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Do convection-permitting regional climate models improve projections of future precipitation change?

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ABSTRACT

Regional climate projections are used in a wide range of impact studies, from assessing future flood risk to climate change impacts on food and energy production. These model projections are typically at 12-50km resolution, providing valuable regional detail but with inherent limitations, in part due to the need to parameterise convection. The first climate change experiments at convection-permitting resolution (kilometre-scale grid spacing) are now available for the UK, Alps, Germany, Sydney Australia and western USA. These models give a more realistic representation of convection, and are better able to simulate hourly precipitation characteristics that are poorly represented in coarser resolution climate models. Here we examine these new experiments to determine whether future mid-latitude precipitation projections are robust from coarse to higher resolutions, with implications also for the tropics. We find that the explicit representation of the convective storms themselves, only possible in convection-permitting models, is necessary for capturing changes in the intensity and duration of summertime rain on daily and shorter timescales. Other aspects of rainfall change, including changes in seasonal mean precipitation and event occurrence, appear robust across resolution and therefore coarse resolution regional climate models are likely to provide reliable future projections, provided that large-scale changes from the global climate model are reliable. The improved representation of convective storms also has implications for projections of wind, hail, fog and lightning. We identify a number of impact areas, especially flooding, but also transport and wind energy, for which very high resolution models may be needed for reliable future assessments.

(Capsule Summary) **Climate change experiments at very high (kilometre-scale) resolution are now available which provide potential added value to future projections for convective precipitation, wind gusts, hail, fog and lightning.**

1. Introduction

A recent step change in climate modelling capability has allowed a number of international groups to carry out very high resolution (kilometre-scale) regional climate model experiments. This provides an opportunity to review the extent to which currently available regional climate projections from coarser resolution models are reliable. In this paper, we examine whether very high resolution models provide new or different precipitation projections from traditional coarser resolution climate models, and equally importantly where results are robust across resolutions. Our aim is to provide guidance on the extent to which current regional and national climate scenarios, all of which are based on coarse resolution model output, provide reliable information with which to inform policy decisions and impacts assessments, and which information must be updated using very high resolution projections.

Global climate models (GCMs) are our primary tool for understanding how climate may change in the future with increasing greenhouse gases. These typically have coarse resolutions with grid spacings of 60-300km. To provide regional detail, higher resolution regional climate models (RCMs; 12-50km grid spacing) are often used, which only span a limited area. Since different models typically represent key small-scale processes in the climate system in slightly different ways, an ensemble of multiple GCMs and RCMs is often used to give an estimate of modelling uncertainty in regional climate projections. Recent examples of coordinated regional climate modelling experiments are the ENSEMBLES (Hewitt and Griggs 2004), NARCCAP (Mearns et al. 2009), NARCliM (Evans et al. 2014) and CORDEX (Giorgi et al. 2009) projects, which use a multi-model approach to downscale to 12-50km resolution. An alternative approach was taken by the UK climate projections (UKCP09, Murphy et al. 2009) which used a perturbed physics ensemble, whereby uncertain model parameters were varied within a single GCM to give probabilistic projections which sampled both parameter uncertainty and internal climate variability. Information from a multi-model ensemble was also incorporated, as well as information from observations to weight different model versions depending on their ability to accurately simulate the historical climate. In UKCP09, the GCM simulations were run at a resolution of 300km and were then downscaled using an ensemble of RCMs at 25km resolution.

Although these ensemble based approaches give some estimate of modelling uncertainty, they do not reveal uncertainties that arise from limitations inherent in all models at those resolutions. At typical climate model resolutions (10-100 km) many important processes (such as those in clouds) occur on spatial scales too small to be resolved explicitly on the model grid and are therefore represented using parameterisations. A good example of this is convection parameterisation, which aims to describe the average properties of convection over a model grid box but leads to deficiencies in the diurnal cycle of convection, precipitation occurrence and extremes (Dai 2006; Hohenegger et al. 2008; Stephens et al. 2010).

The first climate change experiments at very high resolution (<5km grid spacing) have recently been completed for the UK (Kendon et al. 2014), the Alpine region (Ban et al. 2015), central Germany (Tolle et al. 2014), southwestern Germany (Fosser et al. in press), Sydney Australia (Argueso et al. 2014), the Colorado headwaters (Rasmussen et al. 2014) and the western USA (Pan et al. 2011). At these resolutions, the deep convective parameterisation scheme can be switched off, with the use of shallow convective parameterisation varying between studies. Deep convection schemes are not designed to operate in km-scale models, and many of the assumptions of these schemes (e.g. that the cloud coverage is small compared to the grid square) are violated at these resolutions. Shallow plumes typically have smaller horizontal length scales and without some kind of parameterisation there is a missing process (small cumulus clouds are too small to be explicitly represented on the grid), but the use of shallow convective parameterisation is only appropriate if the scheme has been designed to operate at km-scale. At this scale, the model is termed 'convection-permitting' because larger convective storms are 'permitted' but convective plumes and smaller showers are still not resolved. Such convection-permitting models are commonly used in short-range weather forecasting, where they have been shown to give a much more realistic representation of convection and can be used to forecast the possibility of localised high-impact rainfall not captured at coarser resolutions (Done et al. 2004; Lean et al. 2008; Weisman et al. 2008; Weusthoff et al. 2010; Schwartz 2014). However, due to their high computational cost, they have not commonly been applied at climate-time scales. Convection-permitting models do not necessarily better represent daily mean precipitation (Chan et al. 2013), but have significantly better sub-daily rainfall characteristics with improved representation of the diurnal cycle of convection (Ban et al. 2014), the spatial structure of rainfall and its duration-intensity characteristics (Kendon et al. 2012), and the intensity of hourly precipitation extremes (Chan et al. 2014b; Ban et al. 2014; Fosser et al. 2015), which are typically poorly represented in climate models. Prein et al. (2015) provide an excellent review of the added value of convection permitting climate modelling, showing added value emerging when and where deep convection is dominant and in regions of strong spatial heterogeneities (mountains and urban areas). Although convection-permitting models still contain errors, e.g. smaller showers are not properly resolved leading to a tendency for heavy rainfall to be too intense (Kendon et al. 2012; Fosser et al. 2015), they provide a step change in our ability to represent convection and an opportunity to examine the importance of representing local storms for future climate projections.

In this paper, we bring together results from climate change experiments performed at 1.5km resolution over the southern UK (Kendon et al. 2014) and 2.2km over the Alpine region (Ban et al. 2015) to explore commonalities, and also refer to findings from Numerical Weather Prediction (NWP) and convection-permitting climate studies recently completed for other regions. The UK simulations span the southern UK and are driven by a 12km RCM which spans Europe and is in turn driven by a 60km GCM, with all models being configurations of the Met Office Unified Model (Walters et al. 2011). The Alps simulations span the greater Alpine region and are driven by a 12km European RCM, which is in turn driven by a T63 spectral ($\sim$200km) resolution GCM. In this case the RCM is the COSMO-CLM model, whilst the GCM is the Earth System Model of the Max Planck Institute (MPI-ESM-LR) (Stevens et al. 2013). In both cases the simulations are for two $\sim$10-year periods, one corresponding to the present-day and the other to the end of the century under RCP8.5 (the exact period and run length varies between experiments, see Supplementary Material for details). Given in each case we are restricted to only one model realisation, we are unable to assess uncertainty in the climate change signal. However where commonalities in the effect of resolution are identified across different regions and different climate models, we have greater confidence in the result.

This paper complements the review of Prein et al. (2015), which mostly focussed on the added value of convection-permitting simulations for present-day climate variability, by assessing whether such very high resolution models are needed for reliable future projections. We focus on rainfall projections, since these are expected to be most sensitive to model resolution and the explicit representation of convection. We also consider implications for other climate variables, including wind, hail, fog, lightning and soil moisture.

2. To what extent do precipitation projections agree between coarse and high resolution RCMs?

a. Coarse resolution RCMs are likely to provide robust projections of changes in seasonal mean rainfall, providing that large-scale changes from the GCM are reliable.

We find that projected changes in seasonal mean rainfall are in close agreement between high resolution (convection-permitting) and coarser resolution (convection-parameterised) regional climate models, driven by the same large scale conditions. For example, Figures 1 and 2 show projected changes to winter and summer rainfall over the southern UK for a 1.5km and 12km RCM (described in Kendon et al. 2014). Similar agreement in projected changes in summer mean precipitation is found in Ban et al. (2015) for 2.2km and 12km RCMs over the Alps and in Fosser et al. (in press) for 2.8km and 7km models over SW Germany. For summer, this agreement is probably because the convection scheme is able to (and indeed designed to) simulate time-average precipitation, even if the diurnal cycle is incorrect (too strong midday peak) and short-timescale intensity is too weak; and for winter, because mean rainfall is dominated by larger-scale dynamical rainbands that are well captured at 12km. We note that Rasmussen et al. (2014) found reduced biases in the representation of mean summer rainfall in a convection-permitting model over the Colorado headwaters, which may impact on future projected changes, but the improvement here is likely to be linked specifically to the improved representation of complex topography at high resolution.

