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Use of very high resolution climate model data for hydrological modelling: estimation of potential evaporation

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Short title: Estimation of potential evaporation using high resolution climate model data

Abstract

Climate model data are increasingly used to drive hydrological models, to assess the possible impacts of climate change on river flows. Hydrological models often require potential evaporation (PE) from vegetation, alongside precipitation, but PE is not usually output by climate models so has to be estimated from other meteorological variables. Here the Penman-Monteith formula is applied to estimate PE using data from a 12km Regional Climate Model (RCM) and a nested very high resolution (1.5km) RCM covering southern Britain. PE estimates from RCM runs driven by reanalysis boundary conditions are compared to observation-based PE data, to assess performance. The comparison shows that both the 1.5km and 12km RCMs reproduce observation-based PE well, on daily and monthly time-steps, and enables choices to be made about application of the formula using the available data. Data from Current and Future RCM runs driven by boundary conditions from a Global Climate Model are then used to investigate potential future changes in PE, and how certain factors affect those changes. In particular, the importance of including changes in canopy resistance is demonstrated. PE projections are also shown to vary to some extent according to how aerosols are modelled in the RCMs.

Keywords

Canopy conductance, climate change, high resolution, potential evaporation, regional climate model, stomata

Introduction

There is increasing concern about the potential impacts of climate change on the hydrological cycle (Stocker *et al.* 2013). Modelling the possible hydrological impacts is particularly important as changes in the water cycle can affect people and ecosystems both directly (e.g. via changes in water availability and flood frequency) and indirectly (e.g. via changes in food and energy production) (Jiménez Cisneros *et al.* 2014).

Using Regional Climate Model (RCM) data as an input to hydrological models allows investigation of how climate change may affect river flows (e.g. Ott *et al.* 2013, Kay and

Jones 2012). Many hydrological models require inputs of potential evaporation (PE) from vegetated surfaces, alongside precipitation (Bartholomeus *et al.* 2015). Unlike precipitation, PE is usually not available directly from RCMs, so has to be estimated from other variables. The meteorological variables that influence PE are temperature, radiation, humidity and wind speed. In addition, vegetation factors such as leaf area and roughness affect the transpiration component (Kay *et al.* 2013). Many formulae exist for estimating PE, ranging from the physically-based Penman-Monteith formula (Monteith 1965) to much simpler empirical formulae like that of Oudin *et al.* (2005), and the choice can affect the results of subsequent hydrological modelling (e.g. Seiller and Anctil 2014, Kay and Davies 2008). There is much disagreement on the best approach when deriving PE from climate model data for future periods, with concerns about empirical formulae not explicitly including changes in all the influencing variables, but also concerns about data quality when using more complex formulae (see discussion of Kay *et al.* 2013).

As part of a recent Natural Environment Research Council (NERC) Changing Water Cycle project, CONVEX, the Met Office ran a very high resolution (1.5km) RCM for southern Britain, nested in a 12km RCM driven by global atmospheric reanalysis (ERA-Interim) boundary conditions (1989-2008). They also ran Current (1996-2009) and Future (~2100s) climate simulations, with both aerosol climatology and full aerosol modelling setups, nesting the RCMs in a global climate model (GCM). Kendon *et al.* (2012) found that rainfall in the 1.5km RCM is more realistic than in the 12km RCM. In the 12km there is a tendency for heavy rain events to be too persistent and widespread, and not heavy enough. Conversely, the 1.5km RCM has a tendency for heavy rain to be too intense, but it still gives a much better representation of duration and spatial extent.

This paper uses the RCM data from the CONVEX project to estimate PE for short grass, using the Penman-Monteith formula. The following questions are considered

- How do RCM estimates of PE compare with observation-based PE?
- How do the 12km and 1.5km estimates of PE compare?
- How might PE change in the future due to climate change, and what factors influence this PE change?

PE estimates from the ERA-driven RCM runs are compared against observation-based PE from MORECS (Met Office Rainfall and Evaporation Calculation System; Hough *et al.* 1996), as MORECS is the closest to an observational estimate of PE and is widely used by the hydrological community in Britain. Also, the RCM PE estimates are required for an investigation of the use of very high resolution data for hydrological modelling, in which the hydrological models to be used are tuned using MORECS PE along with observed precipitation data (Crooks *et al.* 2014; Bell *et al.* 2012). However, MORECS PE is only produced on a 40x40km grid of squares across the UK. The RCM data thus provides the opportunity to estimate PE using a much finer resolution. The comparison includes an assessment of several choices available within the PE estimation method.

Future changes in PE are investigated using the GCM-driven Current and Future RCM simulations. Relatively few studies have looked at potential future changes in PE in Britain, and even fewer have looked at historical changes, either in Britain or globally, but the studies that do exist generally suggest increases (Kay *et al.* 2013). However, most of these studies have calculated PE changes only from changes in (some of) the meteorological variables; PE can also be affected by increases in the atmospheric concentration of CO_2 via changes in stomatal resistance (Bell *et al.* 2011, Pan *et al.* 2015). The effect of changes in stomatal resistance is considered here, as is the influence of the method of including aerosols in the RCMs.

Although the focus of this paper is use of RCM data to produce PE estimates that will subsequently be used to drive hydrological models, the issues highlighted will be of wider interest. For example, PE can be an important component in crop modelling (Lovelli *et al.* 2010) and ecological modelling (Fisher *et al.* 2011).

Methodology

Regional Climate Model

The 1.5km RCM is a climate version of the UK Met Office 1.5km weather forecast model (UKV) (Kendon *et al.* 2012) but with a smaller domain, spanning southern England and Wales (Figure 1). The 1.5km RCM lateral boundary conditions are supplied by the 12km RCM, which is a limited-area (European domain) atmosphere-only version of the Met Office Hadley Centre Global Environmental Model. For the ERA-driven simulations, the 12km RCM is driven at its lateral boundaries by the latest European Centre for Medium-Range Weather Forecasts Re-Analysis (ERA-Interim, Dee e*t al.* 2011) for the period 1989 to 2008. For the GCM-driven simulations the 12km RCM uses boundary conditions from the HadGEM3 GCM, for Current and Future periods. Table 1 summarises the various RCM simulations available, including two versions of the GCM-driven runs with different aerosol formulations (see below). Kendon *et al.* (2012) found that it takes a few months for soil moisture to spin up in the 1.5km RCM, therefore only data from January of the first full year of each run are included.

