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RMetS Royal Meteorological Society

A case study of possible future summer convective precipitation over the UK and Europe from a regional climate projection

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ABSTRACT: Climate change caused by green house gas emissions is now following the trend of rapid warming consistent with a RCP8.5 forcing. Climate models are still unable to represent the mesoscale convective processes that occur at resolutions ~O(3 km) and are not capable of resolving precipitation patterns in time and space with sufficient accuracy to represent convection. In this article, the UK Met Office precipitation observations are compared with the simulations for the period 1990–1995 followed by a simulation of a near-future period 2031–2036 for a regional nested weather model. The convection-permitting model, resolution ~O(3 km), provides a good correspondence to the observational precipitation data and demonstrates the importance of explicit convection for future summer precipitation estimates. The UK summer precipitation is reduced slightly (~10%) for 2031–2036 and there is no evidence of an increase in the peak maximum hourly precipitation magnitude. A similar pattern is observed over the whole European inner model domain. The results using the Kain–Fritsch convective parameterization scheme at a resolution ~O(12 km) in the outer domain increase summer precipitation by ~10% for the UK. The average precipitation rate per event increases, dry periods extend and wet periods shorten. As part of the change, 10-m winds of <3 m s^{-1} become more common – a scenario that would impact on power generation from wind turbines through calmer conditions and cause more frequent pollution episodes.

KEY WORDS Convection; Precipitation; Regional Climate

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1. Introduction

A critical variable for many sectors of industry, e.g. water resources, agriculture, civil protection, energy, transport and tourism is precipitation amount, intensity and frequency. It is thus important to understand the impact of climate change on precipitation patterns. Regional convection-permitting models are promising tools for improved future climate research (Prein *et al.,* 2015) as they allow convection-scale motions to up and downscale energy to the larger scales from the convective scale (Nastrom and Gage, 1985). Weisman *et al.* (1997, 2008) demonstrated this with the Weather Research Forecasting Model (WRF) and that the upper bound on the required resolution is less than 4 km. Below this resolution, important mesoscale dynamical structures are too poorly resolved to capture these multi-scale interactions, leading to error in precipitation patterns and precipitation response to climate change. It is in this framework that this study is presented. In this article detailed precipitation observations and model results over the UK for a 6-year control period (1990–1995, inclusive) are compared with model results for 2031–2036, inclusive.

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2. Background

Kendon *et al.* (2012)) and Berg *et al.* (2013)) specifically address precipitation scenarios. Berg argues that spatial and temporal convective precipitation is more sensitive to temperature increases and increasingly dominates extreme precipitation. This is supported by the review article examining the Clausius–Clapeyron effects in a warming atmosphere (Westra *et al.*, 2014). Other articles (Kendon *et al.*, 2012, 2014; Chan *et al.*, 2014a, 2014b, 2016; Blenkinsop *et al.*, 2015) discuss the realism of these scenarios (Berg *et al.*, 2013). The recent article by Prein *et al.* (2017) summarizes these results and argues that the precipitation scaling rates increase, although dependent

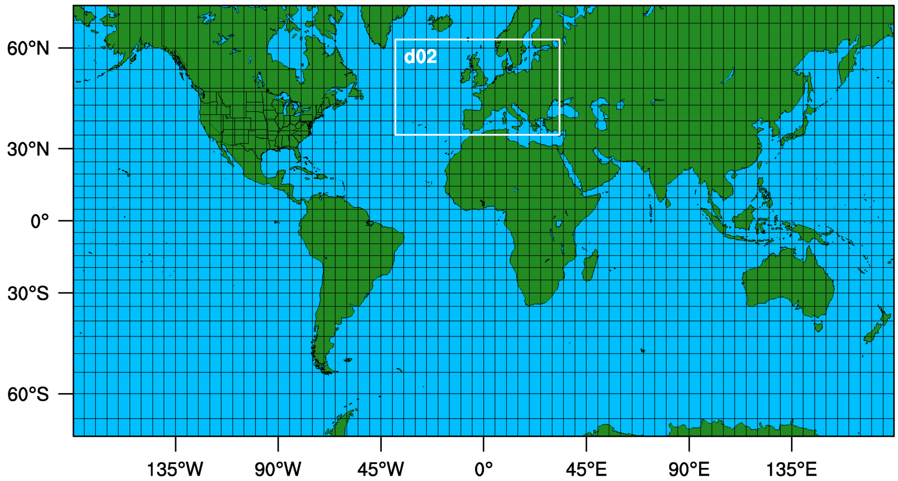

Figure 1. Domain structure for the simulation. The outer domain (d01) resolution is 20 km at ±30° and 8 km at 68°N/°S. The inner domain (do2) is one way nested at a ratio of 5 : 1. [Colour figure can be viewed at wileyonlinelibrary.com].

on temperature, are also strongly regionally dependent due to moisture availability and do not necessarily follow the expected ~7% per degree warming increase. Prein's study applies to northern United States and concludes that there is an increase in heavier precipitation, but also accompanied by large variations over the domain. A question arises if this is symptomatic also in western Europe or is a consequence only found in a large continental land mass. Kendon *et al.* (2012, 2014) uses a localized nested domain model over southern England to show that the peak maximum precipitation intensity increases. A question here is whether this small domain is representative of a larger domain of Europe and allows enough time for convective development. This study explores how the precipitation change varies between a coarser grid with a convective parameterization scheme simulations and a grid-permitting explicit convection.

The aim of this study is to determine the changes in convective precipitation and surface winds over western Europe in response to a warming climate as defined by a RCP8.5 forcing (IPCC, 2000, 2014). Specific focus is on changes in short-lived, sub-daily, summer convective precipitation, as explained in more detail in Section 3. The WRF model (Skamarock *et al.*, 2008), version WRF3.5.1, which has been demonstrated to be successfully applied for convection-permitting model simulations, is used (Weisman *et al.*, 1997, 2004, 2008; Done *et al.*, 2004). An advantage of explicit models is that they have to satisfy the numerical Courant–Friedrichs–Lewy (CFL) stability criteria and thus often have less numerical diffusion compared with semi-Lagrangian time step formulations (Duran, 2011). In this simulation, a time step of 10 s is required to resolve the convective motions in the inner domain.

3. Approach and methodology

A nested regional approach is utilized. High-resolution global models are currently too expensive in computer time and storage requirements to model global convection. Done *et al.* (2015) uses the WRF model to demonstrate the value of the nested approach in capturing mesoscales for the case of tropical cyclones in the West Atlantic. Figure 1 shows the domain structure used, with resolution from <3.2 to 2.0 km at 35 and 68 N in the inner domain, d02, increasing by a factor of 5 for the outer domain, implying resolutions ~O(3 km) and ~O(12 km). The design reflects a compromise in maximizing the resolution while also tolerating the increased computing requirements. Fifty-one vertical stretched levels are used, with a lid at 10 hPa. 1731 east–west grid points in both domains and 907 and 1001 grid points in the north–south directions in the outer and inner domains, respectively, provide the required discretization.