Changes in daily and hourly rainfall are, however, more important than changes in seasonal averages for many climate impacts. In particular, changes in the intensity and duration of rainfall are crucial for understanding future flood risk and changes in the occurrence of rainfall are important for water resource planning and agriculture. Hence we now turn our attention to examine whether these aspects of rainfall change are robust from coarser to higher model resolution.

b. Changes in rainfall occurrence are largely consistent between convection-permitting and coarser resolutions in summer and winter

We find that changes in rainfall occurrence are largely consistent between the convection-permitting and parent 12km RCM, in winter and summer, for both the UK and Alps simulations (Figures 3 and 4) with large decreases in rainfall occurrence in summer at both resolutions. For the UK, this is despite present-day biases being quite different between the two different resolution models, with the 12km RCM tending to have too many wet hours and wet days, whilst the 1.5km RCM has too few especially in summer. Fosser et al. (in press) also show a similar decrease in summer rainfall occurrence in 2.8km and 7km models, despite quite different biases across model resolution for the present-day. Large RCM biases for the Alps simulations are largely inherited from the driving GCM, with biases for European Reanalysis (ERA) Interim (Dee et al. 2011) driven simulations being much smaller (see Supplementary Figures 1 and 2). Known problems with radar over mountainous regions, and sampling errors associated with gauge observations, may also contribute to the apparently larger biases over the Alps compared to the UK. The tendency for too much low intensity precipitation in the Alps simulations in winter is most apparent on the hourly timescale, since when averaging over longer periods, multiple hourly occurrences still give the same daily count as a single occurrence on that day. We note that although the differences between the Alps and UK results are probably in part due to the driving model differences and/or verification data, there are also likely to be some differences that come from the contrast in topography and nature of the rainfall between the two regions (Alps drier in winter and more convective in summer in comparison to the UK). We expect high resolution to be beneficial for both frontal and convective rain over regions of steep orography, with the occurrence and spatial patterns of rainfall better captured over mountainous regions (Prein et al. 2015), whereas in flatter regions frontal rain (especially in winter) is sufficiently well captured at coarser resolutions. In general, the improved representation of orography at high resolution is expected to impact rainfall on longer temporal scales, with model biases focussed on the hourly timescale expected to be more related to the representation of convection.

Chan et al. (2014a) show that over the UK the large-scale conditions from the driving GCM control whether precipitation is triggered or not, but how long the precipitation lasts once triggered is sensitive to the RCM model physics (and is different between convection-permitting and convection-parameterised models). The former (i.e. changes in triggering) dominates the future decrease in summer rainfall occurrence, whereas the latter (i.e. how long it lasts) leads to the resolution dependence of present-day biases. Thus coarser resolution RCMs are likely to be sufficient for projecting changes in the occurrence of rainfall where this is dominated by changes to the triggering of events. Since dry spell length is determined by the sequence of rainfall events (synonymous with triggering), we expect changes in dry spell length to also be robustly captured at coarser resolution. We note this result may not extend to those tropical regions where large-scale forcing is less dominant in triggering events, although may apply in some tropical areas where the large-scale matters more (e.g. African Easterly Waves, Indian Monsoon).

c. Changes in rainfall intensity are robust across model resolution in winter, but show significant differences in summer

We find good agreement between convection permitting and 12km RCM results, for both the UK and Alps simulations, for change to winter precipitation intensities (Figure 5). This is despite resolution-dependent model biases for the present-day in some cases. The agreement in changes across resolution can be explained by the fact that changes in intensity over Europe in winter come predominantly from frontal rain from mid-latitude weather systems with greater moisture availability (Kendon et al. 2014) - a process well captured by coarse resolution climate models. In summer, by contrast, convection-permitting models show significant increases in rainfall intensity over the southern UK and the Alps (Figure 6), that are not captured by the parent 12km RCM, for a comparison made at the 12km scale (Kendon et al. 2014; Ban et al. 2015). This can be explained by the 12km RCM being constrained by the behaviour of the convection parameterisation. These increases become larger in relative terms at finer spatial and temporal scales. It is notable that the pattern of future changes across space and time-scales, and across resolution, is remarkably similar between the southern UK and the Alps simulations. The convection-permitting model tends to have reduced biases in summer, although in the case of the Alps simulations, there are large RCM biases inherited from the driving GCM (see Supplementary Figures 3 and 4). Fosser et al. (in press) found contrasting results with similar increases in intensity for 2.8km convection-permitting and 7km convection-parameterised models over SW Germany, although with different spatial patterns. The agreement across resolution in this latter study may be due to the relatively high resolution of the convection-parameterised model (7km compared to 12km in Kendon et al. (2014) and Ban et al. (2015)).

We note that Ban et al. (2015) found greater consistency between the 2.2km and 12km RCMs for a metric of heavy rainfall (specifically percentiles of all values instead of only wet values, and hence a measure of rainfall intensity and frequency combined). However further analysis for the UK reveals such agreement does not extend across a range of percentiles. Thus the finding that changes in summertime rainfall intensity are resolution-dependent does not appear to simply be an artefact of the chosen metric.

d. Convection-permitting resolution is needed to capture changes in the duration of summertime rainfall

Projected changes in the duration of summertime rain are quite different between convection-permitting and coarser resolution models over the southern UK (Kendon et al. 2014, and figures therein). In the 12km RCM precipitation tends to be too low-intensity and too long-duration, with these biases largely eliminated in the 1.5km model due to the better representation of convective rain (Kendon et al. 2012). Fosser et al. (in press) found contrasting results with similar changes in the intensity-duration characteristics of rainfall in 2.8km and 7km models over SW Germany. This better agreement may be due to the relatively high resolution (7km) of the convection-parameterised model or the small size of the 2.8km model domain, which may limit the RCM's ability to generate its own small-scale features.

e. Changes in daily and hourly rainfall extremes are not robust across model resolution, particularly in summer

For the UK, projected changes to extreme hourly rainfall differ markedly between 1.5km and 12km resolution in summer, to the extent that they differ in sign (Chan et al. 2014a). This discrepancy is also found for daily extremes, although to a lesser extent. Extreme events (with return periods of greater than 20 years) in the 12km RCM are linked to single grid-point storms or storms with unphysically large updraught regions, providing low confidence in projections. Results for the Alps are consistent with results for the UK: Ban et al. (2015) find considerable discrepancies in projected changes in extreme hourly intensities in summer between 2.2km and 12km resolution. In winter, there is some suggestion that projected changes in UK extreme daily rainfall over orography may be greater at convection-permitting resolution (Chan et al. 2014a). This may be explained by a stronger response associated with the more accurate representation of orography in the high resolution model, which may affect daily rainfall accumulations more than 1-hour accumulations. We may expect the benefit of high resolution to be different over orography, with improved representation of topography as well as improved representation of convective storms impacting on precipitation. On hourly timescales, the most intense rainfall is from convective storms rather than orographic rain, and hence on shorter timescales the improved representation of convective processes should dominate as realised by commonalities between the Alps and UK results.

3. Implications for other climate variables

In this section we consider how the improved representation of convection at the km-scale has implications for other climate variables. In particular we consider wind, hail, fog, lightning and soil moisture that in turn impacts local temperature. We note that the improved representation of local topography and surface heterogeneities in convection-permitting models will also have significant impact, for example for projections of urban temperature (Trusilova et al. 2013; Argueso et al. 2014, 2015) and climate over mountainous regions (Knote et al. 2010; Rasmussen et al. 2014). However, a discussion of this is beyond the scope of the current paper, which focuses on the implications of the improved representation of the local storm dynamics.

a. Convection-permitting resolution is needed to capture changes in severe wind gusts

Kilometre-scale models allow a more accurate representation of local wind, in part through the better representation of topography (e.g. sea-breezes, mountain effects), but also as a consequence of capturing convective storms. Modelling convective wind gusts requires a convection-permitting model, for example derechoes are severe convective squall lines with intense winds which can only be represented at convection-permitting scales. Over the UK, such systems are rare and only likely to occur in summer. In winter, the highest winds on sub-daily timescales are typically associated with cyclonic storms, and coarse resolution models ($\sim$12-25km grid spacing) with appropriate gust diagnostics are able to reasonably well represent these. However, there will still be some situations when local processes dominate in the smallest mesoscale systems (e.g. embedded convection or small 'sting-jets' (Browning 2004)).

b. Convection-permitting resolution is likely to give more reliable projections of future changes in hail, but further research is needed

Hail is of particular interest, being responsible for increasingly significant economic damages to buildings, crops, cars and other infrastructure. Two events in central and southern Germany on 27 and 28 July 2013 caused the highest insured loss from a natural hazard in Germany to date. A number of studies have shown that convection-permitting climate models are able to provide useful guidance of the occurrence of hail (Trapp et al. 2011; Gensini and Mote 2014). Mahoney et al. (2012) investigated future changes in hail in convection-permitting simulations using a case study approach and found that although more hail was generated within the cloud with storm intensification, little reached the surface due to enhanced melting. It is unclear, however, whether such high resolutions are required to provide reliable projections of future changes in hail and whether the hail produced by microphysics schemes and post-processing algorithms is sufficiently good. In particular, coarser resolution models may be sufficient, if post-processed hail diagnostics (e.g. Hand and Cappelluti 2011) are sufficiently accurate, although hail diagnosis from convection-permitting models should still give a better physical representation and is less reliant on arguably tenuous links between large-scale environmental conditions and small-scale weather extremes (Mahoney et al. 2012).

c. Further research is required to assess whether very high resolution is needed for projecting future changes in fog

The UKCP09 25km models suggest the frequency of fog will be reduced in future across the UK in many regions and seasons, but with considerable uncertainties. Where changes in fog are driven by large-scale variables such as temperature and humidity, we may be able to make confident statements about large-scale changes in fog. However on the local scale, fog depends on many different variables including topography, aerosol amounts and local turbulent fluctuations. These processes may be better represented in a convection-permitting model, although it is unclear whether km-scale models provide more accurate future projections compared to post-processed coarse model output. Boundary layer clouds may require resolution of turbulent eddies in some cases, which would require grid scales of 'Large Eddy Simulation' models (tens of metres).

d. Convection-permitting resolution has the potential to provide more accurate lightning projections, but further research is needed

A lightning diagnostic has been developed for convection-permitting configurations of the Met Office Unified Model which uses a physically-based link between cloud properties and lightning flash rate (Wilkinson and Bornemann 2014). In particular lightning flash rate is determined from the upward flux of graupel (McCaul et al. 2009), which in convection-parameterised models tends to be too low. An alternative commonly used by convection-parameterised models is to link the flash rate to bulk cloud properties (e.g. Price and Rind 1992). However, this statistical approach removes the link between the cloud microphysical processes. It is only in the convection-permitting model that we are able to use actual physical processes in the cloud to determine lightning. This latter approach shows good skill in forecasting the timing and occurrence of lightning but overpredicts its extent, although its behaviour is yet to be fully determined over a long period.

e. Convection-permitting models may give different soil moisture conditions and feedbacks

The more realistic representation of rainfall in convection-permitting models impacts soil moisture conditions. In particular, in the present-climate, the southern UK 1.5km RCM has drier soils than the 12km RCM due to the more sporadic nature of rainfall, which is less effective at wetting the soils. Soil moisture conditions and surface evapotranspiration may in turn have a considerable impact on local temperature changes (Tolle et al. 2014). If soils become dry enough they can limit evaporation, leading to hotter temperatures. Soil-moisture precipitation feedbacks were also found to be very different in a convection-permitting model compared to a convection-parameterised model over the Alps (Hohenegger et al. 2009). The extent to which future projected changes in soil moisture are resolution-dependent is currently unexplored. However, the fact that soil moisture conditions and potentially their future change may be quite different in convection-permitting models has important implications for changes in temperature extremes and also for climate change impacts for example on agriculture.

