Long title: A regional lightning climatology of the UK and Ireland and sensitivity to alternative detection networks.

Short title: A regional lightning climatology of the UK and Ireland.

Leah Hayward[1], Dr Malcolm Whitworth[1], Dr Nick Pepin[1], Professor Steve Dorling[2]

[1] School of the Environment, Geography and Geosciences, University of Portsmouth, Burnaby Building, Burnaby Road, Portsmouth, PO1 3QL, United Kingdom

[2]School of Environmental Sciences, University of East Anglia, Norwich Research Park, Norwich, NR4 7TJ, United Kingdom.

Correspondence to: Leah Hayward (leah.hayward@port.ac.uk), 07492306404

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Abstract

A total lightning (cloud-ground and cloud-cloud) climatology of the UK and Ireland is presented combining 3 different ground-based lightning location systems over a 12-year period (2008-2019). The study area is divided into seven geographical regions using k-means clustering to identify areas with distinctive seasonal distributions of lightning flashes per km²/yr (referred to as flash density or FD). Different regions exhibit contrasting summer thunderstorm seasons (for example from April to August in the South-east of England and May to July in Southern England coastal regions). Summer FD peaks in July in the English Channel and south-east and midland areas of England range from 0.1-0.3 FD whilst the southern England coastal region sees FDs in the range 0.03-0.06 FD. Regions more prone to winter thunderstorms are identified as having Northwest facing coastlines (<0.02 FD in Northwest Scotland). Diurnal lightning distributions are also shown to have regional dependence with stronger afternoon peaks over-land (0.05-0.1 FD in the South of England), while in the South coastal and English Channel regions early morning or overnight peaks (0.03-0.09 FD) are more pronounced relative to afternoon FDs (0.015-0.03). This study has demonstrated the benefit of using multiple lightning detection networks to mitigate the effects of inhomogeneities within any one data source. It is also shown that significant additional insight comes from taking a regional approach to analysing temporal distributions of lightning.

1.Introduction

Thunderstorm hazards include lightning, heavy rainfall, hail, thunder-snow, strong winds and tornadoes (Meyer et al., 2013; Wapler, 2013). This hazardous weather can cause flooding; damage to property, infrastructure and crops; disrupt transport and outdoor maintenance; cause injury and pose a risk to life (Elsom et al., 2018; Piper et al., 2016). Thunderstorm climatologies therefore provide valuable information for decision makers, including the public, and experts on how to reduce the risk of exposure to thunderstorm hazards (Brooks et al., 2018). This information can be used for preparedness, scheduling high risk activities at low-risk times and for supporting forecasting. A total lightning climatology (including cloud-ground, cloud-cloud and intra-cloud lightning) provides quantification of exposure to thunderstorm hazards because the presence of lightning is the only product of a thunderstorm that confirms a convective event as thundery (Hayward et al., 2020) and is therefore an appropriate proxy for thunderstorm distribution and behaviour.

This paper refines our understanding of UK and Ireland lightning and thunderstorm distributions to a regional level. To date, whilst regional and seasonal lightning variations are discussed within the literature, a detailed investigation focused upon the boundaries of the UK and Ireland has not been completed. Additionally, whilst studies have thus far relied upon one source of lightning data, this paper investigates the use of multiple lightning detection networks as a means of mitigating inhomogeneous detection and enhancing confidence in the results.

1.1 History of study into lightning within the UK region

The UK and Ireland have been included in several previous Europe-wide thunderstorm climatologies. Thunderstorm frequency, based on human observations of thunderstorm occurrence (van Delden, 2001), demonstrated a general trend of decreasing thunderstorm frequency per year moving north-westward across the British Isles. The UK and Ireland as a whole, however, experiences a relatively low frequency of thunderstorm events compared to mainland Europe.

This pattern of thunderstorm frequency is also evident in lightning climatologies compiled across Europe using ATDnet data (Anderson & Klugmann, 2014; Enno et al., 2020). Using 5 years of data, 2008-2012 Anderson & Klugmann (2014) presented a European lightning density map (total lightning per km^2 per year for each 0.2° x 0.2° grid cell) and showed that the ATDnet average annual lightning flash density (FD) over most of England is between 0.12 and 0.75 FD, while Southwest England, Wales, Scotland, Northern Ireland and Ireland see between 0.03 and 0.12 FD. The vast majority of lightning activity is shown to occur in the summer season with much lower activity in spring and autumn, and virtually none is visible on the winter FD maps. This temporal distribution is corroborated by another Europe-wide study, which employed EUCLID and Zeus lightning data, soundings, ERA-Interim and surface observations (Taszarek et al., 2019). ERA-Interim was used to calculate convective available potential energy (CAPE), convective precipitation and WMAXSHEAR which is an estimate of an updraft's vertical velocity and shear (Taszarek et al., 2021); these diagnostics were combined to identify thunderstorm producing conditions. The use of several datasets proved beneficial in this case as ERA-Interim re-analysis data alone was found to overestimate thunderstorm occurrence both over the UK and to the immediate west over the Atlantic compared with the other datasets. ERA5 reanalysis data has subsequently been used, in much the same way, to calculate CAPE and WMAXSHEAR to create a climatology of thunderstorm environments across Europe and to assess how the frequency and intensity of these environments is fluctuating as a result of climate change (Taszarek et al., 2021). This study concludes that thunderstorm producing environments in northern Europe have increased in frequency over the last 41 years.

Some studies have focused entirely on the UK, including using the ATDnet lightning dataset to ascertain how many strikes occur over the UK land area with a view to establishing a more accurate estimation of risk to life, e.g. 1 death per 59,000 counts (Elsom et al., 2018) and to relate lightning activity to lightning injury occurrence and distribution in Northern Ireland (Sleiwah et al., 2018). ATDnet data between 1990 and 1999 was used to calculate the distribution of thunderstorm days (TD) in the UK (Holt et al., 2001). Focusing on the UK allowed thunderstorm activity to be distinguished when occurring during very low activity times, especially in the winter when TDs are concentrated on western facing coastlines and ocean areas. During summer, spring and autumn peaks in activity occur over land and ocean areas between the UK and Europe with little activity in ocean areas to the west of the UK.

Table 1 is a summary of thunderstorm environments previously identified in the literature for the study area of UK and Ireland. This will act as a benchmark against which the results of this study will be compared, to help identify causation mechanisms for thunderstorm activity.

Building upon these earlier studies, further work is required to produce a detailed thunderstorm climatology across the UK in order to establish temporal and spatial distributions at a regional level which defines the regions with unique distributions. Lightning is identified as being of medium to high risk to transport and digital infrastructure as well as high to very high risk to energy infrastructure in the UK Climate Change Risk Assessment 2022 (DEFRA, 2022). The availability of lightning data of at least 10 years' duration in the UK and Ireland provides the opportunity to obtain high resolution spatial distributions of lightning flashes. Previously, lightning climatologies that include the UK and Ireland have been conducted on a continent-wide basis which therefore use a scale which may obscure local variations in lightning flash activity. The overall aim of the study is therefore to produce a regionally-specific climatology of thunderstorm and lightning hazard, including all types of lightning both cloud-to-ground (CG) and cloud-based, intra-cloud and cloud-to-cloud lightning (IC) / (CC). The inclusion of CC lightning, whilst not particularly hazardous in itself, is an indicator of thunderstorm activity and intensity which may translate to other thunderstorm hazards such as rainfall, wind and hail. To satisfy this aim our objectives include dividing the study area into regions of temporally distinct lightning distribution and to evaluate the use of multiple lightning location systems (LLS) in production of thunderstorm and lightning climatologies.

Three lightning location systems are used in this paper to compile FD maps and temporal trends. The main advantage of using multiple datasets is that trends evident in more than one dataset (despite different technologies and sensor placements used for detection) provide confidence that they are not the result of spatial or temporal inhomogeneity on the part of an individual lightning location system. Detection efficiency (DE) for example can vary spatially and diurnally (Bennett et al., 2010; Poelman et al., 2013). Where there is little similarity between the lightning distributions derived from different networks, confidence in the results is reduced. This ensemble approach provides a range of possible FD values for a point in space and time and helps with the quantification of uncertainty.

2. Method

The study area shown in Figure 1 includes the United Kingdom and Ireland and all land and ocean areas within the maximum bounds of 48° to 64° N and 12° W to 4° E. The southern bound of this area was chosen to include the English Channel and Channel Islands and therefore also includes a section of Northern France.

2.1 Data

Ground-based LLS collect data on lightning strikes that occur within range of their sensor networks. This data is point-based and records the time, date, latitude and longitude of a lightning strike. Some datasets are able to differentiate between cloud-to-ground lightning (CG) and lightning that remains in the cloud (CC or IC). This research will use time, date and location data. Lightning data is obtained from 3 different sources outlined below.

LINET

The LINET system detects electromagnetic emissions from lightning in the low and very low frequencies. LINET technology utilises the time of arrival technique to identify the lightning's time and location using a proprietary model to calculate the origin point given various environmental factors affecting wave propagation (Betz et al., 2009; Nowcast, 2021). This system is able to identify both IC and CG lightning events with a high degree of accuracy and reports an average location accuracy of 75m (this is based on measurements from Germany where sensor density is greatest).

ATD

ATDnet is a very low frequency long range lightning location system also exploiting the time of arrival technique for locating the origin point of lightning emissions (Enno et al., 2020). The system is designed to detect CG lightning events by identifying their distinctive “return stroke” but also detects some IC lightning. In France, ATDnet has been demonstrated to detect up to 25% of IC flashes and 90% of CG flashes (Enno et al., 2016).

Météorage

Météorage utilises a combination of sensor types including the time of arrival technique and also sensors which can calculate the angle of arrival of an electro-magnetic wave in the very low frequency. The system can detect both IC and CG events and differentiate between them. In France in 2015 Météorage detected 97% of the 119 flashes recorded on high speed video with a calculated median location accuracy of 120m (Publications and Technical Notes | Météorage).

Lightning data processing

The lightning flash data was provided by each lightning location system operator; the grouping of individual lightning strokes into lightning flashes (based on temporal and spatial proximity) had already been performed by the data providers. Lightning strokes are the individual discharges within a lightning strike (lightning flash) that often occur very quickly and are what causes a lightning strike to appear to flicker. These strokes can be detected as separate events by lightning location systems and thus need to be grouped into flashes. Whilst each network operator may use different grouping criteria it is not anticipated that this would bias this study; Drüe et al. (2007) show that where lightning strokes that occur within a 1 second time step are grouped into flashes the grouping remains accurate for distance thresholds up to 50km. Most studies follow the definition of a flash as all strokes occurring within 1s and 10km of each other (Cummins & Murphy, 2009).

Each dataset was filtered to fit the spatial extent of the study area. The focus of this study is not intended to be a cross evaluation of datasets, particularly since the actual lightning distribution is unknown. The results are therefore anonymised and referred to as datasets A, B and C hereafter. Table 2 provides details of the temporal and spatial extent of data provided by each network operator.

Lightning data limitation

These lightning locations systems are subject to a number of potential limitations (S.-E. Enno et al., 2016). Detection efficiency (DE) measures the percentage of total lightning strikes detected while location accuracy (LA) measure the median distance at which the location of lightning strikes are misassigned (Hayward et al., 2020). It is important to this study to note that there is currently no published research on DE and LA performance of these LLS in the British Isles and it is not known whether performance data obtained in continental Europe reflects the performance in this study area. Due to the unknown nature of potential spatial and temporal inhomogeneity it can be difficult to establish how such performance may impact identified trends in lightning activity. Further detail on LLS limitations may be found in the supplemental information.

2.2 Variable grid size method

Compiling a lightning climatology at a fine enough resolution suitable for analysing local differences in the spatial and temporal distribution of lightning can be problematic in an area which experiences relatively low lightning frequency. This is because where FD is calculated by counting lightning flashes within a grid, it is not known how many flashes are assigned to the incorrect grid cell due to location detection inaccuracies. It has been established that where the average flash count per grid cell is greater than or equal to 80 that this uncertainty should not exceed 20% (Diendorfer, 2008). This threshold is consistent across grid cell sizes with a minimum grid size of 1km x 1km. In low frequency lightning areas, it may not be possible to satisfy the 80 flash criteria without resorting to a coarse grid with cell sizes of 1° to 2°. Therefore, this study proposes a novel variable grid size method as an alternative solution in order to both maintain the cell count of at least 80 throughout the study and maximise the spatial resolution where possible.

Seven separate grids were created each with cell sizes; 0.06°, 0.125°, 0.25°, 0.5°, 1°, 2° and 4° squared using the ArcMap fishnet tool across the whole study area. For each dataset, flashes were counted per grid cell for each size grid. To create the variable size grid, cells with less than 80 flashes were discarded and the flash data counted in a courser grid cell size instead. Where there was a spatial overlap between the remaining cells of the different size grids, the finest size cell was retained and the coarser sizes deleted. The seven variable sized grid layers were then joined to produce one variable sized grid unique to each LLS. An example of the grid is contained in Figure S1 in the supplemental information.

2.3 Thunderstorm days

Thunderstorm days (TD) are calculated for the whole study area as the number of days per 0.5° grid cell which produced at least two lightning flashes in a 24-hour period. This follows a similar methodology to that employed by Taszarek et al. (2019) and the 0.5° grid is of fixed resolution across the study area. Where TD were calculated on a regional basis they were defined as at least two flashes in a 24-hour period anywhere in the region. A TD is defined as the 24-hour period from 00:00 to 23:59 UTC.