Convective parameterization is only applied in the low-resolution outer domain as it is not required for the 3-km inner convection-permitting domain. The Kain–Fritsch (K–F) scheme (Kain and Fritsch, 1993; Klemp, 2006; Weisman *et al.*, 2008; Done *et al.*, 2015) is used as National Center for Atmospheric Research (NCAR)'s preferential approach for their regional climate modelling simulations. On some occasions it produces precipitation bands and enhanced precipitation especially and only in the spin-up period, thus is not important for our continuous simulations. Convection parameterization schemes commonly diffuse precipitation but we consider that K–F performs reasonably well and is regarded as one of the best (Gilliland and Rowe, 2007). The Yonsel University (YSU) boundary layer scheme, WRF single moment (WSM) 6 class scheme microphysics, International Global Biosphere Programme-MODIS (IGBP-MODIS) and a four-layer Noah land surface schemes (Weisman *et al.*, 2004, 2008; Hong and Lim, 2006; Cohen *et al.*, 2015) are used.

The Community Atmospheric Model (CAM) short-wave and long-wave schemes and vegetation schemes were utilized (Collins *et al.*, 2004). Some similar structured simulations in the regional modelling experiment European

Table 1. Six-year average UK precipitation totals for summer months JJA for the control period 1990–1995 from the CEH observations and model simulations.

Boundary data	Domain/ source	Period of simulation	Seasonal average precipitation (mm)
Era-Interim	d01 ∼*O*(12 km)	1990–1995	236
Era-Interim	d02 ∼*O*(3 km)	1990–1995	221
CESM version 1	d01 ∼*O*(12 km)	1990–1995	225
CESM version 1	d02 ∼*O*(3 km)	1990–1995	204
CEH observations	Met Office data	1990–1995	205
CESM version 1	d01 ∼*O*(12 km)	2031–2036	188
CESM version 1	d02 ∼*O*(3 km)	2031–2036	182

Precipitation averages for the period 2031–2036 are also included for both domains.

CORDEX project (EURO-CORDEX) (Kotlarski *et al.*, 2014) have been conducted for the European domain. In particular, our setup is similar to Public Research Centre, Luxembourg (CRP-GL) (Table 1). These simulations are ∼0.11° horizontal resolution and use convective parameterization, and of the same spatial resolution as the outer domain (d01). The detailed parameters chosen for our simulation can be found on the web link (http://www.env.leeds.ac.uk/~alan/namelist.input). These choices were made as they are widely recommended by the NCAR WRF team for climate simulations. They are also consistent with the CAM3 boundary forcing data.

Specifying the surface and lateral boundary forcings is important in this regional approach. The model outer domain d01 is driven by the lower boundary sea-surface temperature (SST) condition and the northern and southern channel boundaries. The two domains are one way nested, with the boundaries of domain d02 driven by d01 data. ERA-Interim data (Dee *et al.*, 2011) are used for the control runs, using data from 1989 to 1995. Community Earth System Model (CESM) version 1 data are also utilized for another comparison control run (1989–1995) and for the future run (2030–2036).

Like all General Circulation Models (GCMs), CESM contains biases due to its coarse resolution and limitations in its representation of physical processes. As these biases can adversely affect the dynamical downscaling results, it is important to first bias-correct these data before using it to drive WRF. The bias correction approach is justified (Bruyère *et al.*, 2014) with a detailed technical description (Bruyère *et al.*, 2015) of the CESM data (Monaghan *et al.*, 2014) all detailing the manipulation of the required input parameters for the boundary conditions. In summary, this method uses global and surface reanalysis to correct the mean bias in the CESM fields. The bias correction method only corrects the mean state while retaining the CESM synoptic and climate-scale variability. This is achieved by combining a 20-year mean annual cycle from the reanalysis data with 6-hourly perturbation terms from CESM. The bias correction data are then used as initial and boundary conditions for the WRF model. No nudging was performed for these simulations.

The results related to 1990–1995 and the future (2031–2036) simulations are discussed in this article; the data produced for the first year of each simulation, 1989 and 2030, are ignored allowing for model spin-up. The control period 1990–1995 was slightly (half a standard deviation) wetter than the average for all 6-year periods (1960–2010), for the UK. The year 1995 had an anomalous dry 2 months in the summer, and the whole control period was warm. However, it was chosen because of the availability of both early ERA-Interim and bias-corrected CESM data, the ability to cross-check with a parallel programme being conducted by NCAR. Use of other periods was considered but the availability and need for a relatively 'old' consistent data set, which was neither too wet nor too dry, was the determining factor.

It is appreciated that 6 years is a very short period of time in such studies but the large computational resources required limited the lengths of the periods. However, the approach is justified on the grounds that this study focuses on the processes driving short, sub-daily, convective events and is meant as a study to compare the impact of different modelling scenarios. The purpose of the study is to examine a 6-year long, summer convective period to determine how the dry and wet spell durations and the precipitation density and intensity possibly change in 2031–2036. The calculations will include many thousands of sub-daily convective events. The signal being examined is therefore not specifically the climate change signal, but the signal generated by short convective events and cloud processes.

The statistical significance of the results is not presented here. Many significance tests are dependent on Gaussian distributed variables, which is not an appropriate assumption for extreme precipitation. Nonparametric tests such as Kolmogorov–Smirnov, on the other hand, can introduce unwarranted confidence in the results if biases are not accounted for through boot-strapping or similar. Additionally, given the volume of data, and the aim to compare convective precipitation representation, significance testing is considered to be outside of the scope of the article. Extreme value analysis is not considered appropriate as the 'climate base state' is warmer and the cloud processes being studied will change over time.

4. Validation of control simulations using precipitation data

Validation of the model precipitation data needs to include a comparison with both observational data for the simulation periods and climatological averages. The UK data are used because of their availability. The UK Met Office observational data (UK Met Office, 2017) are available, as image only (Figure 2(a)), for the years 1981–2010. This visual data provide a longer-term climatological summer average with which to compare the 6 years of model simulations from 1990 to 1995. Observational data, specifically for 1990–1995, from the Centre for Ecology and Hydrology (Tanguy *et al.*, 2015) are also considered in Figure 2(b). The 6-year specific period studied was drier (Figure 2(b)) than the 30-year averages (Figure 2(a)).

