Update to UKCP Local (2.2km) projections

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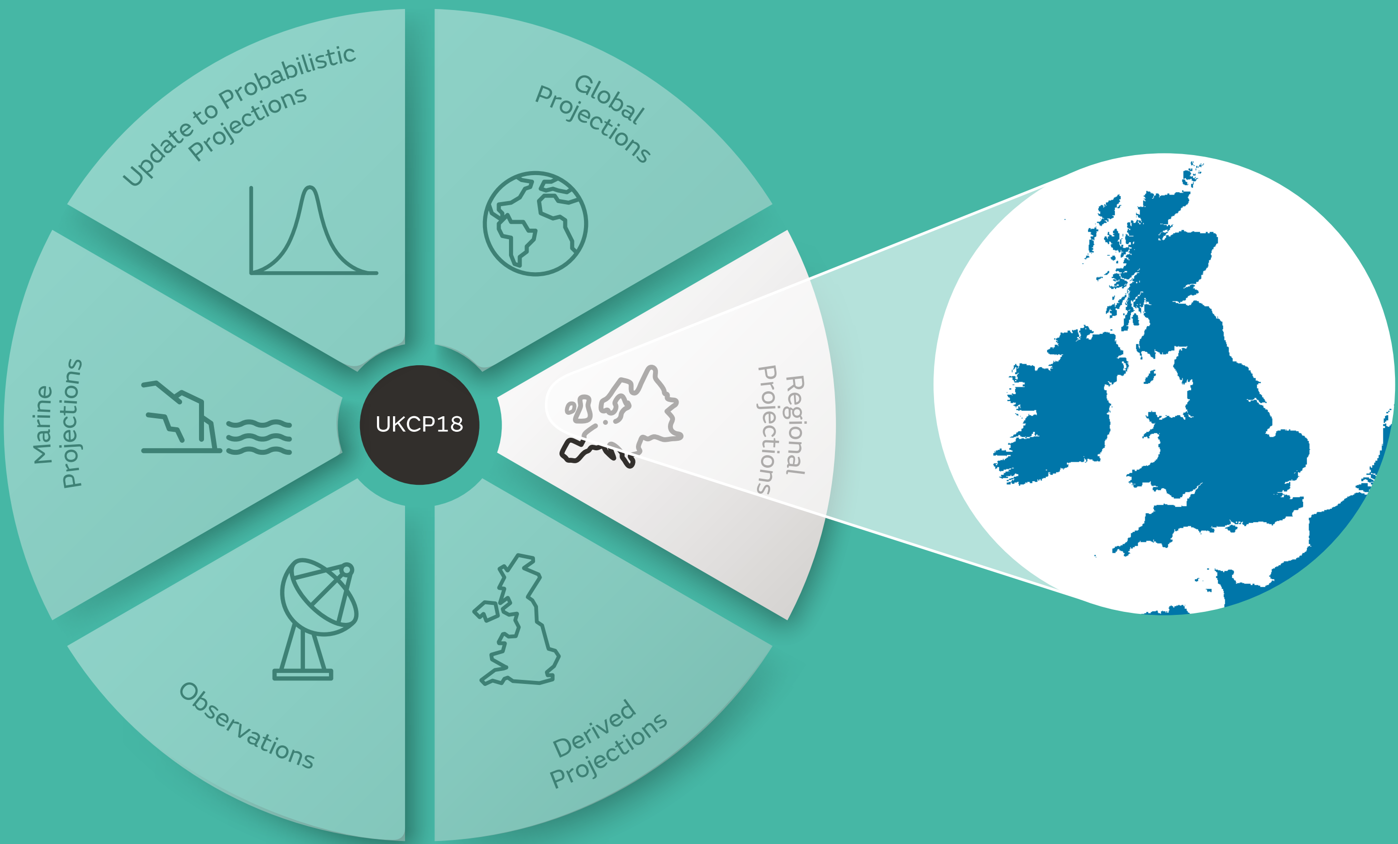

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Non-technical summary

This report describes an update to the UKCP Local (2.2km) projections that were released in September 2019 (Kendon et al, 2019). This consists of an additional set ('ensemble') of 12 simulations at 2.2km resolution for the UK for three time periods (1981-2000, 2021-40 and 2061-80). In these new 2.2km projections, we have fixed a code error and made some additional science improvements. Thus, these new 2.2km projections replace the original UKCP Local (2.2km) projections and become the recommended 2.2km dataset for all new applications.