4. Discussion

National climate change scenarios are currently available for many countries worldwide, for example, for the UK (UKCP09, Murphy et al. 2009), Netherlands (KNMI 2015) Switzerland (CH 2011) and U.S. (Melillo et al. 2014). These inform adaptation planning and often feed into downstream impact assessments to inform decisions in sectors such as transport, healthcare, water resources and flood protection. However, the quality of these national climate scenarios depends on the ability of the underlying model experiments to capture key processes and all are based on coarse resolution climate model simulations. In this paper we have demonstrated how new, very high resolution, regional climate models allow us to assess the robustness of current national climate scenarios. We conclude by providing users information on where currently available projections are reliable and, conversely, where it is necessary to use results emerging from very high resolution model experiments.

We have identified a number of aspects of mid-latitude precipitation change which disagree significantly between convection-permitting and coarser resolution RCMs, and for which very high resolution (km-scale) models are needed for accurate future projections. These include changes in:

- summertime rainfall intensity and duration
- hourly and daily rainfall extremes in summer
- daily precipitation extremes over mountains in winter

Other aspects of precipitation change appear to be reliably captured in currently available projections from regional climate models, providing large-scale changes from the driving GCM are reliable. These include changes in:

- seasonal mean precipitation
- rainfall event occurrence
- precipitation intensity in winter

In addition, we have identified other climate variables for which km-scale climate models are likely to be needed for future projections, e.g. severe wind gusts; whilst for others, including hail, fog and lightning, further research is required. A summary of these conclusions is presented in Figure 7.

It is encouraging that the resolution dependence of projections for simulations over the UK and the Alps show considerable consistency. This suggests firstly, that with increases in model resolution climate projections from different models may show convergence. Secondly, it indicates that the conclusion that the local storm dynamics (only represented in convection-permitting models) are needed for future projections of short-duration extremes is more widely applicable in other regions, for convectively-dominated regimes and seasons. This is supported by some observational evidence (Lenderink and van Meijgaard 2008). Although these results are for mid-latitude summer precipitation, they are likely to be similar throughout the tropics, where much more precipitation arises from smaller scale motions.

A move towards very high resolution climate modelling seems necessary for quantification of certain impacts, particularly around extremes. Reliable projections of rainfall extremes are important for understanding future flood risk, and hence for informing decisions regarding urban planning, flood protection and the design of resilient infrastructure. Surface water flooding and flooding from drainage networks is the predominant source of flooding in urban areas as a direct response to high intensity short-duration rainfall. In a recent pilot study, Dale et al. (2015) showed that estimates of rainfall intensity change from the UK 1.5km climate model were higher than existing UK climate change allowances, leading to projections of more frequent sewer overflow spills in future. This is only one example but is indicative of the fact that current climate change guidance based on national climate scenarios, e.g. current allowances for changes in peak rainfall intensity in the UK, may not be adequate. There is a need to revisit current guidance in the light of emerging results from very high resolution climate models. New information from these models may also help to inform redesign of existing critical infrastructure systems. A number of recent major flood events in the UK has brought this starkly into focus.

Our findings also have implications for a number of other impact areas (Table 1).

a. Extreme winds can cause significant disruption to electricity infrastructure and transportation, and an understanding of future wind risk will inform prioritisation of adaptation investments. Km-scale models are needed to give improved projections of future change to severe wind gusts. These are also needed by the wind energy industry for the planning, design and operation of wind turbines.

b. Lightning strikes can cause significant disruption to electricity infrastructure, and the potential for more accurate lightning predictions from convection-permitting climate models is likely to be of considerable interest to utility companies.

Multi-model ensemble experiments such as ENSEMBLES (Hewitt and Griggs 2004), NARCCAP (Mearns et al. 2009), NARCliM (Evans et al. 2014) and CORDEX (Giorgi et al. 2009) are limited by the inherent deficiencies in traditional convection-parameterised models. Although they provide valuable information about uncertainties in projections of seasonal mean rainfall and dynamically driven frontal systems, they cannot provide reliable estimates of changes in summertime rainfall intensity and duration or other convectively driven phenomena such as severe wind gusts. For this, explicit representation of convective storms, only possible in convection-permitting models, is crucial. However, currently only single model realisations over small domains are available at these resolutions. There is a need for an international effort, e.g. CORDEX, to provide co-ordinated multi-model experiments at convection-permitting resolutions over a series of common domains to estimate modelling uncertainty at these scales. This would allow a comprehensive evaluation of the potential for improving simulations of not only precipitation characteristics, but other aspects of climate such as land-atmosphere interactions, convective systems, and mountain or urban effects that are impacted by the improved representation of surface heterogeneities.

In the UK, an update to the UKCP09 projections is currently underway. This will include a downscaling component, running an ensemble of km-scale models over the UK. This will hopefully allow projections to be provided on sub-daily and local scales, with some estimate of uncertainty, which was beyond the UKCP09 modelling capability. We note however the very high cost of convection-permitting simulations means it is not possible to run simulations at these scales for many regions and for large ensembles of driving data. This impacts our ability to fully explore uncertainties at these scales. This is of critical importance for climate change projections, which are necessarily probabilistic and need to incorporate uncertainty due to natural climate variability as well as modelling uncertainty. A potential approach for future progress could be through combined statistical and dynamical downscaling. For example, it may be possible to sub-select periods and ensemble members for dynamical downscaling from the large-scale conditions, and thus achieve effective targeting of km-scale simulations. In particular, early work suggests statistical regression relationships based on the large-scale climate state may be skilful in identifying when local precipitation extremes may occur (although not their intensity or duration) and hence when information from a convection-permitting model is needed. It should be noted although the signal coming from the convection-permitting model is conditional on the larger-scale environment, it still provides a considerable improvement in local projections compared to solely relying on coarser resolutions.

Despite the advent of km-scale regional climate models our confidence in projections is strongly controlled by the ability of global climate models to represent relevant large-scale processes and changes in large-scale circulation patterns. In parallel with developments in convection-permitting regional climate modelling, there are now a number of examples of high resolution experiments with global climate models. Long climate experiments have been performed within the UPSCALE project (Mizielinski et al. 2014) with GCMs at 25km grid spacing. At resolutions of 60km or higher, large-scale moisture transport seems to have converged in the mid-latitudes (Demory et al. 2014). The representation of many other processes is also found to improve with increasing model resolution, e.g. atmospheric blocking (Scaife et al. 2011; Berckmans et al. 2013) and regional modes of variability (MacLachlan et al. 2014), however, the convergence of these processes with model resolution is not yet robustly established. The two simulations in the main examined here used very different resolution driving GCMs. The Alps simulations showed significant biases in large-scale conditions inherited from a $\sim$200km resolution GCM. These were found to impact rainfall frequency and intensity over Switzerland in downscaling simulations (Supplementary figures 1-4). By comparison, 60km GCM-driven downscaling simulations over the UK gave comparable biases to ERA-Interim driven simulations (Supplementary figures 5-8), suggesting that the 60km GCM is able to capture the synoptic and mesoscale variability important for constraining local rainfall in this region. In general, present-day biases will only be a good guide of the reliability of future projections, where the biases relate to the same processes which are controlling the future change. It is essential that GCM ability to capture the key large-scale processes driving future changes, which will vary between regions, is established before any regional downscaling is attempted.

This study is not a comprehensive assessment of the reliability of regional projections from coarse resolution models. It only gives an indication of the robustness of projections going from coarser to higher resolution, and in particular to convection-permitting scales. The experiments available to date are limited to single model realisations for different mid-latitude regions, and so no estimate of modelling uncertainty in the climate change signal is possible. There are also many other potential deficiences and in some cases relating to limitations that are common to all current climate models. For example, there are large uncertainties in earth system processes that impact on atmospheric CO_2 concentrations for given CO_2 emissions, as well as provide feedbacks on climate change; and uncertainties in processes occurring on very small scales, such as cloud microphysics. One important question is the extent to which we may expect changes to be robust on going to even higher resolutions. In the foreseeable future, it will likely become possible to run climate simulations at convection-resolving scales (grid scales of order 10m) for very small domains. Initial indications from numerical weather prediction are that the representation of convection does not necessarily improve with further increases in resolution once in the regime of being able to explicitly represent convection (Hanley et al. 2015), given our current knowledge about the representation of turbulence and microphysical processes. However, what we can say is that even at km-scale resolution, these models generate new climate projections with potentially profound implications for a number of sectors.

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LIST OF TABLES

Impact area	Currently available future climate projection	New information from high resolution climate modelling
Flash flooding (important in urban areas and small steep catchments)	Heavy daily rainfall is expected to increase globally, with projected increases across northern Europe and the UK in winter. Coarse resolution climate models are unable to provide reliable projections of future changes in short duration intense rainfall.	First evidence that intense rainfall events, associated with severe flash flooding (30mm in an hour), could become several times more frequent by the end of the century (Kendon et al. 2014).
Renewable energy (wind energy)	Future changes in wind are uncertain. 12-25km resolution models with appropriate gust diagnostics can represent cyclonic storms and their associated winds, but not the most severe convective wind gusts.	Kilometre-scale models are needed to represent severe wind gusts, associated with convective squall lines.
Transport (flooding, visibility, strong winds and snow)	Heavy daily rainfall is expected to increase (depending on region and season) with an associated increase in large scale flooding, but see above for flash flooding. There is large uncertainty in fog projections at 25km. Coarse resolution models should be sufficient for projecting changes in cyclonic storms and temperature-driven changes in snow.	See above for flash flooding. High resolution models are needed to adequately represent severe wind gusts and convective snow storms. High resolutions may be required for accurate projections of local fog and snow over mountains.
Electrical distribution (lightning)	25km models suggest increases in the number of lightning days in future across the UK, but there is considerable uncertainty in the accuracy of coarse model lightning diagnostics.	New lightning diagnostics, developed for kilometre scale models, have the potential for more accurate lightning predictions.