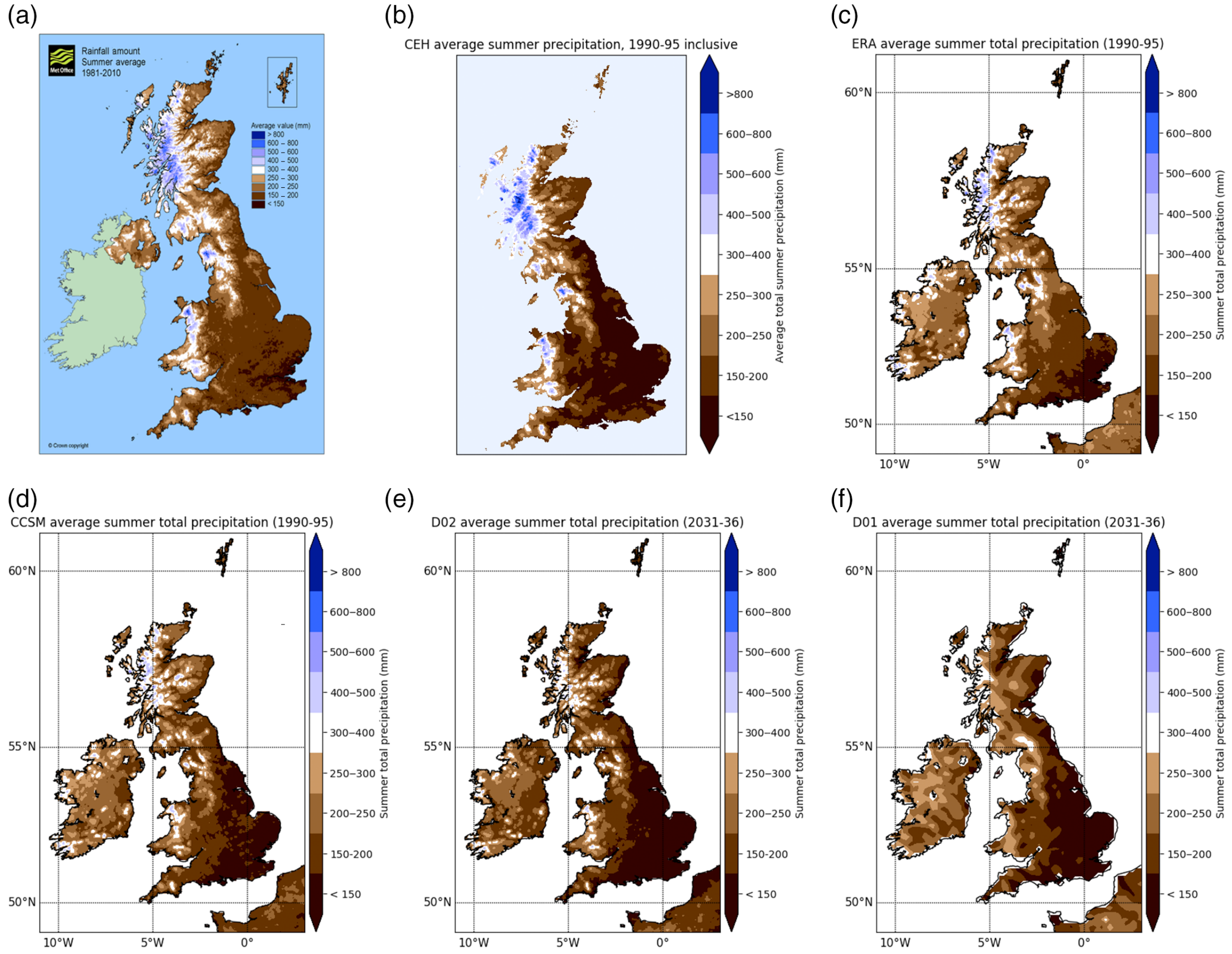

Figure 2. Comparison of current and future precipitation patterns for the UK. Panel (a) indicates the UK precipitation amounts for summer (JJA) (1981–2010). Panel (b) indicates the UK precipitation amounts for summer (1990–1995) from the CEH. Panel (c) indicates the corresponding values from the high-resolution $\sim O(3\,\text{km})$ simulations driven by the ERA-Interim data and panel (d) driven by CESM data for 1990–1995. Panels (e) and (f) show the model output data for years 2031–2036 driven by CESM data, for the inner and outer domains, with resolutions $\sim O(3\,\text{km})$ and $\sim O(12\,\text{km})$, respectively. All plots use the same colour scale. [Colour figure can be viewed at wileyonlinelibrary.com].

This may be indicative of the natural variability of the precipitation observations, as discussed below.

Figures 2(c) and (d) show the results from the control simulations driven by the ERA-Interim and CESM boundary conditions for the inner domain (d02). Both runs underestimate the precipitation volume over the high ground in the west. The southern and eastern areas of the UK are dryer than the observations, particularly when using the CESM boundary data. The ERA-Interim-driven simulations (Figure 2(c)) qualitatively appear to give better fit to the observational extremes. There are lower-precipitation magnitudes in the southeast UK, but more consistent with the 30-year Met Office data set and also a better fit for the elevated wetter regions for the specified years, than the CESM-driven simulation (Figure 2(d)). Both sets (c) and (d) appear to demonstrate reasonable consistency with the observations (a) and (b) and provide a useful foundation from which to explore future changes. The summer precipitation results using data from the outer domain (d01) low-resolution Kain–Fritsch (K–F) convective parameterization scheme (plots not shown) are wetter (up to a maximum of ∼50 mm) in many regions of the UK.

The UK average summer (JJA) observational precipitation data from Centre of Ecology and Hydrology (CEH) are available for comparison for 1990–1995 and included in Table 1 (row 5). Comparable results for both the outer domain (d01) simulations at low resolution $\sim O(12\,\text{km})$ and the inner domain (d02) higher-resolution $\sim O(3\,\text{km})$ simulations using both the ERA-Interim and CESM outer boundary conditions are included on rows 1–4. The higher-resolution CESM calculations provide a 6-year average of 204 mm for the UK, row 4, compared with CEH observations of 205 mm. The ERA-Interim-driven values of seasonal precipitation values are higher by ∼10% than the observations. Both have an average ∼10% higher for the convection scheme low-resolution values compared with the higher-resolution convective-permitting calculations. From the table, the precipitation results using the higher-resolution convection-permitting simulations provide a closer comparison to the observations than the lower-resolution K–F convective parameterization

