Future changes in lightning from the UKCP09 ensemble of regional climate model projections

UKCP09 technical note
Future changes in lightning from the UKCP09 ensemble of regional climate model projections

I Introduction

The latest set of UK Climate Projections (UKCP09) was launched in June 2009. The centrepiece of these consisted of probabilistic projections of changes in a set of key climate variables, expressed as changes in 30-year averages for a set of overlapping periods during the 21st century, relative to a baseline historical period of 1961–1990. Projections were provided for separate ‘High’, ‘Medium’ and ‘Low’ pathways of possible future emissions of greenhouse gases and aerosols. For each emissions scenario, results were provided on a 25 km grid, and also for aggregated river-basin and administrative regions. The projections were derived from a comprehensive methodology involving several ‘perturbed physics ensembles’ of global projections carried out using alternative variants of version 3 the Met Office Hadley Centre climate model (HadCM3). These were designed to sample uncertainties in model parameters controlling the simulation of key physical and biogeochemical processes. The ensembles amounted to more than 300 simulations in all, augmented by projections from an ensemble of 12 alternative climate models developed by international modelling centres. These were converted into probabilistic projections using a suitable statistical framework. This allowed the model projections to be combined with expert assessment of uncertainties in model parameters, and observational constraints on model credibility derived through evaluation against a set of historical climate observations. Finally, the global model results were downscaled to a resolution of 25 km using 11 variants of the current configuration of the Met Office Hadley Centre Regional Climate Model (RCM), derived from HadCM3 (Murphy et al. 2009).

However, it was not possible to produce probabilistic projections for all climate variables of potential interest to users, for a variety of reasons. Therefore, a further set of reports has been produced to summarise the advice that can be given for several additional variables, specifically wind speed, fog, lightning and snow. In all cases, the advice is based on the ensemble of eleven RCM projections* run at 25 km resolution (PPE_RCM), forming part of the wider suite of simulations carried out for UKCP09 (see Section 4 for more details). This report describes projections of the frequency of occurrence of lightning derived from the RCM simulations.

* In the case of wind speed, further development since UKCP09 launch has made it possible to produce probabilistic projections, in addition to the report describing results from the PPE_RCM ensemble. The probabilistic projections are described in a further report (Sexton and Murphy, 2010).
2 Why are we interested in changes in lightning?

Lightning is an electrical discharge which occurs in thunderstorms, usually accompanied by thunder. It occurs in clouds with vigorous convection where enough electrical charge is separated through the movement of cloud droplets and precipitation particles. One main impact of lightning strikes comes from damage to electrical power lines, resulting in supply interruptions, and it is also important in other activities such as explosives handling.

Little previous work has been reported on lightning changes expected as a result of future climate change. Price and Rind (1994b) showed an increase in global lightning activity of about 30%, with indications of an increase in annual mean lightning frequencies over the UK, for an equilibrium model experiment in which the concentration of carbon dioxide was doubled. The report accompanying the UKCIP02 projections (Hulme *et al.* 2002) gave little advice, commenting only that the number of lightning strikes over southwest England was expected to remain about the same (increases in the peak lightning flash rate per convective event being balanced by reductions in the expected number of thunderstorms), and that over Scotland and Northern Ireland little change was simulated in the amount of lightning per thunderstorm. This advice pertained to changes for the 2080s, for the Medium-High emissions scenario.

3 How do we estimate lightning days from model simulations?

Lightning is not a quantity produced directly by the climate model. Instead we use convective available potential energy (CAPE*), which is diagnosed by the model, to calculate lightning offline. Lightning is inferred from CAPE using an empirical algorithm (Price and Rind, 1992) which has been validated against observations (Price and Rind, 1994a), and has been used in Met Office operational weather forecasting. This empirical relationship relates CAPE (J/kg) empirically to lightning flash frequency $F$ (flashes/min) as follows:

$$F = \left(\sqrt{\frac{2 \times \text{CAPE}}{2 \times 14.66}}\right)^{4.5}$$

![Figure 1. The relationship between CAPE and lightning flash rate given by Price and Rind (1992).](image)

