the temperature difference between the air and the surface was more pronounced at night. This scenario probably led to the formation of heavily electrified thunderclouds. As a result, the most energetic strokes appeared exclusively at night and in the morning hours and nearly 3 % of the detected lightning strokes were superbolts with an energy above 1 MJ. The obtained large fraction of single stroke flashes (83 % of all events) strongly suggests an excessive amount of positive lightning which are known to have a low multiplicity (Adhikari & Liu, 2019; Schulz et al., 2005). We showed that the superbolts also were predominantly single stroke flashes (86%) and that their subsequent strokes never reached megajoule energies. This effect may occur due to the fact that the total amount of the charge available in the thundercloud for the whole flash was mostly neutralized during the first stroke and other energetic strokes could not be produced shortly after the first one. These unusual lightning characteristics are probably related to a special microphysical composition of thunderclouds, which allowed initiation of extra strong discharges.

Our results show that numerous very energetic and thus dangerous lightning hit the British Islands and Northern Europe during the extreme phase of the NAO. In connection with successful efforts to improve decadal climate predictions in the North Atlantic region (Müller et al., 2012; Boer et al., 2016), our findings may be used to predict a severe thunderstorm season with particularly dangerous nighttime lightning discharges in the coastal areas whenever an extreme NAO is forecasted.

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Authorship: OS and IK designed the study, interpreted the results and wrote the paper. IK and KR performed the data analysis.

Competing interests: The authors declare that they have no competing interests.

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Figure 1:

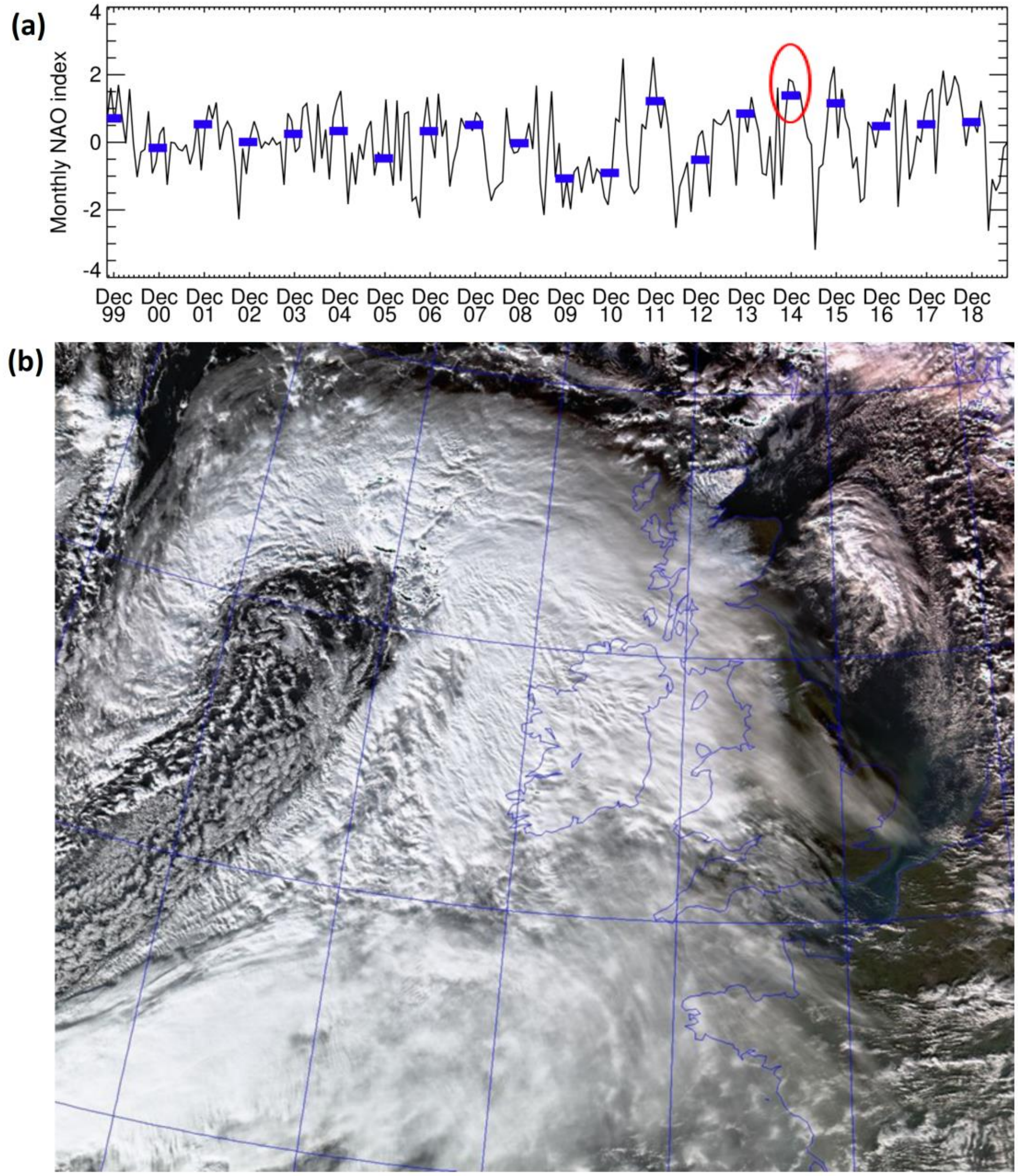

Fig. 1 a) Variation of the monthly NAO index (black line) together with the October-March median values (blue rectangles). The red oval identifies the winter season exhibiting the most positive NAO index since 1999. b) Infra-red image collected by the polar-orbiting NOAA19 satellite shows the storm Rachel that threatened the UK and Ireland on 14 January 2015.

Figure 2:

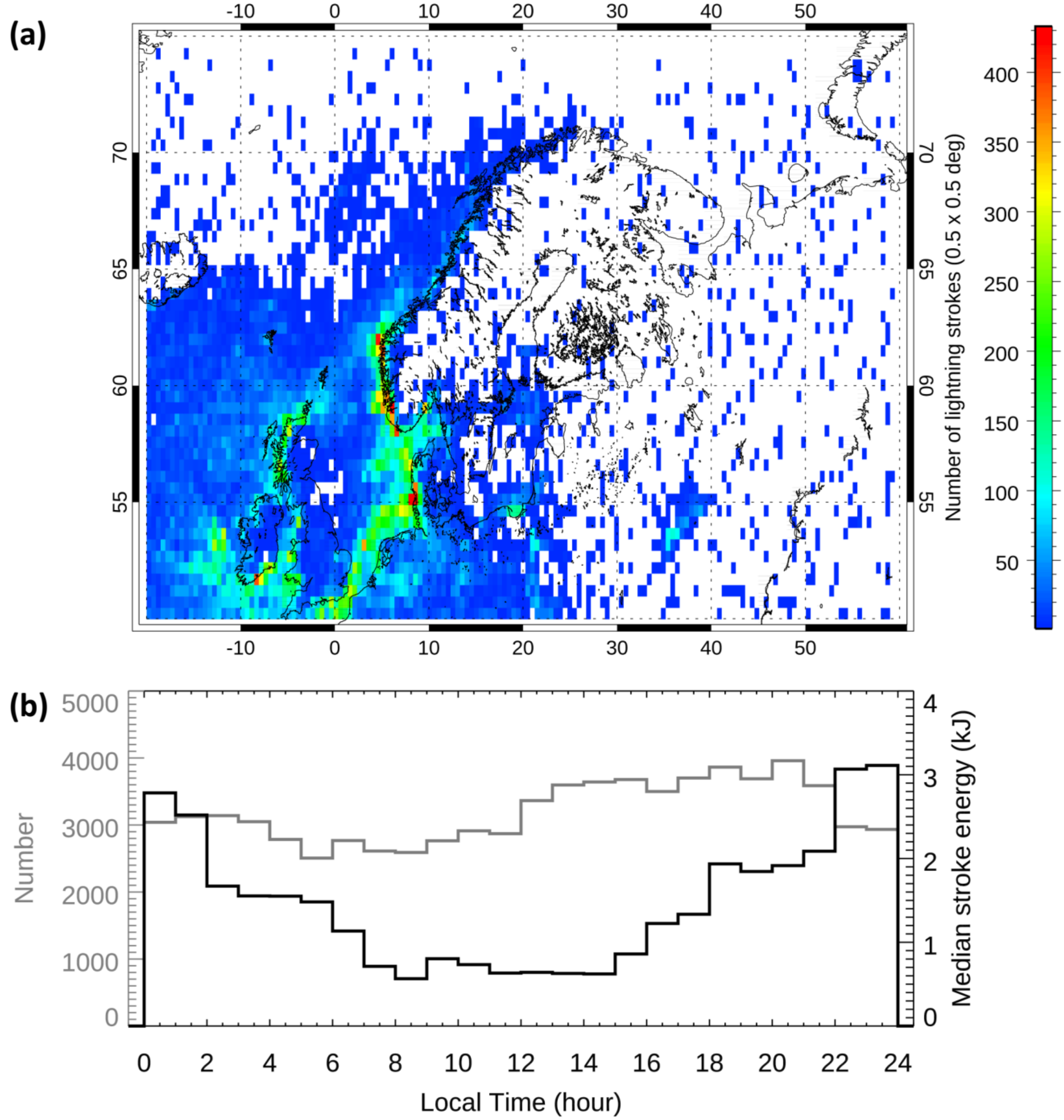

Fig. 2 a) Spatial distribution of all detected lightning strokes in the 0.5° x 0.5° bins. b) Temporal distribution of all lightning strokes (grey line) and their hourly median energies (black line) as a function of the local time.

Figure 3:

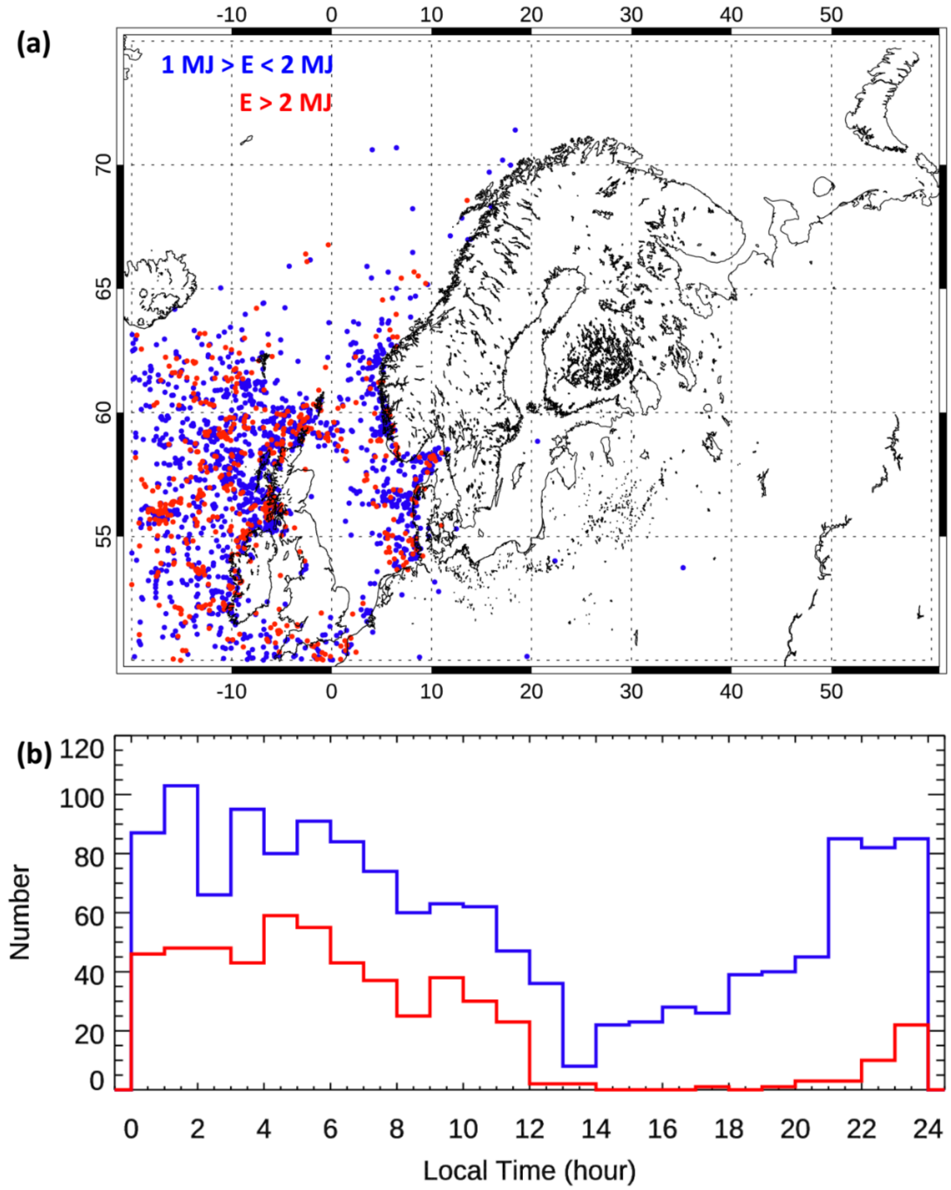

Fig. 3 a) Spatial distribution of superbolts (strokes with energies between 1and 2 MJ and above 2 MJ are respectively represented by blue and red color). b) Temporal distribution of superbolts as a function of the local time.

