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Contrasting future lightning stories across Europe

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Abstract

Thunderstorms are the most common source of hazardous weather at local scales, but are poorly represented in conventional climate models, resulting in high uncertainty in future changes. How these changes manifest in terms of lightning is even more uncertain, with previous studies giving conflicting projections. Here, for the first time, we use a km-scale model that explicitly resolves convection across Europe; suggesting more convection by 2100 under RCP8.5. Our ice-based lightning scheme indicates a highly altered lightning climatology-the consequence of general increases in instability, partly limited by convective inhibition, along with huge increases in melting level height and less cloud ice. A northward shift in favourable weather regimes increases lightning frequency at higher latitudes, and favours more thunderstorms over the Alps, but lightning decreases over lower terrain elsewhere and over the sea. Our results suggest the need to re-evaluate lightning risk to wildfires, properties, and human life across Europe.

1. Introduction

A warmer earth might intuitively suggest an increase in lightning, with thunderstorms occurring more frequently at higher temperatures. This makes sense as higher temperatures increase evaporation rates and thus atmospheric moisture, and higher latent instability when the vertical temperature profile is suitable. Yet, thunderstorms also need a trigger: a mechanism to lift the moist- and less dense-air parcel to its critical level (level of free convection (LFC) (Johns and Doswell III 1992). Convection is highly sensitive to variations in low level moisture and uncertainties in temperature profiles, but the location, timing, and even existence of this third ingredient (triggering) depends on many smaller-scale factors such as local winds, topography, spatial distribution of moisture and temperature, and pre-existing outflows from nearby convection cells. This makes it difficult to successfully represent thunderstorms in any weather or climate model. However, very high resolution convection-permitting climate models (CPMs, with km-scale grid spacing) explicitly resolve some of these processes and much better simulate convection and individual extreme rainfall events (Chan *et al* 2014, Kendon *et al* 2014).

As coarser-resolution climate models rely on parameterization schemes to represent small-scale processes, future changes in thunderstorms and lightning are typically analysed using environmental conditions. For instance, Rädler *et al* (2019) used a lightning proxy mainly based on lifted index (LI) and relative humidity to analyse the EUROCordex regional ensemble, projecting an increase in lightning frequency across most of Europe but a decrease in parts of the south. Another lightning proxy proposed by Romps *et al* (2014) is the product of convective available potential energy (CAPE) and simulated precipitation rate (CAPExP), projecting increases across the U.S. of $\sim$12% per C. This proxy is in line with the seasonal and diurnal distribution of lightning (Romps *et al* 2018), but less representative in the warm season (Tippett *et al* 2019). Based on this proxy, permafrost areas are projected to experience a summer lightning increase by the end of the century (2081–2100, Chen *et al* 2021). Observations already indicate an increase in Arctic lightning (Holzworth *et al* 2021) and convective storms are projected to triple in frequency and extend to the northernmost regions of Alaska under future climate conditions (Poujol *et al* 2020).

For parts of Germany, CAPExP has been found to be less accurate than an approach considering cloud microphysics: Yair *et al* (2010)'s lightning potential index applied within a CPM (Brisson *et al* 2021). This is perhaps unsurprising since the importance of cloud ice for lightning is evident (e.g. Han *et al* 2021), and CPMs allow the inclusion of key ice-based processes within future lightning predictions. Projected changes in lightning including ice-based processes can be very different from those from CAPE-based proxies. For example, while CAPExP indicated increases, Finney *et al* (2018) found significant decreases in projected lightning using an ice-flux proxy, especially over lower latitudes and parts of the midlatitudes, including most of Europe. Over Africa for a high emissions scenario, Finney *et al* (2020) projected lightning increases of 2% using a CPM. A comparative study (Romps 2019) found robust increases in lightning with climate change for both a CAPE-based and (a modified version of) ice-flux proxy over the US, while changes were not as clear for the tropics.

CPMs with ice-based lightning prediction schemes likely provide the most robust estimates of lightning changes in a warmer climate, yet there are very few studies to date (Finney *et al* 2020, Brisson *et al* 2021).

In this study, for the first time, we use a graupel and ice flux-based scheme applied to a pan-European simulation of the UK Met Office Unified Model (UM) at CPM resolution (2.2 km) to assess future changes in lightning under a high emissions scenario. Our simulation results lie within the range of a 12-member ensemble of UK-focused simulations using the same CPM (supplement figure s1). We evaluate the results by exploring relevant processes, using an ingredients-based methodology motivated by thunderstorm forecasting.

2. Methods

2.1. km pan-European climate simulations

The pan-European climate simulations carried out at the UK Met Office Hadley Centre spanning 10 years for the current (1998–2007) and future (∼2100, under RCP8.5) climate are used. Although RCP8.5 is a high emissions scenario and not considered the most likely, it is still a plausible scenario, which is important for planning purposes. RCP8.5 gives a high signal-to-noise ratio, meaning that it is easier to detect any climate change signal above natural climate variability. This is particularly important for relatively short climate simulations as used here.

A spin-up period of one year for each simulation (prior to 10 years) has been omitted. UK Met Office UM (v10.1) with 2.2 km grid spacing is configured with a rotated-pole grid structure to optimize distances across the European domain, having 1536 × 1536 horizontal grid points with 70 atmospheric levels and four soil levels. For the analysis, 70 grid points from each boundary is removed. The initial and boundary conditions are taken from HadGEM3 global climate change simulations with N512 (approximately 25 km) grid spacing (Mizielinski *et al* 2014). 'ENDGame' dynamical core (Wood *et al* 2014), and Met Office operational UKV model physics (Roberts and Lean 2008) with updated microphysics and planetary boundary layer schemes (Boutle *et al* 2014a, 2014b) are used. All convection is assumed to be explicitly resolved, as no cumulus parameterization is used. For the future simulation, sea surface temperature is derived from 1999–2008 observations, by adding 20 year mean 'delta changes' which are extracted from global coupled model simulations for 1990–2010 and 2090–2110. Detailed configuration information and the success of simulation suite in representing extremes can be found in the literature (Berthou *et al* 2020, Chan *et al* 2020).