2.4 Thunderstorm regions

Dataset A was chosen as the input data to identify the thunderstorm regions because this data has the longest record (11 years). FD was calculated for each month using a 0.25° grid for this 11-year period. 0.25° cell size was chosen for this analysis because all the cells which do not meet the 80 flash criteria are restricted to the marine areas to the Northwest of the study region. It is very unlikely that any mis-assignment of strikes between cells in this part of the study area will bias the results. K-means clustering was then carried out using the kmeans function of r coding language (R Core Team, 2020). The K-means clustering method (Hartigan & Wong, 1979) takes a matrix of values, in this case the objects being the cell IDs of each cell in the 0.25° grid and the variables for each cell being flash density calculated for each of the 12 months. The optimal number of clusters (regions) calculated for this analysis is 7 for which the function randomly assigns a cell ID to serve as an initial cluster mean (cluster centre) for each of those clusters. The function then partitions each object (cell ID) into one of these clusters based on the Euclidean distance between the mean of each cluster centre and the mean of each object so that each object is partitioned to its closest cluster. As a result, we obtained a data matrix where each cell ID was assigned a cluster ID. Further detail on this method can be found in the supplemental material.

Post-classification smoothing was carried out on the resulting regions in ArcMap. The smoothing removed isolated cells with unusual classifications (0.25° size) and replaced them with their majority neighbour.

2.5 Weather patterns

A set of 30 weather patterns have previously been defined to summarise synoptic conditions that occur over the UK and Ireland (Neal, et al., 2016). These have been used to identify which conditions are more likely than not to produce thunderstorms (Wilkinson & Neal, 2021). To identify the regional variation of the patterns leading to thunderstorm occurrence, dates on which thunderstorms occurred were compiled for each region using the TD method outlined in 2.3. The dates of thunderstorm occurrence include any day identified as a TD by either of the three LLS. The frequency of occurrence of each weather pattern type on TDs for each region for each season was calculated. Relative frequency was calculated by dividing the frequency per TD by total weather pattern frequency to ensure that the results are not skewed by weather patterns which occur more regularly than others. Details of how the weather patterns were identified and how they have been assigned to any given day within the study duration are covered in Neal et al. (2016) and Wilkinson & Neal (2021). Figure S4 of the supplemental materials presents Figure 1 from Neal et al. (2016) depicting the mean sea level pressure anomalies for each weather pattern.

3. Results

3.1 Large-scale spatial and temporal variability of lightning within the UK and Ireland

FD for the UK and Ireland for each dataset is shown in Figure 2. Each map employs a different scale to best depict the spatial variation in FD. Larger versions of these maps are available for observation of local-scale variations in lightning activity in Figures S5 to S10 of the supplemental materials. All three LLS show a higher FD over land areas, as observed by Anderson and Klugmann (2014), and a sharp decrease in lightning activity towards the Northwest of the study area, which aligns with known TD distributions (Webb et al., 2009). The contrast between ocean and land FD is most pronounced for Dataset A (Figure 2a).

There are several areas of localised increase in FD (left hand panels of Figure 2) evident in all three LLS. An example of this is the area surrounding the Wash (Figure 1), where an increase of FD (approx. 1 to 0.5 FD across all three datasets) corresponds with an increase in flashes per thunderstorm day (FPTD) increasing between 20 and 100 FPTD across all three datasets (right hand column). TD does not increase in this area (Figure 3) which indicates that the increase is not primarily due to increased thunderstorm activity, rather the fact that the thunderstorms that occur are more electrically active. Another example of interest is an increase in FD along North-facing coasts of Ireland, Northern Ireland, Scotland and Wales (particularly in datasets A and B). There is also a slight increase in FPTD in some of these areas (e.g., Anglesey, the north coast of the Scottish Highlands and Donegal), and along the Scottish coastline an increase in TD, indicating that these areas experience slightly more frequent and more active thunderstorms than areas nearby. The mechanism for a coastal increase in FD /

thunderstorms covered in Table 1 include the result of differential land vs ocean heating, relatively warm sea surface temperatures (SST) (Holley et al., 2014), updraught of sea breeze circulation over land (van Delden, 2001) and/or general or winter orographic uplift (Holt., et al. 2001). With regard to the influence of topography, the Cairngorms exhibit increased FD in all three datasets, corresponding with an area of increased FPTD.

TD “hot spots” are coincident with Greater Manchester (19 to 21 thunderstorm days /yr (TDPY)) and Greater London (19 to 24 TDPY) in all three datasets (Figure 3). There is a hotspot coincident with Dublin in datasets A and B (10 to 15 TDPY). Manchester and London have been previously identified as generating elevated thunderstorm activity relative to the surrounding areas which has been attributed to the urban heat island effect where city regions are warmer, sometimes triggering convection (Wilkinson & Neal, 2021). The Glasgow area may also coincide with an increase in TDs however, the hot spot appears to be more centred on the uplands to the south of Glasgow rather than the city itself.

Seasonal and diurnal regimes in FD within the study area as a whole are presented in Figure 4. The three datasets produce similar temporal distributions to each other but differ in magnitude providing an upper and lower bound for lightning activity. The main thunderstorm season is from April to September and peaks in July, consistent with the hail season (Webb et al., 2009). The diurnal distribution has the majority of lightning activity happening in the afternoon and evening between 1200 and 2000 UTC. There are also smaller peaks in activity in datasets A and B between 0300 and 0500 UTC and around midnight in datasets B and C. It is not possible to discern whether this overnight distribution difference is the result of spatial or temporal inhomogeneity in one of the LLS. Datasets A and C produce similar magnitudes of FD throughout the year with Dataset B’s flash density being approximately double. Diurnally datasets A and C again detect similar magnitudes of FD save for overnight where dataset C’s FD is up to 0.005 greater. Dataset B again produces the largest FD at around double the amount but exceeds this in the afternoon peak (4pm). This suggests that the DE for at least one of the datasets is diurnally variable.

3.2 Lightning regions of the UK and Ireland and their temporal variability

A map of the cluster assignment for each 0.25° grid cell following k-means clustering is shown in Figure 5. Each cluster will be referred to as a region which can be characterised by its spatial distribution as follows:

1 Mainland continental region. This region is restricted entirely to European land areas.

2 UK continental region. Occurs mostly over the England land area but also some areas of the European coastline.

3 English Channel. Coastal and marine areas between England and France.

4 South coastal. South facing coasts and marine areas in the South of England, Wales and Ireland.

5 Maritime. Includes most areas over the sea but also a large amount of the UK and Ireland land areas, mostly in the north and west, and is by far the largest region identified.

6 Northwest coastal. North and Northwest facing coasts and marine areas to the north of Scotland and Ireland.

7 Northwest Scotland. Subset of Northwest coastal occurring along the Northwest facing Scottish coastline.

Regions 1 and 2 occur mostly over land areas. FD in the UK continental region (2) is generally between 0.4 and 1.9 for all 3 LLS in common with previous studies (Enno et al., 2020). Using multiple LLS' and the variable sized grid has allowed for greater resolution in this region than was previously possible. Each LLS has a different length of record (outlined in table 2) which has been averaged by year for each LLS to enable comparison.

There are four regions which appear to occur mostly in near-coastal areas namely South coastal (4) and English Channel (3) in the south and Northwest coastal (6) and Northwest Scotland (7) in the North. These areas likely reflect transitional zones between regions of continental and maritime dominated thunderstorm generating processes. Whilst (4) seems to merge into (3) in the narrowest parts of the English Channel, (7) appears to be a distinct subset of (6), the former covering only a very small area. Coastal areas producing different seasonal distributions of lightning or thunderstorms have been identified in Scotland and Ireland as a result of winter orographic lift of unstable polar maritime air (Table 1; Holt et al., 2001; Wilkinson & Neal, 2021) and in the English Channel (Holley et al., 2014), Welsh coast, Devon and Cornwall forced by SSTs (Perry & Hollis, 2005). Table 3 shows the thunderstorm days reported by Taszarek et al. (2019) for these coastal regions. In this study we obtained a range of thunderstorm days, due to having data from multiple LLS, Taszarek et al. (2019) reported thunderstorm days are similar but at the lower end of this range. This shows that using multiple LLS with different technologies and record lengths has not only identified a range of values for these regions but also provides an upper value greater than previously thought.

Lastly, the maritime region (5) includes not only areas over the sea but also a large amount of land area. The land areas which are included within this region are areas which, due to their western or northern locations, are less dominated by proximity to Europe and associated land heating processes. The regions as identified by K-means clustering agree with known regional / seasonal variation of lightning activity and for the first time we can quantify the seasonal and diurnal distributions of these regions.

The objective identification of regions which appear to be characterised as either mainly land, marine or coastal likely reflects the findings of previous Europe wide studies which identified the fact that land areas in Europe exhibit a different seasonal distribution of FD to those found at sea (Anderson & Klugmann, 2014; Enno et al., 2020).

The seasonal and diurnal distributions of FD differ between regions (Figure 6 & 7). Whilst the three LLS reveal broadly similar distributions, confirming that the overall conclusions regarding FD distribution are robust, the magnitude often differs with some LLS clearly detecting larger numbers of flashes in some regions but not others.

Regions (1) and (3) have a consistent level of FD (Figure 6a) and TD, relative to other regions, (Figure 6b) during the thunderstorm season from April to September. Summer thunderstorms are primarily driven by solar heating of the land (Anderson & Klugmann, 2014; Enno et al., 2020). Region (3), whilst not land based, is close to the European continent and will therefore also be affected periodically by plumes of this warm summer air and thunderstorms which track into the region. Region (3) also has an increase in TD (Figure 6b) during the winter, forced by SSTs, but little accompanying increase in FD (Figure 6a) confirming the relatively low intensity of these winter storms. A combination of the troposphere being shallower in winter, thus limiting the height to which thunderstorm clouds can build, a reduction in ground heating during winter, producing a smaller vertical temperature gradient, plus lower atmospheric moisture, leads to this reduction in winter thunderstorm intensity. Figure 8 shows the average SSTs for the study area for the month of December, ranging between 10 and 12°C in region 3, substantially higher than average air temperatures at this time of year.

Regions (2) and (4) have a summer season of lightning activity mainly occurring between April and September although with a sharp increase of activity in July. TDs in the same regions follow a steady increase from March to the end of summer and dropping abruptly into autumn reducing in number until February. The autumn occurrence of TD seems to decline slightly later (a few weeks to a month) than FD suggesting that as the season transitions from summer to autumn thunderstorms first weaken in intensity before they become less frequent. It was noted by Holley et al. (2014) that thunderstorms transition to coastal areas in the autumn and so this may be related to relatively warm SST and cooling air temperatures during this period.

Region (5) sees a gradual increase in TD from April to August (relative to FD which increases sharply between May and August) followed by a decline to February / March. The difference between the TD and FD annual trends shows that thunderstorms increase in intensity during the summer months. As there is little difference between the number of winter TDs and summer TDs this suggests that thunderstorm activity is driven equally by relatively warm sea surface temperatures in the winter (Holt et al., 2001), as shown in Figure 8, and solar heating in the summer.

Lastly, in regions (6) and (7) we can see a short summer thunderstorm season as well as a winter increase in FD. FD is slightly higher overall in the summer but there is a comparable TD peak produced in winter in (6) and a slightly higher peak in (7). Figure 8 shows that the SST in these regions remains as high as 8°C to 10 °C in December in higher latitudes where atmospheric temperatures are relatively cool due to polar air-masses. This difference in SST relative to atmospheric temperature is large enough that it is able to trigger thunderstorm producing convection. In southern areas the air mass temperature is warmer and the relative difference between SST and atmospheric temperature is not often great enough to trigger thunderstorm convection. Whilst there are similar numbers of thunderstorms during winter as during summer in these northern regions, they are more electrically active in the summer.

Whilst the regional annual distributions of FD are similar for all three datasets, there are some differences in magnitude which vary between the regions showing that there are likely regional variations in LLS performance. During the summer, dataset B produces a much larger FD than A or C. This difference is greatest in the mainland continental region and as regions become further from continental Europe, FD for dataset A reduces relative to the other datasets. This could be for a variety of reasons such as sensor placement or differences in sensor technology employed meaning that there is a spatial variation in the LLS ability to detect all types of lightning. Interestingly, where there was the greatest difference of magnitude in regions 1, 2 and 3 for FD, but for TD in these regions TD magnitudes were very similar. There is a disparity of TD figures for regions 4, 5 and 6 where dataset A produces the highest amount in most months and dataset C the lowest.

The diurnal distributions (Figure 7) support the suggestion that most lightning activity and thunderstorm activity in UK continental (2) is surface heating based with the majority of thunderstorms and lightning activity occurring in the afternoon. There is a smaller peak in the early hours of the morning which suggests that at least some of these thunderstorms persist overnight. Overnight storms may be the result of cold fronts passing over relatively warm land surface areas or as existing afternoon storms being reinvigorated by cloud top cooling. As night-time cloud tops radiate heat into space they cool, steepen the atmospheric gradient and trigger further instability. In contrast to this the diurnal distribution of English Channel (3) is interesting because most lightning occurs in the evening and overnight whereas, most TDs occur in the afternoon meaning that the overnight / evening storms are less frequent but more intense. This suggests that the diurnal FD distribution may be influenced by less frequent but much more intense thunderstorms which are known to travel from France overnight into the UK during Spanish Plume events (Lewis & Gray, 2010).

South coastal region (4) has a similar diurnal distribution of TD to (2) but FD is dominated by a large overnight peak. Similar to (3), this overnight peak may be the result of relatively infrequent but intense storms which are known to travel northwards from France.

The diurnal distribution in the maritime region (5) has a main peak in TD and FD occurring in the afternoon, decreasing towards mid-morning before picking up again in the early hours. The afternoon increase in lightning and thunderstorm activity in this region suggests that solar heating remains the main driver for lightning activity, likely in association with nearby land masses. The early morning increase in FD is more pronounced than in the TD distribution indicating that there are fewer but more active storms overnight. This may therefore be the result of summer land-based storms travelling out to sea either because they are intense enough to persist overnight like Spanish plume formed storms or as a result of cloud top cooling.

