Lightning activity in Northern Europe during a stormy winter: disruptions of weather patterns originating in global climate phenomena

Ivana Kolmašová[1,2], Ondřej Santolík[1,2], Kateřina Rosická[2]

[1] Department of Space Physics, Institute of Atmospheric Physics, Czech. Acad. Sci., Prague, 141 00, Czechia
[2] Faculty of Mathematics and Physics, Charles University, Prague, 121 16, Czechia

10   *Correspondence to*: Ivana Kolmašová (iko@ufa.cas.cz)

Abstract. In this study, we use the World Wide Lightning Location Network data and investigate properties of more than ninety thousand lightning strokes which hit Northern Europe during an unusually stormy winter 2014/2015. Thunderstorm
15   days with at least two strokes hitting an area of 0.5° x 0.5° occurred 5-13 times per month in the stormiest regions. Such frequency of thunderstorm days is about five times higher than a mean annual number calculated for the same region over winter months in 2008-2017. The number of individual winter lightning strokes was about four times larger than the long-term median calculated over the last decade. In colder months of December, January and February, the mean energy of detected strokes was by two order of magnitude larger than the global mean stroke energy of 1 kJ. We show for the first time that winter
20   superbolts with radiated electromagnetic energies above one mega joule appeared at night and in the morning hours, while the diurnal distribution of all detected lightning was nearly uniform. We also show that the superbolts were often single stroke flashes and that their subsequent strokes never reached MJ energies. The lightning strokes were concentrated above the ocean close to the western coastal areas. All these lightning characteristics favors a hypothesis that the intense winter lightning activity might have originated in an anomalously warm sea surface in the eastern North Atlantic which made the thundercloud
25   charging more efficient. The increase of the sea surface temperature and resulting unusual production of lightning in winter 2014/2015 might have been caused by a starting super El Nino event, by a positive phase of the North Atlantic Oscillation or by a combination of both these large-scale climatic events.

1 Introduction

30   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). A necessary

meteorological condition for generation of wintertime thunderclouds is the spread of a cold air over a warmer lake, ocean or seawater (Williams, 2018) which can result in an ascent of the air warmer than its surroundings. Therefore, there are only three regions at the northern hemisphere where the winter storms regularly produce numerous lightning flashes: Japan,

35 Mediterranean and the USA (Montanyà et al., 2016). Taszarek et al. (2019) investigated the climatology of thunderstorm days (TDs) in Europe using the data from the European lightning detection network EUCLID (European Cooperation for Lightning Detection) for the period of 2008-2017 (their Fig. 4). To determine TDs, the area of Europe was divided in 0.5° x 0.5° bins. A TD was defined for each bin as a day with at least two detected strokes. They found that during winter seasons there were on average 3-7 TDs in individual bins per month in Mediterranean but only 1-2 TDs per month in the Northern Europe and in

40 British Islands. That is why an occurrence of winter lightning in these regions is rare and can attract the attention of scientists and journalists. This happened at the beginning of the twentieth century, when winter lightning unexpectedly occurred above the British Islands. The British Meteorological Office asked 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 eye witnessed by the Nature readers living in different parts of the British

45 Islands were published (Bower, 1926; 1927).

Today, we do not need to relay on eyewitnesses and their postcards. Lightning strokes excite electromagnetic pulses, which are now routinely used to localize lightning by triangulation techniques based on networks of radio receivers, and data provided by lightning location networks are ordinarily used for different lightning studies. Montanyà et al. (2016) used the data from

50 the World Wide Lightning Location Network (WWLLN; Rodger et al., 2004) and provided for the first time world maps with winter lightning activity. Adhikari and Liu (2019) searched for thundersnow events in WWLLN data from 2010-2015 in regions with very low surface temperatures. Ninety percent of snow lightning events were found to occur over high mountainous regions. Low-elevation thundersnow events were observed exclusively above land. The thundersnow events occurred more frequently in evening and pre-midnight hours. Holzworth et al. (2019) examined the WWLLN data from 2010

55 to 2018 focusing 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 predominantly over water. Similarly, Turman (1977) analysed satellite-based optical measurements and found a majority of superbolts (defined here as strokes with the optical power above 3×10^{12} W) located over the oceans or in coastal

60 areas. Numerous studies in the past have shown that the intensity of lightning strokes over the oceans is greater than over the land (Fullekrug et al., 2002; Light et al., 2003; Said et al., 2013; Zoghzoghy et al. 2015). An absence of a clear explanation of this phenomenon raises a question if the land/ocean lightning intensity contrast is natural or if it can be due to different methods of detection and their efficiency, their frequency band (ELF, VLF, VHF), or propagation effects of these radio waves. Nag and Cummins (2016) analysed differences in the velocity of negative first stroke leaders occurring during the oceanic and land

65 thunderstorms. They hypothesized that the observed difference originates in different thundercloud charge structures, when

oceanic thunderclouds lacks a turbulent mixing of cloud hydrometeors which results in more extensive main negative charge regions necessary to produce energetic lightning strokes. The increase of the lightning cadence at the French Atlantic coastline was reported by Seity et al. (2001), and explained by a sudden vertical development of the thundercloud at the coastline allowing more efficient cloud charging. Asfur et al. (2020) recently performed laboratory experiments, which showed that

70   intensity of discharges increased exponentially with the concentration of dissolved salts in the water. Chronis et al. (2016) examined the temporal and spatial variations (2004–2010) of the peak current of the first return stroke of the cloud-to-ground lightning flashes across land/water boundaries over the contiguous United States. They showed a significant increase of the peak current exactly at the coastal boundaries especially during the convective wet summer season. They found that none of the inspected parameters (salinity of the ocean water, size of hydrometeors) can individually explain the land/ocean contrast.