2.2. McCaul lightning scheme

The McCaul lightning scheme (McCaul *et al* 2009) is an ice flux-based scheme, which takes the flux of ice at the −15 °C isotherm and total ice in the column of the atmosphere into account. The total lightning flash rate in a horizontal grid is assumed to be 95% due to the mixed-phase region of the thunderstorm cloud (r_1), and 5% due to larger, widespread production of lightning (r_2), so these are weighted as:

$$\text{Total flash rate} = 0.95\, r_1 + 0.05\, r_2$$

Here, r_1 is a function of upward flux of graupel at the −15 °C level:

$$r_1 = 0.042\, w q_g[-15\,^\circ\mathrm{C}]$$

where w is the vertical velocity and q_g is the graupel mixing ratio at the mentioned isotherm level;

and r_2 is a function of the sum of graupel water path and total ice water paths:

$$r_2 = 0.2\,(\mathrm{GWP} + \mathrm{TIWP})$$

where TIWP includes all forms of ice except graupel. The GWP and TIWP are calculated on all 70 vertical levels. Overall, all cloud ice (including graupel) is considered for total flash rate calculations.

Integrated within the UM, the scheme successfully produces the lightning distribution for the UK (Wilkinson 2017), Africa (Finney *et al* 2020), and the world (Field *et al* 2018). On the other hand, Fierro *et al* (2013) suggested that the McCaul scheme produced lightning for a wintertime storm case which was not observed (based on their figure 14). An issue was found with the time units in the lightning code, such that units of minutes were used instead of 5 min; which resulted in an approximate 5× overestimation of lightning. This is addressed here by dividing all the results by 5. Another minor bug, which cannot so straightforwardly be resolved is in the graupel units for the first equation, with a net effect of overestimated lightning counts for some instances. Despite these issues, the overall results are very similar to the corrected ones in case studies, in terms of lightning areas per storm and peak values.

2.3. ATDNet data

Met Office long-range very low-frequency lightning location system, arrival time difference network (ATDnet, Anderson and Klugmann 2014) detects electromagnetic fields produced by lightning, and using the time difference information from multiple antennas, estimates the location and time of every flash. ATDnet system mainly records cloud-to-ground lightning, rather than intra-cloud occurrences (Enno *et al* 2016). ATDnet suffers from interference due to the height of the ionosphere, and so periods of nocturnal lightning are not detected (Bennett *et al* 2011).

The ATDNet data used is for the last 10 years (2012–2021), which is aimed to cover the recent years, in order to have a representing distribution, with observational network to be stable, without major upgrades during operations.

Based on the analyses of the ATDNet data and another global dataset, World Wide Lightning Location Network, lightning in Europe mostly occurs in the summer, but peaks around the Mediterranean Sea in autumn (Anderson and Klugmann 2014, Enno *et al* 2020, Kaplan and Lau 2021). The highest observed density (7.8 flashes per km^2 per year) is observed around the Alps (Enno *et al* 2020). The frequency decreases gradually towards the north, with minimum values in Scandinavia and the British Isles (Enno *et al* 2020).

2.4. Significance test

Using the bootstrapping method, 1000 resamples of lightning counts for current and future seasons are produced for each grid point. Future changes are calculated for each 1000 resample, with their corresponding counterpart. Then, the changes are sorted and if 5th to 95th percentile confidence interval overlaps zero, the change is assessed as not significant at the 10% level. Grid points with insignificant signals based on this approach are masked in white. Similar process is performed for ATDNet observations vs control simulation, to assess model biases.

2.5. Calculating UC and PUC case ratios

The main approach is to look for changes in deep moist convection frequency—which is affected by changes in thermodynamics as well as circulation and weather regimes—and favourable microphysics (ice and graupel content) for lightning.

The 'unstable case' (UC) proxy assumes the atmosphere is unstable when the LI value is −2 K or less. As the availability of vertical levels with 3 h intervals is limited, we prefer using LI instead of CAPE, which is comparable (e.g. Púčik *et al* 2017, Rädler *et al* 2019). Especially Púčik *et al* (2017) shows a good agreement between MLCAPE and LI for European environments. Here, the LI is calculated as follows:

The availability of the 3D atmospheric data from the climate model output with 3-hour intervals is on 6 pressure levels; 925 hPa, 850 hPa, 700 hPa, 500 hPa, 300 hPa, and 200 hPa. Equivalent potential temperature (ThetaE) is calculated using temperature and specific humidity data for these pressure levels, with 3 h intervals during the 10 years of current and 10 years of future simulation data on each grid point. Then, for each instance, ThetaE of the lowest three levels are subtracted from that of 500 hPa level. Within these three values, the lowest one is considered as the LI value, such that the most unstable parcel in the lower atmosphere is represented. For grids with higher altitude, hence, missing data for lower pressure levels, only the available level(s) are processed.