For the Current and Future GCM-driven runs, there are both aerosol climatology and fully coupled aerosol modelling runs. The aerosol modelling runs differ from the aerosol climatology runs in that aerosol concentrations are calculated interactively, with advection and deposition of aerosols described. In the case of the 12km RCM, the aerosols are fully coupled to the microphysics, so that aerosol concentrations determine the number of cloud condensation nuclei. A comparison is made of PE from both pairs of model runs for the 12km RCM, as data are available for the full period of ~13 years. The equivalent 1.5km RCM aerosol modelling runs are only about five years in length (Table 1) and are therefore not included in this analysis.

Estimating PE from atmospheric data

PE is generally considered as the amount of water that would be lost to the atmosphere if there were no limits to soil-moisture supply (Kay *et al.* 2013). The Penman-Monteith method is recommended by the United Nations Food and Agricultural Organisation (FAO) for deriving grass reference PE (Pereira *et al.* 1999) and is used by the UK Climate Projection 09 weather generator (Jones *et al.* 2009). Penman-Monteith PE (mm/s) is given by

$$PE = \frac{1}{\lambda}\frac{\Delta R_n + \rho_a c_a (e_s - e_d)/r_a}{\Delta + \gamma\left(1 + r_s / r_a\right)}, \quad (1)$$

where λ is the latent heat of vaporisation (Jkg^{-1}), Δ is the rate of change of saturated vapour pressure with temperature (kPa ^{o}C^{-1}), R_n is the net radiation (Jm^{-2}s^{-1}), ρ_a is the near surface air density (kgm^{-3}), c_a is the specific heat of air (Jkg^{-1} ^{o}C^{-1}), e_s is the saturation vapour pressure at screen temperature (kPa), e_d is the screen vapour pressure (kPa), γ is the psychometric constant (kPa ^{o}C^{-1}), r_a is the aerodynamic resistance to vapour transfer in the atmosphere (sm^{-1}) and r_s is the bulk surface (canopy or bare soil) resistance (sm^{-1}). The saturation vapour pressure e_s at temperature T (^{o}C) is given by

$$e_s(T) = 0.611 \exp\left(\frac{17.27T}{T + 237.3}\right), \tag{2}$$

so $\Delta = de_s/dT = 17.27 \times 237.3\, e_s(T)/(T+237.3)^2$.

Two different formulations are considered for calculating vapour pressure e_d from relative humidity RH (%) and temperature (°C); one uses mean temperature T

$$e_d = \frac{RHe_s(T)}{100}, \tag{3}$$

and the other uses the min and max temperature (T_{min}, T_{max}) (Allen *et al.* 1994)

$$e_d = \frac{RH}{\left(\frac{50}{e_s(T_{\min})} + \frac{50}{e_s(T_{\max})}\right)}. \tag{4}$$

The aerodynamic resistance r_a is calculated from the 10m wind speed U_{10} (ms^{-1}) using

$$r_a = \frac{243.489}{U_{10}}, \tag{5}$$

which includes a logarithmic correction for wind height (Hough *et al.* 1996), and surface resistance r_s is calculated using

$$r_s = \frac{1}{((1-A)/r_{sc}) + (A/r_{ss})}, \tag{6}$$

where $A=0.7^L$, L is leaf area index (LAI), r_{sc} is crop resistance and r_{ss} is bare soil resistance ($100sm^{-1}$) (Hough *et al.* 1996). MORECS monthly values of r_{sc} and LAI for short grass are used (Hough *et al.* 1996) (Table 2).

The climate model variables used for the calculation of PE are thus 1.5m temperature, 1.5m relative humidity, 10m wind speed and net surface downward longwave and shortwave radiation (which sum to R_n).

Estimating PE for Future RCM runs

PE can be affected not just by changes in meteorological inputs, but also by changes in the behaviour of vegetation. In particular, higher CO_2 concentrations can lead to plant stomata opening less widely, resulting in higher stomatal resistance, but can also enhance plant growth, leading to a greater leaf area and more stomata (e.g. Bunce 2004, Keenan *et al.* 2013). Here, following Kruijt *et al.* (2008), changes in crop resistance are considered but changes in leaf area are not, as it was found by Bunce (2004) that there is a lack of response in LAI due to elevated CO_2 concentrations in all functional types, except trees; only grass PE is considered here.

For the Future RCM runs, the equation of Kruijt *et al.* (2008) is used to estimate appropriate values of grass r_{sc} and then r_s. Kruijt *et al.* (2008) found that the average change in grass and herbal crop conductance ($g_{sc}=1/r_{sc}$) per 1ppm increase in atmospheric CO_2 concentration is -$9.3 \times 10^{-2}\% \pm 1.5 \times 10^{-2}\%$ (under well-watered conditions). The increase in atmospheric CO_2 for RCP 8.5 emissions up to year 2100 is 562ppm, therefore the increase in r_{sc} is 109.5%, or

$$r_{sc\_F} = 2.095 r_{sc\_M}, \tag{7}$$

where r_{sc_M} are the monthly MORECS grass r_{sc} values and r_{sc_F} are the values adjusted for the future climate (Table 2). Surface resistance r_s is then calculated from r_{sc_F} using Eq. (6). The subsequent r_s values compare well with other approaches to estimating future r_s, such as taking the average change in r_s from members of the UKCP09 RCM ensemble (Murphy *et al.* 2009) and applying pattern scaling (Mitchell 2003) to allow for differences in emissions scenarios (not shown), and r_s changes used by Moratiel *et al.* (2011).