TABLE 1. Summary of currently available future climate projections and new information from high resolution climate modelling, for selected impact areas

LIST OF FIGURES

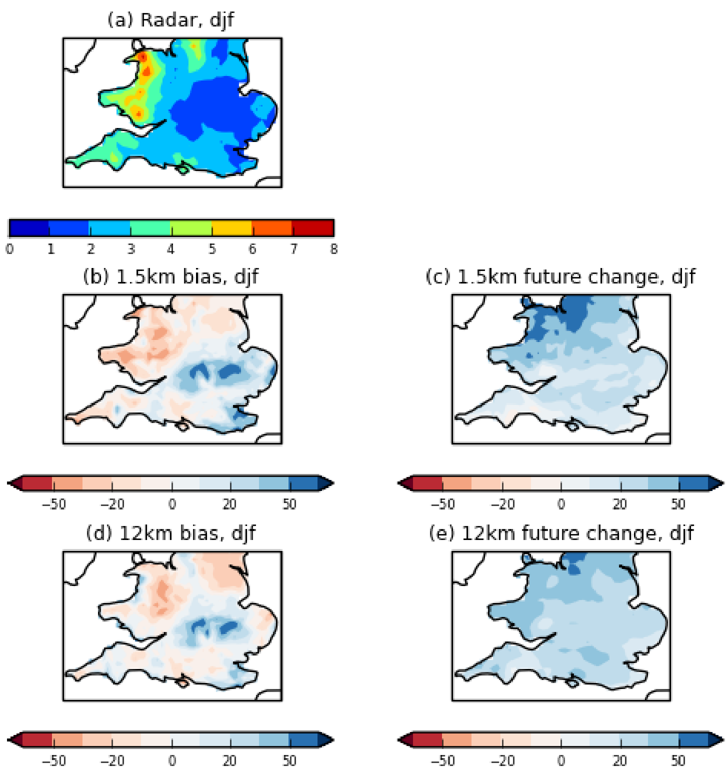


FIG. 1. Seasonal mean rainfall (mm/d) over the southern UK for winter (DJF) in the (a) radar, and (b,d) model-radar differences (%) and (c,e) future changes (%) for the 1.5km and 12km RCMs. The RCM simulations are for 13-year present-day (1996-2009) and 13-year future (2100, under RCP8.5 scenario) periods. Radar data are for the period 2003-2012. Results are only shown over UK land points.

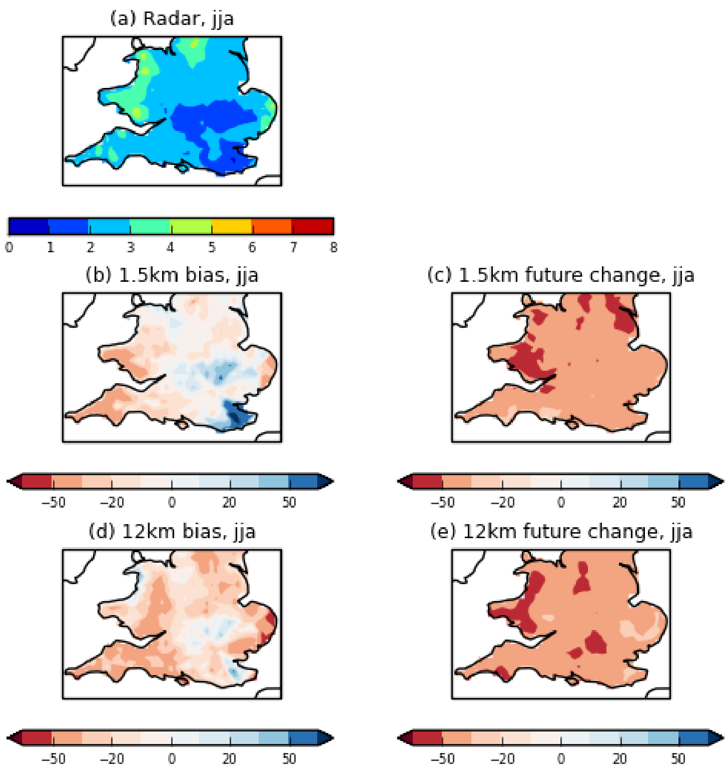


FIG. 2. As Figure 1 but for summer (JJA).

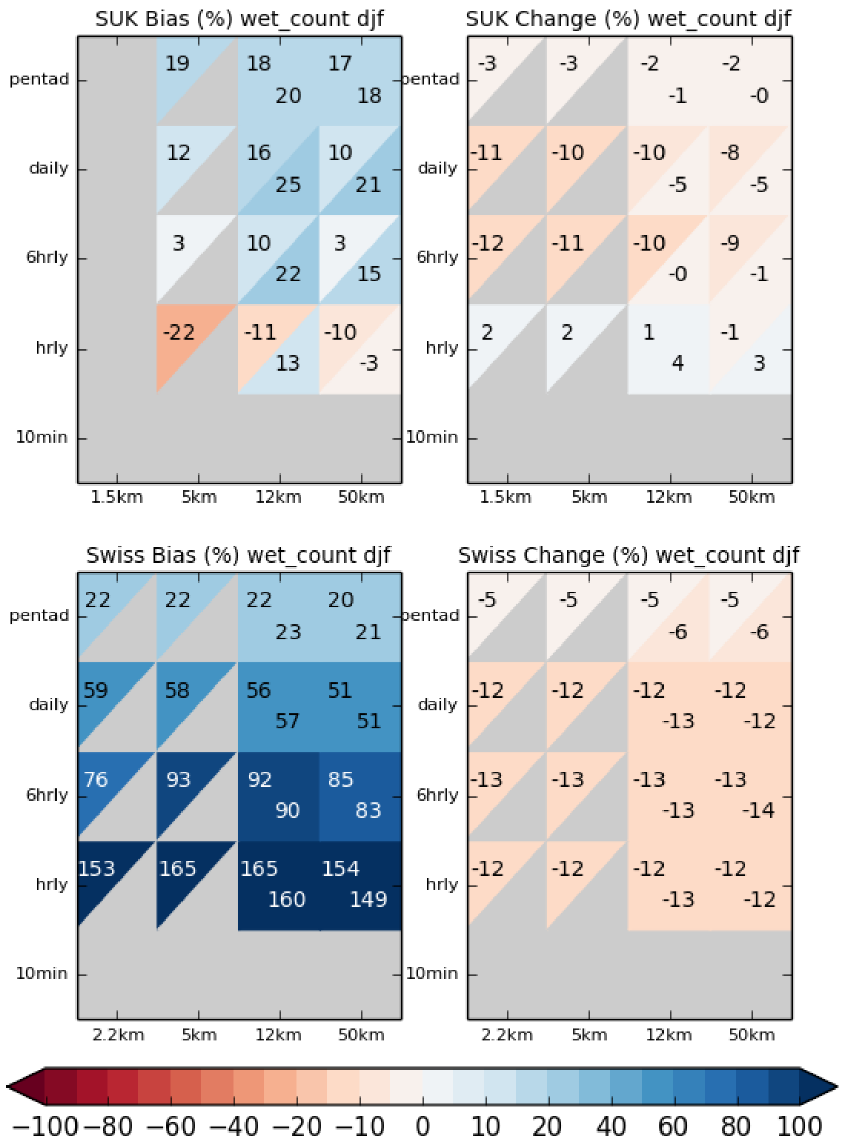


FIG. 3. Biases and changes (%) in rainfall occurrence across space and time scales averaged over the (top) southern UK and (bottom) Switzerland, in winter (DJF). Biases are calculated as model-observation differences, using hourly 5km Nimrod radar data for the UK for 2003-2012 (Golding 1998) and 1km RdisaggH combined radar-gauge observations for Switzerland for 2004-2010 (Wuest et al. 2010). Changes correspond to differences between decadal-length present-day and future (end of century, under RCP8.5) simulations. Results for the convection-permitting (1.5km or 2.2km) RCM are shown in the upper left triangle and for the 12km RCM in the lower right triangle. Grey indicates where results are not available. A threshold of 0.1mm per accumulation period is used to define rainfall occurrence.