75   They speculated that an increased humidity might play an important role in the thundercloud microphysics and its influence on the thundercloud charging.

The occurrence of winter lightning can be also influenced by large scale climatic phenomena as the North Atlantic Oscillation (NAO) or the El Nino Southern Oscillation (ENSO). A positive NAO phase, which is characterized by an intensified Azores

80   High and weakened Iceland Low, was found to lead to above-average precipitation and severe winter storms over British Isles and other parts of north-western and northern Europe including occurrence of extreme cyclones (Pinto et al., 2009). Lightning data from the Optical Transient Detector (OTD) from 1995 to 2000 for the North Atlantic Ocean and Western Europe were analyzed (de Pablo and Soriano, 2007) with respect to the NAO. The authors found a correlation between positive phase of NAO and increases of lightning rates at latitudes above 50°N. Williams et al. (2021) analyzed multi-station observations of

85   Schumann resonances (SR) in order to investigate changes in the global lightning activity during two super El Niño events (1997 and 2014-2015). They found an increase of lightning activity in the transition from cold to warm phase during both events and confirmed their results deduced from the SR observations by independent analysis of the OTD and WWLLN data.

The number of strokes per flash (flash multiplicity) is an interesting quantity, which is thought to reflect variations in climate

90   and terrain (Schulz et al., 2005) through the changes in the amount of available charge in thunderclouds. 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. Slightly different combinations of parameters were used in different studies: the maximum inter-stroke distance was 10 km, while the

95   maximum inter-stroke interval (ISI) was either 0.5 s (Rakov & Huffines, 2003; Schulz et al., 2005; Pédeboy, 2012) or 1s (Cummins et al., 1998). A study of cold season lightning flashes using National Lightning Detection Network (NLDN) data (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 (cold season is defined by 2-m surface temperature lower than 0 °C, ISI =1 s). About 16% of flashes were positive, with a larger fraction of single stroke flashes. In another study conducted in Austria

100   with the EUCLID data from 1992 to 2001 (Schulz et al., 2005; ISI = 0.5 s), a multiplicity of negative lightning flashes was ~ 2.5 in contrast with a multiplicity of ~ 1.2-1.3 of positive lightning flashes. The global multiplicity of flashes detected by WWLLN was investigated using a comparison of WWLLN data and observation of the Lightning Imaging Sensor (LIS, on the Tropical Rainfall Measuring Mission satellite) in 2012-2014 (Burgesser, 2017). Spatially adjacent pixels exceeding the background threshold during one 2-ms window on the LIS sensors are clustered in groups. A set of groups, which are separated

105   in time by no more than 330 ms and in space by no more than 5.5 km, is defined as a flash. It was found that WWLLN can detect multiple strokes during one LIS flash, when 70% of the matched LIS flashes were coincident with a single WWLLN stroke. A mean time difference and distance of 114 ms and 10 km, was respectively found between consecutive strokes multiple-stroke WWLLN flashes. Based on this finding, the global multiplicity of flashes detected by WWLLN estimated to 1.5 (Burgesser, 2017). This value is not directly comparable with the multiplicity derived from measurements of commercial

110   lightning detection networks as NLDN or EUCLID because of lower density of WWLLN sensors, lower frequency range, and different grouping algorithm.

It is obvious from previous studies that occurrence of winter lightning in Europe at latitudes above 50°N is rare, and that spatial and temporal properties of winter lightning might reflect changes in global climate phenomena as NAO and ENSO which

115   disrupt normal weather patterns. Nevertheless, a detailed analysis of properties of eastern North Atlantic winter lightning is still missing. In the present paper we report results of our analysis of lightning detected by WWLLN in the eastern North Atlantic and Northern Europe region during the winter 2014/2015, when the amount of winter lightning strokes exceeded three times a long-term average (four times a long-term median) calculated over the last decade (winter seasons 2010/2011 – 2019/2020). During the winter 2014/2015, UK, Germany, Poland, and Scandinavia suffered from extremely strong storms,

120   which caused huge power outages, damages of buildings, and collapses of traffic paralyzing the daily life. An infrared image of the storm Rachel that threatened the UK and Ireland on 14 January 2015 was collected by the polar-orbiting NOAA19 satellite, and is shown in Fig. 1 as an example of a severe winter storm occurring in the analysed season. The occurrence of strong lightning was 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

125   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 and Kolmašová, 2017) for the first time in Europe.