Results

ERA-driven RCM runs

In order to choose a calculation of vapour pressure (Eq. (3) and (4)) the 12km and 1.5km estimates of PE are compared with MORECS PE at different timescales, daily and monthly, for three sites in Britain (Figure 1) for the year 1990. The sites were chosen to give spatial coverage across the UK; a southern site (Lyneham), a midlands site (Nottingham) and a northern site (Galashiels) (not covered by the 1.5km domain). Figure 2 shows the PE using Eq. (3) for vapour pressure; equivalent figures for PE calculated using Eq. (4) are similar (not shown). Both estimates of PE are comparable to MORECS, however Eq. (3) was chosen as it compares slightly better to MORECS PE.

To estimate monthly PE, two different averaging methods were compared (for 1990 data): a) Calculating daily PE from daily meteorological variables and then averaging, and b) Calculating monthly averages of the meteorological variables and then calculating monthly PE from them. The two methods yield almost identical results (not shown) so daily PE are made and then the monthly average is calculated (the monthly plots in Figure 2 use this method). This test was done as, although daily data were available here, it can be the case that only monthly data are available, or that it is impractical to obtain all the required data at a daily rather than monthly time-step. In such situations, use of monthly data to calculate monthly PE is unlikely to cause problems (as also suggested by Allen *et al.* 1998).

Figure 3 presents maps of the seasonal mean PE for MORECS and the 12km and 1.5km ERA-driven RCMs for 1990-2007. It shows that the RCMs compare well with MORECS and with each other. The comparison looks to be best for spring (MAM) and winter (DJF). The 12km RCM might be slightly overdoing summer (JJA) PE in the south-east compared to MORECS and the 1.5km RCM.

Current and Future RCM runs

Figure 4 shows maps of seasonal mean PE from the Current and Future aerosol climatology RCM runs, and the percentage change between them. The Current PE for the 12km and 1.5km RCMs are similar to each other in magnitude and spatial pattern, with the highest PE in the summer in the southeast and the lowest PE in winter, as for MORECS and the ERA-driven runs (Figure 3). The Future PE from the 12km and 1.5km RCMs is also similar, but consistently higher than Current PE; PE increases across the country and throughout the year. The percentage change in PE for the 1.5km run looks larger in winter compared to the 12km run, however the other seasons look more similar between the two resolutions.

Figure 5 shows the seasonal mean percentage change in PE for three different setups. The left hand column is for the aerosol climatology 12km RCM with fixed MORECS values of crop resistance (r_{sc}), the middle column is for the aerosol climatology 12km RCM with adjusted values of future r_{sc}, and the right hand column shows the equivalent plot for the aerosol modelling 12km RCM with adjusted future r_{sc}. This shows that the percentage changes in seasonal mean PE are much more similar between the aerosol climatology and full aerosol modelling runs (middle and right) than between the adjusted future r_{sc} and fixed MORECS r_{sc} runs (middle and left). For the adjusted future r_{sc} runs, the summer and autumn percentage changes in PE are larger in the aerosol climatology run than the aerosol modelling run, although the winter and spring changes are similar. Not accounting for the change in stomatal resistance gives a much larger increase in PE from the Current to the Future (left column of Figure 5).

To take a closer look at the difference in PE changes between the RCMs, Figure 6 shows how the monthly mean percentage change in PE varies for the three MORECS sites (Figure 1). As well as re-emphasising that the percentage change in PE using the fixed MORECS r_{sc} values is consistently higher than the other two runs, these plots also show that the percentage change in PE for the full aerosol modelling run is lower than that from the aerosol climatology run, for June to September. For the other months the values are more comparable. Fully modelling the aerosols appears to have the effect of lowering the summer PE.

Figure 7 shows the seasonal mean percentage change in shortwave (solar) and longwave radiation for the aerosol climatology and aerosol modelling runs. It shows a larger percentage change in summer radiation in the aerosol climatology run (left column) compared to the aerosol modelling run, especially for shortwave radiation. The seasonal mean percentage change in temperature, relative humidity and wind are more similar for the aerosol climatology and aerosol modelling runs (not shown), so the differences seen in the estimated PE are likely to be due to the radiation differences.

Discussion and conclusions

Estimates of PE from high-resolution (12km and 1.5km) RCM data have been produced, using the physically-based Penman-Monteith formula, with the aim of making PE suitable to use as input for hydrological modelling. Using ERA-driven RCM data, and a comparison with the observation-based MORECS PE, choices were made about the method to use. The comparison shows that both the 1.5km and 12km RCM PE estimates are very similar to each other and comparable to MORECS, spatially and at selected locations, at daily and monthly time-steps.

PE estimates from Current and Future RCM runs driven by GCM boundary conditions have been used to investigate potential future changes in PE, and how certain factors affect those changes. It is found that the seasonal mean PE and its change are in close agreement between the 1.5km and 12km models; this is perhaps not surprising because the large scale changes in humidity, temperature and circulation are common to both RCMs (inherited from the driving GCM). It is also found that future PE is likely to be larger than at present, with the largest increases in summer, autumn and (to a lesser extent) winter. This PE change is influenced by the changes in temperature, relative humidity, wind and radiation as well as stomatal influences through increased CO_2. Not accounting for the stomatal influences can inflate the future PE estimates, consistent with the findings of Bell *et al.* (2011) for UK annual and seasonal mean PE, and such differences can affect subsequent flow projections (e.g. Bell *et al.* 2012, Prudhomme *et al.* 2014).

PE projections are also shown to vary to some extent according to how aerosols are modelled in the RCMs. The PE differences from aerosol differences are in the summer/early autumn and this could potentially be important for hydrological modelling as autumn PE that is too high could delay the rewetting of soils in the lead-up to the main flood season in Britain (Bayliss and Jones 1993). The smaller percentage changes in PE for the aerosol modelling run appear to be related to smaller changes in radiation. The potential hydrological importance of aerosol concentrations, via their influence on radiation and so evaporation, is also shown by Gedney *et al.* (2014), who identify a link between solar dimming, due to rising atmospheric concentrations of aerosols from 1980, and increases in runoff.