* CAPE is the vertically integrated positive buoyancy of an air parcel lifted from an originating level of convection up to a higher level of neutral buoyancy. The model diagnostic is based on a “dilute CAPE” formulation which allows for modification of convecting air parcels by mixing with environmental air (e.g. Zhang, 2009).
Figure 1 shows this relationship graphically. However, this relationship implies that any day with a value of CAPE greater than zero will have a non-zero value of F and, could hence be counted as a day of lightning. However, in our case the CAPE values fed into the above equation represent spatial averages over 25 x 25 km$^2$ regional model grid boxes, whereas we aim to infer lightning occurrences as would be observed at specific locations, as this is what the verifying observations (see Section 6.1) represent. We would not necessarily expect to observe lightning at all locations within such a region when the spatially-averaged value of CAPE is non-zero; therefore we introduce a threshold below which lightning is assumed not to result. This prevents the diagnosis of excessive numbers of lightning days from the model output, compared to observations. Here we do not distinguish the diurnal distribution of lightning, and simply use the maximum value of CAPE output by the model on a given day as an indicator of lightning occurring at any time within a 24 hour period. The value of the threshold in maximum daily CAPE is determined by comparison with observations, as discussed in Section 6.2. Using this threshold value applied to maximum daily CAPE in the model determines whether or not the day is a day of lightning for a typical location within each model grid box.

4 What projections can we give for lightning?

As mentioned in Section 1, the UKCP09 methodology included an ensemble of 11 variants of the Met Office Hadley Centre Regional Climate Model, each sampling different but plausible values for multiple model parameters controlling key surface and atmospheric physical processes. The PPE_RCM ensemble provided downscaling information which was used to convert projections specified at 300 km scale from GCM simulations to a finer resolution of 25 km, hence playing a key role in the probabilistic projections made for UKCP09. It is this ensemble of RCM variants that are used in this report to provide projections of changes in the number of ‘lightning days’.

The 11 PPE_RCM ensemble members were run from 1950 to 2099 under the UKCP09 Medium emissions scenario, using the European domain shown in Figure 3.8 of Murphy et al. (2009). They were driven at the lateral boundaries by time series of atmospheric variables (such as temperature and winds) saved from an ensemble of projections using 11 variants of the Met Office Hadley Centre GCM. Time series of sea surface temperatures and sea-ice extents were also prescribed from the GCM simulations. Each of the 11 variants in the PPE_RCM ensemble was configured from the corresponding variant of the GCM ensemble, using the same representations of atmospheric dynamical and physical processes, including perturbations to model parameters matching those implemented in the relevant driving global projection. Like most global climate models, members of the GCM ensemble simulate the main characteristics of the observed atmospheric circulation with considerable skill; however there are inevitably also biases at regional scales.

The potential advantages of projections from RCMs are that they can capture detailed spatial contrasts not resolved in the global models, particularly those arising from mountains and coastlines, and that they can capture climate variability and extreme events more faithfully, particularly aspects arising from regional-scale processes. However, they also inherit larger scale biases from their driving global simulations. In addition, the way in which lightning is diagnosed from the model is also subject to uncertainties.
Figure 2: Observations of number of days of thunder heard in summer, averaged from 1961 to 1990. Left: 1 km resolution; Right: interpolated onto the RCM 25 km grid (including only model land points).

Figure 3: Number of days on which thunder is heard, averaged over the period 1961–1990, for the four seasons, interpolated onto the RCM 25 km grid.
5 Why can’t we do probabilistic projections of lightning?

CAPE, the specific model diagnostic required for our calculation of lightning frequency, was archived from the 11 PPE_RCM projections discussed above, but not from the larger suite of 300-plus GCM projections used to produce probabilistic projections. It is not possible to provide probabilistic projections without appropriate data from the GCM projections, as the PPE_RCM ensemble in isolation only samples a subset of the range of the known modelling uncertainties which must be accounted for to provide credible probabilities (see also Section 6.3). Even if CAPE had been saved from the GCM projections, the same diagnostic would not necessarily have been available from other international climate models which are included in the probabilistic methodology developed for UKCP09. We use one particular approach in this report (see Section 3), but other plausible methods would need to be considered in any probabilistic calculation.

6 Validation of lightning in the RCM

Before using climate model simulations to estimate future changes in any variable, it is important to validate the model’s historical simulation of that variable, by comparing simulated and observed climatological values for a baseline period – taken here as 1961–1990.