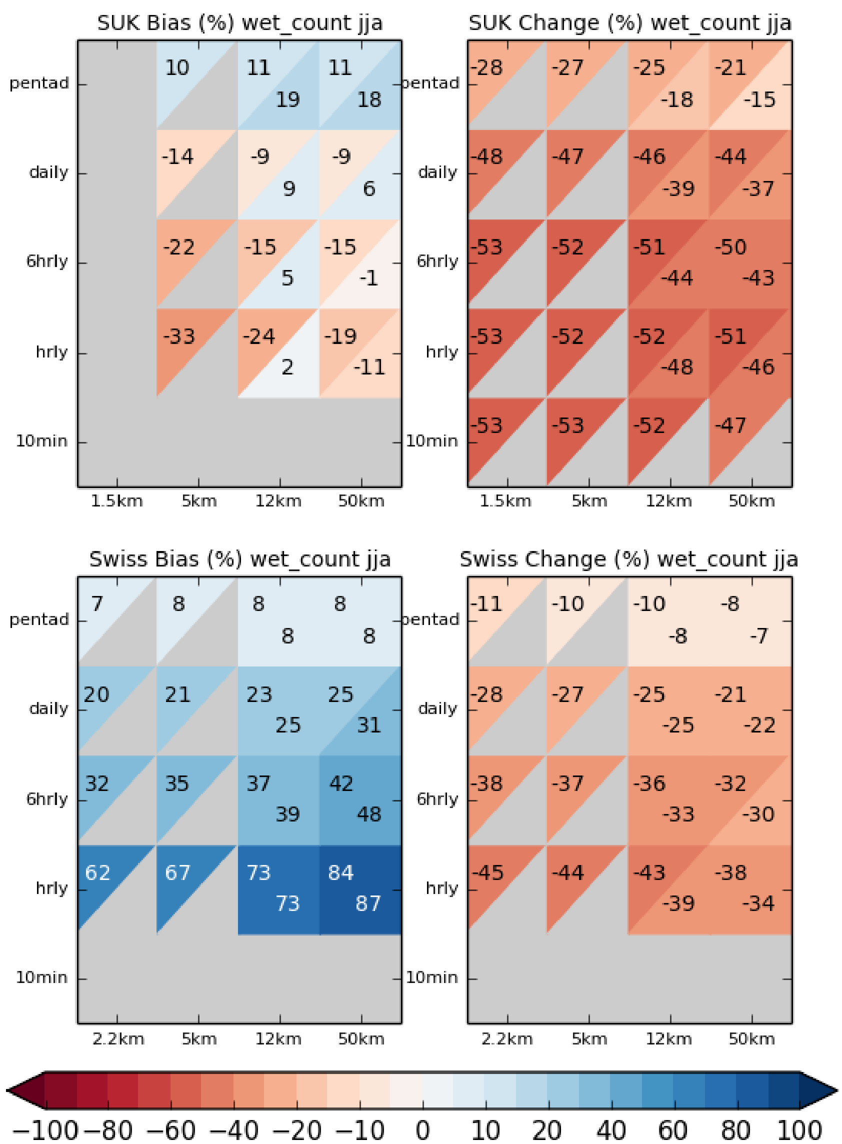
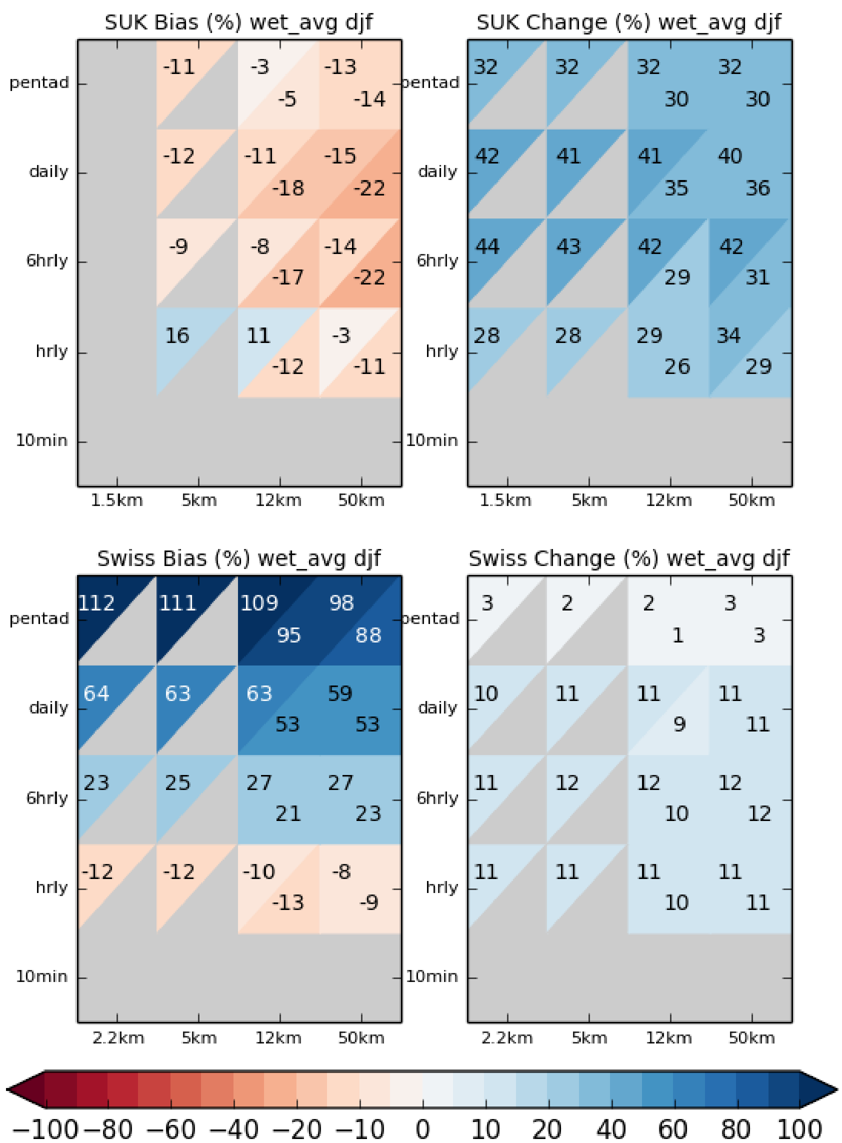


FIG. 4. As Figure 3 but for summer (JJA).



669 FIG. 5. Biases and changes (%) in rainfall intensity across space and time scales averaged over the (top)
670 southern UK and (bottom) Switzerland, in winter (DJF). Rainfall intensity is defined as the mean of wet values
671 (>0.1mm per accumulation period). Definitions are as in Figure 3.

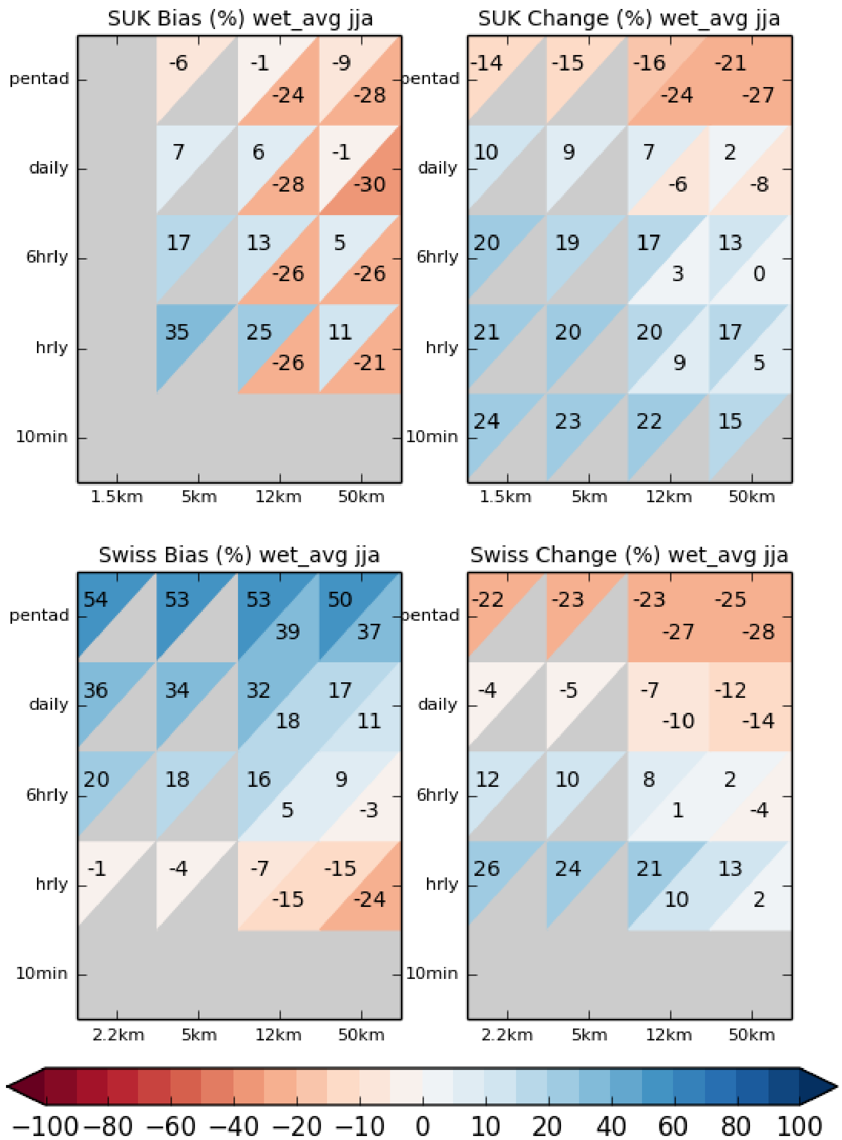
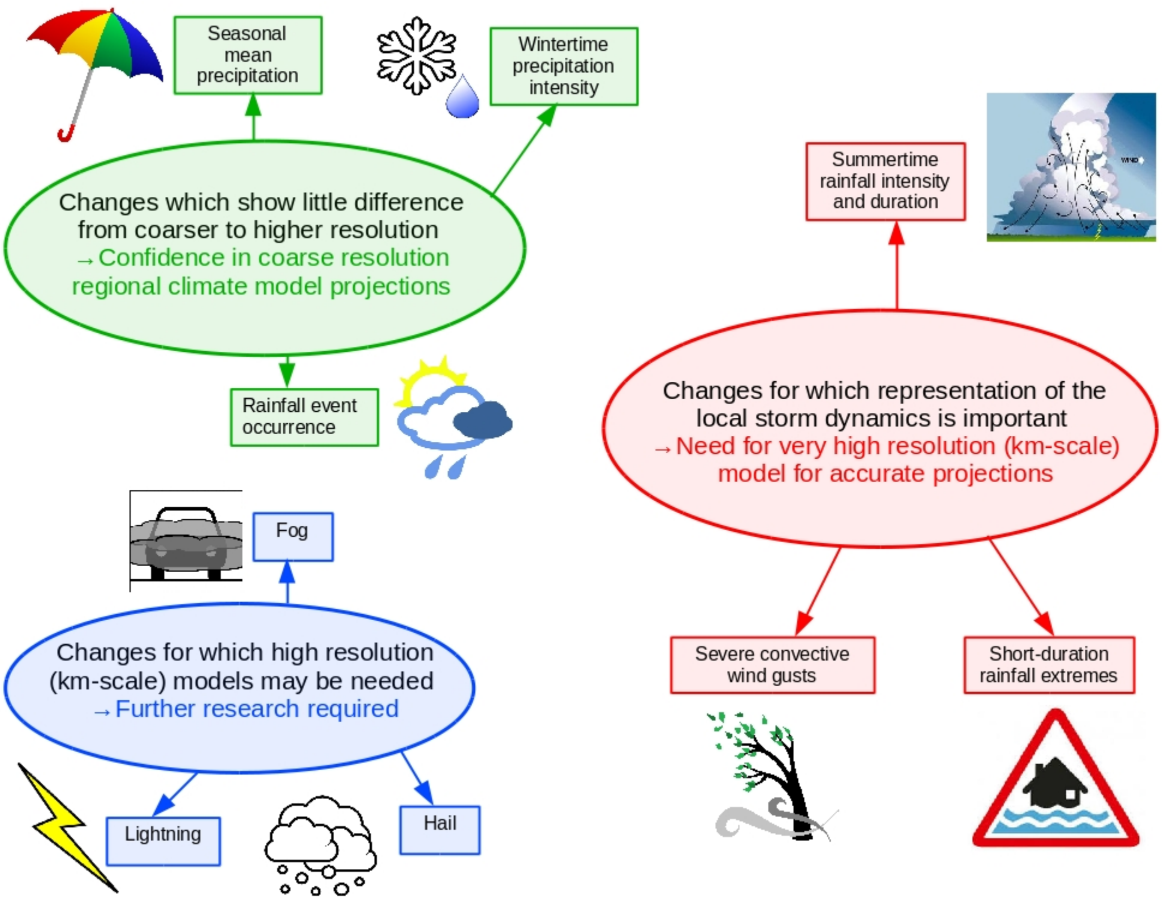


FIG. 6. As Figure 5 but for summer (JJA).