Use of the Penman-Monteith PE formulation enabled specific application of changes to crop resistance alongside future changes in meteorological variables. This is not possible (at least in such a straightforward way) with most of the simpler PE formulae, where empirically-derived coefficients replace many of the factors present in the more physically-based formulae (see for example the summary of 17 PE variations given by Oudin *et al.* (2005)). There are already concerns about the application of empirical formulae under changing climates (e.g. Donohue *et al.* 2010, Bartholomeus *et al.* 2015), and the need to also consider changes in canopy resistance is an added complication (Kay *et al.* 2013). The use of fixed crop coefficients to estimate crop PE from reference PE is an additional factor that requires consideration under climate change (Bartholomeus *et al.* 2015), both for hydrological modelling and crop modelling, as different crops may react differently to the same change in CO_2 concentrations (Kruijt *et al.* 2008). Even for hydrological models that do not specifically require PE inputs, similar considerations are likely to apply in the model's internal calculation of evaporation when applied under changing climatic conditions.

Future work will involve running CLASSIC-GB (Crooks *et al.* 2014) with the high-resolution RCM data to investigate the effect of model resolution, and future climate changes, on peak river flows in southern Britain. As the 1.5km full aerosol modelling run is not full length, the aerosol climatology run will be used to get sufficient length to look at flood frequencies.

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Tables

RCM run	Run ID		Time period	Other details
	12km	1.5km		
ERA-driven baseline	ajtyr	akigd	Apr 1989 – Nov 2008	
GCM-driven Current (clim)	alqtj	alxmc	May 1996 – Nov 2009	aerosol climatology
GCM-driven Future (clim)	alqtk	alxme	as above but for ~2100s	aerosol climatology, RCP 8.5 emissions
GCM-driven Current (mod)	alqtl	alxmk	May 1996 – Nov 2009 (12km). Jun 1996 – Mar 2002 (1.5km)	aerosol modelling
GCM-driven Future (mod)	alqtm	alxml	as above but for ~2100s	aerosol modelling, RCP 8.5 emissions

Table 1 Summary of 12km and 1.5km RCM runs, with run IDs and time periods.

Month	Leaf area index (LAI)	Current crop resistance r_{sc_M}	Future crop resistance r_{sc_F}
Jan	2.0	80	168
Feb	2.0	80	168
Mar	3.0	60	126
Apr	4.0	50	105
May	5.0	40	84
Jun	5.0	60	126
Jul	5.0	60	126
Aug	5.0	70	147
Sep	4.0	70	147
Oct	3.0	70	147
Nov	2.5	80	168
Dec	2.0	80	168

Table 2 Monthly leaf area index and crop resistance for Current (r_{sc_M}) and Future (r_{sc_F}) periods, for short grass. LAI and r_{sc_M} are from MORECS, and r_{sc_F} is calculated from r_{sc_M} using Eq. (7).

Figures

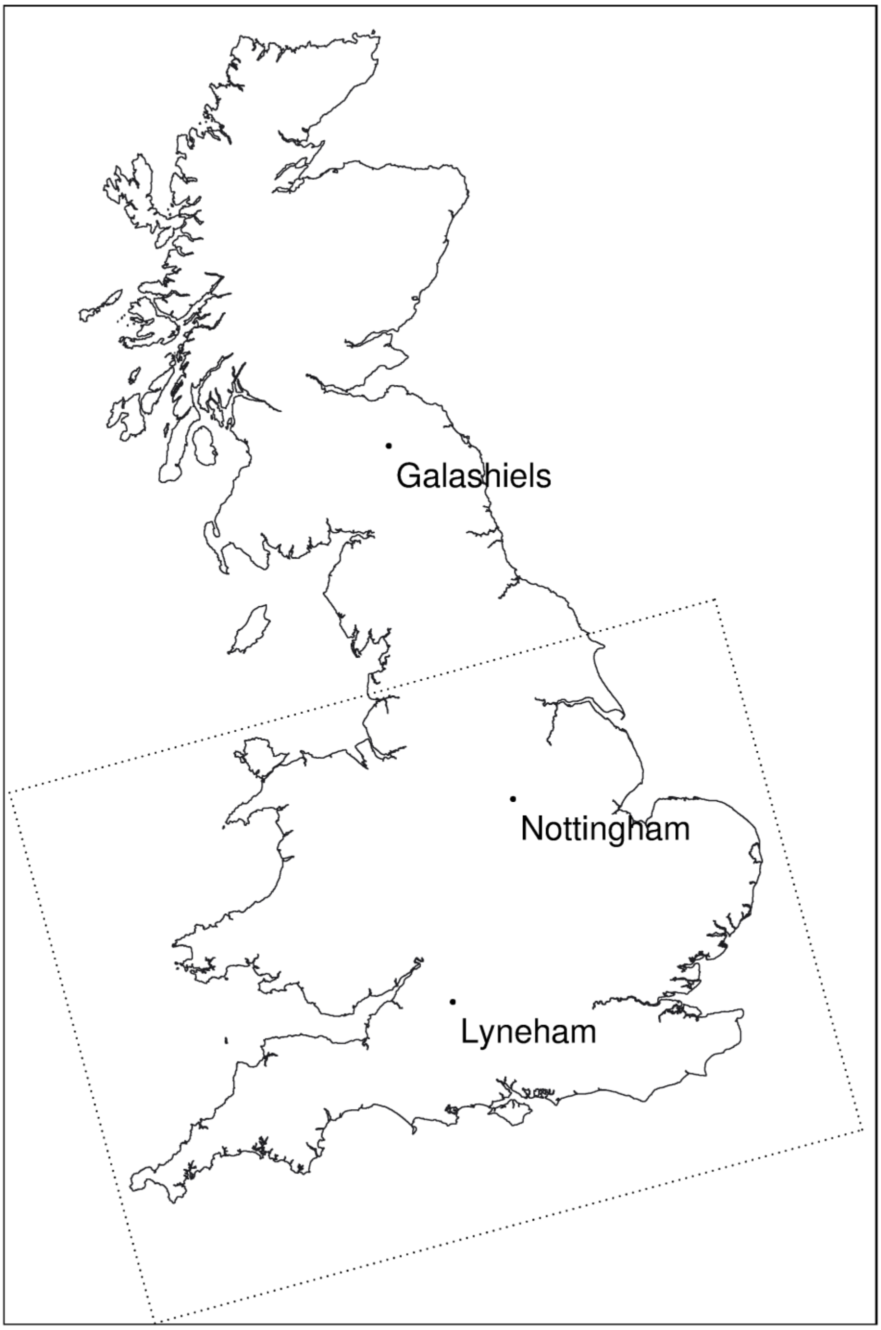

Figure 1 Map showing the 1.5km RCM domain (dotted line) and the locations of three MORECS sites used in the analysis (points).