The 'precipitating unstable case' (PUC) is aimed to be a proxy for deep, moist convection, and is a subset of UC, such that UCs with simulated precipitation equal to or more than 1.0 mm in the upcoming hour (analysis with 0.1 mm threshold gives similar results). One limitation of this approach is that some PUCs may not be associated with convective precipitation, but could be of stratiform nature. Additionally, some convective storms will not be captured, as the UC could cause precipitation in an adjacent grid cell rather than at the same point; or later within the 3 h time frame not sampled. However, despite these limitations, it is still possible to draw broad conclusions of changes to convective activity and unstable environments with respect to warming, when a decade-long simulation is used.

UC and PUC case ratios refer to the percentages of UC and PUC on all times during the simulations respectively; i.e. 10 years × 360 d × 8 data times per day = 28 800 data times for current simulation, and 28 800 data times for the future simulation. The case ratios are simply the fraction of the number of cases per 28 800 data times.

3. Lightning climatology of Europe and its future change

Based on both ATDNet observations from 2012–2021 and the pan-European 2.2 km simulations (1998–2007), all of Europe is prone to thunderstorms (figure 1). The peak season for land areas is summer, whilst the Mediterranean Sea and adjacent coastal zones have a peak in autumn. Northern

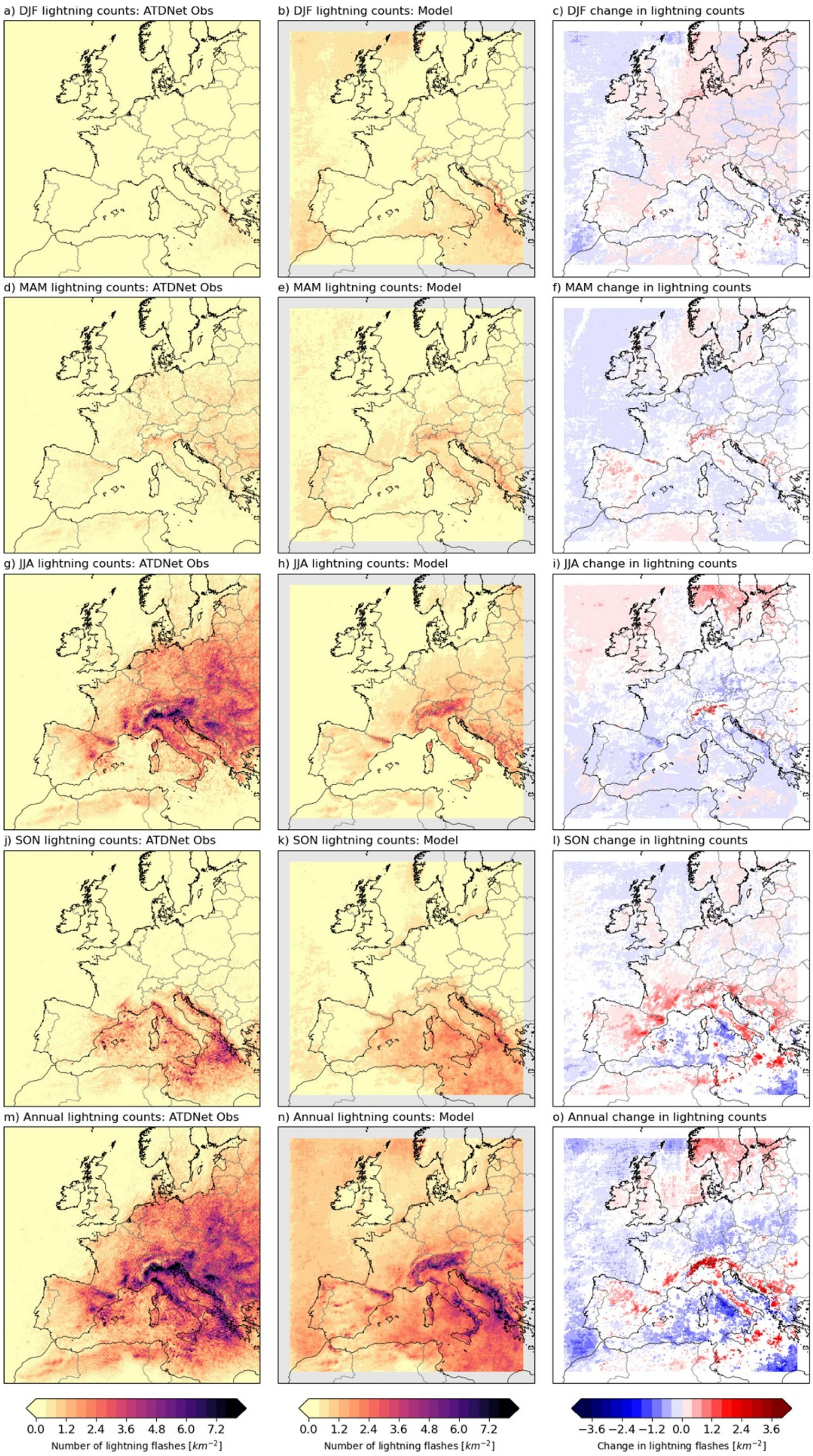

Figure 1. Average (a) lightning counts based on ATDNet observations between 2012 and 2021, (b) lightning counts based on the control simulation for 1998–2007, (c) change in lightning counts in the RCP8.5 future climate simulation (10 years corresponding to ∼2100) for December, January, and February, (d)–(f) same as (a)–(c), but for March, April, and May; (g)–(i) same as (a)–(c), but for June, July, and August; (j)–(l) same as (a)–(c), but for September, October, and November; (m)–(o) same as (a)–(c), but for whole year. Future changes are masked in white, where results are not significant at the 10% level, based on 1000 bootstraps.

landmasses have the lowest lightning density and lightning days. The overall lightning occurrence is reasonably well simulated both in terms of the seasonal cycle and spatial distribution, but there are differences particularly in land/sea contrast (supplement figure S2). There is evidence of a bias over land in summer, with the model underestimating lightning counts. These differences may be a result of model representation, or to a lesser extent, observational errors, or natural variability, as the best lightning observations are from 2012 to 2021, yet the CPM control simulation is for 1998–2007. A limitation with the ATDNet observations is that it primarily measures cloud-to-ground lightning, with cloud-to-cloud strikes having weaker signals.