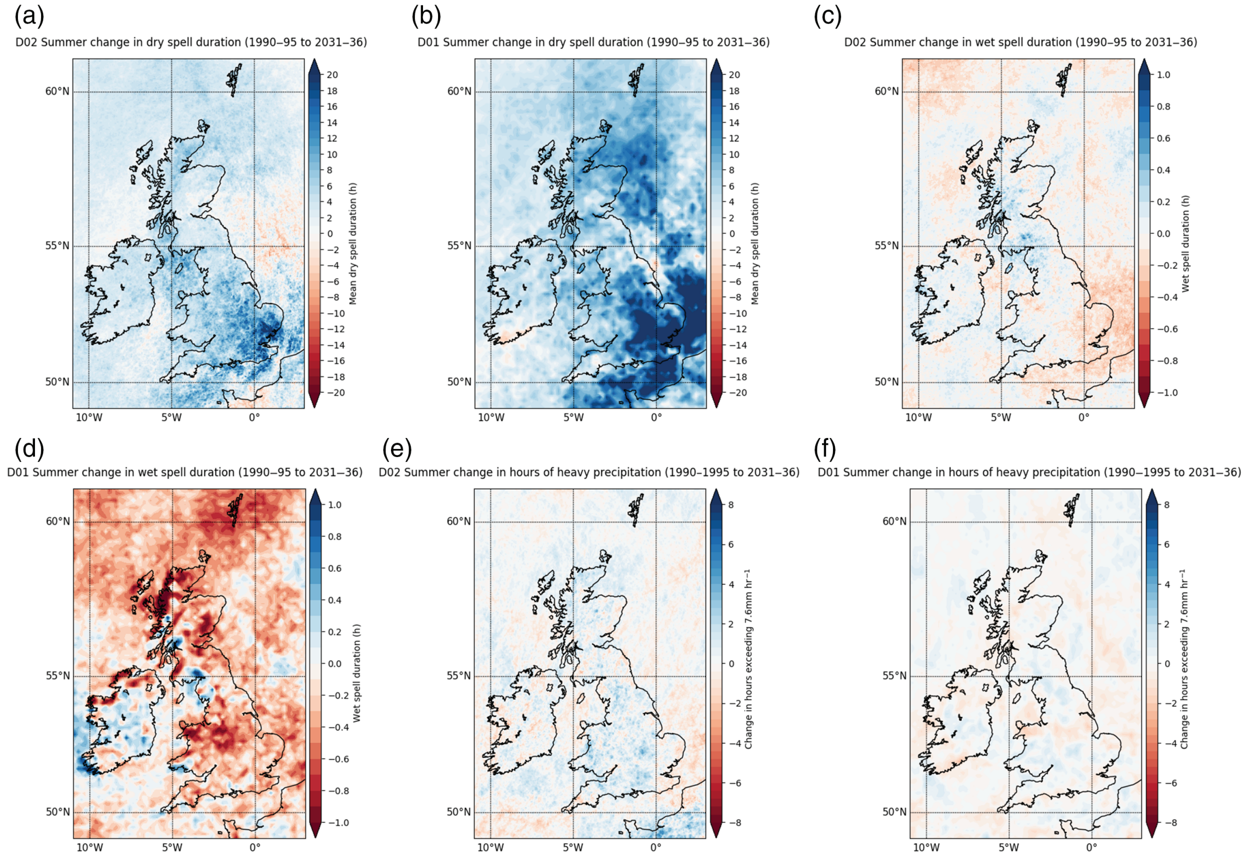

Figure 3. Summer (JJA), UK plots. Top row: changes in dry spell duration, for the high resolution $\sim O(3\,\text{km})$, domain, d02, calculations (a) and lower resolution $\sim O(12\,\text{km})$, D01 (b). Second row: changes in wet spell duration from both high and low-resolution solution (c) and (d). Third row: changes in heavy precipitation ($>7.6\,\text{mm}\,\text{h}^{-1}$) for high-resolution (e) and low-resolution (f) simulations. In (a)–(f), the changes are produced by subtracting the 1990–1995 from the 2031–2036 average values at each pixel. [Colour figure can be viewed at wileyonlinelibrary.com].

calculations. It is not clear why the CESM boundaries provide a better comparison with the observations than the ERA data, but both sets appear to provide a good basis to make a comparison for future decades. In the 2031–2036 simulations the predicted summer precipitation is reduced to 182 and 188 mm, respectively, for the high-resolution convection-permitting and lower-resolution convectively parameterized simulations. These have been included in the table for comparison (rows 7 and 6).

Over the western Europe land mass, the precipitation rate during precipitation events is less intense by approximately $1\,\text{mm}\,\text{h}^{-1}$ for the low-resolution simulations $\sim O(12\,\text{km})$ compared with the higher-resolution $\sim O(3\,\text{km})$ convection-permitting simulations (plots not included). The reduced precipitation rate is consistent with the hypothesis that convective parameterization schemes have difficulty in representing heavier summer convective precipitation and stresses the importance of using an explicit representation of convection for summer precipitation.

5. Future scenarios

5.1. Overall summer precipitation

A comparison of the precipitation produced for simulations 2031–2036 with the control 1990–1995 shows a small reduction in mean summer precipitation over the UK (Figures 2(e) and (d)) for inner domain high-resolution $\sim O(3\,\text{km})$ simulations which explicitly represent convection and as in Table 1. However, the east regions of the UK become dryer with less than 150 mm of precipitation (Figure 2(e)) despite stronger convective precipitation, see below. This pattern is not true for other seasons; winter and spring time comparison indicates an increase in precipitation (up to 180 and 120 mm, respectively); these increases are larger than the annual standard deviation and will be discussed in a later publication. Figure 2(f), for the lower-resolution data from the outer domain and with K–F convective parameterization, suggests that the precipitation is more diffuse and spread more evenly over more of the upland areas of the UK. Over the oceans the precipitation rates are similar in both domains for the high-resolution convection-permitting and low-resolution convectively parameterized simulations, suggesting that it is over the land masses that the major differences occur (plot not shown).

5.2. Dry spell duration

The results (Figure 3) of the changes in summer precipitation indicate the increasing importance of the relatively short-duration convective events. The mean dry spell (precipitation <0.1 mm) duration between precipitation events, in the convection-permitting analysis ∼O(3 km), as in Figure 3(a), increases in 2031–2036 by ∼20 h in the southeast of the UK, from an average 1990–1995 of ∼40 h, with a standard deviation of ∼60 h for both 1990–1995 and 2031–2036 simulations. In the north and west of the UK the dry spell duration increase is much shorter ∼12 h. Overall, the whole of the UK exhibits an increase in the dry spell duration in the future simulations.

For the same UK area, the lower-resolution ∼O(12 km) K–F convectively parameterized simulations provide a larger signal (Figure 3(b)). There is a similar pattern with the characteristics of the parameterization scheme producing longer dry spells.

5.3. Wet spell duration

There is a small marginal decrease in the wet spell event duration over the UK in the convectively permitting simulations (Figure 3(c)). The wet spell duration is defined as the length of time where precipitation is greater than 0.1 mm h^{-1}. The average wet spell duration decreases by approximately by ∼0.2 h, from an average of ∼2 h (1990–1995), with a standard deviation of ∼0.5 h in the southeast UK. In the north and west of the UK, the mean wet spell duration increases slightly. It is greater than 3.0 h (1990–1995), with a standard deviation of about 4.5 h for both 1990–1995 and 2031–2036. In these northerly regions, the increases in wet spell precipitation are small. In autumn, there is a general decrease in wet spell duration from ∼5 to ∼4.5 h, albeit with a standard deviation of ∼4 h using an hourly model data output frequency, and this is discussed in a later publication.