In this study, 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. In section 2, we describe our dataset. In section 3 we analyse properties of the whole dataset, including the characteristics of superbolts. In section 4 we show results on the

130   stroke multiplicity, and in section 5 we discuss and summarize our findings.

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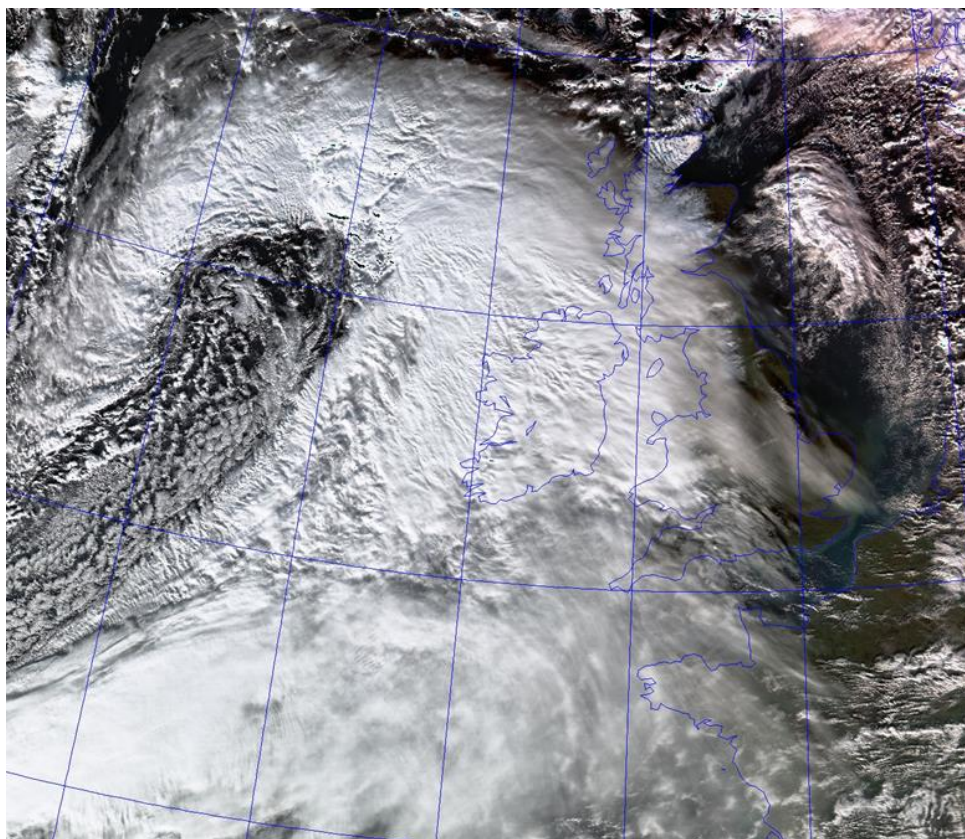
Figure 1: Infrared image collected by the polar-orbiting NOAA19 satellite shows the storm Rachel that threatened the UK and Ireland on 14 January 2015.

2 Dataset

WWLLN is a global network of about seventy lightning location sensors operating in the VLF band at frequencies from 3 to 30 kHz. WWLLN predominantly detects impulsive signals generated by lightning return strokes called sferics, which can propagate thousands of kilometres in the Earth-ionosphere waveguide. WWLLN provides the time of occurrence and location of detected strokes. The location algorithm is based on the time of group arrival technique which requires information from at least five WWLLN sensors. For the majority of strokes, WWLLN also delivers data about their energy with the uncertainty estimates. The information about the number of the WWLLN stations entering the algorithms for localization and energy

150 estimation of individual strokes is also available. To determine the energy radiated by individual strokes, the root mean square (RMS) electric field of the triggered waveforms recorded at individual stations is used. The RMS electric field is calculated over a window of 1.33 ms in the 6–18 kHz band (Hutchins et al., 2012a). The U.S. Navy Long Wave Propagation Capability code (Ferguson, 1998) is used to model the propagation of the electromagnetic signal emitted by lightning strokes in the VLF band and to calculate the stroke energy needed to produce the measured RMS electric field values at individual WWLLN sensors. The energy radiated by individual strokes can be converted into the peak current using an empirical formula (equation

155 2 in Hutchins at al., 2012b), which was obtained by comparison of WWLLN detections and data from the New Zealand Lightning Location Network NZLDN. The polarity of the strokes cannot be derived from the WWLLN waveform measurements because the ground wave, which carries the information about the direction the current flowing in the lightning channel, is usually attenuated after travelling more than one thousand km from its source lightning to the receiver. WWLLN also provides a relative detection efficiency for each hour and each 1° x 1° bin. The detection efficiency changes in time not

160 only because of the network upgrades, sensitivity of the sensors or data processing methods, but also during the day/night hours due to VLF wave propagation (Hutchins et al., 2012a).