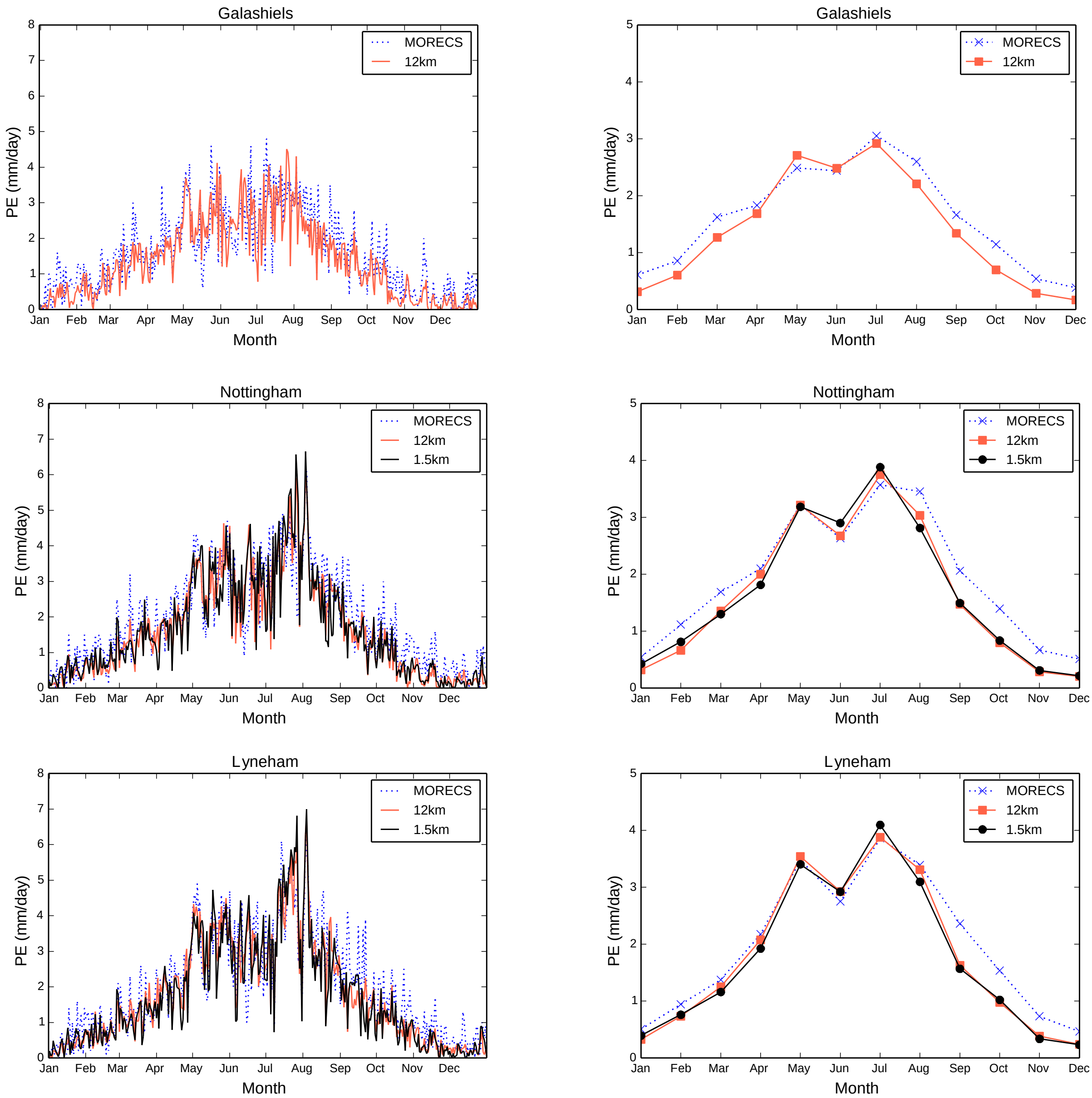

Figure 2 Comparison of daily and monthly MORECS PE and ERA-driven RCM PE for 1990, for three MORECS sites