Global warming brings a very complex pattern of change in lightning density across Europe (figure 1). While there is a net increase in lightning counts over southern parts of the Nordic countries, the British Isles and parts of the Atlantic Ocean further west, lightning counts decrease over most of Europe (except for higher terrain, especially in the south). The summer increase in lightning in the north and decrease in central Europe suggests a circulation regime shift. This is consistent with analysis of lightning changes across a 12-member ensemble (UKCP Local) with the same CPM and resolution over the UK (supplement figure S1). Some individual UKCP Local realisations suggest different outcomes (even of opposite sign), likely relating to differences in circulation changes. Other recent research also projects increased lightning at high latitudes, such as the Arctic circle (Chen *et al* 2021, Holzworth *et al* 2021), and Alaska (Poujol *et al* 2020), even with CAPE-based proxies, since instability changes are the primary driver of increases.

Changes in lightning counts in winter and spring across Europe are more limited. A local hotspot of december, january, february (DJF) change is the North Sea. The highest increases are found near to and over southwest Norway and Denmark, which experience very little lightning currently. In spring, there is no strong signal in lightning except for small increases over mountainous regions in southern Europe.

4. Physical drivers of lightning changes

Lightning occurrence requires: (a) deep, moist convection, and (b) sufficient graupel and cloud ice within the convective updraft. Deep moist convection requires three 'ingredients': instability, moisture, and lift. Here we explore these ingredients to understand the physical drivers of lightning changes. We use LI values of -2 K or less to indicate 'unstable cases' (UCs), identifying the co-existence of instability and moisture. Then we add another parameter, the existence of precipitation >1.0 mm in the upcoming hour when there is a UC, identifying a 'precipitating unstable case' (PUC). For a PUC, it is assumed that convection is realised, i.e. the third ingredient, lift, is satisfied. Overall, PUC is used as a proxy for deep, moist convection.

Where deep, moist convection exists, microphysics determines the efficiency of lightning production. Graupel amount is closely tied to lightning density, giving very similar changes (supplement figure S3). However, here we include the changes to microphysics by focusing on change to mean cloud ice. This is a more fundamental measure, which is more directly linked to the large-scale thermodynamic changes, including increases in melting level height (MLH). Graupel is additionally affected by the frequency of convective storms, and so does not purely measure the microphysical component.

For each region, we interpret changes in PUC as changes in convective storm frequency, changes in UC as combined changes in moisture and instability, UC/PUC as the role of convective inhibition (CIN), and MLH, as well as mean cloud ice, as microphysical changes stemming from warming.

We find decreases in lightning counts across most of Europe (especially in summer, figure 1) are accompanied by a pronounced reduction in mean cloud ice (figure 2), resulting in fewer lightning strikes per thunderstorm. Less cloud ice means fewer particles to collide and less electrification. This reduction in lightning counts is despite a sharp increase in the fraction of UCs. In addition to microphysics changes, this may be explained by a decrease in convective initiation, perhaps due to an increase in CIN. As convective initiation is the most uncertain element in thunderstorm formation, projected increases in UC should not be seen as direct evidence of increases in thunderstorm frequency.

In the autumn, a massive (up to 1.5 km) increase in MLH leads to a large reduction in cloud ice, especially over northern and central Europe; meaning that increases in PUCs do not necessarily result in increases in lightning. This MLH increase is also evident in observations, but to a lesser extent (Prein and Heymsfield 2020). Over Southern Europe there are increases in all metrics except mean cloud ice. Here lightning increases over land correlate well with an increased frequency of UCs and PUCs (with only small changes in mean cloud ice). In future, there are a number of episodes of high lightning counts in southern Europe in autumn, associated with dense moist advection from high sea-surface temperatures in the Mediterranean. The land/sea contrast in lightning (and PUC) changes in the south suggests that in the future, diurnal heating and topographical lift will play a bigger role in triggering deep convection, and initiation could be more limited over the sea, perhaps due to enhanced CIN (Chen *et al* 2020).

Winter North Sea increases to both lightning days (supplement figure S4) and density (figure 1) occur with a very modest increase of UCs and PUCs, but a pronounced increase in mean cloud ice. In the spring, Southern European mountains experience increases in lightning, which follow local increases in PUCs (figure 2). In fact, this metric agrees well with lightning counts for southern land areas for all seasons, but is less consistent in the north (where convection is likely shallower, without or with very little lightning).