6.1 Observations

Ideally, we would wish to compare the RCM climatology of lightning days with observations of the same quantity. However, although lightning observations are made by the Met Office using the Arrival Time Difference (ATD) method (Holt et al. 2001), no long-term gridded climatology of this data is available. The only related climatology which is available is that of days of thunder heard. This is compiled from the network of observing stations across the UK, based on reports at 09Z of whether or not thunder was heard at any time during the previous day. These observations have been used by the National Climate Information Centre to construct long term monthly-average datasets at 1 km resolution, for the standard baseline period 1961–1990. In order to compare with the RCM simulations, this was first regridded onto the RCM 25 km grid: Figure 2 shows an example of this for summer. Figure 3 shows the interpolated 25 km resolution observations of days of thunder for each season, and demonstrates that summer (JJA) has the most days of lightning and winter (DJF) has the least. The spatial distribution of days of thunder is broadly similar in spring (MAM), summer and autumn (SON), with the maximum number of days in each season occurring in East Anglia or the south east of England and the fewest in the north west of Scotland. The largest values occur in south-east England in summer, however observed climatological frequencies never exceed 10 days per season. In winter, occurrences are slightly larger than elsewhere in parts of south-west England, and in some southern and western coastal areas. In order to use this data for model validation, we have assumed a correspondence between number of days of thunder heard and the number of days of lightning in the same period.
Figure 4. The percentage bias in lightning days for 1961–1990 in the ERA-RCM model simulation for December to February (DJF), March to May (MAM), June to August (JJA), September to November (SON), based on a CAPE threshold of 250 J/kg.
In Section 3, we described how CAPE from the model can be used to determine the frequency of days of lightning, as long as we have an appropriate threshold for daily maximum CAPE, below which lightning is assumed not to occur. In order to obtain the optimum value of this threshold, we compare model simulations of frequency of lightning days with that observed (of thunder) for a range of possible values of the threshold, and choose that value which minimises the difference between model and observed data. To perform this optimisation, we use data from a single run of the RCM driven by 6-hourly global fields from the ECMWF 40 year Reanalysis (ERA – see Uppala et al. (2005) for details). The ERA data provide a widely-used estimate of how the observed atmosphere evolved over the baseline 1961–1990 period. The RCM simulation driven by ERA (hereafter ERA-RCM) therefore allows us to assess uncertainties in how to link a CAPE threshold to a lightning day for comparison with observations. In the ERA-RCM simulation, these uncertainties arise specifically from uncertainties in CAPE introduced by errors in the simulation of regional physical processes in the RCM, plus uncertainties associated with the diagnostic CAPE-lightning relationship (Figure 1) as applied over the UK. In the PPE_RCM ensemble used for the future projections, biases in the large-scale atmospheric circulation of the driving global climate model simulations introduce a further source of error.

Using the ERA-RCM data, the mean number of days of lightning for each season was calculated for the period 1961–1990 with thresholds in maximum daily CAPE ranging from 25 to 650 J/kg at 25 J/kg intervals. In each case the model estimate of lightning frequency was compared to the observed thunder climatology described in the previous section. The bias was calculated as a UK mean value, weighting all land grid points equally. From this comparison we found that the best overall agreement, across all locations and seasons, was obtained using a threshold of 250 J/kg. Recognising that most lightning occurs in summer, we performed the same exercise using only summer modelled and observed data, and obtained the same optimum threshold.

Figure 4 shows the bias between model simulation and observations for each season. It can be seen that while 250 J/kg gives the best results, there is a residual negative bias in the average across all locations and seasons. This residual mean bias could potentially be reduced by further work to fine-tune the CAPE threshold between the 225 and 250 J/kg values that we tested. Figure 4 also shows regional and seasonal variations in the bias. This is not surprising, given that the ERA-RCM run, while provided with a more-or-less correct realisation of the synoptic-scale circulation, will still suffer from biases in its simulation of CAPE due to the errors in the simulation of regional physical processes, as pointed out above. For example, relevant factors could include errors in the simulation of surface or atmospheric moisture content, the amplitude of the diurnal cycle of near-surface temperature; and the rate at which the model’s convection scheme removes CAPE. In percentage terms, the regional biases are substantial in many cases. In spring, for example, negative biases exceed 30% over most of the UK, and this is also the case for south east England in summer. Note, however, that since the observed baseline values are often small (for example less than one day per season over most of the UK in winter, and over parts of Scotland in all four seasons – see Figure 3) large percentage biases are often associated with relatively small biases in absolute terms.