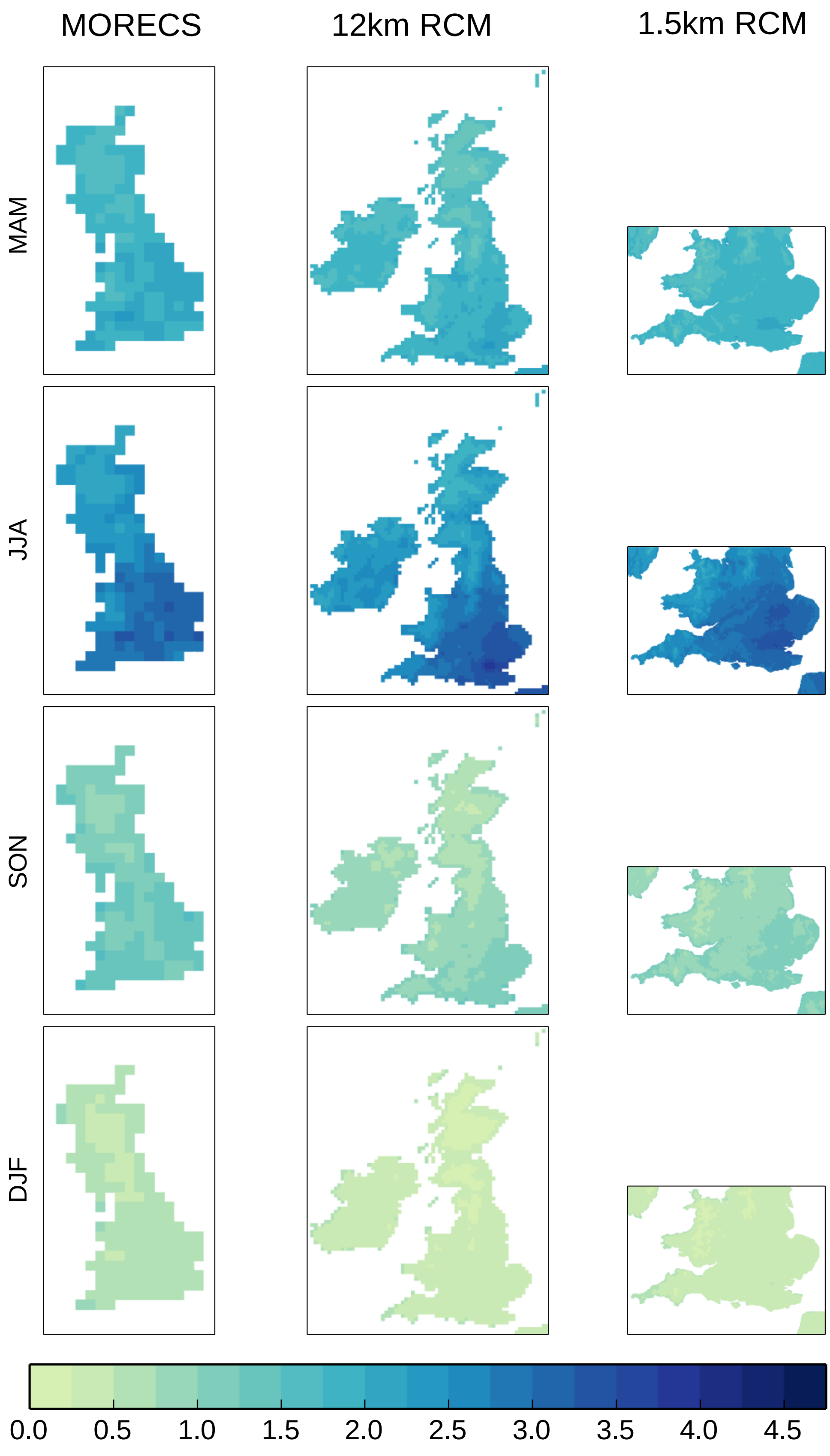

Figure 3 Comparison of seasonal mean PE (mm/day) from MORECS and the 12km and 1.5km ERA-driven RCMs, for 1990–2007.

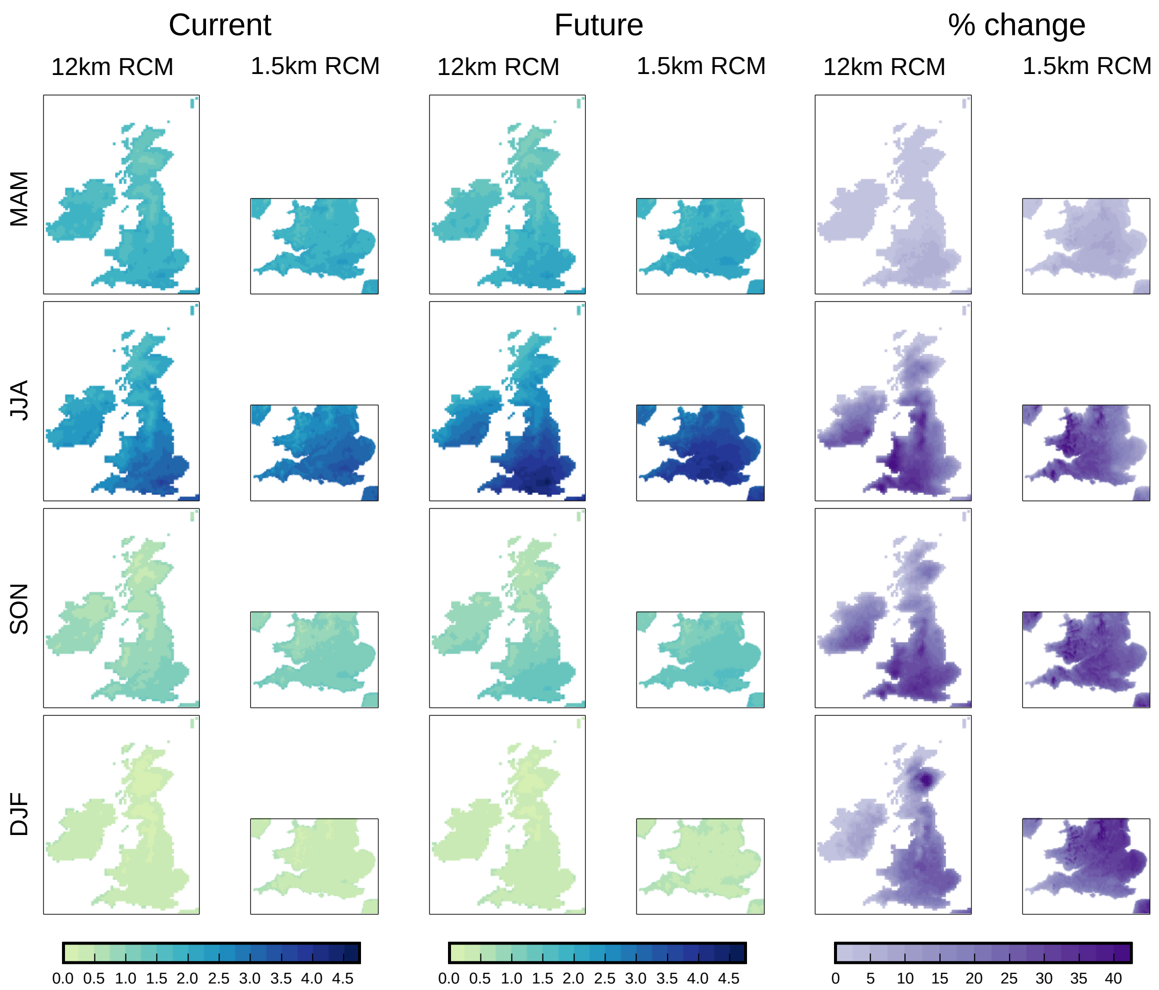

Figure 4 Seasonal mean PE (mm/day) under climate change, including the effect of changes in stomatal resistance. The averages are for 1997–2008 for the Current RCM and for 12 years in the 2100s for the Future RCM. The percentage change between the Current and Future PE is also shown.