We used the WWLLN data from 2010 to 2020 and determined the number of detections in ten winter seasons (October – March) in the area of our interest limited by 50°N, 20°W and by 60°E. The annual amount of detections varied from 9 066 to

165 53 182 with an exception of the winter season 2014/2015 when WWLLN detected 102 866 lightning strokes. The average and median values of the yearly number of North-European winter strokes calculated over the last decade are respectively 35 and 24 thousand strokes. We selected the stormiest winter 2014/2015, and analyzed in detail spatial and temporal distribution of lightning strokes, their energies and multiplicity, focusing on extremely dangerous superbolts with megajoule energies. After removing 10 742 erroneous double detections from the originally distributed WWLLN data (i.e., the strokes reported by

170 mistake only tens of microseconds apart, personal communication R. Holzworth), our dataset consists of more than 92 124 localized individual lightning detections which occurred nearly every day between 1 October 2014 and 31 March 2015. We have identified only 14 days (out of 182) without any lightning activity in the whole area. If we use the same methodology as Taszarek et al. (2019) and calculate the number of thunderstorm days in 0.5° x 0.5° bins, we obtain bins with unusually high (taking into account the winter season) numbers of thunderstorm days in the six individual investigated months (7, 9, 13, 11,

175 5, and 6, respectively). To create a subset of strokes with reliable energy estimates we excluded all cases with relative experimental energy uncertainties 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 dataset by 17 %. The stroke energies ranged across five orders of magnitude from tens of J up to units of MJ, with an approximately log-normal distribution (Fig. 2). 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

180 December, January and February (DJF) were ten times stronger (mean energy of 0.2 ± 0.5 MJ, median energy of 6 kJ) than strokes hitting the North Atlantic in October, November and March (ONM) (mean energy of 0.02 ± 0.1 MJ, median energy of 600 J).

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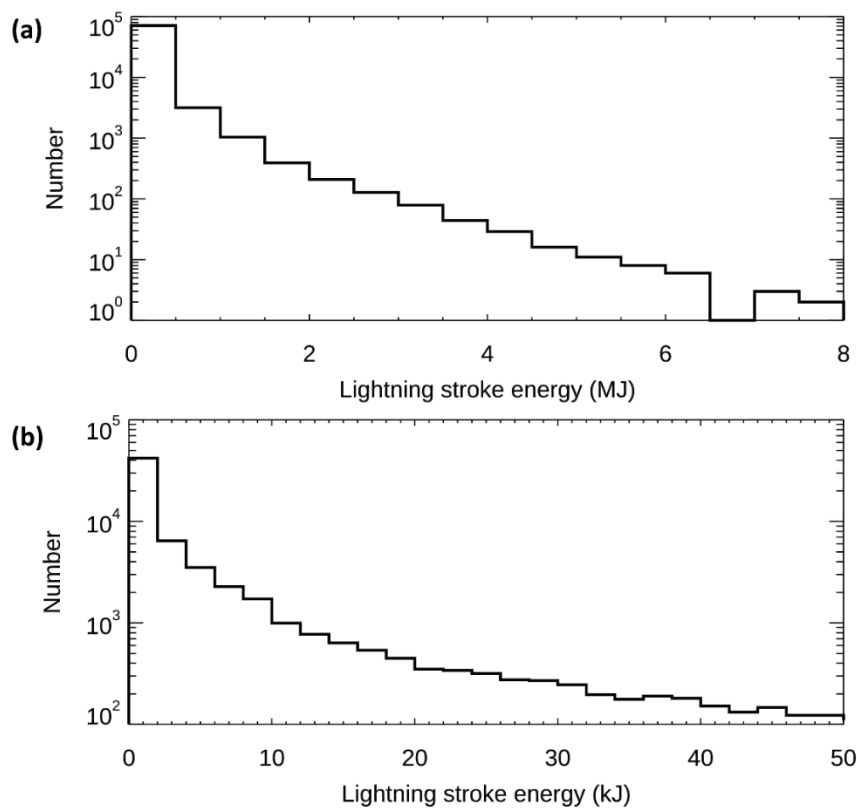
Figure 2: a) Histogram of energies of all lightning strokes detected by WWLLN during winter 2014-2015 in the North Atlantic region, bin size is 500 kJ. b) A detailed view on the weakest part of the stroke energy distribution with a bin size of 2 kJ.

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3 Spatial and temporal distribution of lightning strokes

The map on Fig. 3a 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 analysed period of 6 months, i.e., one stroke per 3.3 km^2. There was nearly no lightning activity

195 detected above the continent.