In addition to using the ERA-RCM, we also compared observations with simulations from each of the 11 members of the PPE_RCM ensemble described in Section 4. Compared to ERA-RCM, each model variant in the PPE_RCM ensemble contains a
Figure 5: The difference between the model simulation of lightning days in and that in the observation of thunder days, both for the summer season averaged over the period 1961–1990, expressed as a percentage bias, for each of the PPE_RCM members. The bottom right panel shows the ensemble mean of the percentage biases.
different representation of regional physical processes due to the application of parameter perturbations (see Section 4). We therefore tested alternative choices of CAPE threshold (variations around 250 J/kg in 25 J/kg intervals) for the PPE_RCM members, as a sensitivity test. The results showed that the minimum level of space-and time-averaged bias for the ensemble mean is achieved with 250 J/kg. This supports the results obtained from the ERA-RCM, and confirms that a choice of 250J/kg provides the best overall basis for estimating lightning occurrences, taking into account uncertainties in the relationship between regional physical processes, CAPE and lightning.

However, it is inevitable that biases in the inferred occurrence of lightning will vary between members of the PPE_RCM ensemble, due both to variations in the representation of regional processes, and also because these simulations inherit biases in the large-scale atmospheric circulation from their driving global climate model simulations (in contrast to the ERA-RCM simulation). This is shown in Figure 5, where the percentage bias from 1961 to 1990 summer observations is shown for each of the PPE_RCM members. Some members produce negative biases across the whole country, and in some cases the spatially averaged biases are considerably larger than found in ERA-RCM (cf Figure 4). Other ensemble members show a mixture of positive and negative biases, with positive biases tending to occur over northern Scotland and in western coastal regions. It is not clear to what extent these results reflect errors in the model representation of CAPE over high ground, or a possible undersampling of elevated regions in the observed climatology. In a few ensemble members the UK average bias is actually smaller than in ERA-RCM, perhaps due to compensations between the effects of errors in regional physical processes and the large scale circulation. These variations in behaviour between different model variants illustrate some of the uncertainties associated with attempts to project lightning from currently available climate models, and demonstrate the need for caution when interpreting the RCM projections discussed in the next section.

7 Projected changes

Each of the model variants in the PPE_RCM ensemble was run from 1950 to 2099, forced from 1990 by the UKCP09 Medium emissions scenario, as described in Section 4. The daily maximum value of CAPE was used to determine the occurrence of a lightning day, using the optimum threshold of 250 J/kg. These were then averaged over two periods, 1961–1990 (used for the validation described in Section 6) and the 2080s (2070–2099), for each season. The ensemble mean baseline and future values are shown in Figure 6 for each season. In addition, the absolute and percentage changes from each PPE_RCM variant were calculated, and the ensemble averages of these changes are also shown in Figure 6. Note, however, that the ensemble averages shown in Figure 6 may be no more credible than any of the individual projections, and may not represent a “most likely outcome”.

In winter and spring, the PPE_RCM ensemble simulates small lightning frequencies which never exceed 2 days per season in the ensemble mean. In these seasons, the future projections show small increases in the number of lightning days; however these increases exceed 1 day per season only over some southern and western coastal regions in winter. In percentage terms, the changes (where an ensemble mean value can be defined) can be locally very large; however these local variations are not statistically robust, due to the small values found in the baseline period. Increases in lightning frequency are also found in summer and autumn. In absolute terms, the increases typically exceed 1 day per season in summer, and
exceed 2 days per season over parts of northern England, Scotland and Northern Ireland. In percentage terms, the summer changes are largest over Scotland and Northern Ireland, where the historical baseline values are smaller. Over south east England, the increases are typically in the range 25–50%. In autumn, the largest changes (exceeding 2 days per season) are largest over southern England and some western coastal regions. In percentage terms, the autumn changes are generally larger than in summer, because the baseline values are relatively small (as in winter and spring). In particular, the very large percentage increases seen over parts of northern England, Northern Ireland and Scotland in autumn reflect baseline values smaller than one day per season, rather than large changes in frequency, and should not be taken as statistically robust.

Thunderstorms are accompanied by precipitation, so it is instructive to compare changes in both these quantities to see if they are qualitatively similar. In summer, the UKCP09 central projection is for seasonal average precipitation to decrease over all areas of the UK, with biggest reductions in the south-west of England. In the case of extremes, the central estimate of changes to precipitation on the typical ‘wettest day’ of the summer (taken to be the 99th percentile) is for reductions in the southernmost regions of England, with little change or slight increases further north. Thus these projected changes in mean precipitation and the wettest day do not show similar behaviour to those in the number of lightning days. Further analysis of the RCM simulations of the baseline period and the 2080s (not shown here) reveals that there is no simple relationship between the CAPE values used to infer lightning occurrence, and daily accumulations of precipitation. This may be because the calculation of lightning uses the maximum value of CAPE in the day. As CAPE is calculated at every 5 minute model timestep, the maximum value could capture a short peak of convective activity sufficient to trigger the occurrence of lightning. This is appropriate for lightning diagnosis, as the corresponding observable (thunder days) is based on occurrence at any point within a 24 hour period. However, short-lived events are only one of many ways in which a non-zero daily accumulation of precipitation can occur, and may not necessarily play a dominant role in determining the climatological distribution of daily values.