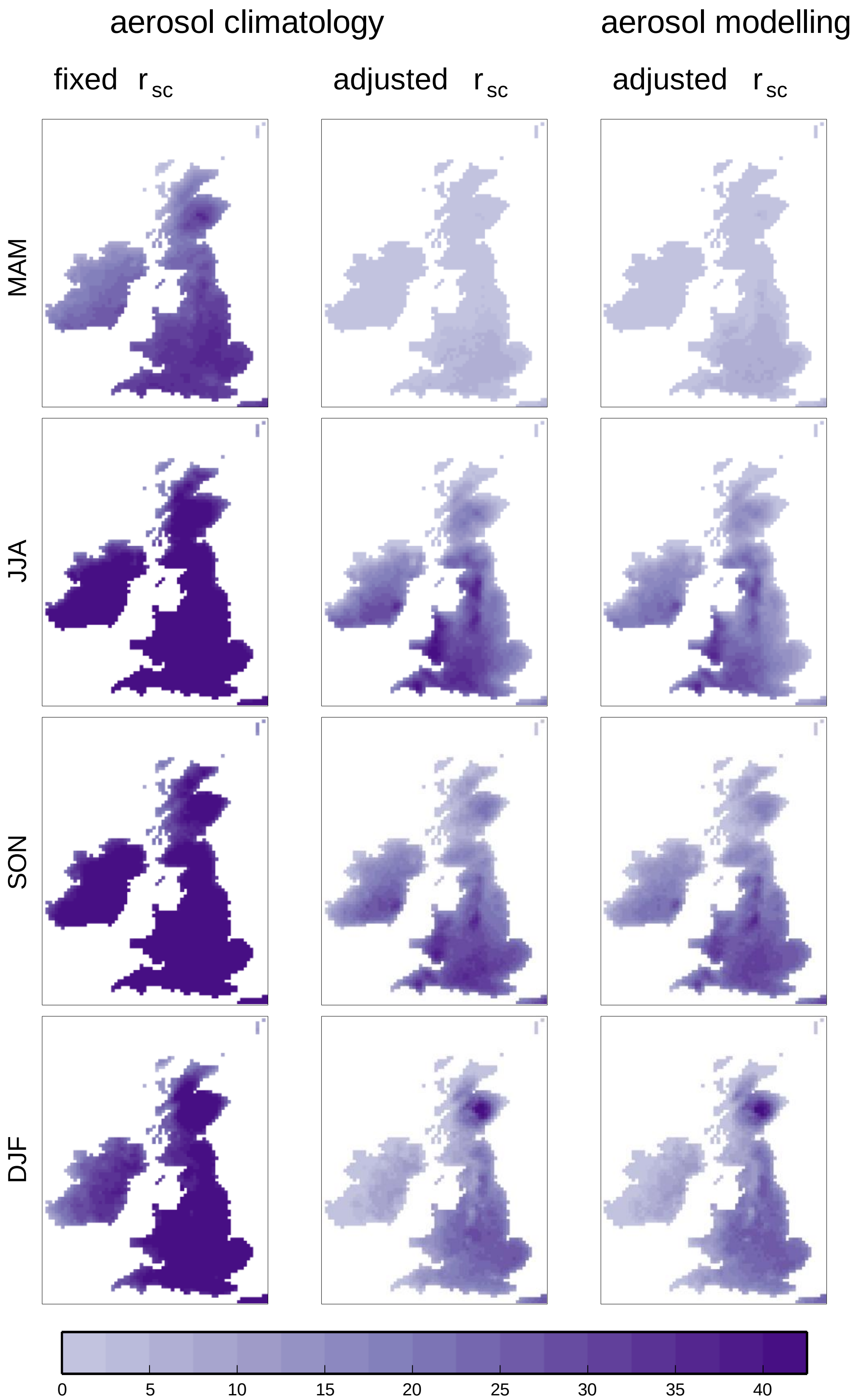

Figure 5 Seasonal mean percentage change in PE for the 12km RCM. Left is fixed MORECS r_{sc} for both Current and Future, with aerosol climatology. Middle is MORECS r_{sc} for Current and adjusted r_{sc} for Future, with aerosol climatology. Right is MORECS r_{sc} for Current and adjusted r_{sc} for Future, with full aerosol modelling.