The 2.2km "convection-permitting" model (CPM) provides a step forward in our ability to simulate small scale behaviour seen in the real atmosphere, in particular atmospheric convection – a key process driving many of our extreme weather events. Due to the high spatial resolution, compared to more traditional climate models, it also represents better the influence of mountains, coastlines and cities. UKCP18 was the first set of national climate scenarios to include climate change information at such a high resolution, on par with operational weather forecasting. The 2.2km data provides access to credible information on how climate change may impact extremes of weather for your local area (Kendon et al, 2019).

The UKCP Local (2.2km) projections sit alongside other UKCP18 tools to look at climate change (Murphy et al, 2018). These include probabilistic projections, a set of 28 global 60km climate simulations and a set of twelve regional 12km simulations. The UKCP Local (2.2km) projections are useful for impacts assessments that require enhanced spatial detail or information on changes in extreme weather at local and hourly timescales.

Each 2.2km projection represents a plausible realisation of the future climate assuming greenhouse gas emissions increase further, with the ensemble members differing due to natural climate variability and uncertainty in the global model physics. The CPM ensemble therefore gives an indication of uncertainties in future changes on kilometre and hourly scales for use in risk assessments, providing locally relevant information to inform decision making. However, the Local (2.2km) projections only downscale versions of the Hadley Centre climate model, and so sample a narrower uncertainty range than the global or probabilistic projections. In particular, the set of 2.2km simulations samples only outcomes with a relatively high rate of global warming. It is therefore important that users are aware of the other UKCP products and the advantages of each for their application. Further guidance on which UKCP product(s) to choose and how to use them in combination is available from Fung et al, (2018).

Subsequent to the release of the original UKCP Local (2.2km) projections, we found an error within the 2.2km climate model in the scheme that represents graupel, which are soft small ice pellets with higher densities and fall speeds than snow. Graupel is typically smaller than hail and often forms within convective clouds. We rapidly carried out test simulations, which demonstrated that this error could have a significant impact on some variables (Kendon et al, 2020b), and therefore we decided to rerun the Local (2.2km) projections. We also fixed some other minor code errors and used the rerun as an opportunity to improve the representation of the snowpack.

No other UKCP product is affected by the graupel code error, and top-level messages from UKCP18 in terms of climate change in the UK (Murphy et al, 2018) are unchanged.

Use of new 2.2km projections

- For all new users of the Local (2.2km) projections, the new rerun projections (CPM_new) should be the preferred dataset.
- Regarding the original UKCP Local (2.2km) data, the variables primarily affected are snow, winter temperature and hourly precipitation extremes. For these variables, the original 2.2km data (CPM_orig) should not be used. For surface winds, there are some significant[1] impacts of the rerun, mainly over the ocean but also some localised regions over Ireland and the Scottish mountains, where CPM_orig should not be used. For winter precipitation and heavy daily precipitation events, the present-day values are affected, but future changes are not significantly impacted by the rerun. Existing studies for these variables can still potentially be used, though extra care should be taken in assessing the credibility of the results, including comparison with the reruns. The variables unaffected are summer temperature (including mean and extremes), summer mean precipitation, and cloud.
- For hourly precipitation extremes, on fixing the graupel code error, CPM_new gives better agreement with observations for the present-day and greater future increases (for an event that occurs typically once every two years, CPM_new projects an increase of 29% compared to 25% in CPM_orig). We have greater confidence in the new rerun projections due to the role of graupel in convective storms.
- On fixing the error, the simulation of lightning is considerably improved, allowing it to be provided as a user diagnostic from CPM_new.
- The CPM_new results largely reinforce results from the 12km driving regional climate model (RCM) simulations, in terms of UK seasonal mean changes, with consistency generally increased compared to CPM_orig. One exception is for changes in winter precipitation where CPM_new (and similarly CPM_orig) shows greater increases compared to the RCM. The difference relates to the improved representation of wintertime convective showers in the CPM, that are triggered over the sea and move inland (Kendon et al, 2020a). This suggests that projections based on conventional coarser resolution climate models may underestimate "upper-end" responses in winter mean precipitation.
- For snow, CPM_new projections also differ from the RCM projections, likely due to the improved representation of wintertime convective showers and the better resolution of high terrain in the CPM.
- For summer mean precipitation, and soil moisture, CPM_new and the RCM provide similar projections of future decreases. This agreement gives us additional confidence that projections from the RCM, which follow the driving global model, are plausible. The CPM provides added spatial detail but underestimates the uncertainty range due to the lack of information from other international climate models, which suggest that more modest reductions or small increases in summer precipitation should also be considered.
- For seasonal mean and daily temperature, there is no evidence to suggest that the CPM_new projections are either more or less plausible than those from the RCM. There are some differences locally, that can be explained by the better representation of mountains and urban areas or drier soils in the CPM. For temperature changes, we recommend use of information from the UKCP Probabilistic or Global projections given the more comprehensive view of uncertainties, except where fine spatial detail is required.