Finally, as mentioned earlier, the diurnal distributions for Northwest coastal (6) and Northwest Scotland (7) differ between the LLS. This makes it difficult to interpret with any certainty because it is not known which LLS shows the correct distribution. Datasets A and B both show an early morning and afternoon peak in FD in these regions which is likely therefore a real signal. However, the magnitude and in the case of (7) the relative magnitude between the two peaks differs between the LLS. The TD distribution is not very smooth and the distribution is likely to be affected by the small event sample size. The reduced confidence in these results could prove problematic for residents, tourists and industry in the area such as offshore windfarms who may be interested in the best time of the day to safely schedule maintenance.

For most regions, FD calculated for dataset A is less than the other two datasets overnight except for region 7 where it also produces a relatively large peak of FD in the afternoon not evident in the other datasets. Similar to the annual distribution of FD, dataset B provides a greater FD in regions 1, 2 and 3. TD in regions 1 and 2 have a general magnitude difference of around 5 thunderstorm days between the datasets, increasing to 10 in regions 4 and 6. In regions 1 to 4 the magnitude difference is greatest overnight indicating again that there may be some overnight under detection on the part of dataset A. In regions 5 to 7 dataset A produces larger TD values and in the case of the afternoon and morning maritime TD values up to 20 TD larger. The difference between the dataset's TD counts seems to fluctuate diurnally in these regions but less so in others. It is not possible to ascertain whether this is the result of spatial inhomogeneity or diurnal performance variation or potentially a combination of both.

Examining seasonal and diurnal cycles independently does not show any interactions between the two. The combined seasonal and diurnal distributions of FD are therefore represented by contour plots (Figure 9) for northwest coastal, UK continental, maritime and English Channel regions, as examples. The seasonal plots show that, as well as northwest coastal having a relatively short summer lightning season (with peaks around 0400 and 1600 UTC) there is also a winter peak (particularly December) when most lightning occurs before 1000 UTC. Although the mid-winter peak is subdued, northwest coastal is the only region in Figure 9 to show this pattern. UK continental has an afternoon thunderstorm season from April to September, and the early morning peak in lightning activity has a much shorter season occurring between June and August. In the English Channel afternoon and early morning lightning peaks are of similar duration. Maritime has a slightly shorter lightning season for early morning lightning activity but also more evenly distributed lightning activity throughout the day in July.

3.3 Explanatory factors – regional lightning variations

The frequency of weather pattern occurrence on TD was calculated with a view to identifying the synoptic conditions producing thunderstorms in different regions (weather pattern maps referred to in this paper and produced by Neal et al. (2016) are shown in figure S15 of the supplementary materials). The dates of thunderstorm occurrence include any day identified as a TD by either of the three LLS. Figure 10 lists the top 3 weather patterns occurring on TD for each region and season (the relative frequencies for all weather patterns are contained in figure S16 of the supplementary materials). Wilkinson & Neal (2021) conducted a similar study identifying weather patterns with a probability of at least 0.5 (more likely to occur than not) of producing significant thunderstorms. Whilst this focuses on the UK as a whole the frequency of weather pattern occurrence on TD calculated here produces similar results to Wilkinson's weather patterns with probable significant thunder, despite our inclusion of TD of all levels of severity. However, taking a regional approach identified the weather patterns which occur frequently on TD for the UK as a whole, and which weather patterns occur frequently on TD in specific areas. The additional weather patterns identified as frequently occurring on TD which were not identified as probably producing significant thunder by Wilkinson & Neal (2021) were either more regionally influential or more likely to produce smaller less severe thunderstorms. Including all types of TD severity by region is also useful for industries with discrete locations such as wind farms or aviation and which can be disrupted by even small outbreaks of thunder (Wilkinson & Neal, 2021).

Patterns 26, 20, 23, and 30 are identified as frequently occurring on TD. These patterns all feature a low-pressure system over or east of the UK with the flow originating either from the West or the Northwest (usually polar maritime air mass). Air from the West and Northwest is cold relative to sea surface temperatures creating instability. Wilkinson & Neal (2021) identify patterns 26 in spring, autumn and winter, 30 in autumn and winter and 20 in winter as most probably producing thunderstorms. Figure 10e shows that in Winter, patterns 26 and 30 produce lightning in most regions of UK and Ireland because the particularly cold air penetrates far south before warming. During the rest of the year these patterns are only associated with TD in northern regions. Patterns 20 and 23 where the flow is from the West and the air likely not so cold, occur frequently with TD in Northern regions only and in no regions in the summer.

Wilkinson & Neal (2021) describe pattern 5 (figure 10b) as being likely to produce thunderstorms in Spring associated with a Southeast to Northwest orientated trough to the Southwest of the UK producing unstable air and advecting warm moist air from the South. This finding is corroborated by our results which show this pattern occurring frequently with TDs in all four of the southern regions and region 6 (Northwest coastal). However, spring is a relatively low frequency season for thunderstorms and therefore the impact of pattern 5 is reduced relative to patterns producing thunderstorms in Summer.

In patterns 24, 29, 28 and 11 there is a low pressure centred over the UK (figure 10a). Cyclonic conditions with surface heating produce unstable air. Pattern 24 in spring and pattern 11 in summer/autumn are identified as probable thunderstorm producing environments by Wilkinson & Neal (2021). 24 and 11 generally seem to occur frequently with TD in the southern regions from spring through to autumn but not in winter when *in situ* convective heating in low pressure conditions is reduced (except region 1). Pattern 29 occurs frequently from summer to winter and 28 in summer only

Patterns with a North or North-easterly flow, 14, 19 and 1, are not noted by Wilkinson & Neal (2021) to be patterns which produce thunderstorms (figure 10d). However, on a local scale these patterns occur frequently on TD from summer through to winter in the Southeast of the study area (regions 1, 2 and 3). This may be associated with cyclones and instability centred over the near continent. The relatively cold air travels South-Westward across the Southern North Sea creating instability and thunderstorms which then affect the Eastern side of the UK, the English Channel and North coast of France.

In the summer Southerly and Southwest flows bring warm and moist air to the study area producing widespread thunderstorms within a Spanish Plume (pattern 16) or more localised instability where the flow is from the Southwest (patterns 21 and 22) (f10c). All three patterns are noted by Wilkinson & Neal (2021) as probably producing thunderstorms in the summer months. Pattern 21 is one of the most frequent summer patterns for TD in region 6 to the north of the study area. Despite the macroscale southwest flow, the proximity of the low pressure to the Northwest and its strong intensity means that for this region the origin of the air may likely also include some polar maritime air on occasion (post cold fronts), creating instability as it flows into the region. During the winter this pattern also brings cold polar maritime air from the West over relatively warm seas in the South of the region producing thunderstorms in region 4 (South coastal). Pattern 22 advects air from a more Southerly direction which during summer is warm and moist producing instability in South coastal region 4.

It is also interesting to consider patterns that either do not occur on or which only infrequently occur on TD. Patterns such as 17, 18 and 25 have a high pressure directly over the UK which means stable and settled conditions where thunderstorms are very unlikely to occur with little seasonal or regional variation.

3.4 Extreme lightning events

Despite the UK and Ireland seeing relatively little lightning activity compared with mainland Europe, there are occasional significant lightning events (Anderson & Klugmann, 2014). In this study we define extreme events as lightning counts per day in the 99th percentile for each region for any of the three LLS, duplicate days (where the same date was included by more than one LLS) were removed. Figure 11 is a time series of the extreme events between the 1st of January 2008 and the 31st of December 2019 showing their frequency and magnitude. The total number of these events is shown in table 4. In all the regions extreme events occur most years and almost always during the summer season, winter extreme events occurring in Northern regions almost exclusively. Figure 11 shows that the number of extreme events per year varies with 2010 producing no extreme events in any region and more active years occurring on different years in different regions. For example, 2018 produced the most extreme events, with some of the highest flash counts, in the UK continental region but the neighbouring English Channel region only produced one extreme event in this year. These variations likely reflect the different geographies of the regions showing that these extreme events either did not track through the English Channel region or were primarily land based.

As a result of this yearly variability of extreme events, calculated frequencies should be considered conservatively. The frequency of extreme events per year (table 5) for all regions except region 7 (Northwest Scotland), is between 2 and 3. There appears to be a subset of extreme events (these will be defined as exceptional events) that generate a significantly larger amount of lightning in each region, for example in region 5 (maritime) there are two events with more than 30,000 flashes per day whilst the next largest flash count is <18,000. In regions 1 (mainland continental), 2 (UK continental) and 3 (English Channel) the frequency of these exceptional events is between 0.5 and 1 per year. Regions 4 (South coastal) to 6 (Southwest coastal) experience exceptional events much less frequently. Figure 12b and 12d (dataset A was used to produce figure 12 because this LLS provided the greatest spatial extent) shows that lightning, on the most extreme lightning days for regions 2 and 6, occurs in small non-contiguous areas. These non-contiguous areas are situated in regions which experience a much greater amount of lightning, due to southern latitude and proximity to continental

Europe. This means that when a severe thunderstorm occurs in these non-contiguous areas the lightning count dominates that which the main area of the region normally produces.

The events with the highest number of flashes for regions 4, 6 and 7 occurred on 17/07/2014 and 02/07/2009 under weather pattern 16 (Spanish Plume). Figure 12 shows the lightning distribution on those days is concentrated in the south but can also penetrate into Northern areas (region 7). Patterns 7 and 9 also occur on days with the highest regional flash counts despite not being identified as top 3 frequently occurring TDs in section 3.3. Pattern 7 produces the highest number of flashes in regions 3 and 5 on the 29/05/2017 and 02/08/2013 respectively (figure 12, c & e).

Pattern 7 shows a SW to NE orientated trough over the UK with the low-pressure system situated to the West of the UK. These two events occur during the summer and the very end of spring. On the 29/05/2017 (region 3) the lightning is concentrated over the English Channel and the inland areas close to the Southeast facing coastline of the Southeast of England in the early hours of the morning. On the 02/08/2013 (region 5) the lightning activity is widespread with particularly high concentrations in the North-sea. The large flash count on this occasion is caused by multiple large thunderstorm outbreaks.

Pattern 9 is a high pressure centred over the UK with a low pressure-system centred to the Southwest bringing warm moist air from the South over France. This occurs on the largest flash event for region 2 on the 03/06/2018. On this day the lightning occurred on the Northwest coast of France in a possible Spanish Plume style event that was not able to reach the UK and Ireland due to the influence of a blocking high over most of the country.

4. Discussion

In this study we used three different ground-based lightning location systems to produce a total lightning and thunderstorm day climatology for the UK and Ireland. We used K-means clustering to identify sub-regions which exhibit coherent and distinct temporal distributions of FD. The temporal variability of lightning and thunderstorm occurrence within each region was then analysed to produce a more accurate picture of high-risk periods for any given location. Lastly, the potential influence of weather pattern type was investigated to provide additional information on the primary drivers of lightning and thunderstorm activity. A summary of the results for each region is contained in Table 6 as a quick reference identifying high, medium and low risk.

The three LLS showed good agreement with previous studies. The majority of lightning and thunderstorm activity occurs over land areas as noted in Anderson and Klugmann, (2014) and there is a general decrease in lightning and TDs from Southeast to the Northwest (Perry & Hollis, 2005). FD, TD and FPTD also show a local increase in activity on North and Northwest facing coastlines as observed by Holt et al., (2001) and Wilkinson & Neal, (2021). We also identify increased TD activity (between 3 and 6 TDPY more than immediate surrounding areas) over the urban heat islands of Greater Manchester, Greater London and Dublin (Wilkinson & Neal, 2021; Perry & Hollis, 2005).

It therefore seems clear that the general spatial distributions of lightning recorded by LLS A, B and C agree well with a range of other studies, increasing confidence in the reliability of the data whilst also providing greater detail at the local scale, those other studies being based on lightning data, weather station records and human observations. It is interesting that some details are more visible in TD maps (e.g., urban heat islands) while others (e.g., the impact of high elevation such as the Cairngorms) are more evident in FD maps. This underlines the benefit of analysing FD and TD together to establish the details of thunderstorm activity for any given area.

Taking a regional approach to investigating diurnal, annual and seasonal distributions of FD and TD has proved beneficial for an area like the UK and Ireland which is quite geographically diverse. Whilst it is true that some aspects of the distributions do not vary much between regions, such as the annual peak being in July and the diurnal peak of activity usually being around 1600 UTC, there are additional details which can be identified as specific to each particular region. For example, the duration of the summer enhanced thunderstorm/lightning season varies from region to region and additional secondary peaks can be identified in some regions. This means there are other times of the year/day where there is an increased risk of thunderstorms and lightning hazards.

Whilst this study used K-means clustering, this is only one method of sub-dividing the study area into individual regions. Alternative methods such as grids, UK weather regions or factor analysis (Gatidis et al., 2018) have not been investigated in detail or objectively compared with the k-means results, highlighting a useful subsequent research focus. Despite this, the k-means regions as drawn yield encouraging results producing spatial and temporal distributions which align with established thunderstorm generating phenomena (Table 1). For example, Spanish plume mesoscale convective systems are known to travel most often in a Northeastward direction from the European continent into the UK overnight (Gray & Marshall, 1998; Lewis & Gray, 2010; Holley et al., 2014). FD peaks overnight in the English Channel and South Coastal regions of England despite TD peaking in the afternoon. The former is the distribution expected if the most severe storms were to be imported into the UK from France. Winter increases in lightning and thunderstorm activity are expected in coastal and marine areas due to forcing by relatively warm SSTs (Holley et al., 2014; Holt et al., 2001) which are identified in the Northwest coastal, Northwest Scotland, South coastal, maritime and English Channel regions to varying degrees. The regions identified which are restricted to land areas (UK continental and mainland continental) exhibit a typical annual distribution of lightning with a single peak from April to October (Holley et al., 2014).