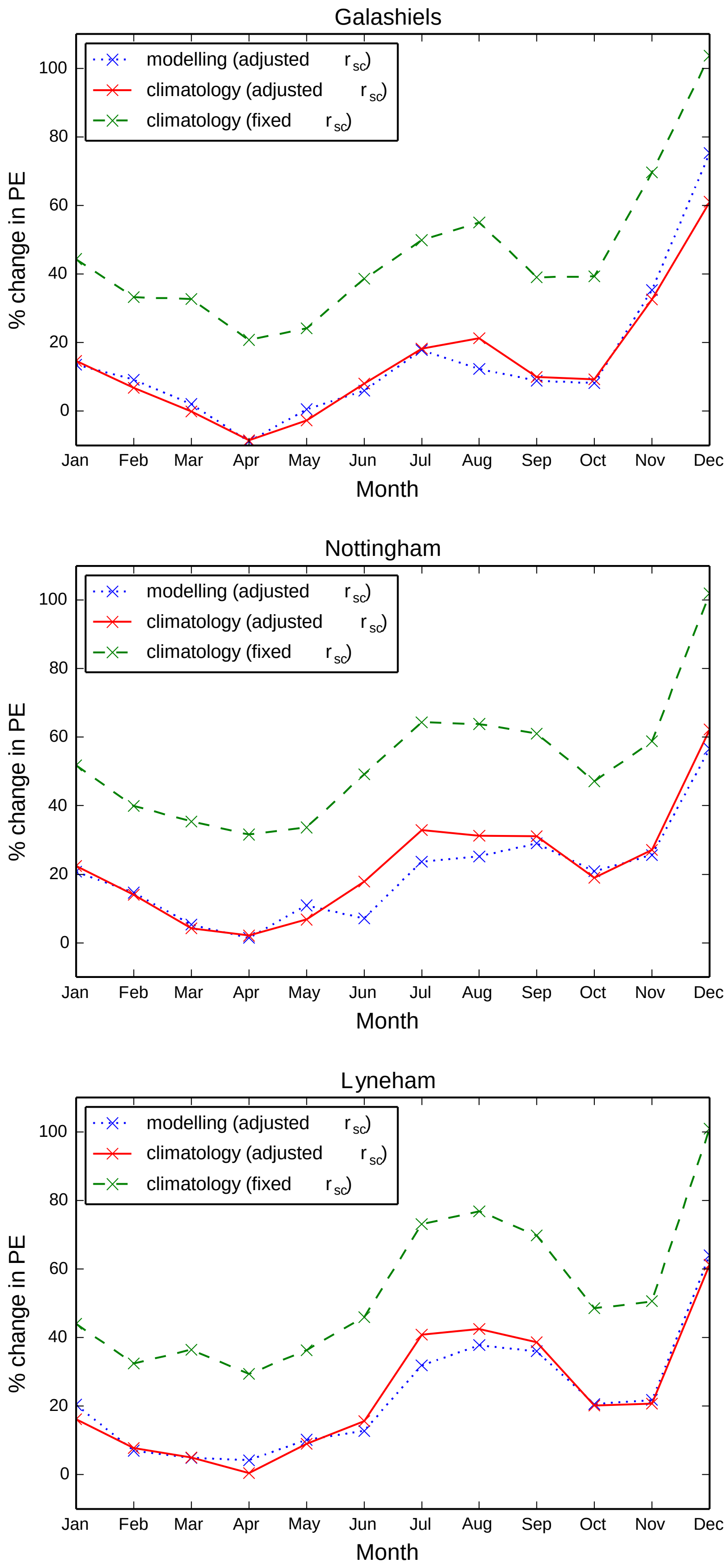

Figure 6 Comparison of percentage change in mean monthly 12km RCM PE for aerosol climatology and full aerosol modelling runs for three MORECS sites.

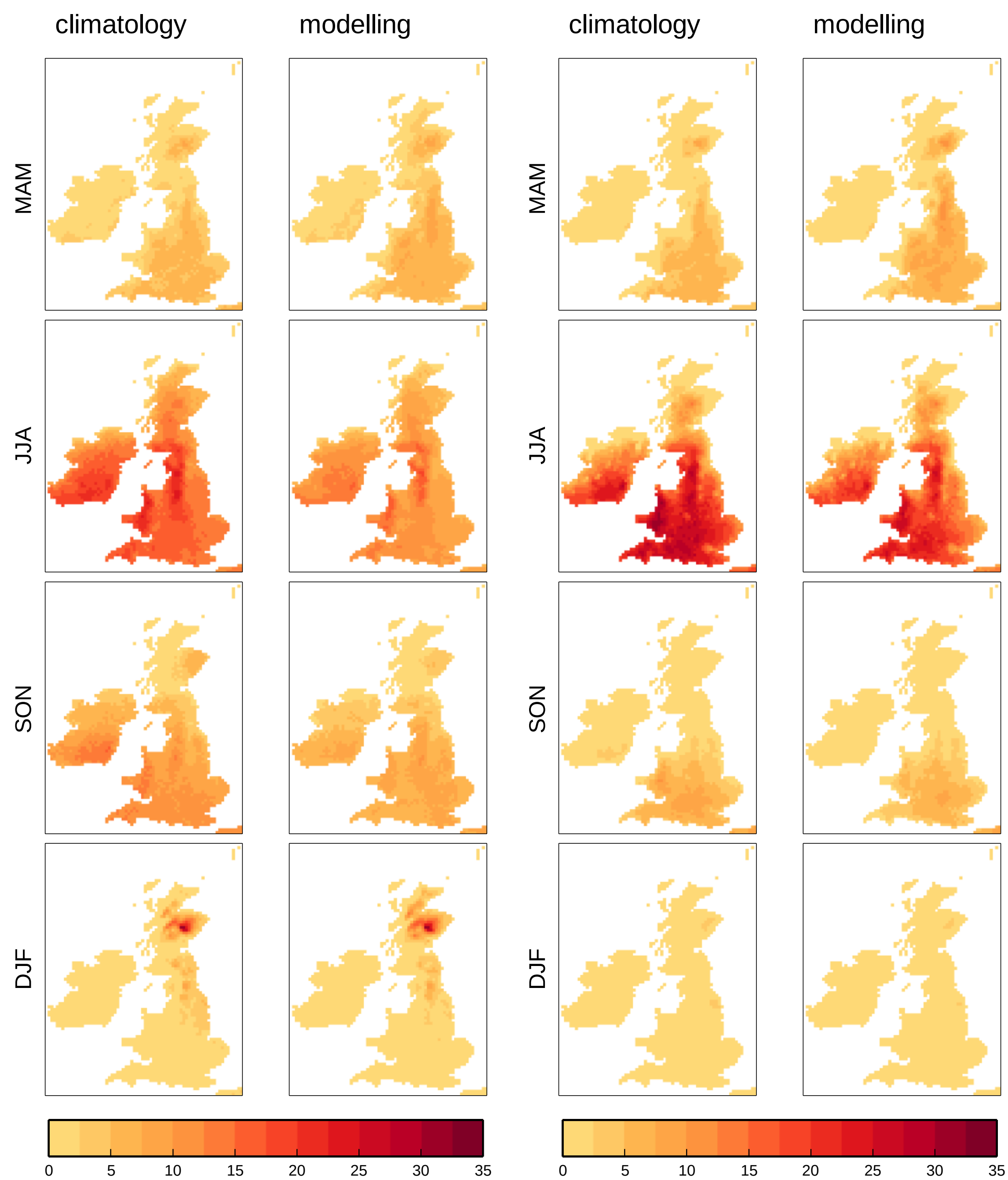

Figure 7 Seasonal mean percentage change in net downward surface radiation (left: shortwave, right: longwave) for the aerosol climatology and full aerosol modelling runs of the 12km RCM.