The more extreme percentiles of daily summer rainfall (above the 99th ) do show more evidence of increases (across the UK as a whole) in some of the members of the PPE_RCM, in qualitative agreement with the projected lightning changes. However, even for extreme rainfall events there is only modest evidence of a relationship with daily maximum CAPE values. This is partly because some extreme daily precipitation totals arise from large-scale precipitation events associated with synoptic scale cyclones (even in summer), rather than from convective events. A more detailed analysis of the relationship between lightning occurrence and heavy daily precipitation events is beyond the scope of this report.

8 Uncertainties in changes

Up to now, we have shown changes in lightning averaged over all eleven members of the PPE_RCM ensemble. In order to show uncertainties in these estimates, Figure 7 shows maps of percentage change in lightning days from each of the RCM variants separately. Ten of the individual projections show increases in frequency in all locations, however the magnitudes of increase vary significantly between the ensemble members. In addition, one simulation shows reductions over much of the UK, showing the importance of considering the entire ensemble (rather than just the ensemble average) to characterise the range of possible outcomes.
Figure 7: Summer percentage change in number of lightning days between 2080s and 1961–1990, under Medium emission scenario, for each member of the PPE_RCM ensemble.
In order to make this uncertainty easier to assimilate, we show in Figure 8 three maps of percentage changes for three seasons (winter is omitted due to the small baseline occurrences discussed in Section 7): the mean over all PPE_RCM members (centre), the lowest values of change in every grid square given by any of the 11 variants (left column) and the highest value of change (right column). Here, the ‘lowest change’ means the most negative or least positive change found at the relevant grid point, and ‘highest change’ denotes the most positive or least negative change. Note also that because the values in the ‘highest change’ map can come from any of the PPE_RCM members, adjoining grid squares may have values taken from different model variants. The same applies to the maps showing the lowest changes.

It can be seen that the highest and lowest changes in any grid square can be very different from the ensemble mean, giving an indication of the uncertainty which should be attached to these estimates. However, the PPE_RCM ensemble represents only a subset of the range of modelling uncertainties included in the UKCP09 probabilistic projections. The latter projections account for a wider range of uncertainty by sampling fully the expert-specified parameter space of surface and atmospheric processes in HadCM3, and also by estimating the effects of uncertainties arising from structural modelling errors in these processes by including results from other climate models, plus further uncertainties arising from carbon cycle, sulphur cycle and ocean transport processes (see also Chapter 3 of Murphy et al. 2009). Consequently, it should not be assumed that the spread of projections from the eleven PPE_RCM ensemble members can be taken as the full range of uncertainty consistent with current understanding.

Users who wish to assess more fully the modelling uncertainty could potentially compare the spread of RCM derived results shown in this report with those from other model projections of time-evolving 21st century climate. Sources would include:

- The 17-member GCM ensemble of perturbed physics variants of HadCM3 global model carried out for UKCP09, which samples a somewhat wider range of process uncertainties than those sampled in the 11 PPE_RCM projections. Data from both the GCM and PPE_RCM ensembles is available from the British Atmospheric Data Centre, at http://badc.nerc.ac.uk/data/

- The multi-model ensemble of projections from alternative global climate models, available from the archive of simulations run for the IPCC Fourth Assessment report (Meehl et al. 2007). Data is freely available for non-commercial purposes from http://www-pcmdi.llnl.gov/ipcc/about_ipcc.php

- The results from the EU ENSEMBLES project completed during 2009, where projections are available from a number of alternative RCMs, driven by several GCM projections contributed by different European modelling centres. Data is available from http://ensemblesrt3.dmi.dk/