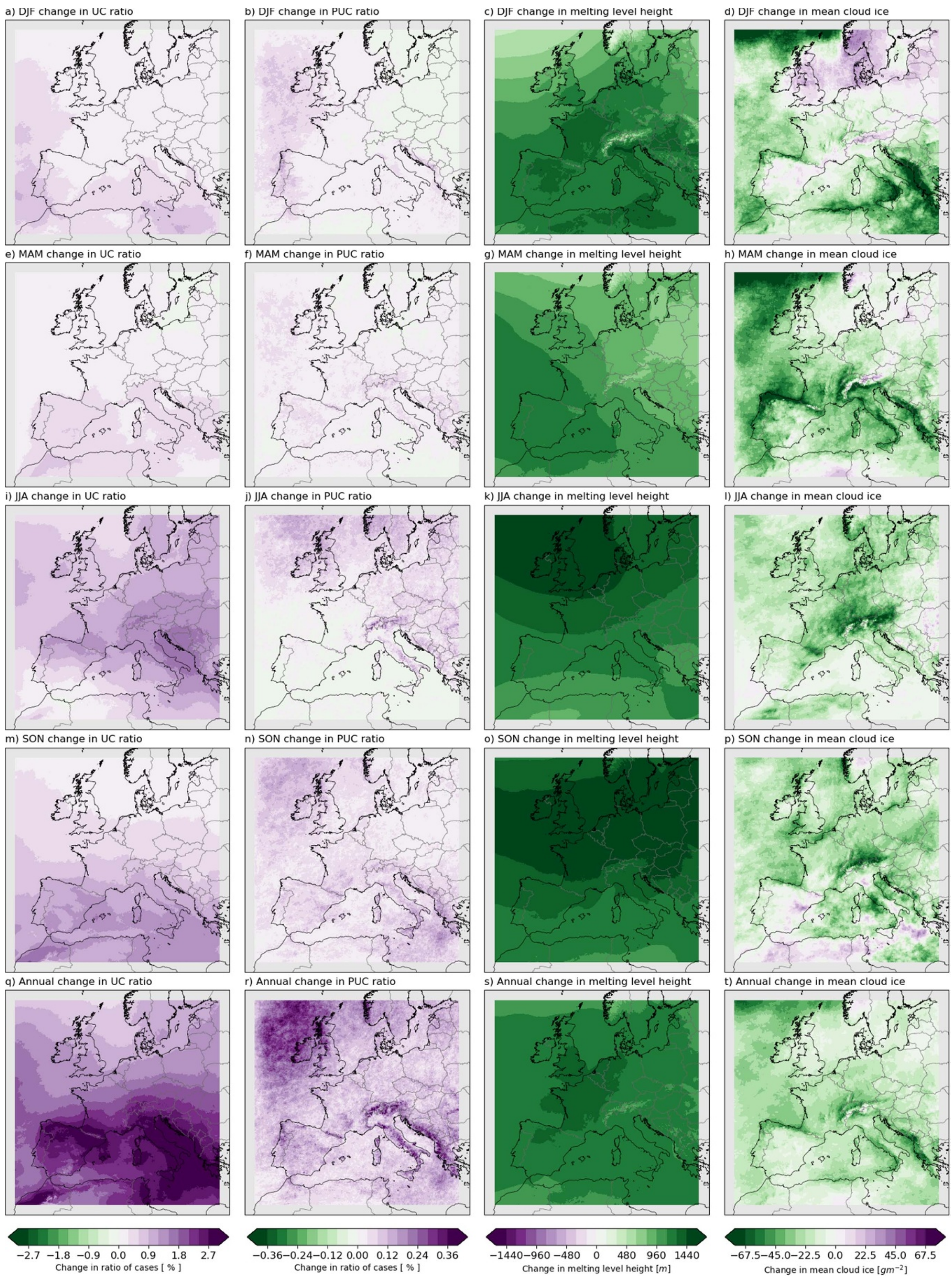

Figure 2. Future changes in (a) unstable case (UC) ratio, (b) precipitating unstable case (PUC) ratio, (c) melting level height, (d) mean cloud ice in December, January, and February; (e)–(h) same as (a)–(d), but for March, April, and May; (a)–(l) same as (a)–(d), but for June, July, and August; (m)–(p) same as (a)–(d), but for September, October, and November; (q)–(t) same as (a)–(d), but for whole year. The changes in unstable and precipitating unstable case ratios are calculated as the change in number of occasions with 3 h intervals over 10 years-long simulations (10 years × 360 d × 8 instances a day).

5. Elevation-based changes

Lightning changes across Europe show a strong relationship with elevation (figure 3). More than three quarters of grid points with 2 km or higher elevation show an annual increase in lightning counts, and more than half of grid points above 3 km show an increase of greater than 25 flashes km^2. In contrast, only a quarter of sea grid points show an increase.

The overall decrease in lightning counts in low-lying regions during the summer (supplement figure S5) may be linked to the Mediterranean warming amplification (Kröner *et al* 2017, Brogli *et al* 2019) or, to a lesser extent, to the widening of the Hadley

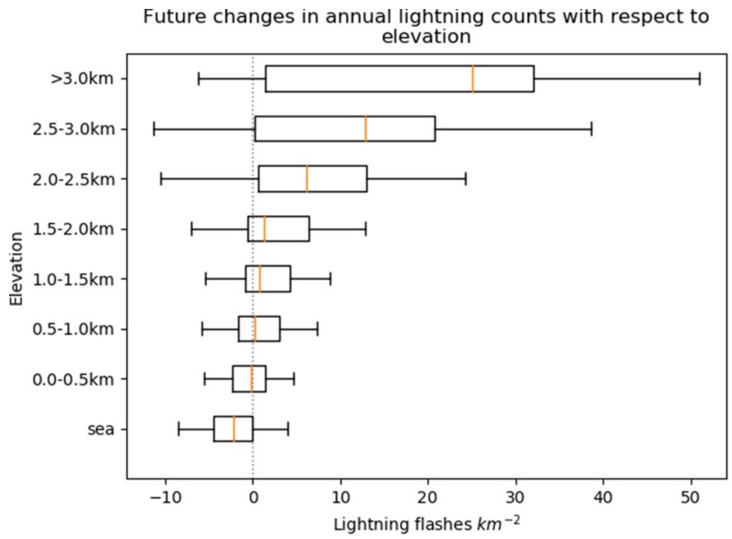

Figure 3. Future changes in annual lightning counts per km^2 for different elevation bins. The boxes span the 25th and 75th percentiles, while the whiskers extend to the 10th and 90th percentiles, for data pooled across all grid points.