672 FIG. 7. Schematic summarising where we have confidence in coarse resolution regional climate model pro-
673 jections, and where very high resolution (km-scale) models are needed for accurate projections

Do convection-permitting regional climate models improve projections of future precipitation change?

Supplementary Material

The UK experiments used here are described in Kendon et al. (2014). They are configurations of the Met Office Unified Model (UM). The 1.5km model spans the southern UK and is driven by a 12km RCM which spans Europe and is in turn driven by a 60km GCM. The 12km RCM and 60km GCM both have the UM Global Atmosphere 3.0 (GA3) configuration (Walters et al. 2011). The 1.5km model has similar model physics, except that the convection scheme has been switched off and Smagorinsky-Lilly turbulence diffusion is applied. The simulations examined here are for 13-year present-day (1996-2009) and 13-year future (2100, under RCP8.5 scenario) periods. Model biases for the present-day have been assessed by comparison with 5km gridded hourly observations from radar, available for the UK for 2003-2012 (Golding 1998).

The Alps experiments used here are described in Ban et al. (2015). The 2.2km model spans the greater Alpine region and is driven by a 12km RCM which spans Europe and is in turn driven by a T63 spectral ($\sim$200km) resolution GCM. The RCMs are the COSMO-CLM model (Steppeler et al. 2003), whilst the GCM is the Earth System Model of the Max Planck Institute (MPI-ESM-LR) (Stevens et al. 2013). In the 2.2km RCM the deep convection scheme is switched off, whilst the shallow convection scheme remains active. The models are run for 10-year present-day (1991-2000) and 10-year future (2081-2090, under RCP8.5 scenario) periods. Model biases for the present-day have been assessed by comparison with 1km RdisaggH combined radar-gauge hourly observations, available for Switzerland for 2004-2010 (Wuest et al. 2010).

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List of Figures

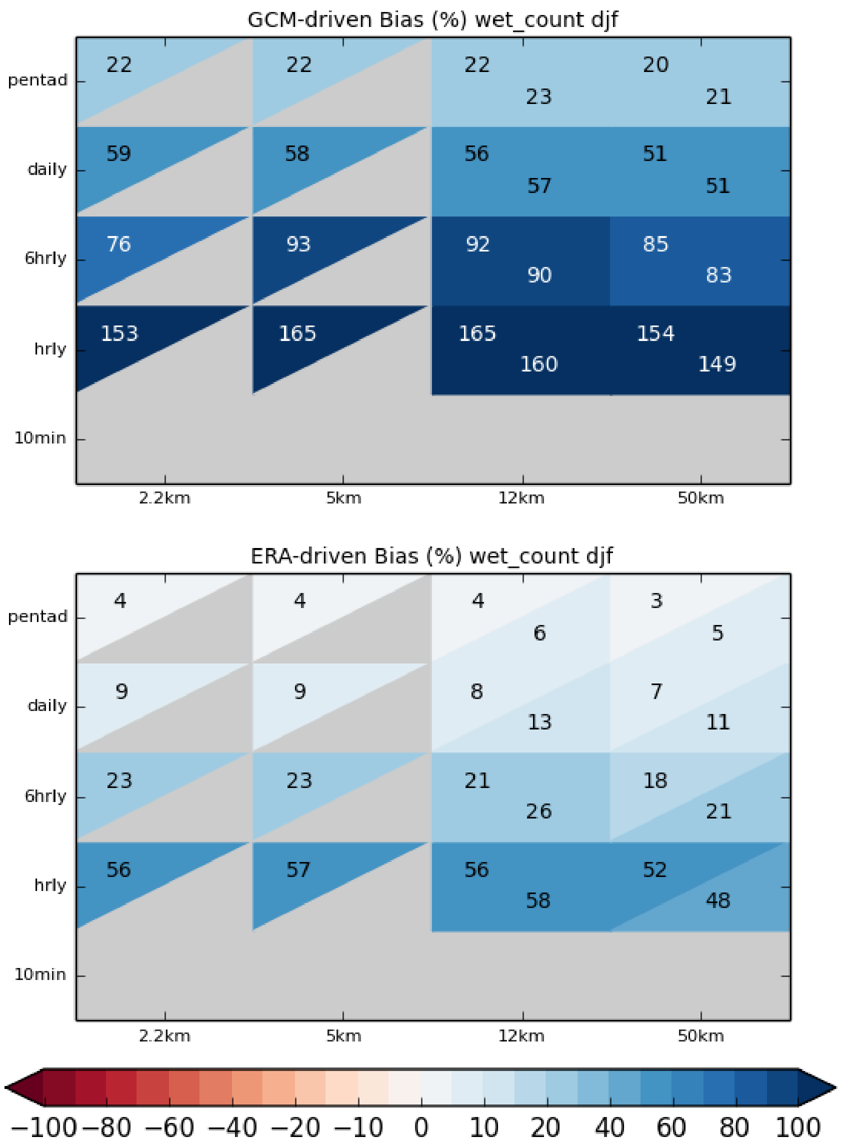

FIG. 1. Biases (%) in rainfall occurrence across space and time scales averaged over Switzerland for RCMs driven by MPI-ESM GCM (top) and ERA-Interim (bottom), in winter (DJF). Biases are calculated as model-observation differences, using 1km RdisaggH combined radar-gauge observations for Switzerland. Results for the convection-permitting (2.2km) RCM are shown in the upper left triangle and for the 12km RCM in the lower right triangle. Grey indicates where results are not available. A threshold of 0.1mm per accumulation period is used to define rainfall occurrence.

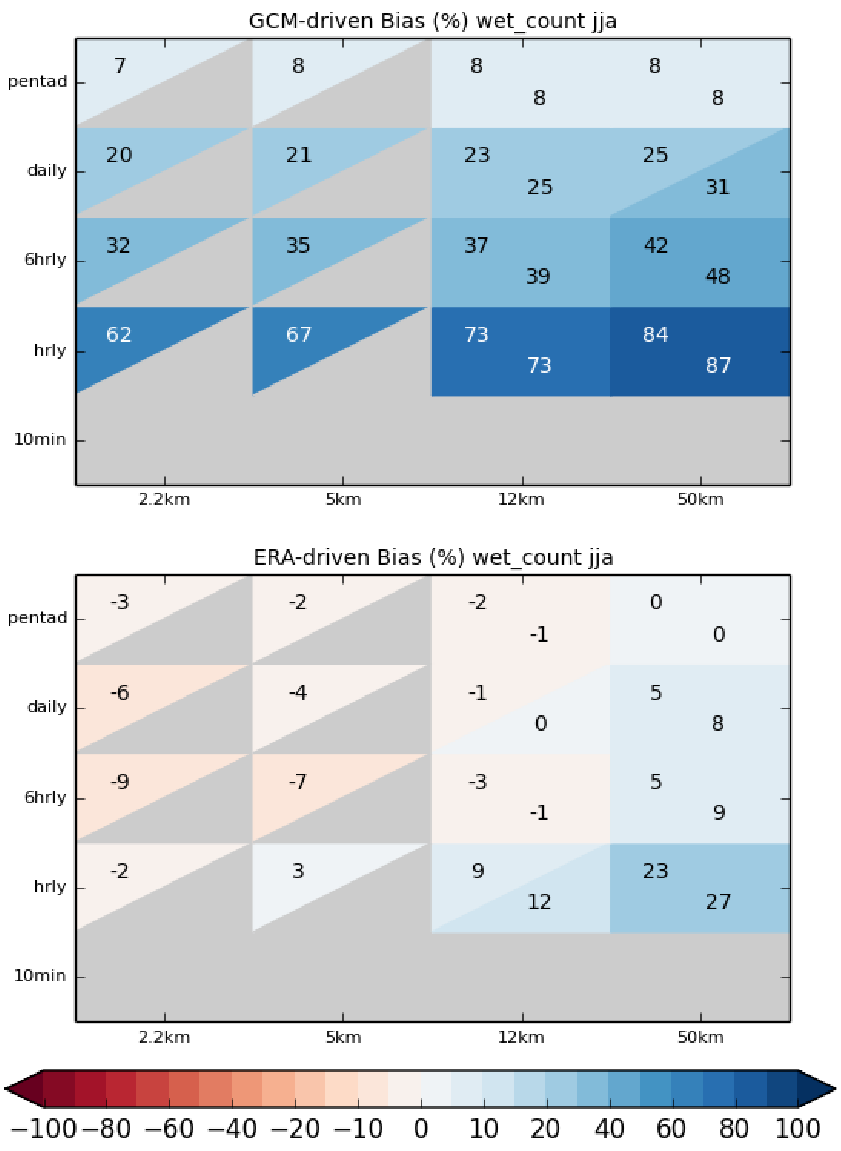

FIG. 2. As Supplementary Figure 1 but for summer (JJA).