The regional annual and diurnal distributions were calculated for each of the three different lightning location system datasets. Comparing the results across LLS can help to highlight and mitigate the impact of potential inhomogeneities present in an individual system. It is encouraging that in most cases the overall shape of the distributions is similar between the LLS and the timing of peaks in lightning and thunderstorm activity are generally similar, providing confidence that the results correctly identify the most active times for each region. Despite the majority of regional distributions being similar between datasets there are some relatively large differences in magnitude. As these differences effect some regions and not others and can vary diurnally, this highlights the potential for spatial and diurnal inhomogeneity when relying on just one dataset for a lightning climatology. A similar finding using multiple datasets was discussed by Tazarek et al., (2019) who successfully used multiple data sources to count TD at distinct locations across Europe. On occasions where there is a difference, such as diurnal distributions for Northwest coastal and Northwest Scotland regions, then there is greater uncertainty in the true FD or TD for any given time period. These two regions are situated at the fringe of two of the lightning location systems' sensor networks and due to the relatively small amount of lightning activity at that latitude any fluctuations in network coverage have greater influence on the distribution. For lightning risk assessments, such results could be employed more conservatively by relying on the highest rates of the three distributions to cover the potential worst-case scenario. Whilst there is a chance that the highest rate may be inflated by false positives, under-detection is more likely to occur systematically according to location due to detection efficiency being strongly related to distance from network sensors. Using only one LLS may fail to identify whether there is a higher potential rate of lightning activity for the region in question.

It has been important to this study to include TD, not just because it can provide important information in its own right, but also because (when employed in conjunction with FD) it provides additional insight into thunderstorm intensity (Soula et al., 2016). This has been particularly useful in this study area. In some cases, a high FD alone might suggest that there is a high risk from lightning activity. However, if the number of TD does not reflect this, it means that the risk has been inflated by infrequent severe storms.

5. Summary and Conclusion

We summarise our main results as follows:

- All three ground-based lightning Location systems produce a lightning climatology of the UK and Ireland which emphasizes an increase of FD from Northwest to Southeast and the majority of lightning occurring over land.
- K-means clustering identified 7 regions which exhibit distinct diurnal and seasonal distributions of FD. Regions were either continental based, marine or coastal (transitional between continental and marine) in nature.
- Marine and coastal regions produced thunderstorms during the winter months and have a much shorter summer thunderstorm season than continental regions. Continental regions produce a strong peak of lightning activity during the afternoon and early evening. Marine and coastal regions have an early morning or overnight peak in lightning density which is larger relative to their afternoon peak compared with the continental regions likely the result of stronger temperature gradients between SST and air temperatures overnight
- Comparing seasonal and diurnal distributions of FD and TD revealed where distributions are skewed by infrequent severe storms, such as, the South coastal region receiving the largest flash densities overnight but experiencing no related peak in TD.
- TDs coincide more frequently with particular weather patterns, but these are distinct to the season and the region, which assists understanding the regional differences in lightning and thunderstorm occurrence.
- Days of extreme lightning were identified by extracting lightning counts per day exceeding the 99th percentile. The vast majority of these events occur in the summer months although in northern regions extreme events have occurred in winter with a frequency 1 to 2 per 10-year period.

- Whilst there was good overall agreement between the datasets when it came to spatial, annual and diurnal distributions, there were some relatively large differences in terms of magnitude and regional distributions.

This study has additionally emphasized the important work still to be done in investigating spatial-temporal variation in thunderstorm activity in the UK and Ireland, despite these areas experiencing a relatively low level of lightning and thunderstorm activity in comparison with mainland Europe and other parts of the world. Further work is required to understand the local scale effects of topography which are likely to vary based on the location within the UK and Ireland as well as detailed analysis of the urban heat island effect. The complex and variable geographic environments of the study area mean that a regional approach was warranted when analysing temporal variations in lightning and thunderstorm activity. Lastly, due to relatively large differences in FD and TD magnitude between the datasets in some regions, as well as some regional specific differences in overall distribution there is some uncertainty in terms of temporal and spatial homogeneity. It is not possible to ascertain which dataset is correct but it is possible to identify the areas and times of uncertainty by using multiple datasets. It is therefore recommended that, where possible, multiple datasets be used to evaluate the risk from lightning and thunderstorm activity, thereby mitigating against any potential data completeness or network coverage limitations.

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Thunderstorm environment	**Characteristics**
Classic Spanish plume	Produces thunderstorms, intense thunderstorms and Mesoscale Convective Systems (MCS). Most activity takes place over SE England. Storms propagating NE, typical track is Bay of Biscay into SE England (Lewis & Gray, 2010). Non-diurnal variation in occurrence and can occur overnight (Holley et al., 2014).
Modified Spanish plume	Produces thunderstorms, intense thunderstorms and MCS Activity taking place in SE England, Northern and Western regions. Cell propagation South to North (Lewis & Gray, 2010).
European easterly plume	Produces thunderstorms, intense thunderstorms and MCS NW/SE orientated from North France to SE England. Propagating NW. Occur less often than Spanish plumes (Lewis & Gray, 2010).
Thundery low / frontogenesis	Cold fronts approach from the West lifting warm air. Environment conducive to thunderstorms, moves East (van Delden, 2001).
Up-draught of sea breeze circulation over land	Coastal peaks in Spring and early summer (van Delden, 2001).
Up-draught of land breeze circulation over sea	Ocean typically in Southern-North Sea peaks in Autumn and early morning / night (van Delden, 2001).
Land heating	Increase in lightning over land in April and decrease in October. Latitudinal decrease S to N as heating is reduced (Anderson & Klugmann, 2014; Enno et al., 2020). Transitions to coastal areas in Autumn (Holley et al., 2014). Increase in occurrence NW to SE in spring and summer. Summer shows orientation in England more West to East (Perry & Hollis, 2005).

Sea surface temperature (SST)	Winter peaks over oceans and sea (Holt et al., 2001). Peaks along coast of English Channel and in Winter within the English Channel, North-Sea, and western sea areas such as the Bristol Channel, off the coast of Cumbria and Wales (Holley et al., 2014) as well as the Welsh coast, Devon and Cornwall (Perry & Hollis, 2005).
Winter orographic uplift of unstable polar maritime air	Peaks on NW- and West-facing coasts of Scotland and Ireland (Holt et al.,, 2001; Wilkinson & Neal, 2021). Shown in outer Hebrides and Shetland in Autumn (Perry & Hollis, 2005)
General orographic lift	Peaks in Cumbria and Manchester basin (Holt et al., 2001).
Urban heat islands	London, Manchester and Dublin – peaks in Spring (Wilkinson & Neal, 2021), hotspot in Manchester in Autumn and Winter (Perry & Hollis, 2005).

Table 1: UK thunderstorm environments previously identified in the literature - characteristics of thunderstorm behaviour and distribution attributed to these environments.

Dataset	Temporal extent provided	Spatial extent provided
Dataset A	01/01/2008 to 31/12/2018	48° to 64° N and 12° W to 4° E
Dataset B	01/01/2010 to 31/12/2018	48° to 62° N and 12° W to 4° E.
Dataset C	01/01/2015 to 31/12/2019	48° to 60° N and 12° W to 4° E.

Table 2: Temporal and spatial extent of lightning data provided in each dataset.

Region	Taszarek et al. (2019) Thunderstorm days per year	This study Thunderstorm days per year
3 English Channel	12	16 - 24
4 South Coastal	2-4	4-12
6 Northwest Coastal	4	4-6
7 Northwest Scotland	4	4-6

Table 3: Thunderstorm days reported for Taszarek et al. (2019) and this study for the identified coastal regions.

Region	*Total events exceeding 99th percentile*
1 Mainland continental	*26*
2 UK continental	*30*
3 English Channel	*18*
4 South coastal	*37*
5 Maritime	*46*
6 Northwest coastal	*27*
7 Northwest Scotland	*7*

Table 4: Total number of events with lightning counts exceeding the 99th percentile for each region.

Region	No. of extreme events	Extreme event f. (per year)	Flashes per day	No. of extreme events	Extreme event f. (per year)	Top three flash counts	Date	Weather pattern
1 Mainland continental	26	2.17	<= 20,000	15	1.25	**68724**	**01/07/2018**	**6**
			> 20,000	11	0.91	63195	27/05/2018	6
						60670	15/08/2017	2
2 UK continental	30	2.5	<= 20,000	23	1.91	**40573**	**03/06/2018**	**9**
			> 20,000	7	0.58	40528	28/06/2012	11
						38832	01/07/2018	6
3 English Channel	18	1.5	<= 7500	12	1	**18967**	**29/05/2017**	**7**
			> 7500	6	0.5	16747	25/07/2019	22
						14400	27/07/2018	22
4 South coastal	37	3.08	<= 15000	36	3	**18550**	**17/07/2014**	**16**
			> 15000	1	0.08	10807	18/07/2017	22
						8451	01/07/2018	6
5 Maritime	46	3.83	<= 20,000	44	3.67	**37081**	**02/08/2013**	**7**
			>	2	0.17	36020	20/07/201	2

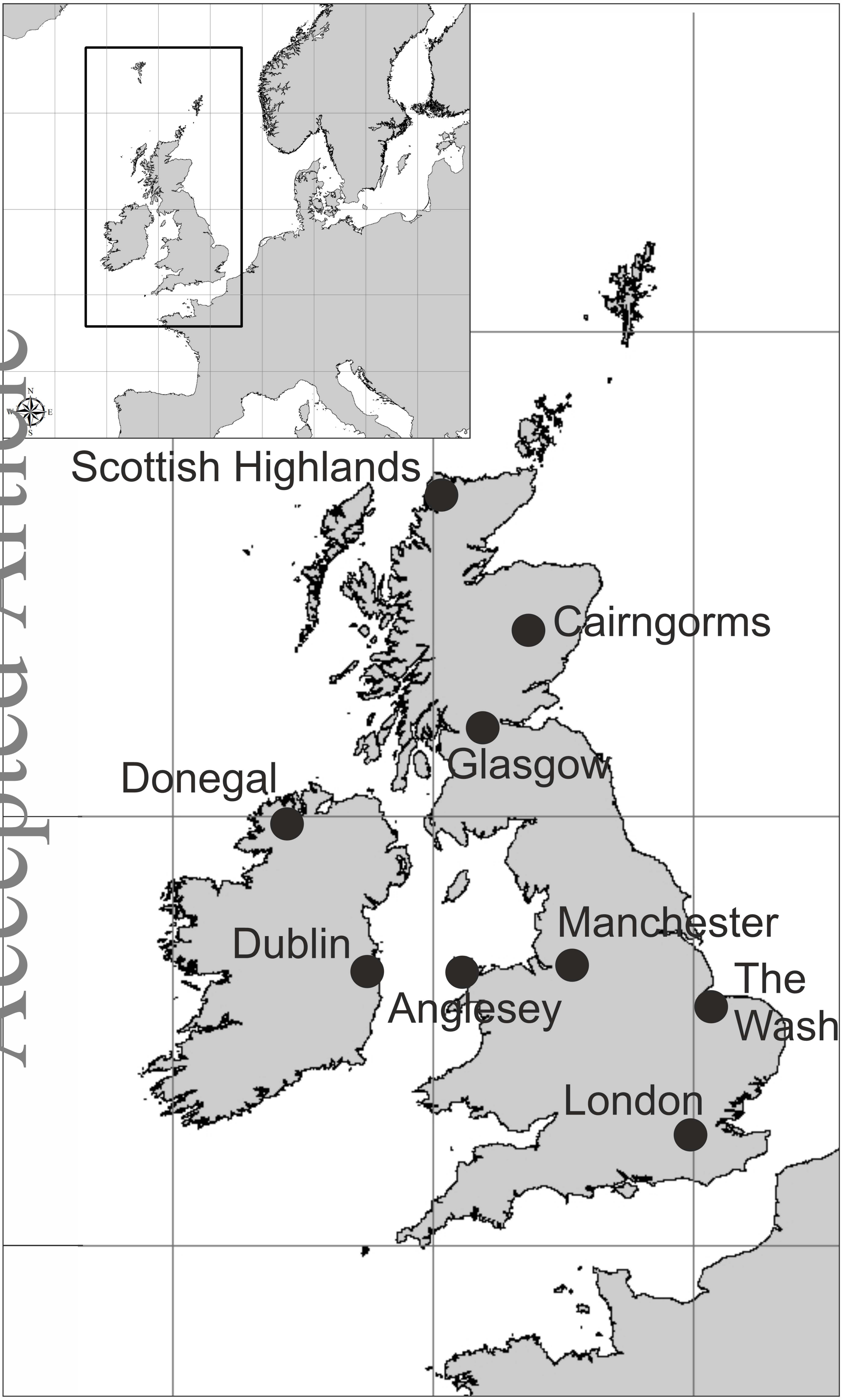
			20,000				6	
						17184	28/06/2012	11
6 Northwest coastal	27	2.25	<= 3000	25	2.08	**5260**	**17/07/2014**	**16**
			> 3000	2	0.17	3346	02/08/2013	7
						2765	20/07/2016	2
7 Northwest Scotland	7	0.58	<= 300	2	0.17	**1080**	**02/07/2009**	**16**
			> 300	5	0.47	898	26/07/2013	11
						840	20/07/2016	2