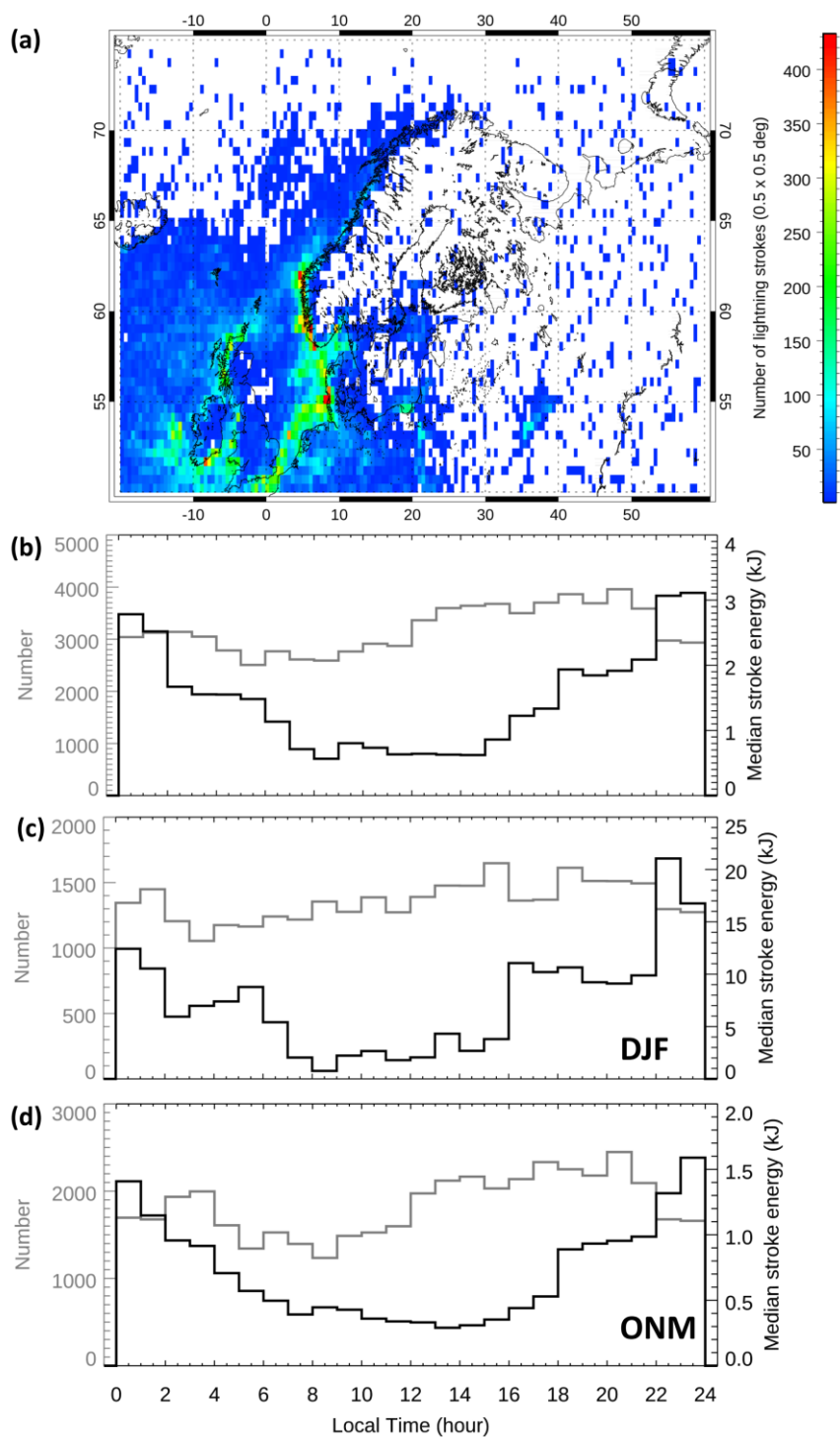



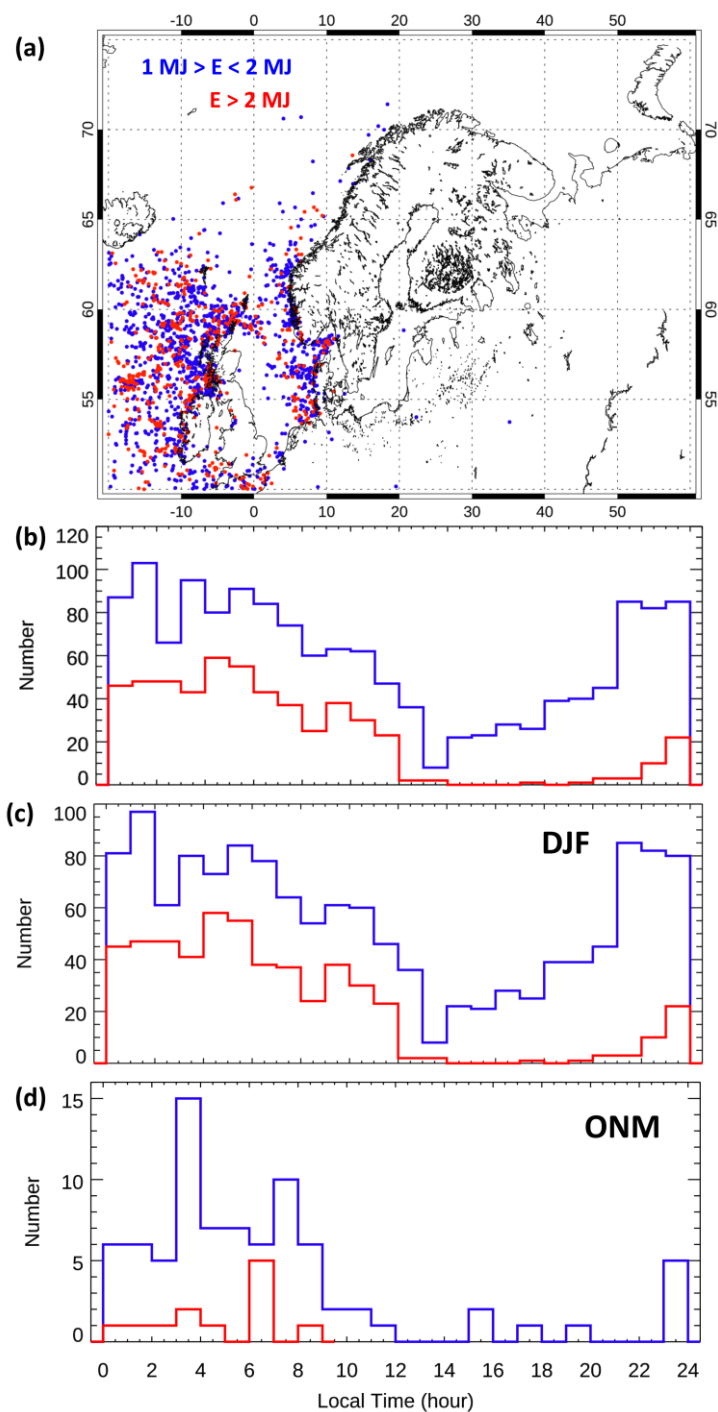
Figure 3: a) Spatial distribution of all detected lightning strokes in the 0.5° x 0.5° bins. b) Temporal distribution of all lightning strokes (grey line) and their hourly median energies (black line) as a function of the local time. The same as in (b), but for DJF (c) and ONM (d).