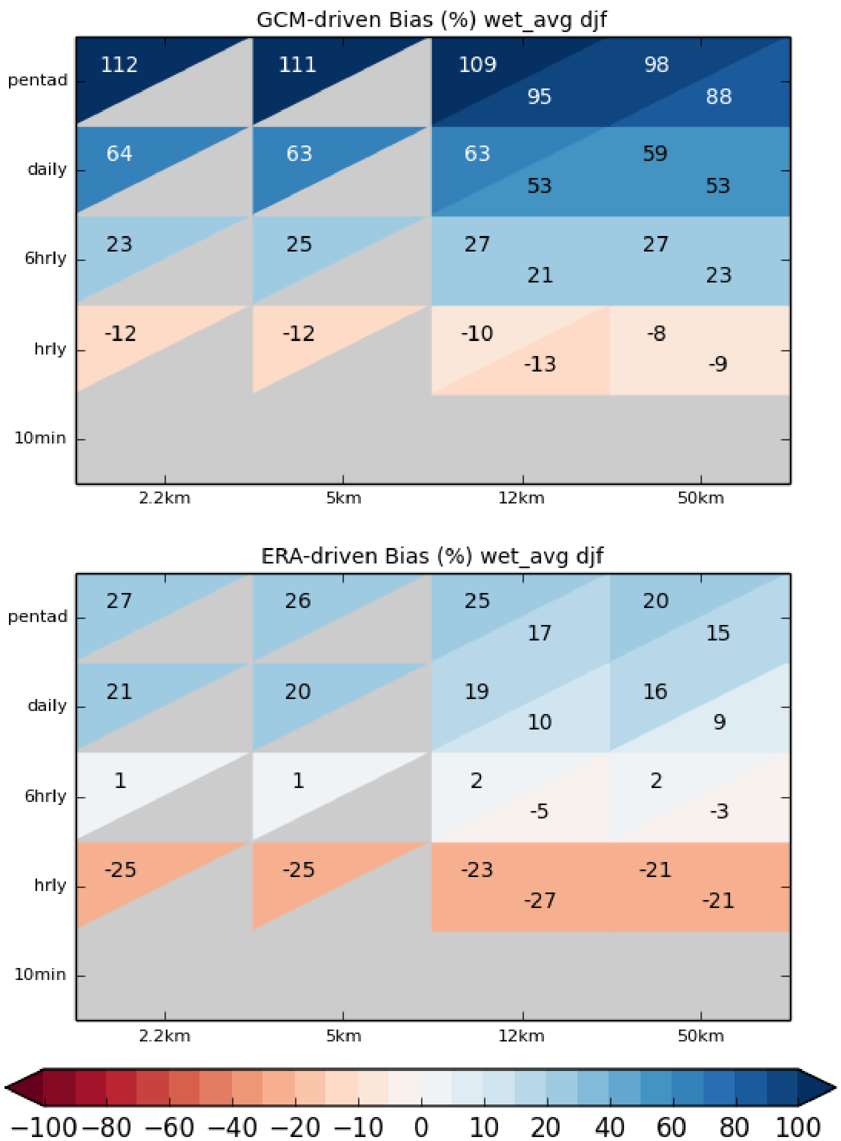

FIG. 3. Biases (%) in rainfall intensity across space and time scales averaged over Switzerland for RCMs driven by MPI-ESM GCM (top) and ERA-Interim (bottom), in winter (DJF). Rainfall intensity is defined as the mean of wet values (>0.1mm per accumulation period). Definitions are as in Supplementary Figure 1.

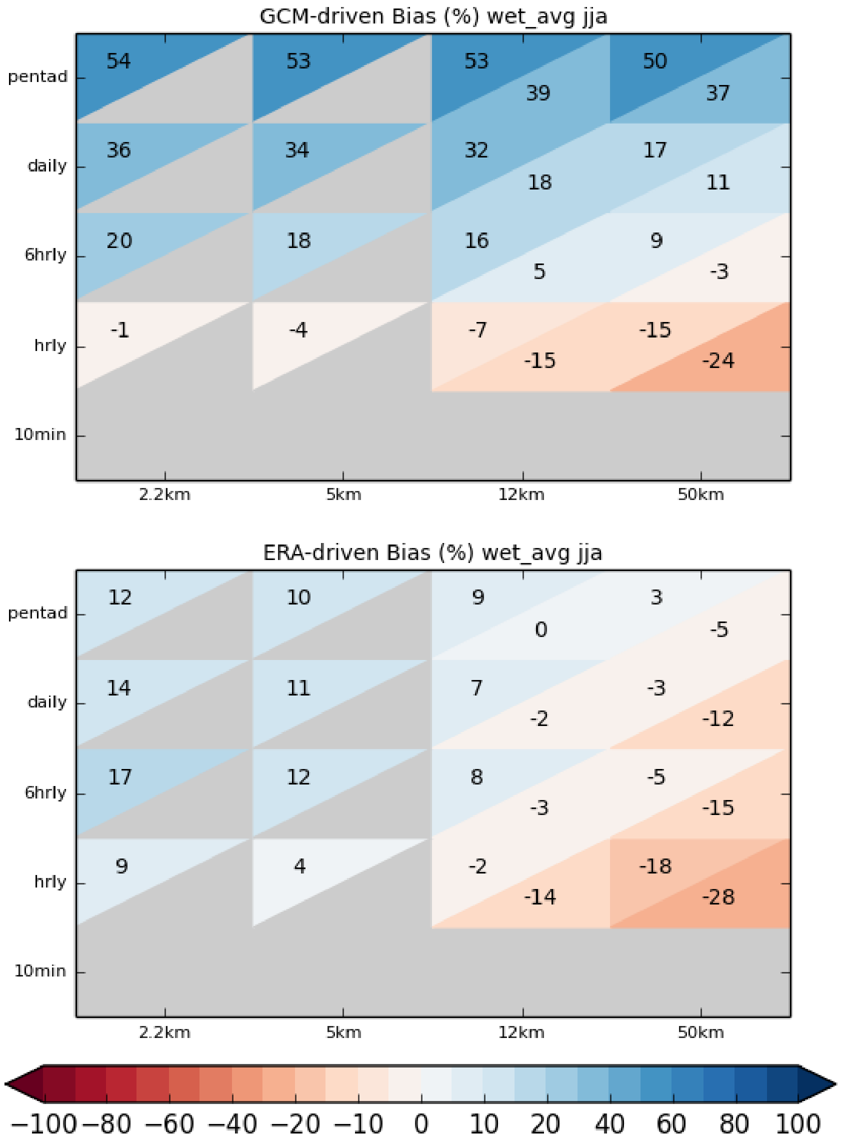

FIG. 4. As Supplementary Figure 3 but for summer (JJA).

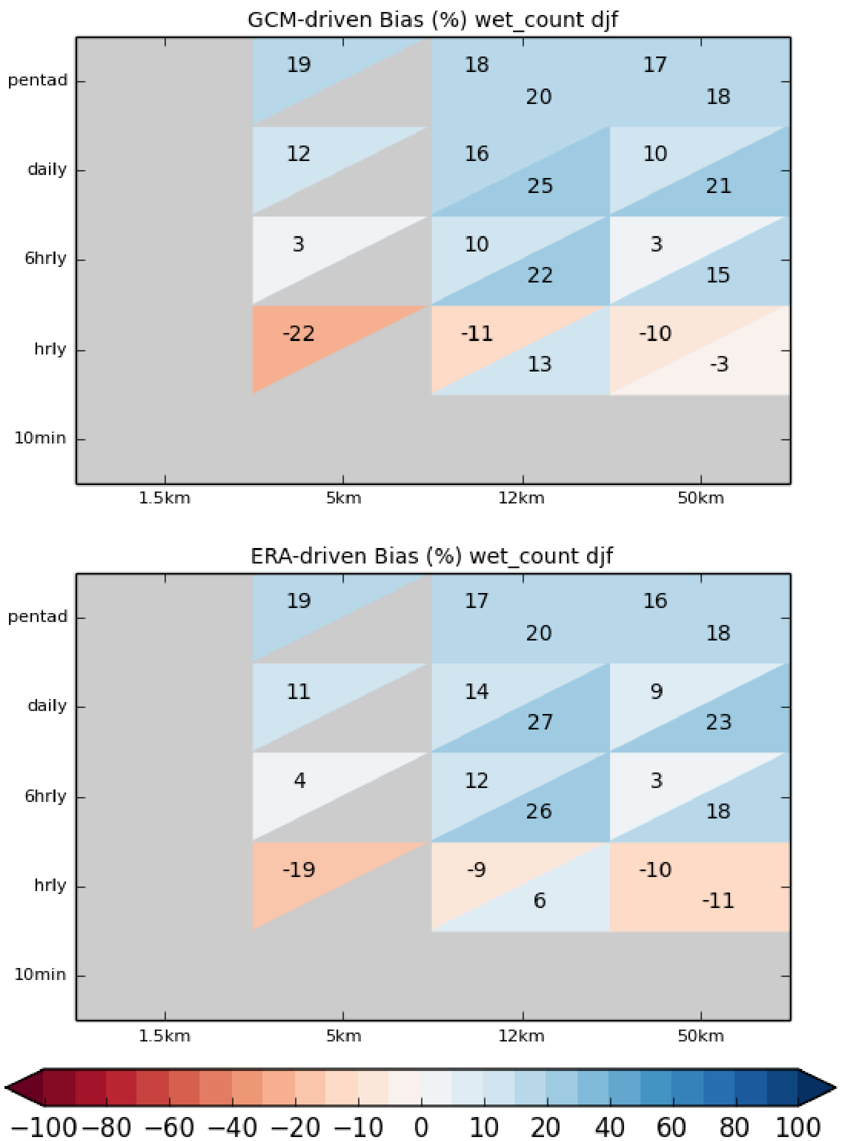

FIG. 5. Biases (%) in rainfall occurrence across space and time scales averaged over the southern UK for RCMs driven by the Met Office UM-GA3 GCM (top) and ERA-Interim (bottom), in winter (DJF). Biases are calculated as model-observation differences, using hourly 5km Nimrod radar data for the UK. Results for the convection-permitting (1.5km) RCM are shown in the upper left triangle and for the 12km RCM in the lower right triangle. Grey indicates where results are not available. A threshold of 0.1mm per accumulation period is used to define rainfall occurrence.