Cell (Hu *et al* 2018), resulting in a shifting of midlatitude cyclone tracks towards the north. The weaker large-scale circulation should lead to less thunderstorms (and lightning) over most of the central part of the continent. However, this weaker circulation, combined with increases in solar radiation (with further contributions from elevation-dependent warming differences, e.g. Giorgi *et al* 1997, Kotlarski *et al* 2015, Mountain Research Initiative EDW Working Group 2015), sets very favourable conditions for the Alpine pumping mechanism; the main trigger for thunderstorms over the region. The faster warming of mountain valleys by solar radiation compared to the plains leads to a pressure gradient driving a thermal circulation mechanism (Lugauer and Winkler 2005, Graf *et al* 2016). The result is a convergence zone over the mountain tops in the afternoons, leading to rising motion in the low levels, enhancing the probabilities of convection initiation locally. So, for the same reason, there is an enormous increase in lightning counts over higher terrain in the warm season (supplement figure S5). Indeed, the highest increase occurs over mountain tops surrounded by large valleys (figures 1(f) and (k)). Our finding is consistent with increases in summer convective precipitation over the Alps derived from a 12 km regional ensemble (Giorgi *et al* 2016), and a significant increase in the number of summer convective-like storms observed recently (Dallan *et al* 2022).

Seasonal analysis indicates that wintertime increases over higher terrain are much more limited (supplement figure S5).

6. Latitudinal analysis and regional changes

Lightning changes in Europe indicate an increase towards the north and south over land areas (figure 4). Projected decreases over the sea are less pronounced towards the north, with local increases over the North Sea and the Baltic Sea. Over land, most lower-terrain areas indicate a decrease, except the north and the topographically complex south (where the highest increases are simulated).

6.1. Southern Europe

Changes to the upper tropospheric circulation as a northward shift (future JJA 300 hPa wind speed maxima is projected to be ~300 km northwards compared to present climate) and weakening of the polar jet in summer affects the occurrence of thunderstorms (supplement figures S6 and S7). Although there is a large increase in UC (figure 2), primarily due to much higher available moisture in the future (Kahraman *et al* 2021), this does not result in a similarly large increase in convective storms (figure 2), as the third ingredient, lift, is missing most of the time. In particular, southwest Europe experiences a slight decrease in PUC (figure 2(j)). This could potentially be interpreted as the result of a broader subtropical high in the future; with less frequent jets, which are associated with troughs and driving upper-level divergence zones, and important in terms of sub-synoptic scale upward motion, which favour thunderstorm environments. As a result of the northward shift of the polar jets, some decreases over the Iberian Peninsula and other southern regions (except the mountains) in summer are evident.

In contrast, the Alps and other mountainous regions in the south experience a large increase in lightning counts and thunderstorm activity in summer, due to the Alpine pumping mechanism. Furthermore, there is evidence of an extension of summer conditions, with more convection and lightning in spring and, especially, autumn across Southern Europe. Future autumns feature some