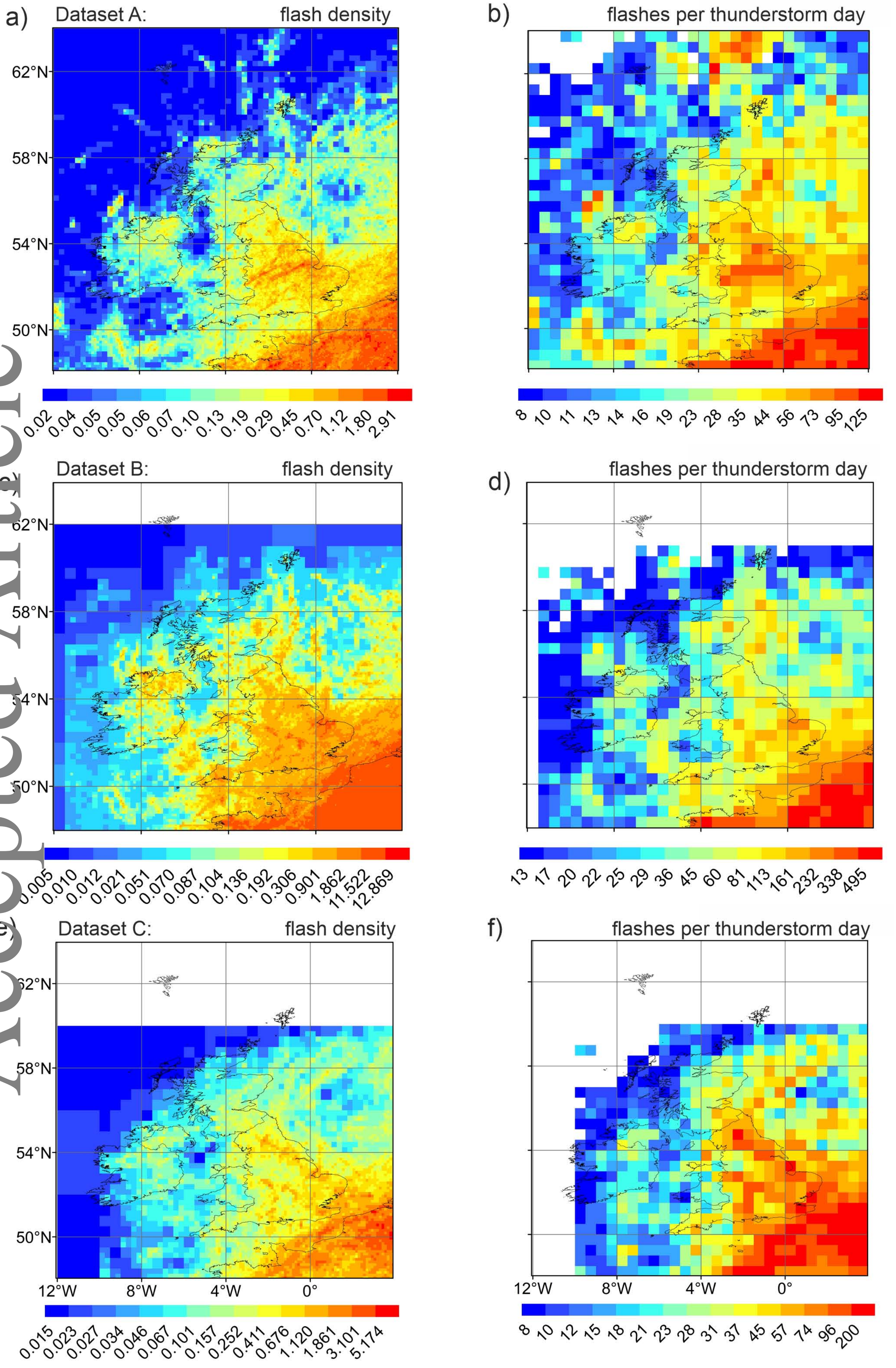
Table 5: Total number of lightning counts per day in the 99th percentile (referred to as extreme events) for each region and their average annual frequency (f) per year. Extreme events are subdivided by lightning flash counts (where there appears to a jump in magnitude). The three extreme events with the greatest flash count for each region are listed with the date of the event and the weather pattern attributed to that day. The extreme events highlighted in bold are shown in Figure 13.

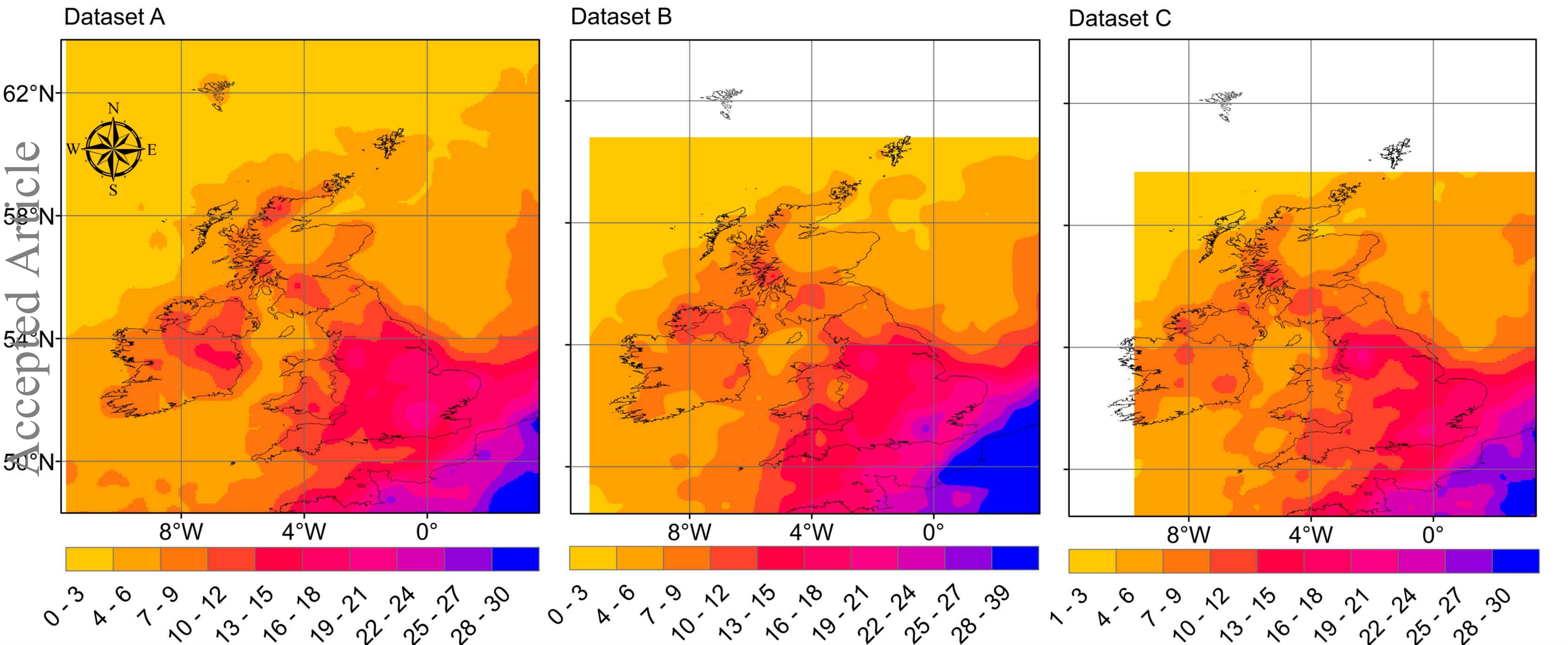
Region	**Annual thunderstorm risk**	**Diurnal thunderstorm risk**
UK continental	Highest: Apr to Aug	Highest: 1200 to 2100UTC
	Medium: Aug to Dec	Medium: 2200 to 0800 & 1000 to 1200 UTC

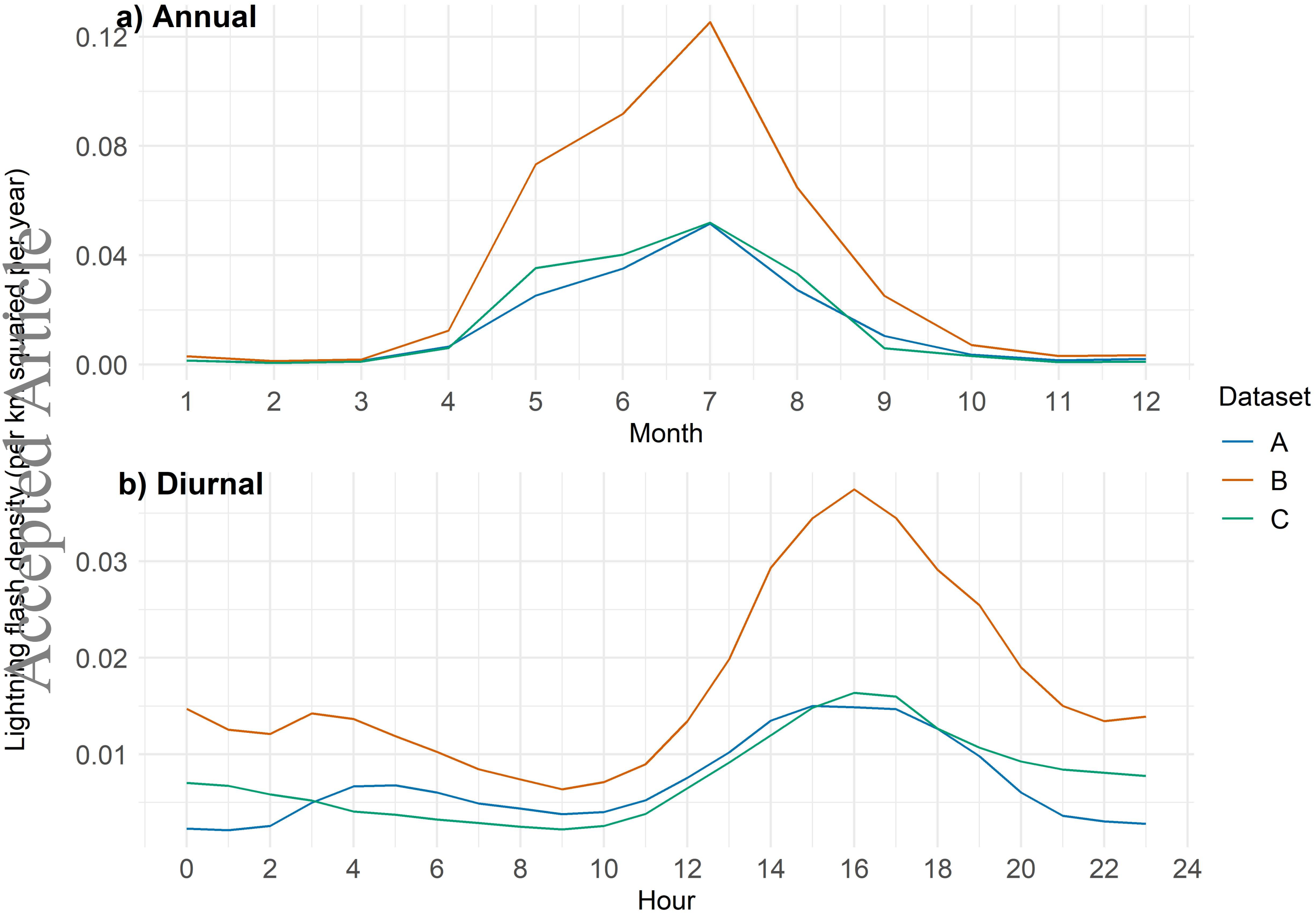
(2)	Lowest: Dec to Mar	Lowest: 0900 UTC
English Channel (3)	Highest: Apr to Aug	Highest: 1300 to 2100 UTC
	Medium: Aug to Dec	Medium: 2200 to 0400 (highest lightning activity) UTC
	Lowest: Dec to Mar	Lowest: 0500 to 1200 UTC
South coastal (4)	Highest: May to Jul	Highest: 1200 to 2000 UTC
	Medium: Aug to Dec & Apr	Medium: 2100 to 0400 (highest lightning activity) UTC
	Lowest: Dec to Mar	Lowest: 0500 to 1100 UTC
Maritime (5)	Highest: May to Aug (Jun/Jul higher intensity storms)	Highest: 1200 to 1800 UTC
	Medium: Aug to Jan	Medium: 1700 to 0400 UTC
	Lowest: Feb to Apr	Lowest: 0500 to 1100 UTC
Northwest coastal (6)	Highest: May to Aug & Oct to Jan (Jun/Jul higher intensity storms)	Highest: 1200 to 1800 UTC
	Medium: Sep & Feb	Lowest: 1900 to 1100 UTC
	Lowest: Feb to Apr	
Northwest Scotland (7)	Highest: July (higher intensity storms), Nov to Jan	Highest: 1200 to 1800 UTC
	Medium: Jan to Mar, May to Jun & Aug to Nov	Lowest: 1900 to 1100 UTC
	Lowest: Apr & Sep	