The pattern is different for the same UK area for the lower-resolution K–F parameterized simulations (Figure 3(d)). Here the simulations indicate that the wet spell duration decreases. However, it should be noted that maximum change in wet spell duration for both resolutions is ∼O(1 h) compared with the more significant dry spell duration maximum change of ∼O(20 h).

5.4. Heavy precipitation occurrence

The change in hours of heavy precipitation (>7.6 mm h^{-1}, as defined by the American Meteorological Society threshold) shows an increase. In Figure 3(e), convection permitting the number of hours of heavy precipitation per event increases by ∼2 h, indicating that when it rains, it rains harder (see also discussion below for the whole European domain, Figure 5). The lower-resolution convection parameterization results indicate no future change, which suggests that the K–F scheme is not so sensitive and the predicted hours heavy precipitation is less (Figure 3(f)).

Figures 4(a) and (b) summarize these precipitation results by plotting the maximum precipitation for each event, against the duration of the event, for the convectively resolving and parameterized results, respectively. This is a critical result. For the convection-permitting solutions, in the future scenarios (Figure 4(a)) there are shorter more intense bursts of heavier rain than in the parameterized runs (Figure 4(b)). A significant increase in precipitation in relatively short ∼2-h rain events is at the expense of longer (∼4 h) lower-precipitation rate events (Figure 3(d)). However, the maximum peak summer hourly precipitation rate does not noticeably increase, indicating that the precipitation is heavier per event while not changing the peak. Kendon *et al.* (2012, 2014) suggest that the peak precipitation may increase and this difference needs further study. A concern is that their small domain boundaries are close to the study area, so this may have impact on the nature of the cycle of convective growth and decay over a few days. Furthermore, our study focuses on simulating convective events, using short time steps to resolve the convection; the use of a longer semi-Lagrangian model time steps in Kendon *et al.* (2012, 2014) and may be another cause of this difference.

For the K–F convectively parameterized simulations, the maximum precipitation rate does not increase so much for the shorter events, but there is a decrease in the longer-duration lower-intensity events (Figures 4(a) and (b)). Figures 4(c) and (d) demonstrate that that for both 1990–1995 and 2031–2036 the nature of the precipitation processes is represented in the model with exactly the same structure in both ‘climates’. Figures 4(a) and (b) reflect on the performance of the K–F convective parameterization scheme (see discussion below). Combined, this suggests that care is required if the K–F convection-permitting results are to be used in future climates to represent short convective precipitation events. For both resolutions, the shorter precipitation events increase in intensity, if not noticeably in peak rate.

Analysis of the percentage of total events under 4 h in duration (short timescale events) indicates that there is a bigger percentage change in the higher-resolution convection-permitting simulations. For the outer convectively parameterized domain, the percentage of these events increases from 66.6% for 1990–1995 to 69.0% for 2031–2036 and in the convectively permitting solutions, values increase from 86.5% for 1990–1995 to 87.4% for 2031–2036. These figures do not necessarily indicate any significant change between the control and future results, but do outline the limitations of the K–F convective parameterization scheme, and support results in Figures 4(c) and (d).

However, for short time scale events of less than 4 h and hourly precipitation of more than 7.6 mm h^{-1} (heavy precipitation) there is a noticeable signal. For the convective parameterization results, the percentage of these events increases by 20% (1990–1995 and 2031–2036) and in convection-permitting results by 18% (1990–1995 and 2031–2036). Increasing the hourly precipitation threshold to be over 10 mm h^{-1}, there are larger corresponding increases of 55 and 25%. The heavier the precipitation threshold, the larger the change in the 2031–2036 period.

A final comparison between the two convection approaches for each of the 1990–1995 and 2031–2036 for heavy (>7.6 mm h^{-1}) precipitation and short time scale events, the difference is 850 and 840%. Again, increasing the precipitation threshold to over 10 mm h^{-1}, the differences increase and are 1160 and 940%, respectively.