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Figure 4: 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. The same as in (b), but for DJF (c) and ONM (d).

205   The temporal distribution of lightning strokes with reliable energy estimates plotted as a function of the local time is represented in Fig. 3b by a grey line. The lightning discharges occurred nearly uniformly 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. 3b), 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. The energy median was calculated over 6

210   months. 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. The same histograms for DJF and ONM respectively shown in figures 3c and 3d illustrate thirteen times stronger strokes in colder months with the largest median of 21 kJ and 1.6 kJ before local midnight for DJF and ONM, respectively. The distribution in ONM is flatter than in DJF. Around

215   the local noon, the difference the median energy values in DJF and ONM is not so prominent (2 kJ for DJF and 0.5 kJ for ONM).

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

220   are respectively represented in the map in Fig. 4a 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. 4b 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 (figures

225   4c and 4d).

4 Flash multiplicity

To investigate the multiplicity of flashes detected by WWLLN, we analyzed our whole dataset (including strokes with unreliable energy estimate) 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

230   17 % of multi-stroke flashes. The number of strokes in individual multi-stroke flashes varied from two to twelve. The multiplicity from our dataset is illustrated in Fig. 5a by grey 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. 5b, 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.

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When we limited our dataset only to energies above 1 MJ (yellow columns in Fig. 5a), 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: in the 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

240   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.
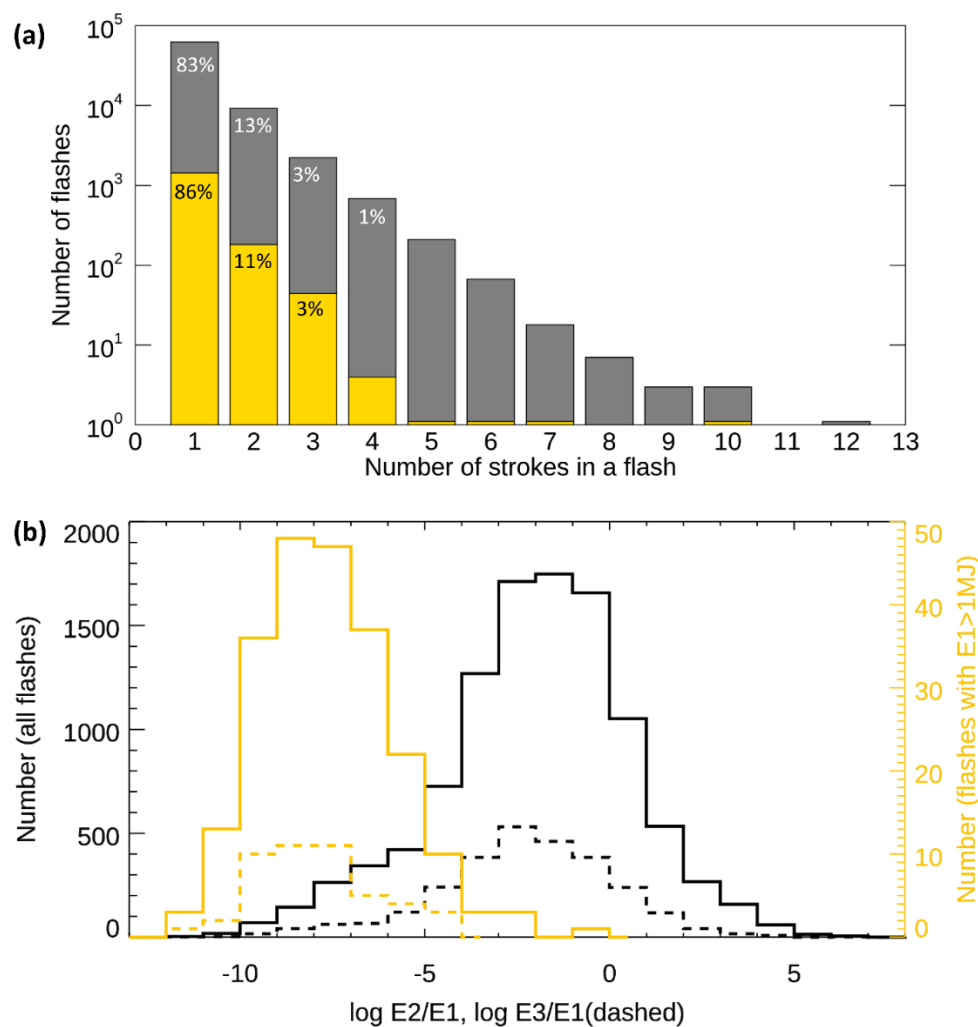
Figure 5: a) Multiplicity determined by a grouping algorithm applied on the whole dataset (grey), multiplicity of superbolts with the