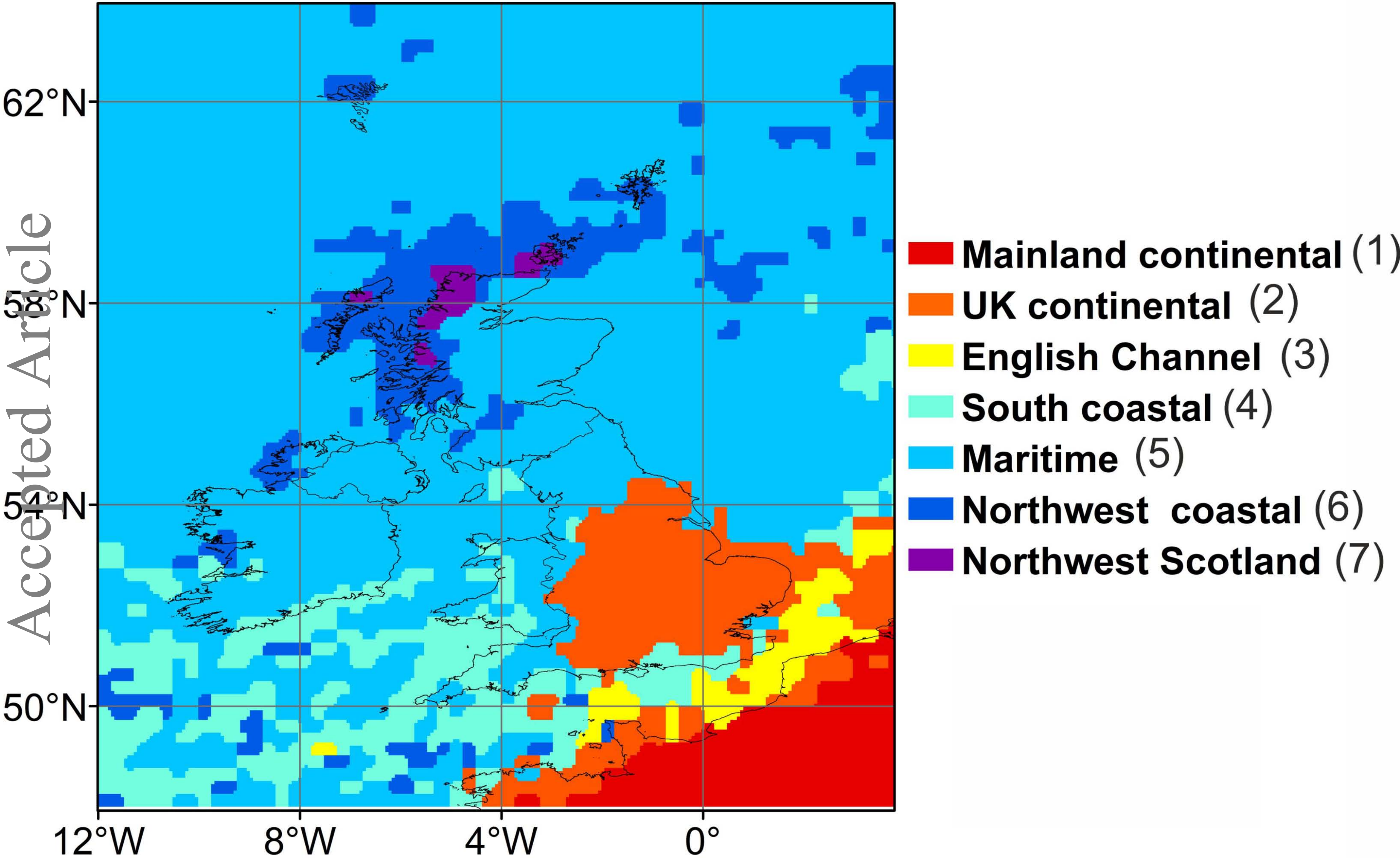
Table 6: Summary of high, medium and low risk for each region and increasing/decreasing risk for distance from the UK coastline.


N
W
E
S
Scottish Highlands
Cairngorms
Glasgow
Donegal
Dublin
Anglesey
Manchester
The Wash
London

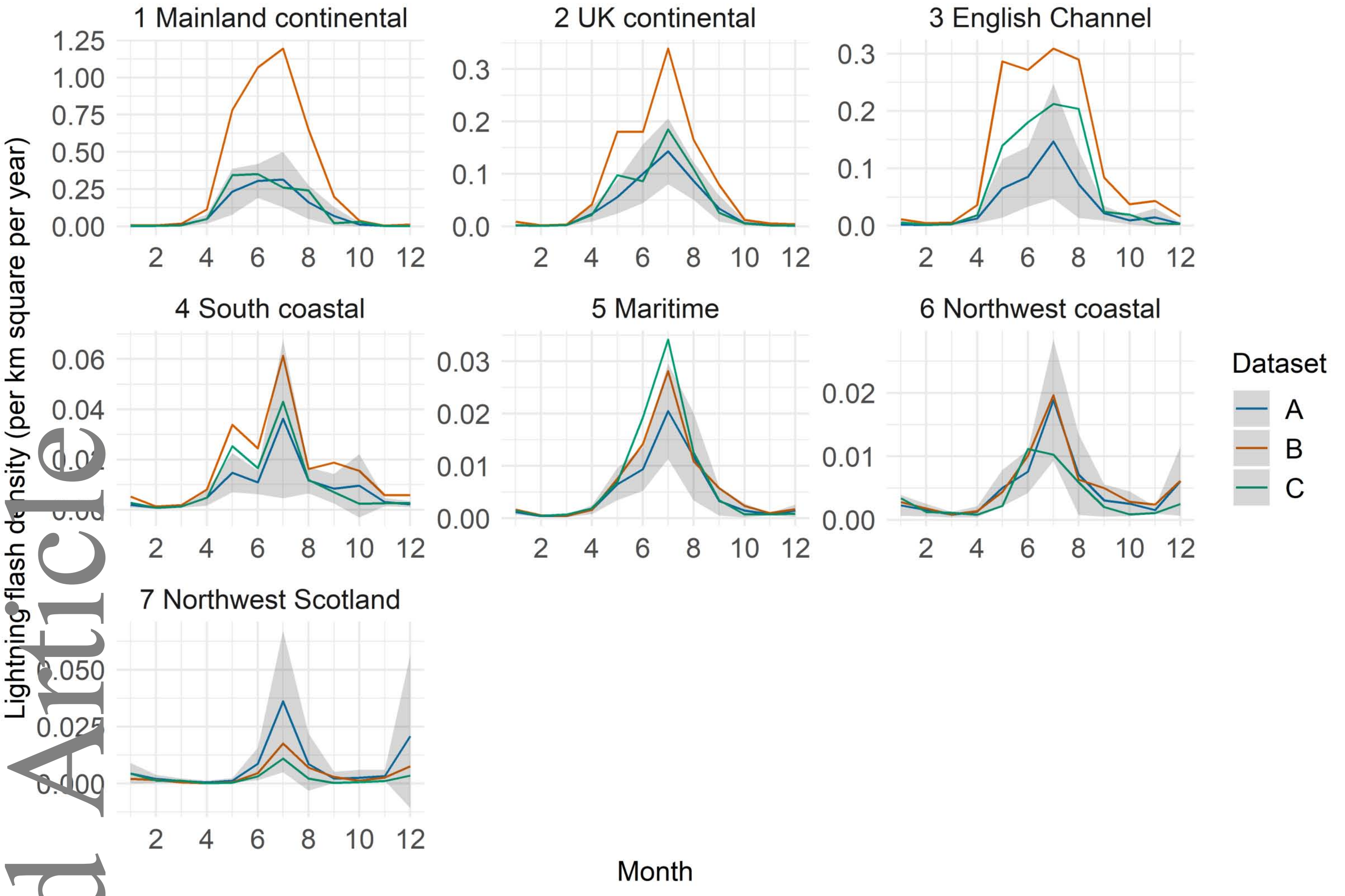

a)
Dataset A:
flash density
62°N
58°N
54°N
50°N
0.02 0.04 0.05 0.05 0.06 0.07 0.10 0.13 0.19 0.29 0.45 0.70 1.12 1.80 2.91
b)
flashes per thunderstorm day
8 10 11 13 14 16 19 23 28 35 44 56 73 95 125
Dataset B:
flash density
62°N
58°N
54°N
50°N
0.005 0.010 0.012 0.021 0.051 0.070 0.087 0.104 0.136 0.192 0.306 0.901 1.862 11.522 12.869
d)
flashes per thunderstorm day
13 17 20 22 25 29 36 45 60 81 113 161 232 338 495
e)
Dataset C:
flash density
62°N
58°N
54°N
50°N
12°W
8°W
4°W
0°
0.015 0.023 0.027 0.034 0.046 0.067 0.101 0.157 0.252 0.411 0.676 1.120 1.861 3.101 5.174
f)
flashes per thunderstorm day
12°W
8°W
4°W
0°
8 10 12 15 18 21 23 28 31 37 45 57 74 96 200


Dataset A
Dataset B
Dataset C
N
W
E
S
62°N
58°N
54°N
50°N
8°W
4°W
0°
0 - 3
4 - 6
7 - 9
10 - 12
13 - 15
16 - 18
19 - 21
22 - 24
25 - 27
28 - 30
28 - 39
1 - 3

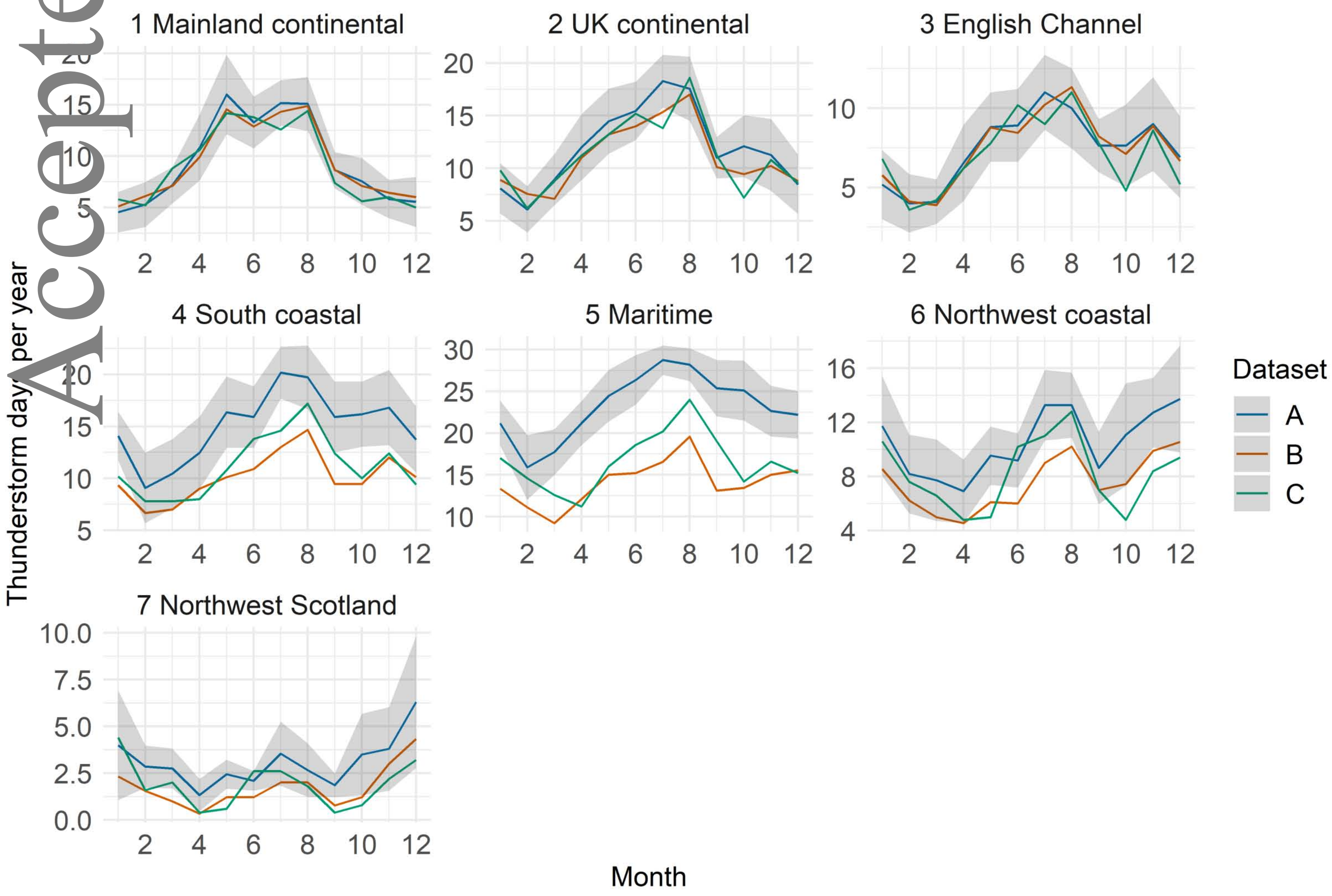

a) Annual
0.12
0.08
0.04
0.00
1
2
3
4
5
6
7
8
9
10
11
12
Month
b) Diurnal
0.03
0.02
0.01
0
2
4
6
8
10
12
14
16
18
20
22
24
Hour
Lightning flash density (per km squared per year)
Dataset
A
B
C


62°N
58°N
54°N
50°N
12°W
8°W
4°W
0°
Mainland continental (1)
UK continental (2)
English Channel (3)
South coastal (4)
Maritime (5)
Northwest coastal (6)
Northwest Scotland (7)