Figure 4:

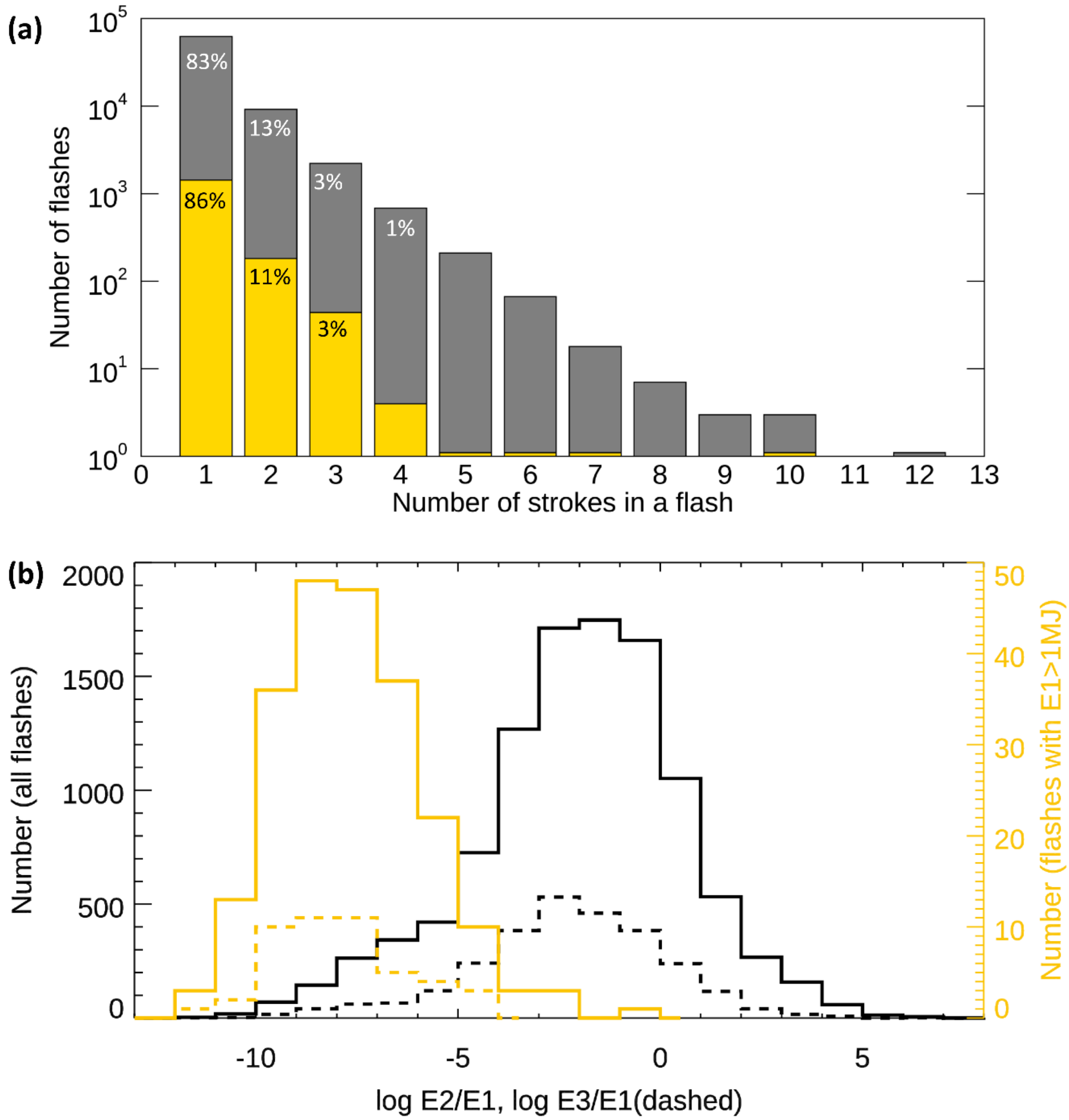

Fig. 4 a) Multiplicity determined by a grouping algorithm applied on the whole dataset (grey), multiplicity of superbolts with the energy of the first stroke in a flash exceeding 1 MJ (yellow). b) Energy ratios of the second and the first stroke (solid line) and the third and the first stroke (dashed line) within all multiple flashes (black) and within superbolt flashes (gold).