[1] Differences are assessed as significant if they are greater than the standard deviation across the 12-member CPM ensemble

- For applications focussing on extremes, particularly those requiring information on fine spatial scales, the RCM and CPM_new products are expected to be the primary source of information. For daily temperature extremes, these should be used alongside the UKCP Global projections to give a more comprehensive uncertainty range. For heavy daily precipitation events, CPM_new projections are more reliable especially in summer, due to the better representation of convection. For hourly precipitation including extremes, projections from convection parameterised models are unreliable and so users should only use the CPM_new projections. However, the CPM_new projections likely underestimate the uncertainty range.
- CPM_new (as is the case for CPM_orig) provides information on changes in hourly precipitation and for local areas, including a better representation of changes over cities (due to the higher spatial resolution and more sophisticated urban scheme) and over regions of complex terrain. This information can be used in local decision making, for example in relation to urban flooding for contingency planners.
- For surface winds, CPM_new projections differ from the RCM projections. Both projections are judged equally plausible, but some added value is expected from the CPM in terms of representing changes over mountains and coastal regions.
- The Local (2.2km) and Regional (12km) projections sample a narrower uncertainty range than the Probabilistic and Global projections, as they currently lack information from other international climate models. Where possible, we recommend that the CPM_new projections are used in combination with other UKCP products, rather than in isolation, in order to give the most complete picture of future climate.
- Table 1 summarises advice on use of the new 2.2km reruns compared to the original UKCP Local (2.2km) projections and other UKCP18 products by impact sector.

Present-day performance

- The ability of the CPM to simulate several aspects of the present-day climate has been verified by comparing the model results with observations of the real world. In general, this along with the improved representation of convection in the CPM, gives us confidence in its ability to project future changes to extreme weather events at local and hourly scales.
- The new 2.2km reruns (CPM_new) are considerably colder than the original UKCP Local (2.2km) simulations (CPM_orig) in winter. This exacerbates cold biases in the north of the UK, for winter mean temperature and cold winter days. CPM_new is also wetter in winter than CPM_orig, particularly over high terrain, leading to slightly increased biases for mean and heavy daily precipitation. Although these biases have increased, we have greater confidence in CPM_new compared to CPM_orig, since differences can be traced to fixing the graupel code error.
- The representation of heavy summer precipitation and hourly precipitation extremes has considerably improved in the new 2.2km reruns, with the tendency for the CPM to overestimate extreme hourly precipitation reduced (by about 20%).
- CPM_new has less snowfall and more lying snow compared to the original 2.2km runs, which is a considerable improvement and directly relates to the improved treatment of graupel and the snowpack.

This leads to better agreement with the RCM, although with a tendency for more snow over high ground in Scotland in CPM_new due to its better representation of high terrain.

- Unrealistic lightning features seen in CPM_orig are no longer found in CPM_new, linked to fixing the graupel code error.
- CPM_new has stronger surface winds in winter than CPM_orig, mainly over the ocean but also over western Ireland and the Cairngorms. These differences are considerably smaller than the differences between the CPM and RCM, with the CPM showing greater daily maximum wind speeds than the RCM particularly over high ground.
- The new 2.2km reruns generally show improved consistency with the RCM, compared to the original 2.2km runs. For temperature, CPM_new shows similar or increased biases in winter temperature and cold spells in the north, but reduced biases in summer mean temperatures and hot days compared to the RCM. These model differences are likely due to differences in the representation of snow (more lying snow in CPM_new), cloud (less cloud in CPM_new) and the tendency for soil to be drier in the CPM.
- For precipitation, CPM_new (and similarly CPM_orig) gives a better representation of how precipitation varies from day-to-day and hour-to-hour compared to the RCM. This leads to overall reduced biases in seasonal mean precipitation in the CPM. In common with climate models more generally, the RCM is unable to capture short intense downpours that can lead to flash flooding. Such events are more realistically captured in the CPM, although they tend to be too heavy (but less so in CPM_new compared to CPM_orig). These improvements in the CPM are due to the more realistic representation of convection, and in mountainous regions, the better resolution of complex terrain.