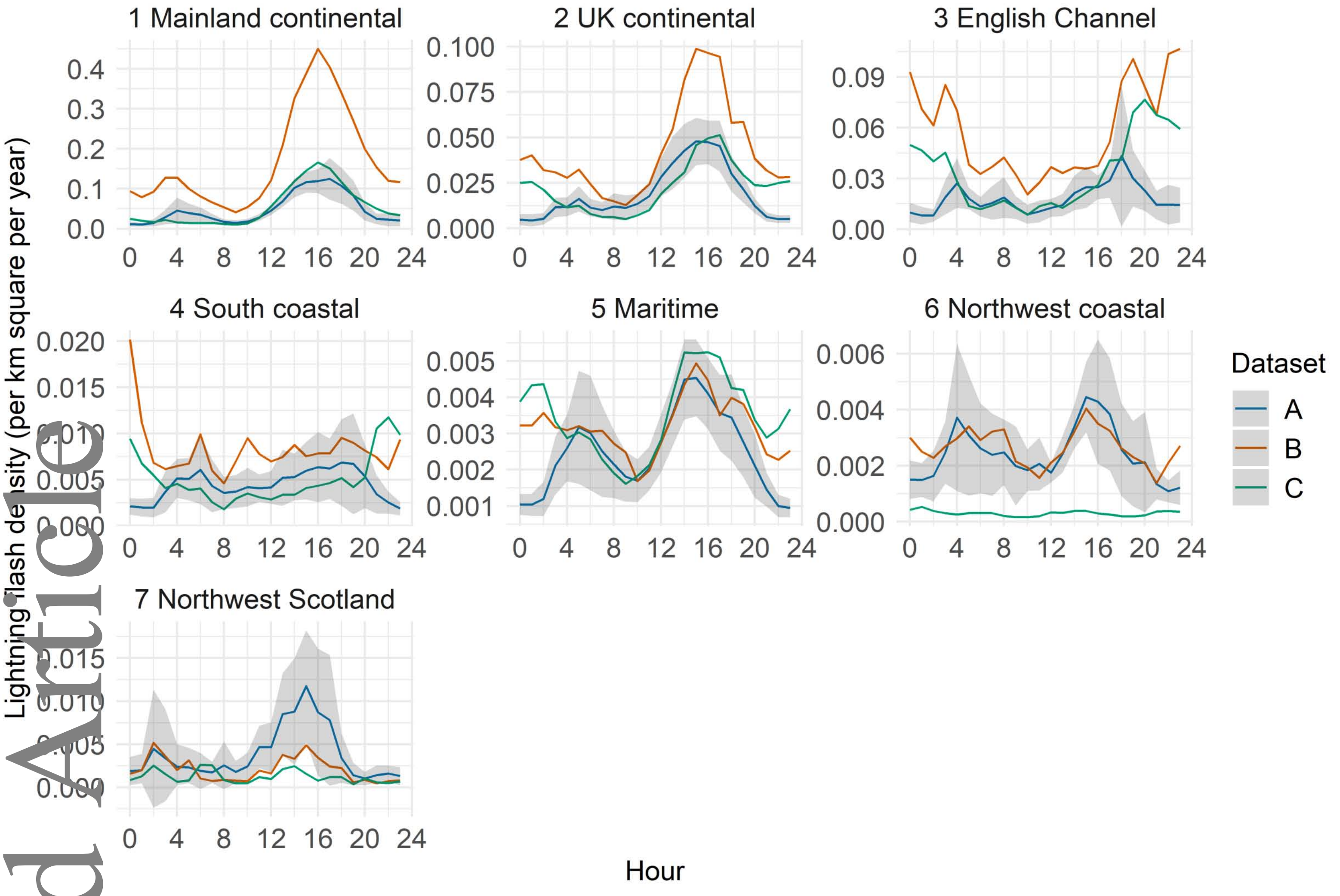
a) Lightning flash density



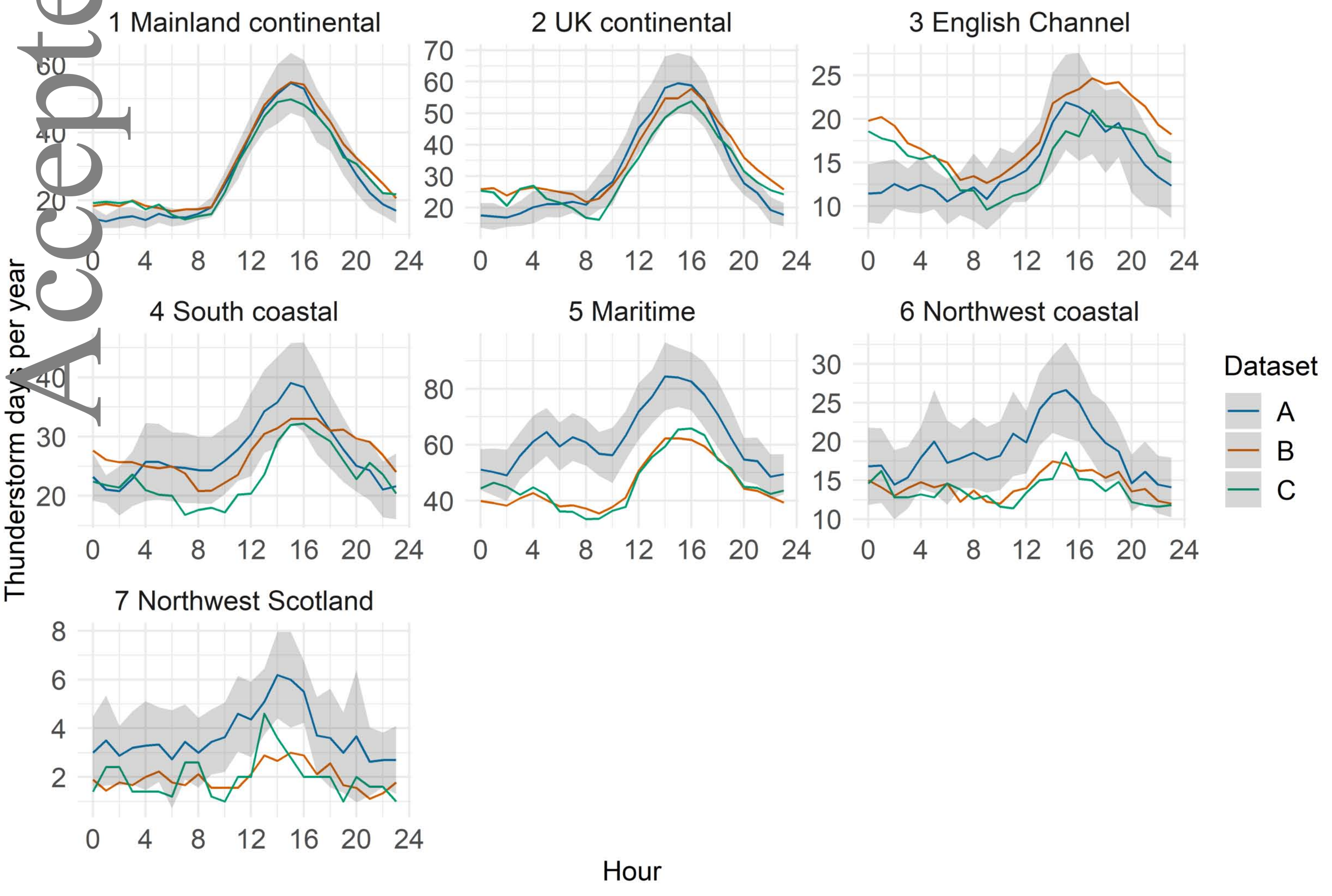
b) Thunderstorm days

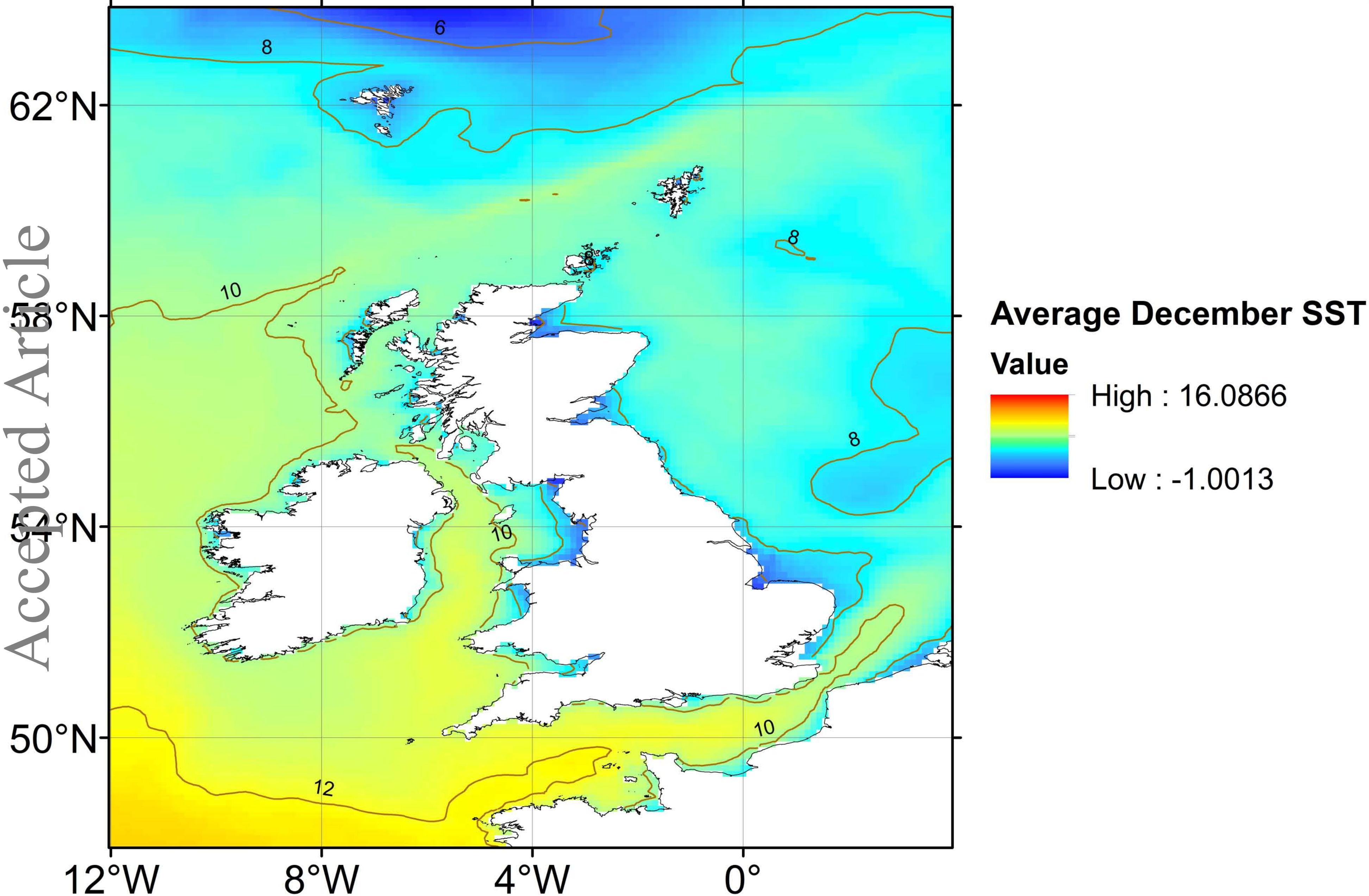


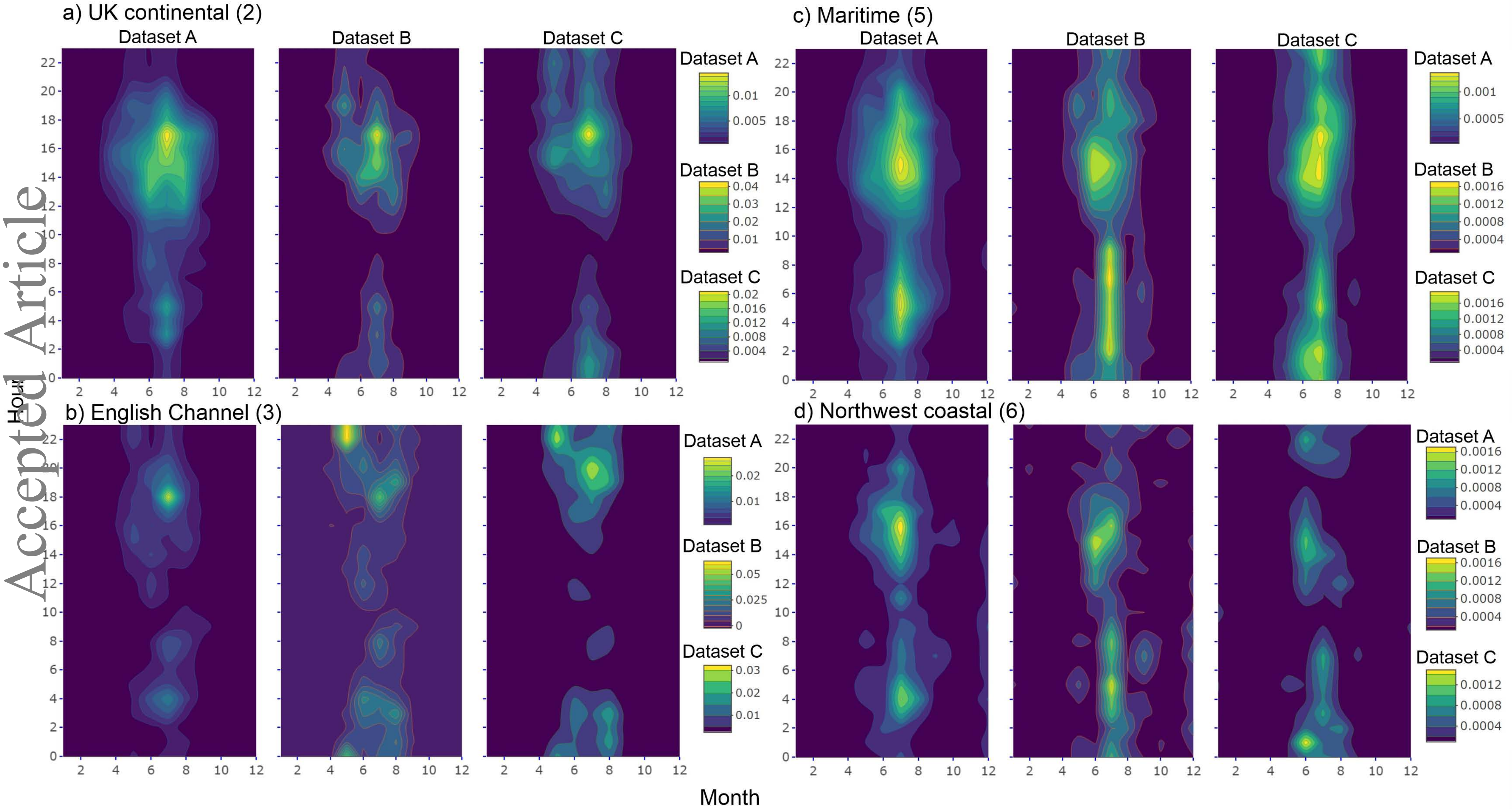
a) Lightning flash density

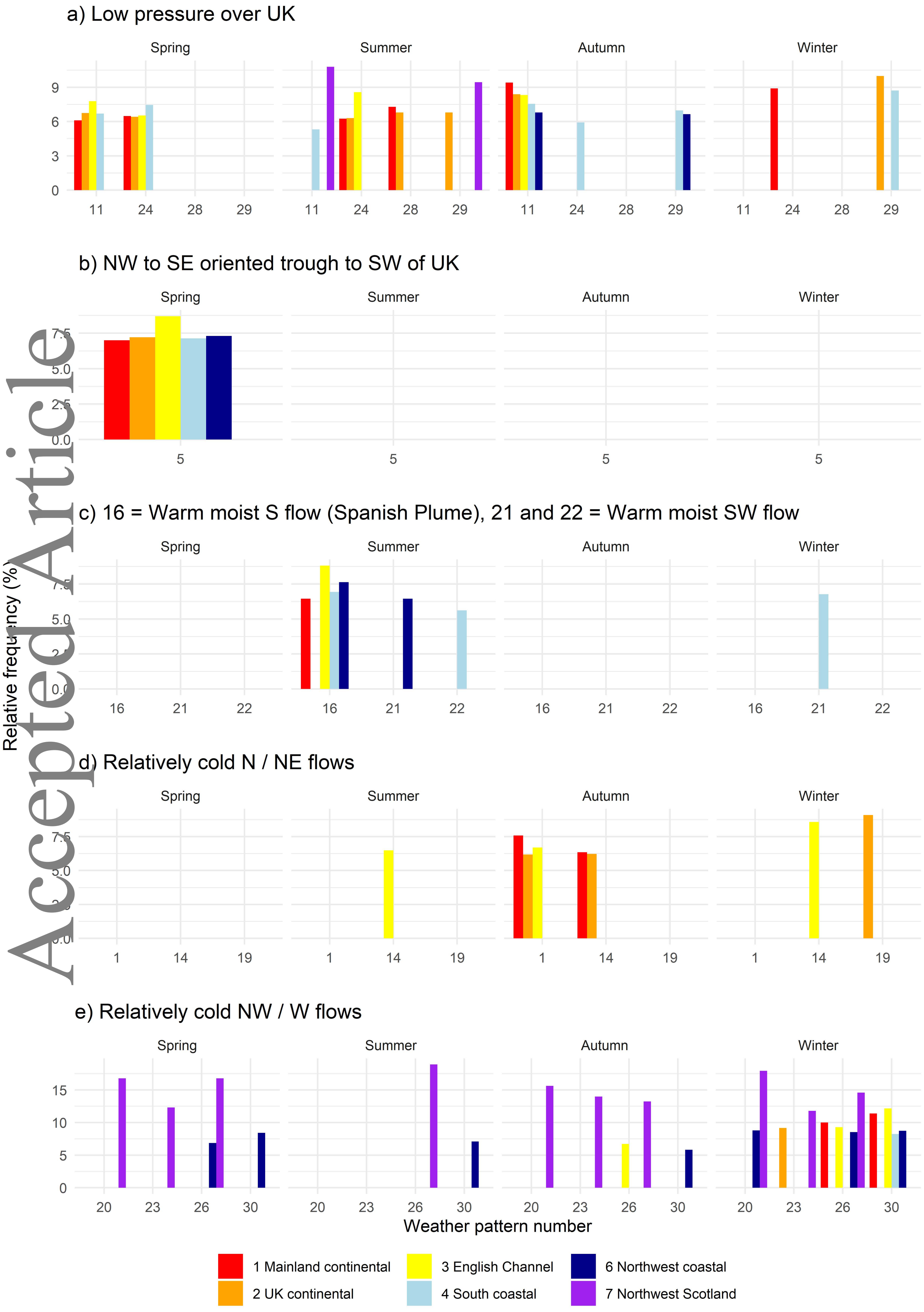


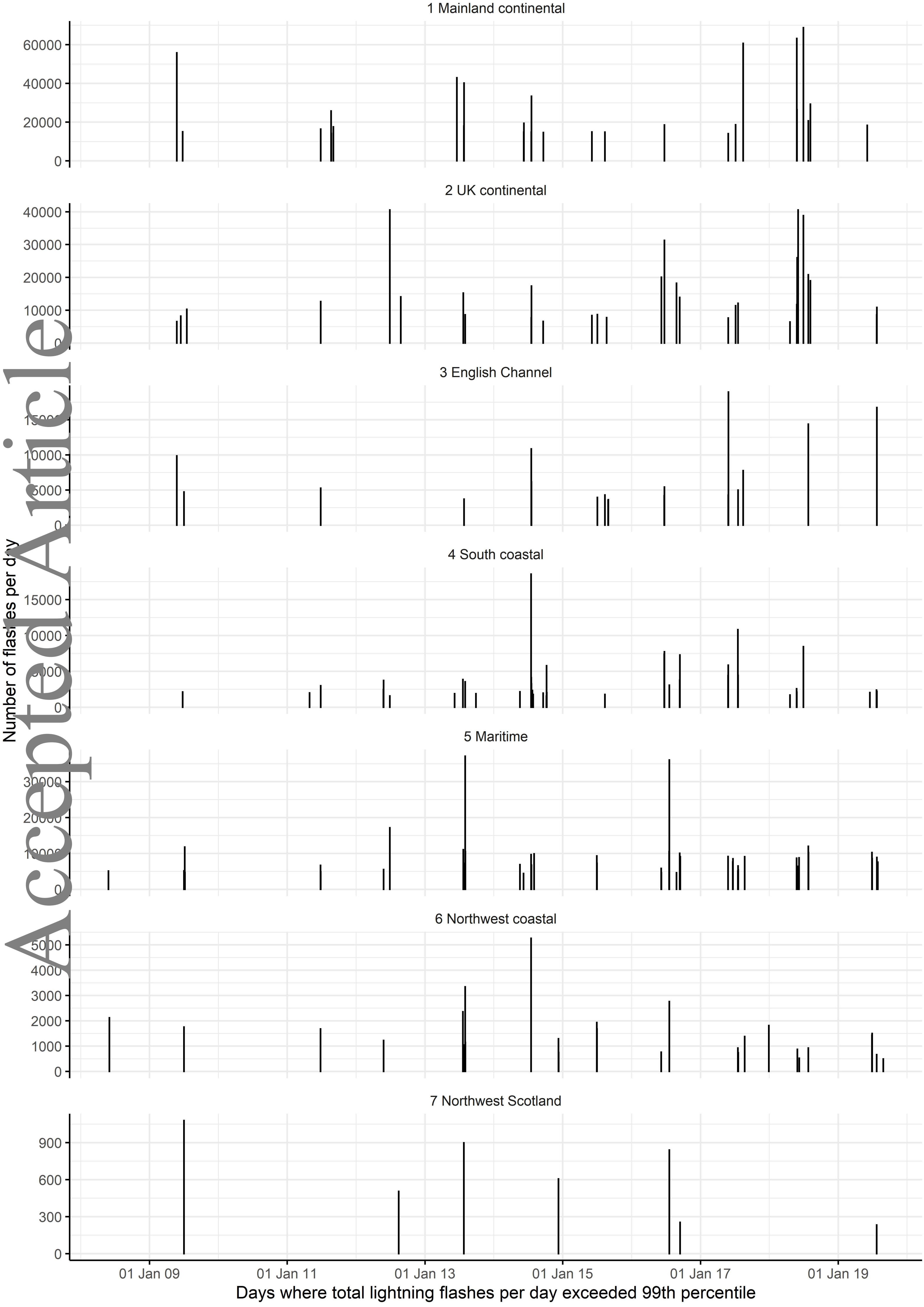
b) Thunderstorm days

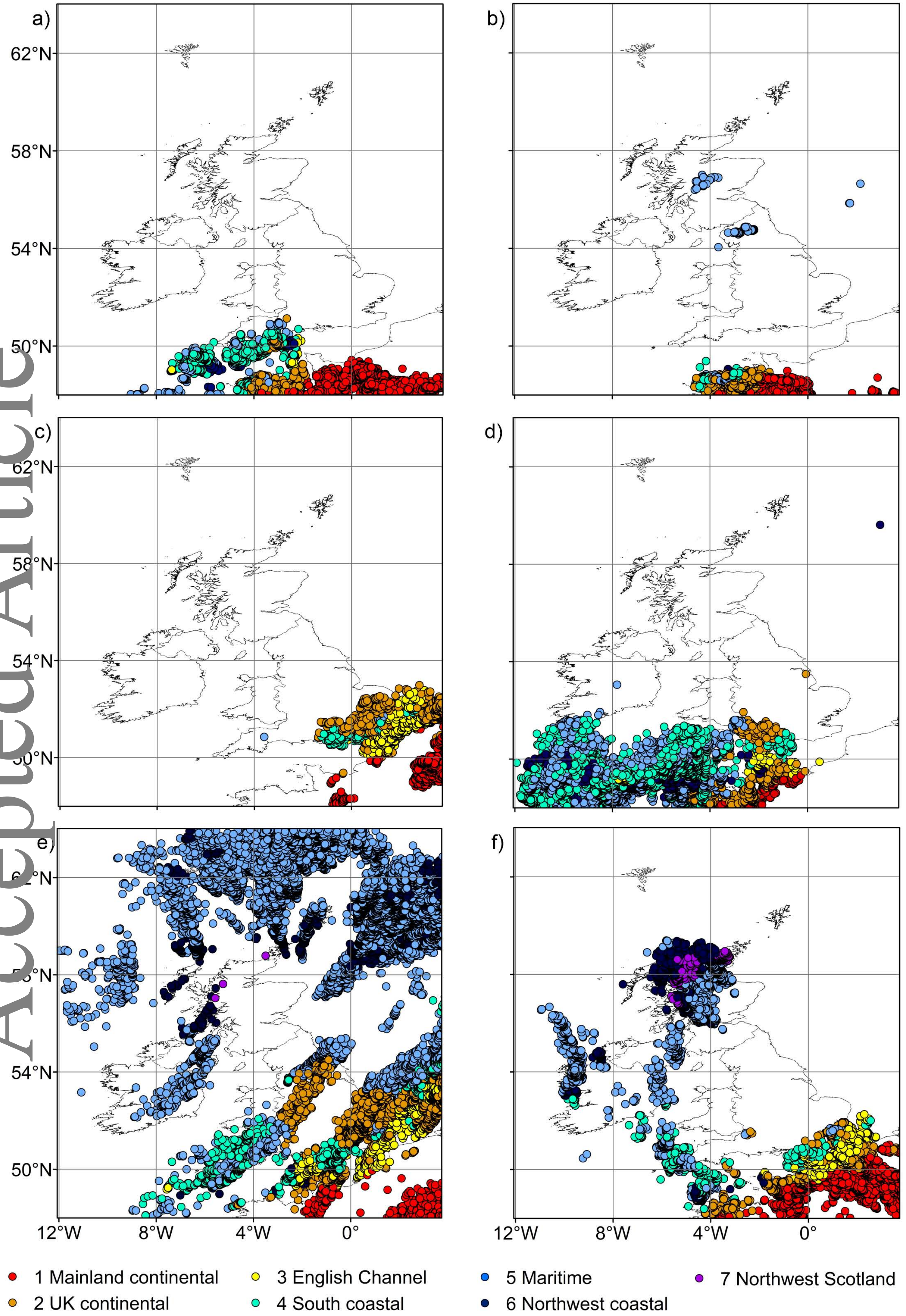



6
8
62°N
8
10
58°N
8
54°N
10
10
50°N
12
12°W
8°W
4°W
0°
Average December SST
Value
High : 16.0866
Low : -1.0013


a) UK continental (2)
Dataset A
Dataset B
Dataset C
c) Maritime (5)
Dataset A
Dataset B
Dataset C
b) English Channel (3)
d) Northwest coastal (6)
Hour
Month
0
2
4
6
8
10
12
14
16
18
20
22
2
4
6
8
10
12
Dataset A
0.01
0.005
Dataset B
0.04
0.03
0.02
0.01
Dataset C
0.02
0.016
0.012
0.008
0.004
Dataset A
0.001
0.0005
Dataset B
0.0016
0.0012
0.0008
0.0004
Dataset C
0.0016
0.0012
0.0008
0.0004
Dataset A
0.02
0.01
Dataset B
0.05
0.025
0
Dataset C
0.03
0.02
0.01
Dataset A
0.0016
0.0012
0.0008
0.0004
Dataset B
0.0016
0.0012
0.0008
0.0004
Dataset C
0.0012
0.0008
0.0004


a) Low pressure over UK
Spring
Summer
Autumn
Winter
0
3
6
9
11
24
28
29