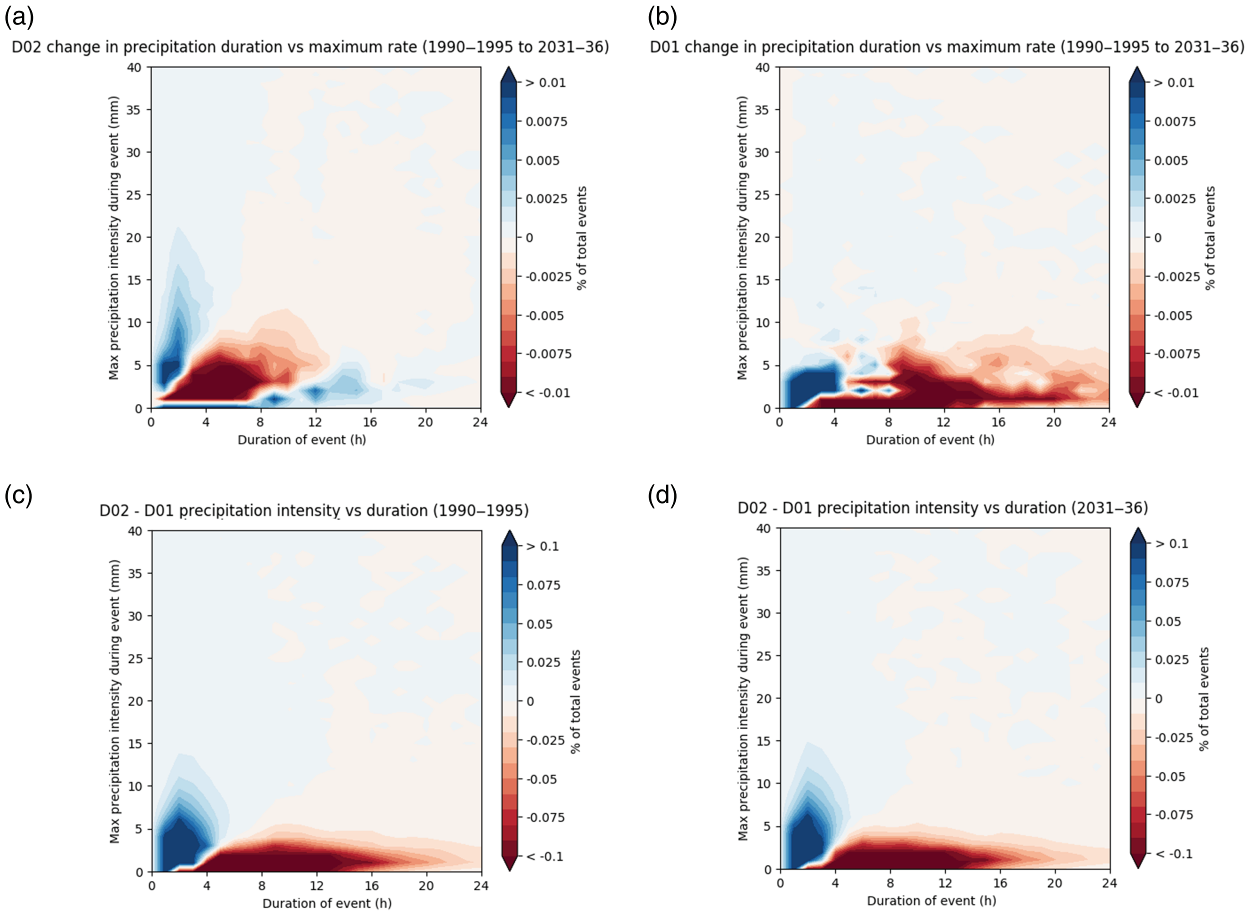

Figure 4. Summer (JJA), UK plots. Intensity *versus* event duration plots for the difference in high-resolution data ~O(3 km), domain, d02, and lower resolution ~O(12 km), d01, data. Top row: difference in precipitation intensity for 1990–1995 and 2031–2036 for inner domain (d02) (a) and for the outer domain (d01) (b), both plotted against event duration. Bottom row: the difference between the inner domain, d02 and outer domain d01 precipitation density for 1990–1995 and 2031–2036. In (a)–(d), the changes are produced by subtracting the 1990–1995 from the 2031–2036 average values at each pixel. [Colour figure can be viewed at wileyonlinelibrary.com].

In summary, the K–F convection scheme simulations undervalue the short time scale heavy rain precipitation events by almost an order of magnitude. The heavier the precipitation, the more the parameterization scheme simulations underestimates the contribution. These results focus on the rare extreme events at the tail of the PDF, which have maximum societal impact.

In summary, the convective-permitting solutions capture about ten times as many of these short heavy precipitation events, and both convection approaches show a ~20% increase in their contribution to precipitation by 2031–2036. This is graphically apparent in the short time scale high-intensity events in Figures 4(a) and (b).

As mentioned above, the precipitation results differ seasonally, and due to lack of space, these will be discussed in further publications. The summer results are atypical, with winter and spring precipitation increases larger than the standard deviations over much of western Europe by 2031–2036 compared with 1990–1995.

5.5. European domain results

Over the whole European domain much of the UK overall average summer precipitation changes are matched.

Table 2. Six-year average European domain precipitation average totals for summer months JJA for the control period 1990–1995 and for the period 2031–2036, for the low- and high-resolution simulations.

Boundary data	Domain/ source	Period of simulation	Seasonal average precipitation (mm)
CESM version 1	d01 ~O(12 km)	1990–1995	264
CESM version 1	d02 ~O(3 km)	1990–1995	196
CESM version 1	d01 ~O(12 km)	2031–2036	254
CESM version 1	d02 ~O(3 km)	2031–2036	177

Table 2 suggests that the overall precipitation using the high-resolution convection-permitting solution reduces by ~10% in the future scenario. However, there is a larger difference in the control 1990–1995 for the K–F convective low-resolution simulations of ~O(60 mm) compared with the high-resolution results. This is even more apparent for the 2031–2036 simulations. These are significant differences by comparison with the UK data in Table 1, suggesting that the convection scheme needs even closer