In principle, each of these data sources could be used to provide information on changes in lightning. However, there are potential complications associated with this. Firstly, models may not diagnose and output a lightning parameter, because lightning is not a primary model variable required to predict the evolution of the climate system. Even if they do, the type of variable, and the way it has been defined and calculated, is likely to be different from that we have described.
Future changes in lightning projections: Technical note

above in the Met Office Hadley Centre RCM. The lack of a direct estimation of lightning in a model could be overcome by using an offline calculation, but the model output required to do this (for example, the maximum daily CAPE) may not have been archived. Users could potentially employ alternative related variables if available, but this raises the second issue, namely that users would then have to use a different off-line relationship to infer lightning. The nature of the off-line relationship would also likely depend on which climate model projection was being used. For example, output from coarse-resolution global simulations would need different conversion relationships to output taken from regional model simulations, due to the issues in converting grid box climate model variables covering some spatial region into estimates of discrete lightning day time series typical of point locations. The existence of appropriate off-line algorithms to deduce lightning from other climate model projections would need to be explored. Thirdly, simulations (for a baseline period, for example 1961–1990) would need to be validated against observations. Fourthly, as in the case of the Met Office Hadley Centre PPE RCM ensemble, none of the other ensembles of projections listed above include the effect of feedbacks in the carbon cycle and its associated uncertainties (which are included in UKCP09 probabilistic projections).

9 Summary

The occurrence of lightning is important to some sectors of the economy, in particular electrical distribution. Projections of future changes can therefore help users plan any required adaptation. A method to derive credible probabilistic projections of changes in lightning is not yet available. However, data from the 11-member perturbed physics ensemble of RCM variants used in UKCP09, together with a diagnostic algorithm to infer lightning from model values of convective available potential energy (CAPE), is used in this report to derive plausible seasonal changes in the number of days of lightning. To do this, we require an appropriate threshold value of CAPE, below which lightning is assumed not to occur. This threshold was chosen such that the model’s 1961–1990 lightning climate is in best agreement with gridded observations over the same period. A suitable observed dataset of lightning occurrence does not exist, however we use a dataset of thunder observations as a proxy. Observations show that thunder is commonest in the summer season, and in the east and southeast. It is heard less than once a season over most of the UK in winter, over Scotland and Northern Ireland in autumn, and over northern Scotland and Northern Ireland in spring. With the chosen CAPE threshold (of 250 J/kg), the model simulations replicate the main observed seasonal and spatial variations in lightning frequency with reasonable skill, however significant regional biases are also present.

For projections of changes to number of lightning days, we apply the chosen CAPE threshold to projections of CAPE from the PPE RCM ensemble, over the period 2069–2099 (the 2080s) under the Medium emissions scenario. Changes in the number of lightning days, averaged over all the ensemble members, relative to the baseline period of 1961–1990, can be summarised as follows.

- Increases in the number of lightning days are projected for all four seasons across the whole of the UK.

Figure 8 (see page 14): Average percentage change in number of lightning days between 2080s and 1961–1990, under Medium emission scenario, for (top to bottom row) spring, summer and autumn. The mean over the PPE RCM ensemble is in the centre column, the lowest change from the ensemble in the left column, and the highest change in the right column. Note that different ensemble members provide the lowest or highest changes at different grid points, so the maps do not represent the change simulated by any particular ensemble member.
• In summer, projected increases are largest (i.e. in excess of 2 days per season) over parts of Scotland and Northern Ireland. When expressed as percentage changes relative to historical values, there is a distinct north–south gradient of change, such that increases are projected to be smallest in parts of south east England, where they can be less than 30%.

• In autumn, the changes in absolute terms are largest over southern England and western parts of Wales (exceeding 2 days per season). Percentage changes are large in most regions, since the baseline values are relatively small compared to summer.

• In spring, small increases (less than 1 day per season) are found at all locations. In percentage terms the changes vary with region, however this largely reflects the small baseline values simulated (and observed) in spring.

• In winter, small increases are also found, with somewhat larger increases (more than 1 day per season) across coastal regions in southern England, and some western coastal regions. These translate into large percentage changes in places; however the percentage changes are not statistically robust, due to the small values found in the baseline climate. Indeed, in many locations in winter, it is not possible to calculate a percentage change for future climate, as some ensemble members simulate zero occurrences in their simulations of 1961–1990.

By examining projections from all 11 RCM variants, we show that the uncertainty in the estimated changes given above is substantial. However, even these uncertainties, derived as they are from a limited number of variants of one climate model, are incomplete. Suggestions are made for sources of alternative ensembles of climate model projections which might allow a more complete analysis. However, postprocessing of model output would be required to derive lightning information from these, and it is likely that different methodologies would be needed to the specific approach used here.
Acknowledgements

With thanks to Dan Hollis and John Caesar for observational data and regridding software.

References