245   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).

5 Discussion and summary

WWLLN detected more than ninety thousand lightning strokes from October 2014 to March 2015. This quantity is four times

250   higher than the median number of detected strokes calculated for the same seasons over the last decade (winter 2010/2011 – winter 2019/2020). There were 5-13 thunderstorm days in individual 0.5° x 0.5° bins and months calculated according to the methodology of Taszarek et al. (2019). The amount of bins with at least two detected discharges (thunderstorm days) was unusually large in comparison with the average number of 1-2 TDs in the same bin size reported by Taszarek et al. (2019) for the same region and the same season for years 2008-2017.

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A median energy of 1.3 kJ for all detected strokes in our study is very close to a value of 1 kJ reported by Hutchins et al. (2012a) for the WWLLN global dataset from 2009-2012. However, the global mean value of 1 kJ related to the same dataset (Hutchins et al., 2012a) is by two order of magnitude smaller than in case of our winter dataset indicating a contribution of very energetic lightning strokes in the high energy tail of the distribution (especially in the colder months of December, January

260   and February). The occurrence of winter superbolts in the eastern North Atlantic is expected (Holzworth et al., 2019). However, the comparison of our results with long-term lightning statistics demonstrates that the winter 2014/2015 was unusually rich on thunderstorm days with intense lightning activity.

Our analysis also shows that lightning predominantly occurred above the ocean and along the western coastal areas. This result

265   is very different from the distribution of snow lightning (Adhikari & Liu, 2019). Nevertheless, it is consistent with the results of the global superbolt study (Holzworth et al., 2019), and we also show the same effect for weaker lightning. A rather surprising result is that 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.

270   When discussing the flash multiplicity, we have to take into account the sensitivity and relative detection efficiency of the particular lightning detection network. The relative detection efficiency of WWLLN is high in the investigated area because of dense network of sensors and a low attenuation of the signals propagating above the salty water. The relative efficiency did not changed during the analyzed period. As any other network, the sensitivity of WWLLN decreases for weak lightning. The comparison of WWLLN detections with the strokes detected by the American NLDN network showed (Abarca et al., 2010)

275   that WWLLN detected at least 10% strokes with currents of ± 35 kA (707 J) and only about 1% of the weakest strokes with peak currents between −3 and −5 kA (13-30 J). We assume that in Europe, the sensitivity to weaker lightning would be similar and very weak subsequent strokes might be not detected by the network, especially when occurring over the ocean. This effect would artificially increase the fraction of single stroke flashes in the WWLLN data set. Nevertheless, the obtained large fraction of single stroke flashes (83 % of all events) is significantly higher than 70 % of single stroke flashes reported for WWLLN

280   dataset globally in tropics and subtropics. We moreover show that the superbolts with energies above one mega joule were

also more frequently single stroke flashes (86%) and that their subsequent strokes never reached mega joule 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.