b) NW to SE oriented trough to SW of UK
Spring
Summer
Autumn
Winter
0.0
2.5
5.0
7.5
5
c) 16 = Warm moist S flow (Spanish Plume), 21 and 22 = Warm moist SW flow
Spring
Summer
Autumn
Winter
0.0
2.5
5.0
7.5
16
21
22
d) Relatively cold N / NE flows
Spring
Summer
Autumn
Winter
0.0
2.5
5.0
7.5
1
14
19
e) Relatively cold NW / W flows
Spring
Summer
Autumn
Winter
0
5
10
15
20
23
26
30
Relative frequency (%)
Weather pattern number
1 Mainland continental
2 UK continental
3 English Channel
4 South coastal
6 Northwest coastal
7 Northwest Scotland


1 Mainland continental
0
20000
40000
60000
2 UK continental
0
10000
20000
30000
40000
3 English Channel
0
5000
10000
15000
4 South coastal
0
5000
10000
15000
5 Maritime
0
10000
20000
30000
6 Northwest coastal
0
1000
2000
3000
4000
5000
7 Northwest Scotland
0
300
600
900
01 Jan 09
01 Jan 11
01 Jan 13
01 Jan 15
01 Jan 17
01 Jan 19
Number of flashes per day
Days where total lightning flashes per day exceeded 99th percentile


a)
b)
c)
d)
e)
f)
62°N
58°N
54°N
50°N
12°W
8°W
4°W
0°
1 Mainland continental
2 UK continental
3 English Channel
4 South coastal
5 Maritime
6 Northwest coastal
7 Northwest Scotland