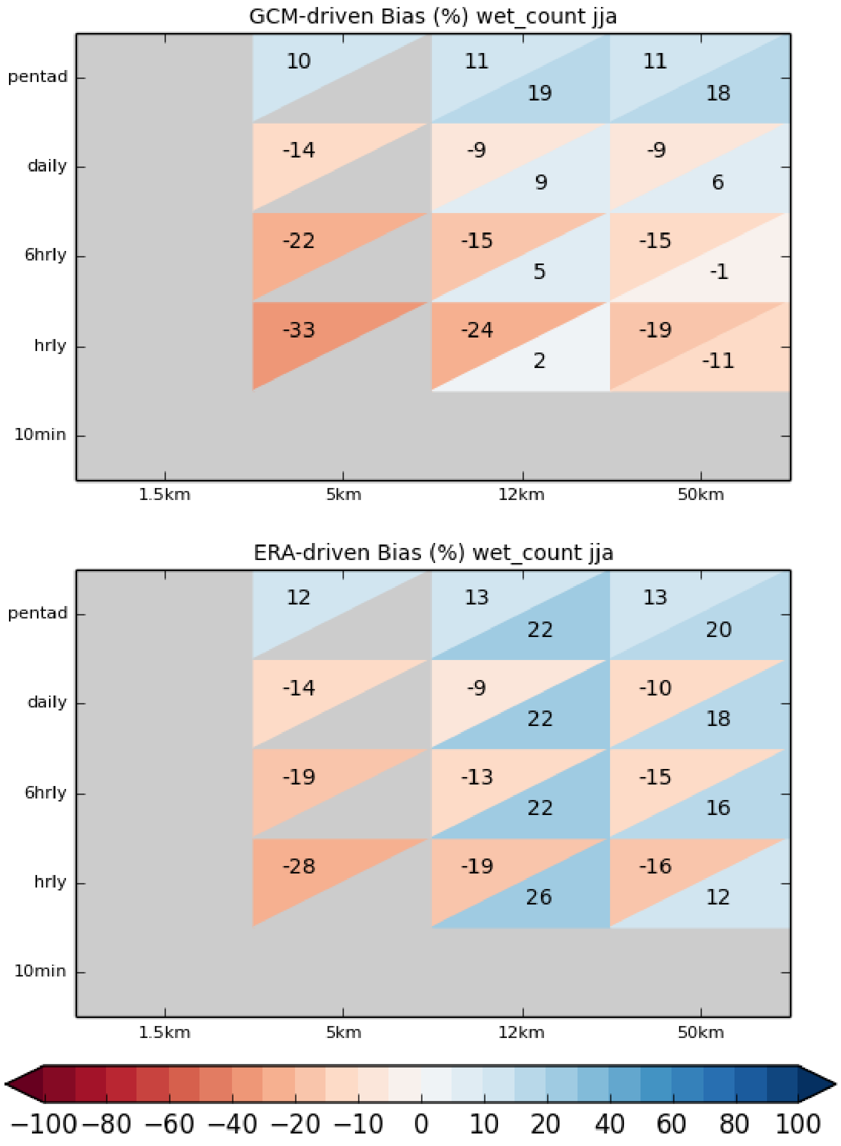

FIG. 6. As Supplementary Figure 5 but for summer (JJA).

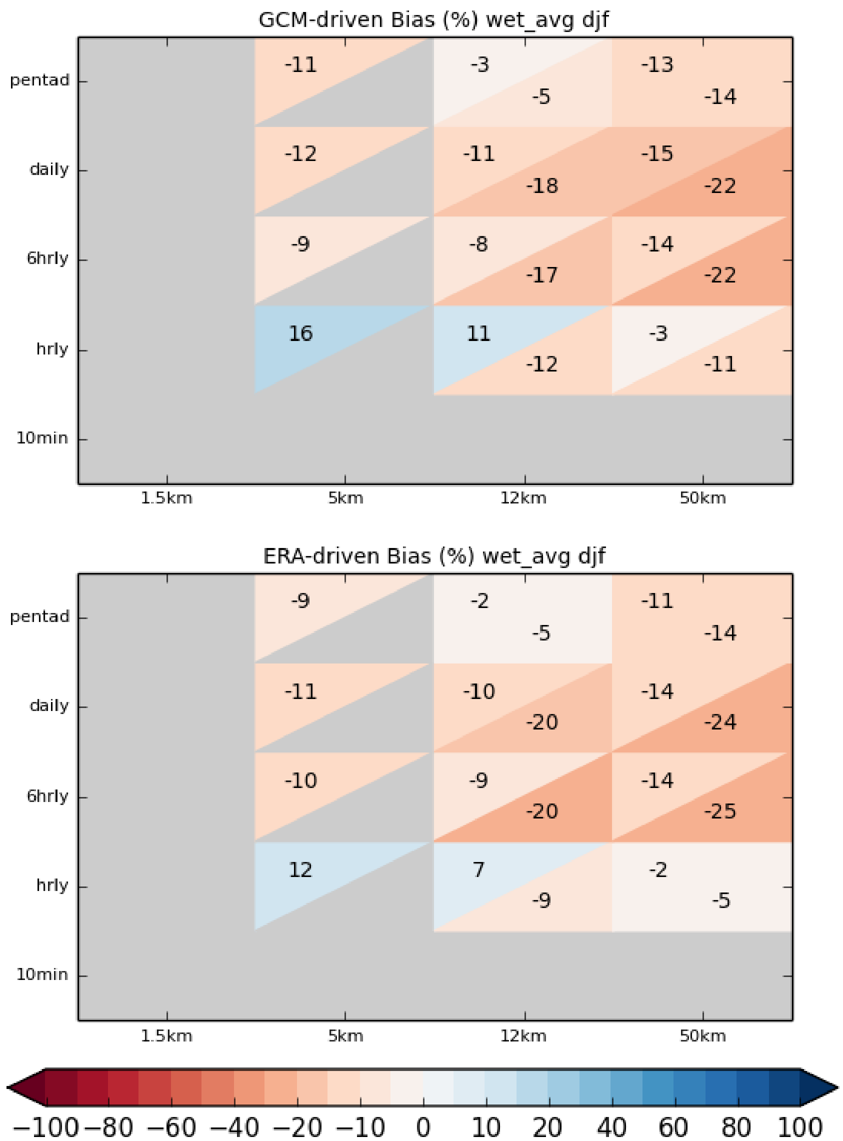

FIG. 7. Biases (%) in rainfall intensity across space and time scales averaged over the southern UK for RCMs driven by the Met Office UM-GA3 GCM (top) and ERA-Interim (bottom), in winter (DJF). Rainfall intensity is defined as the mean of wet values (>0.1mm per accumulation period). Definitions are as in Supplementary Figure 5.

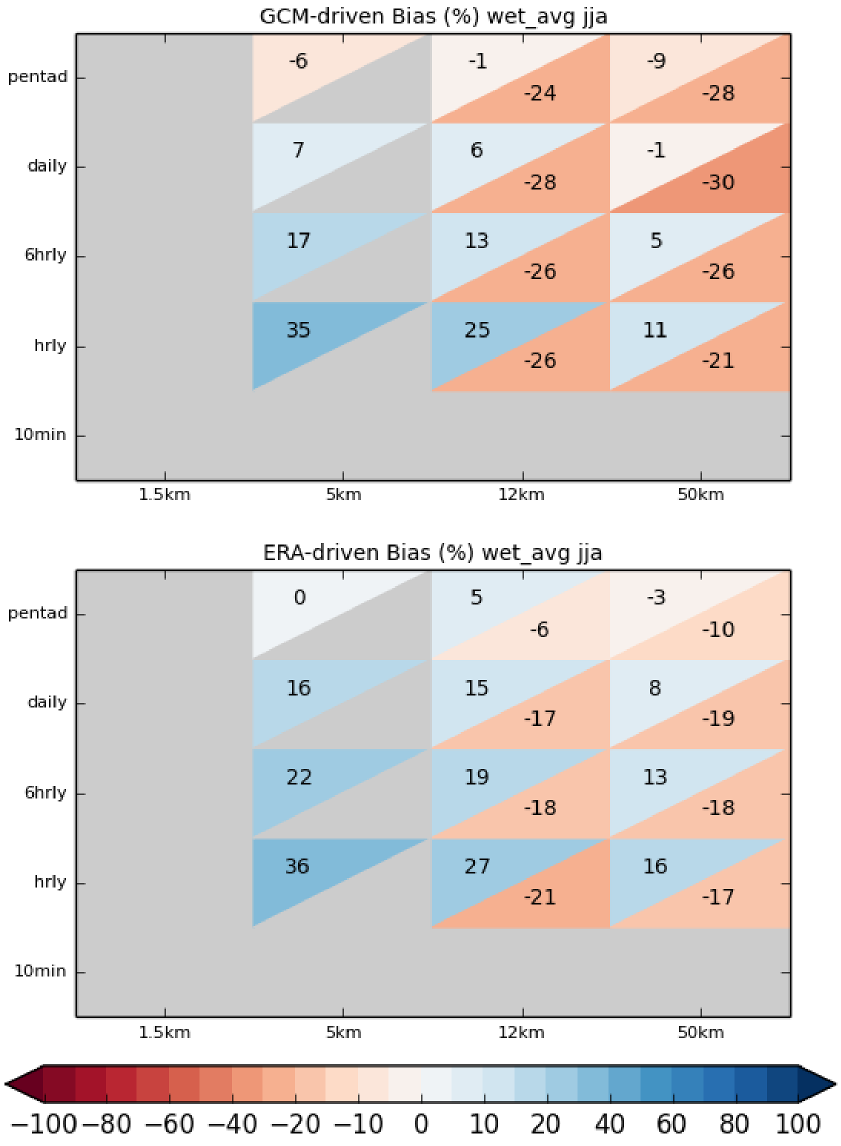

FIG. 8. As Supplementary Figure 7 but for summer (JJA).