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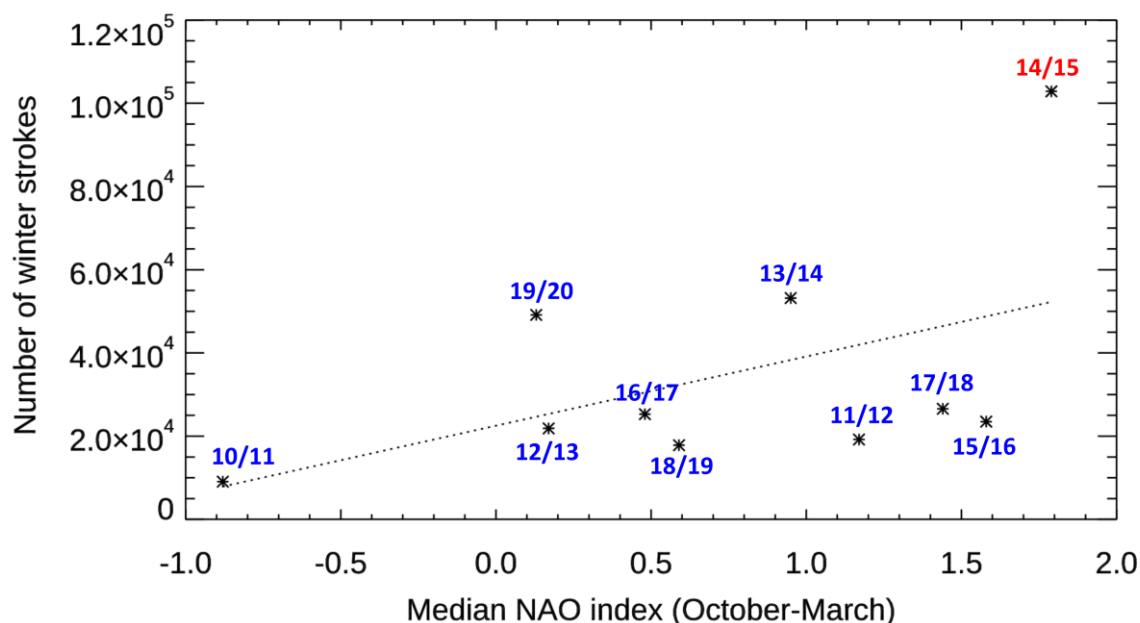
Figure 6: Number of lightning strokes detected by WWLLN in individual winter periods (October-March) as a function of
290   the median NAO index calculated over the same period. The dashed line shows the linear trend.

All the above-mentioned findings indicate that unusually favourable conditions for a formation and electrification of thunderclouds might have arisen in winter 2014/2015. As a mixture of water and ice hydrometeors is needed for a cloud
295   electrification (Rakov and Uman, 2003) we speculate that there might be an unusual enhancement of available atmospheric water vapour in winter thunderclouds (Chronis et al., 2016) leading to changes in the cloud microphysics. This increase of water vapour availability might be due to above average sea surface temperatures (SST) in the eastern North Atlantic region. Such SST anomalies were found to occur during El Nino events (Williams et al., 2021) or during the positive phase of the North Atlantic Oscillation (Qu et al., 2012). The global SST anomaly map available at
300   (https://climate.nasa.gov/climate_resources/185/sea-surface-temperature-anomaly-timeline-1982-2017/) shows a warmer sea surface in winter 2014/2015, when started the second super El Niño event. We have also checked the variations of NAO monthly indexes during last two decades provided by the Climate Prediction Center of the Weather National Service NOAA.

The median values for last twenty winter seasons (October – March) vary from -1.2 to 1.4. The winter season 2014/2015 exhibited the highest median positive value of the NAO within two last decades, and the NAO indexes reached even 1.9 in
305 December 2014 and 1.8 in January 2015. If we plot the numbers of lightning strokes detected in last ten winter seasons as a function of the median NAO indexes calculated for individual winter seasons from monthly NAO indexes (Fig.6), we can see an increase of lightning activity with an increasing NAO index despite the large variance of values. There were more strokes detected in winter 2014/2015 than it might be expected from the trend.

310 In summary, numerous energetic lightning hit the British Islands and Northern Europe in winter 2014/2015. We suggest that this anomalously intense winter lightning activity might have originated in a documented unusually warm sea surface in the eastern North Atlantic. This increase of the surface sea temperature probably allowed setting of the typical meteorological scenario for winter lightning (cold air overblowing a warmer sea water; Williams, 2018). The warmer sea might have changed the typical winter microphysical thundercloud composition, charging processes, and/or electrical conductivity, and could result
315 in a more efficient cloud electrification (Chronis at al, 2016). The evidence in favour of this hypothesis is the observed spatial distribution of lightning. The strokes were concentrated above the ocean and along the western coastal areas with a quite sharp change in the lightning density at the ocean/land boundary. The strokes were very energetic; the mean stroke energy calculated over the whole period of six months was by two orders of magnitude larger than the global WWLLN mean energy of 1 kJ. Three per cent of the detected strokes were the superbolts with an energy exceeding 1 MJ. The most energetic strokes occurred
320 during night and morning hours when there could be a larger vertical temperature gradient in the atmosphere. We estimated for the first time the multiplicity of winter strokes in the WWLLN data using the grouping criteria similar to other lightning location networks. We have found that more flashes than in other seasons and regions were single-stroke flashes and that subsequent strokes in superbolts never reached mega joule energies. Global climate events occurring during analysed period were probably responsible for the increase of the sea surface temperature and for the consequent intense energetic lightning
325 activity: the significant positive phase of NAO and the transition from cold to warm phase of ENSO. Our study therefore indicates that local distribution of lightning can reflect the disruptions in normal weather patterns originating in global climate phenomena.

Data availability

WWLLN archival data are copyrighted by the University of Washington and are available to the public at nominal cost
330 (wwlln.net). The monthly mean NAO indexes are available at

https://www.cpc.ncep.noaa.gov/products/precip/CWlink/pna/norm.nao.monthly.b5001.current.ascii.

Author contribution

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

Competing interests

335   The authors declare that they have no competing interests.

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440