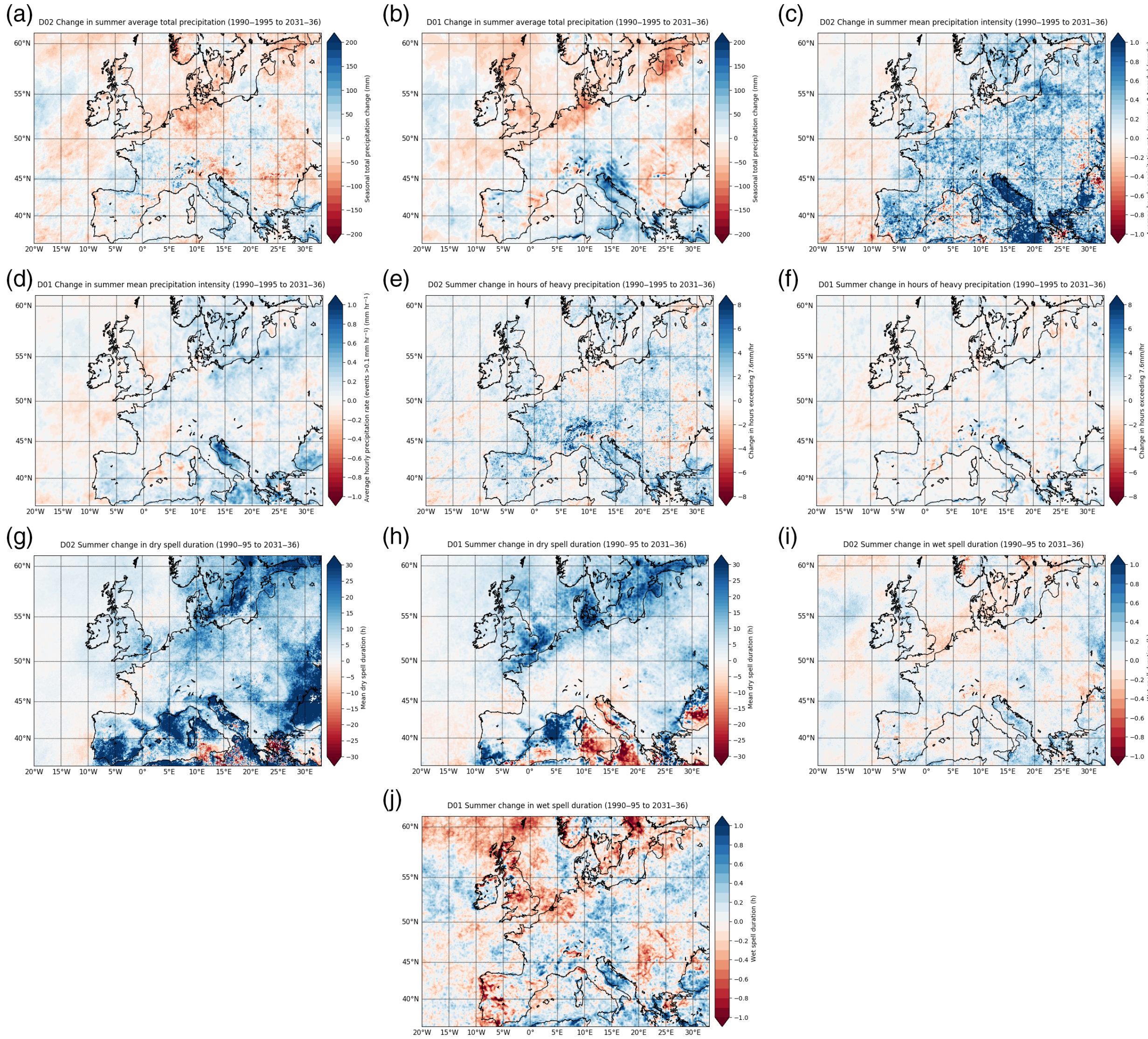

Figure 5. Summer (JJA): changes in total precipitation (a), from the high-resolution simulation $\sim O(3\,\text{km})$ and the low-resolution simulation $\sim O(12\,\text{km})$ (b). Change in mean precipitation intensity for each event from high-resolution simulations (c) and low-resolution simulations (d). Changes in heavy precipitation, $>7.6\,\text{mm}\,\text{h}^{-1}$, for high-resolution and low-resolution simulation are shown in (e) and (f). Change in dry spell event duration, for low- and high-resolution simulations, are shown in (g) and (h). Changes in wet spell duration for low- and high-resolution simulations are shown in (i) and (j). The changes are derived by subtracting the 1990–1995 from the 2031–2036 average values at each pixel. [Colour figure can be viewed at wileyonlinelibrary.com].

investigation in the whole European domain. The effective precipitation efficiency is greater in the K–F convective parameterization scheme calculations. The inner domain, d02, is driven by boundary conditions derived from d01. In summary, this increase of up to 30% in the precipitation over the European and the UK domains reflects on an increased efficiency of removing water in the parameterization scheme compared with the explicit convection.

As with the UK, both low and high-resolution simulations predict a reduction in summer precipitation in the future scenario. The major differences between the high-resolution and low-resolution data are in the Adriatic and the Mediterranean coastal sea areas, as can partly be seen in comparing the difference plots (Figures 5(a) and (b)). A possible explanation is the warming of the land adjacent to sea producing a dynamical monsoon-type effect. With perhaps the exception of France, some parts of Italy, the high mountains of the Pyrenees and the Alps, there is a marginal decrease in summer total precipitation, as in Figure 5(a). However, as in the southern UK the average precipitation rate per event increases, by $\sim 0.7\,\text{mm}\,\text{h}^{-1}$ (Figure 5(c)). The changes in mean rain intensity (Figures 5(c) and (d)) indicate that the K–F convective parameterization scheme does not mirror the increases in the convection-permitting formulation.

The nature of these events is encompassed in Figures 5(e) and (f). For the convection-permitting solution, these short-lived convective events have more hours of heavier ($>7.6\,\text{mm}\,\text{h}^{-1}$) average precipitation (Figure 5(e)), but also noting again that maximum peak precipitation rate appears unchanged from the hourly data available, as in the UK. The convectively parameterized

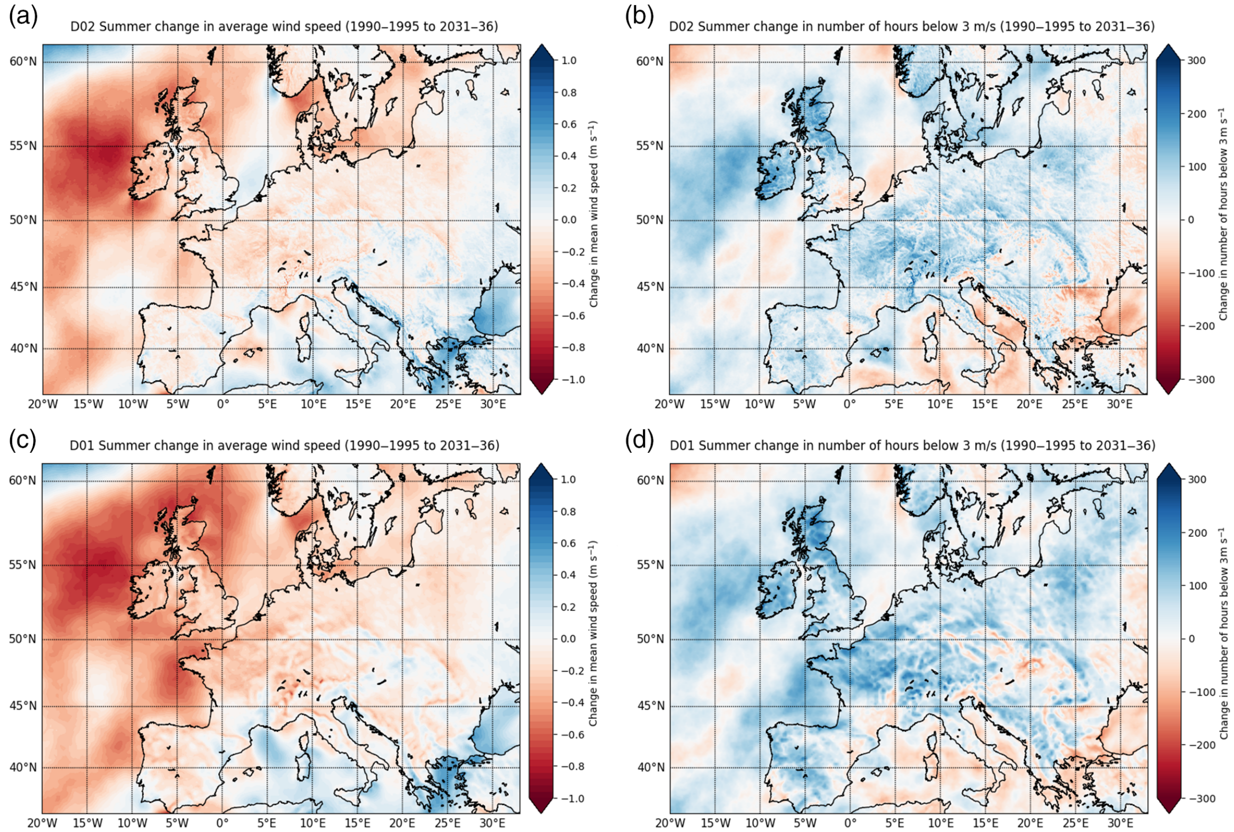

Figure 6. Summer (JJA): changes in 10-m wind speed and the change in the number of hours where the wind speed is less than 3 m s^{-1} at 10 m, using the high-resolution $\sim O$(3 km) simulations (a), (b), respectively. Plots (c) and (d) provide the comparable results from the low-resolution $\sim O$(12 km) simulations. All changes are produced by subtracting the 1990–1995 from the 2031–2036 average values at each pixel. [Colour figure can be viewed at wileyonlinelibrary.com].

results do not exactly mirror this (Figure 5(f)), with little evident change. Figures 5(c) and (e) indicate more hours of heavier precipitation in convection-permitting simulations, but with a smaller reduction in total precipitation (Figure 5(a) and Table 2).