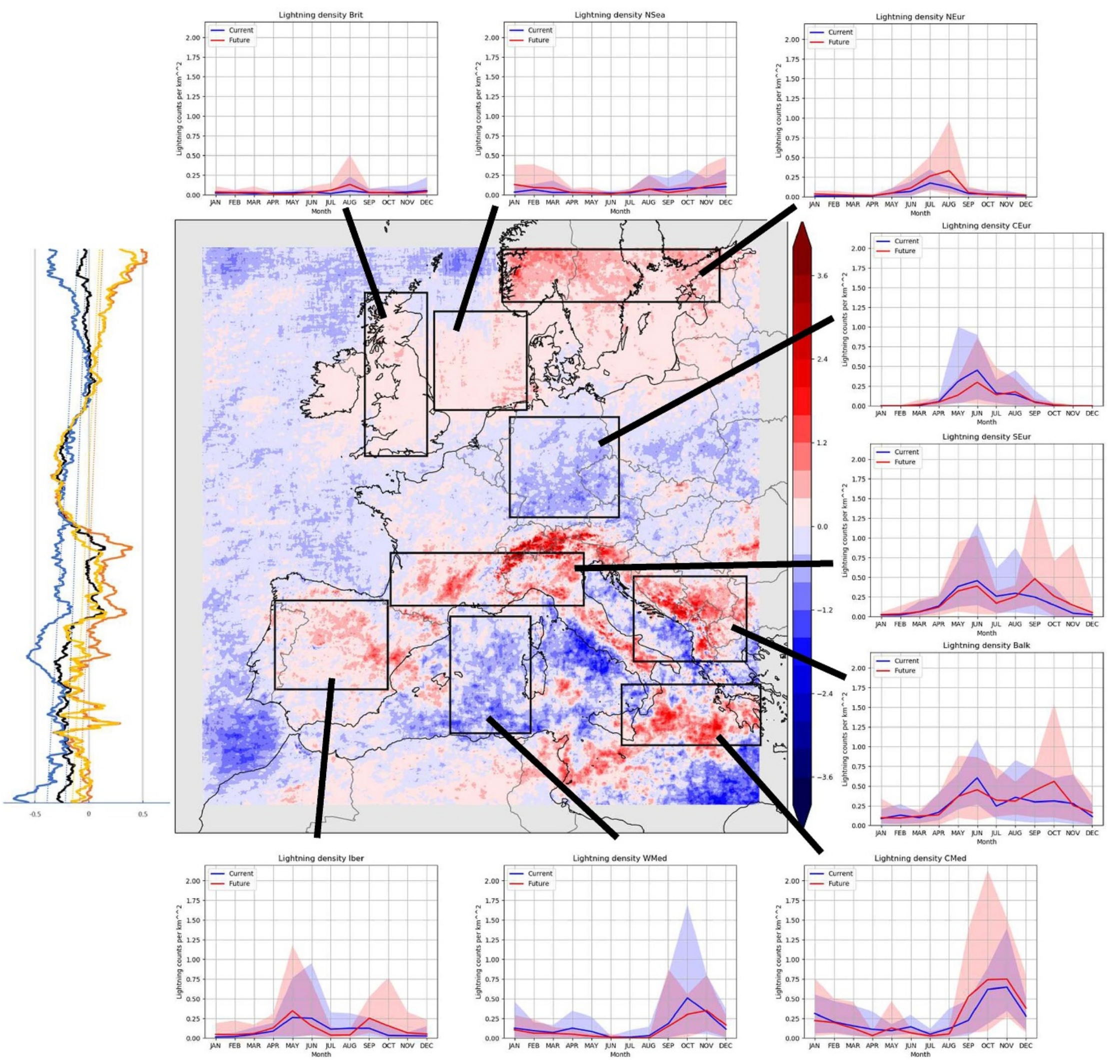

Figure 4. Local changes in lightning density throughout the year. 'Current' refers to 1998–2007, and 'Future' is for ∼2100 under RCP8.5. Latitudinal changes in lightning density for land (orange), land areas between 0 and 500 m altitude (yellow), sea (blue), and all grids (black) are shown on the left. For southern France and northern Italy, the increases in average lightning stem from a few episodes of severe convective storms in one September of the future simulation; if that particular year is excluded, future increase in average September lightning in that region would be 1.47×, compared to 1.95× when included.

extremely severe convection episodes (particularly in one September), presumably from very high sea-surface temperatures in the Mediterranean resulting in plumes of moisture moving towards parts of Southern Europe, while cold air masses aloft are blocked with meandering mid-tropospheric waves (due to the weakening circulation).

To summarize, Southern Europe experiences drier summers with less lightning, but more activity in the autumn.

6.2. Central Europe

A zonal belt of decreasing lightning in Central Europe (from the low countries towards Belarus and Ukraine) is projected, mainly during summer and spring (figure 4), and particularly for May and June. End of century annual lightning counts decrease by up to 1 per km^2 in parts of Southern Germany. This is in line with May and June decreases obtained with the 'lightning potential index' applied to the COSMO CPM, for a section of Germany (Brisson *et al* 2021). In fact, this decrease applies to most of lowland Europe in our simulation, mainly due to less graupel and ice within the clouds, despite increases or little changes in the frequency of PUCs (figure 2). Changes to MLH across Germany and the low countries reach 1.5 km or greater, particularly during July (supplement figure S7), when slightly lower values are valid for the Czech Republic and Poland.

6.3. Northern Europe

In the British Isles, lightning counts are projected to double in July and August; in Scandinavia they increase 2.6×. This increase leads to higher lightning densities in Scandinavia in future August compared to Central Europe in current June (the peak month). The main reason seems to be the increasing frequency of summer thunderstorms in the north, due to the possible northward shift of favourable weather regimes (supplement figure S6). This is despite higher MLH

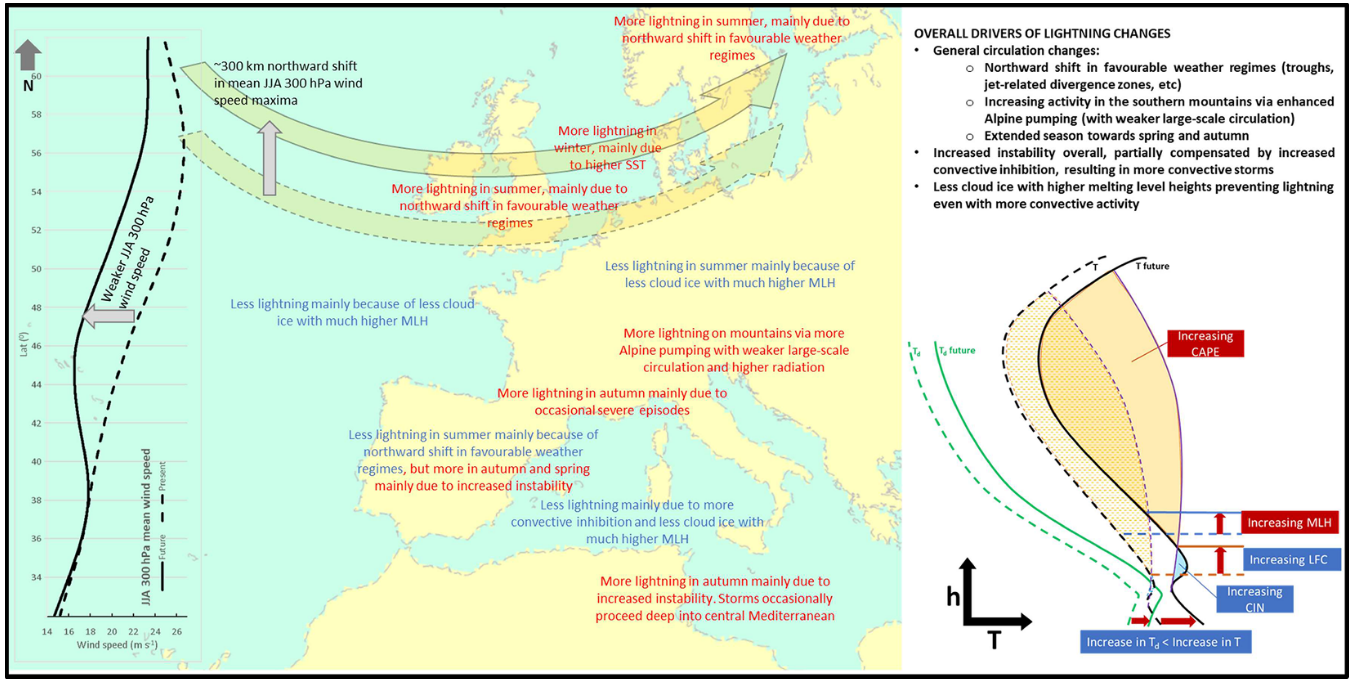

Figure 5. A summary of changes in lightning and their underlying drivers across different parts of Europe under RCP8.5 end-of-century climate. The lower-right sketch illustrates changes in vertical temperature and dew point profiles and importance for convection; 'CAPE' refers to Convective Available Potential Energy, 'CIN' refers to Convection Inhibition, 'MLH' refers to Melting Level Height, 'LFC' refers to Level of Free Convection, 'T' refers to Temperature, and 'T_d' refers to Dew Point Temperature.

and decreasing mean cloud ice in the region. An increase in lightning counts from November to March over the North Sea (figure 4) is also projected. This area has little convection in the present climate. Notably, northern Europe in winter is the only region and season showing a considerable increase in mean cloud ice (figure 2), accompanied by comparably smaller increases in MLH.

6.4. Sea areas surrounding Europe

Lightning density slightly decreases over both the Mediterranean Sea and the Atlantic Ocean. In both, the main contributor is likely lower cloud ice with higher MLH. Lower flash densities in summer over the Mediterranean are due to CIN, with less convection (i.e. PUC) in spite of more frequent instability (increased UC), indicating the importance of triggering for thunderstorm formation. In the autumn, most of the Mediterranean still shows less lightning, while surrounding land areas show an increase. This land/sea contrast might be due to the larger contribution from solar heating or local flows to convective initiation over land in the future (figure 5). Or it could be due to thermodynamical changes in the marine atmospheric boundary layer, such as the higher LFC; thus more CIN to limit the realisation of convection (as detailed in Chen *et al* 2020). Some patches of increases appear near to islands in the western Mediterranean Sea which support this argument. However, a band of increase in the Central Mediterranean autumn is also evident, which seems to be associated with the increase over parts of North Africa.

7. Discussion

To summarize, using the first convection-permitting pan-European simulations, we find no single key driver of changes to lightning but rather a picture of contrasting lightning stories across Europe. Increased moisture with warming leads to increased convective instability. However, this does not come with the same increase in convective storms, due to less convective initiation likely stemming from enhanced CIN. One reason could be circulation changes, i.e. the northward shift in the polar jet with enhancement of the subtropical high. This effect shifts the thunderstorm-feeding weather regimes towards the north, making summertime lightning density much higher in the northern regions, while reducing it in central Europe and low-lying terrain in the south. For high elevation regions, however, weaker large-scale circulation in the south leads to enhanced Alpine-pumping, and consequently more lightning over the mountains. We note, such circulation-driven changes are particularly uncertain, likely explaining different responses in the UKCP members. In terms of lightning changes, microphysical changes are an additional important factor, missing from previous studies using CAPE-based proxies. An enormous increase in MLH leads to decreases in cloud ice, such that even with higher frequencies of convection, less lightning is expected in some regions.

Understanding the underlying drivers of lightning changes allows us to assess their reliability. In particular, decreases due to microphysical changes with warming are expected to be a more robust effect of anthropogenic warming. We note however results here are dependent on the reliability of the large-scale changes inherited from the driving general circulation model (GCM). Also regional simulations driven using a pseudo-global warming method only capture the thermodynamic changes, but not the complex interactions stemming from circulation changes (e.g. Scaff *et al* 2021). Results here suggest these circulation changes, although more uncertain, are likely an important driver of lightning changes in some regions. This should be considered while using these results, as they reflect only one realisation of a possible future climate. Further work to specifically identify the large-scale circulation contribution requires an ensemble of simulations, which are starting to become available through coordinated high-resolution modelling efforts (Hewitt and Lowe 2018, Ban *et al* 2021).

Use of CAPExP, cloud-top height, or similar proxies would not identify most of the decreasing lightning patterns in a warming earth. These proxies will only be representative in regions where microphysical features of storm clouds are important to a lesser extent, and the particular bottle-neck is having a thunderstorm (i.e. polar regions).

We anticipate that the overall patterns of lightning change with more increases in the north and decreases in over central Europe and the Mediterranean are likely to be robust, although the relative magnitude of these changes is uncertain. Also the extension of the lightning season into autumn over Southern Europe, which is primarily driven by thermodynamic factors, is likely to be robust.

Increase over higher terrain might be relatively robust. From an impacts perspective, these results suggest an enhanced risk of wildfire over the mountains and in the north, with relatively less lightning hazards over more populated Central Europe. Offshore wind farms in the North Sea and the Baltic Sea could experience higher lightning risks in the winter, with the opposite in most other sea areas. A re-evaluation of lightning risks on human life and the environment is needed given the new information emerging from convection-permitting simulations, which enable more realistic lightning projections, preferably taking into account the uncertain factors highlighted here.

Data availability statement

The Met Office model data used are under Crown copyright of the UK government, and access may be requested from the Met Office. Due to funder restrictions, the raw model data is currently not publicly available. Derived data can be requested from the corresponding author on reasonable request.

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