The changes in dry spell duration (<0.1 mm h^{-1}) and wet spell duration for the low- and high-resolution simulations are shown in Figures 5(g)–(j). For the convective-permitting solutions (Figures 5(g) and (i)), with the exception of western France, the average dry spells between events becomes larger (~10 h) while the duration of the wet events becomes marginally smaller. Although the dry spell duration in the convection parameterized low-resolution study (Figure 5(h)) is reasonably consistent with the convection-permitting results (Figure 5(g)), both with a maximum increase of about 30 h, the wet spell duration plots (Figures 5(i) and (j)) are not consistent. It should be noted that the maximum changes in the lengths of the wet spells only vary by about an hour on a base value of 3 h. This is consistent with the total summer precipitation in the convectively parameterized simulations reducing by 4%, whereas the convective-permitting simulations reduce by 10% for the future simulations (Table 2). The convective-permitting average dry spell duration, except over the mountains of Europe has a base average of about 40 h. The UK domain result of shorter but with more hours of heavy precipitation is arguably more apparent for the whole European domain.

5.6. Changes in light wind conditions

The changes in precipitation are accompanied by an increase in the prevalence of calmer surface conditions, in the higher-resolution convection-permitting solutions (Figures 6(a) and (b)). This supports the discussion above that the precipitation events arise from short-lived convection, rather than precipitation cells embedded in synoptic events, as found in the spring and winter months, as discussed in a later article.

The summer surface (10 m) wind changes supplement the convective precipitation patterns. A threshold of ~6 knots, 3 m s^{-1}, is taken as a limit for calm conditions. This is also the value for stalling of wind turbines (Trewby *et al.*, 2014), either at hub height or at 10 m. Calm anti-cyclonic weather, especially with stable boundary layers, can indicate a likelihood of poorer air quality and is often associated with high-pressure conditions. Figure 6 shows the changes in low wind speed conditions over the European domain.

In the southeast of the UK, there is little change in the average wind speed (Figure 6(a)) corresponding to the area of increased average precipitation (Figure 3(a)) using the high-resolution convection-permitting results.

Over the rest of the UK, there is a significant reduction of up to 1 m s^{-1}, especially over Scotland, where many wind farms are positioned. Figure 6(b), over the UK, indicates a reduction of up to 300 h maximum and overall more than ~200 h of low wind <3 m s^{-1}. However, this is not true in the southeast UK which coincides with increased convective activity and increased convective precipitation (Figure 5(c)). This is consistent with the wind magnitude changes that are arguably appropriate to more convective activity and with an increased dry spell duration (Figure 3(a)).

Over Europe as a whole, Figures 6(a) and (b) suggest a reduction in wind speed and an increase in the number of hours of wind below 3 m s^{-1}, except in some coastal Mediterranean regions. The largest reductions in wind speed are found over the western approaches. Much of western Europe exhibits a decrease of 1–3 h day^{-1} in the number of hours when the 10 m wind speed is <3 m s^{-1}. This result is obtained from the high-resolution convection-permitting simulation.

The low-resolution results using the K–F convective parameterization are largely different. Over much of Europe there is an increase in average wind speed, especially over the Adriatic region (Figure 6(c)). Here the authors would argue that the K–F scheme has difficulty representing the increase in convection in the warmer climate, and this feeds back into the dynamics. Current convective parameterization schemes have been tuned to describe current conditions and therefore may not necessarily be suitable to simulate different conditions. The changes in the number of hours below 3 m s^{-1} (Figure 6(d)) is again different from the high-resolution, convection-permitting results, and might even be argued to be of the opposite sign of change. The authors would argue that looking at summer surface wind speed even with a model of ~O(12 km) has serious limitations.

6. Conclusions

In summary, the article presents a case study of a regional weather simulation for the first half of the 2030 decade. This study is just is one realization but required 40 million core hours on a CRAY XC30. It enabled an analysis of convective precipitation over the whole European domain at a resolution that allows convection. The domain is large enough to enable several day cycles, with the air crossing the inner domain using time steps that can explicitly resolve air motions. Using results from a high-resolution convection-permitting simulation ~O(3 km) suggests that the lower-resolution K–F convective parameterization ~O(12 km) simulations do not always replicate the convective changes and produce a larger effective precipitation efficiency. The UK only results for 1990–1995 are used for comparison purposes, with good agreement with the 6-year observed precipitation totals with the convection-permitting simulations. The differences in convective precipitation, from the first half of the decades 1990 and 2030, are analysed. For the future simulation (2031–2036), especially in the southeast of the UK, the results suggest that the summers will possibly be drier, with longer dry spells, shorter wet spells and heavier precipitation. Overall, the UK will be ~10% dryer for the periods assessed. The K–F convection parameterization simulations underestimates the importance of short (<4 h) heavy precipitation (>7.6 mm h^{-1}) events, which is more apparent in the future time period. The convection-permitting solutions capture about approximately ten times as many of these short heavy precipitation events, and both convection approaches suggest a ~20% increase in their contribution to precipitation by 2031–2036. The average precipitation intensity per event increases. This may not be the consequence of an increase in the maximum peak precipitation rate per event as suggested in previous work (Kendon *et al.*, 2012, 2014), but a signal of higher averages. The UK domain results are mirrored in the European domain. With longer drier periods and shorter wet events suggested, the results are possibly more pronounced. The increase in average precipitation for each event is even more apparent over the European domain. This will result in more flash floods over Europe in restricted catchments areas and have implications for agriculture. Associated with this is an average increase of approximately 150 h in the occurrence of 10-m summer wind speeds of less than 3 m s^{-1}.

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For numerical stability and for small time steps required to satisfy the CFL condition for convection, the project requires ~40 million core hours on a CRAY XC30 and ~900TB of data storage. The authors acknowledge the use of the ARCHER supercomputer following a UK EPSRC leadership award, NERC computer resources at Jasmin and on the CRAY and resources on the NCAR Yellowstone computer facility. NCAR is sponsored by the National Science Foundation. The authors would also like to acknowledge the work of Goncalo Gomes for data analysis on the EU scale. The data set is available under open access for research purposes. It is currently stored on the National Environment Research Council JASMIN and RDF facilities and can be obtained in the short term by contact the authors Alan Gadian or Ralph Burton. A data article is in the process of being submitted for publication, in which the metadata will be described on a doi allocated. The authors would like to thank the reviewers for their contribution in improving this article.

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