Climate change projections

- The new 2.2km reruns do not change the UKCP18 headline message of a greater chance of warmer wetter winters and hotter drier summers across the UK in future (Murphy et al, 2018). For 2061-80, under a scenario of high greenhouse gas emissions (RCP8.5), CPM_new suggests winters will be warmer by 3.3°C (2.0-3.5°C)[2] and wetter by 26% (15-40%)[2]; whilst summers will be hotter by 4.6°C (3.6-5.0°C)[2] and drier by 29% (17-47%)[2].
- In general, CPM_new reinforces the results from the 12km RCM, projecting similar overall changes to UK climate. This consistency between the CPM and RCM has increased in the new 2.2km reruns compared to the original 2.2km projections. The CPM does provide new information on changes in winter mean precipitation, changes in daily and hourly extremes, and changes at the local scale. These key differences between the CPM and RCM are unaffected by the 2.2km reruns.
- Seasonal mean temperature increases everywhere and in all seasons in future, with the greatest increases occurring in the south. CPM_new shows increases in hot summer days (6.0°C increase by 2070s under RCP8.5), reinforcing results from the RCM projections. CPM_new projects larger future increases in the frequency of hot spells over the southern UK than the RCM, which may reflect drier soils in the CPM in both the historical and future climates. These future changes in summer temperature in CPM_new are unaffected by the reruns.

[2] The range quoted corresponds to the UK-average of the 2nd lowest to 2nd highest responses across the 12-member CPM_new ensemble.

- Future reductions in the severity of cold winter days (5.3°C temperature increase by 2070s under RCP8.5) and the frequency of cold spells are considerably greater in CPM_new compared to the original projections (CPM_orig). Future increases in winter mean temperature are also impacted by the reruns but to a lesser extent (with increases slightly greater in CPM_new). These greater increases in winter temperature are considered more reliable and are due to more lying snow in the present-day in the new 2.2km reruns, which melts in the future amplifying temperature increases.
- Snowfall decreases in future and lying snow disappears almost entirely over low-elevation regions in CPM_new (under RCP8.5). Snowfall and lying snow projections are significantly different between CPM_new and CPM_orig, due to fixing the graupel code error and the snowpack science improvements. For these variables, the original 2.2km projections are considered unreliable. CPM_new projections are more in line with the RCM results, although lying snow in winter persists more into the future over high ground in the CPM.
- Average winter precipitation increases in future, with the exception of northern Scotland where decreases are possible. CPM_new shows much greater increases than the RCM (26% compared to 16% increase), due to the greater increase in the number of wet days. This is related to the better representation of convective showers and their movement inland (Kendon et al, 2020a). This key difference between the CPM and RCM was also shown by the original Local (2.2km) projections (Kendon et al, 2019) and is unaffected by the rerun.
- Average summer precipitation decreases in future, again with the possible exception of northern Scotland. CPM_new shows slightly greater decreases than the RCM and very different underlying changes in rainfall on a day-to-day and hour-to-hour basis. It rains less often in the future, but the rain is heavier when it does – and this shift to more intense rainfall in summer is more pronounced in CPM_new. These changes in rainfall are primarily driven by increased moisture in the atmosphere with warming, leading to heavier rainfall, which is captured by both the CPM and RCM. However, local processes within the storms themselves can amplify increases, and these are only represented in the CPM projections.
- Soil moisture decreases in summer, consistent with the reduction in summer mean precipitation, and results in evapotranspiration being soil moisture limited in the northern and southern UK in future summers.
- Hourly precipitation extremes increase in future. CPM_new shows increases of 29% in the precipitation associated with an event that occurs typically once every 2 years, with similar increases for rarer extremes. These increases are greater than projected by the original 2.2km projections and are considered more reliable.
- Lightning increases in future in summer and spring in CPM_new, likely due to deeper more intense storms. However, in autumn, lightning is projected to decrease in future despite increases in hourly precipitation extremes, which is likely due to the role of ice fluxes in lightning generation.
- Surface wind speeds increase over western parts of the UK and over the ocean in winter. Future changes are similar in CPM_new and the RCM over the ocean, but CPM_new shows a greater tendency for decreasing wind speed over the south and east of the UK. These differences are not impacted by the reruns, with significant differences in future changes between CPM_new and CPM_orig confined to localised regions over the Scottish mountains and over the sea to the NW of the UK.

Impact metric (with some example impact areas)	Continue to use original UKCP Local (2.2km) projections?	Use of new UKCP 2.2km reruns alongside other UKCP18 products?
Snow (e.g. infrastructure inc. transport and energy, natural environment/habitat)	✘ Original UKCP 2.2km data underestimate snow and its future change	Some added value from 2.2km over mountains and due to better representation of winter convective showers. UKCP Global projections provide wider sampling of uncertainty.
Lightning (e.g. infrastructure inc. transport, communications and energy)	✘ Lightning data not released from original UKCP 2.2km	* Available from new 2.2km reruns only
Cold winter temperatures (e.g. infrastructure inc. transport and energy, health, natural environment/habitat)	✘ Original UKCP 2.2km data underestimate future increases in winter temperature (especially for cold winter days and cold spells over Scotland)	Some added value from 2.2km over mountains. UKCP Regional equally plausible. UKCP Global projections provide wider sampling of uncertainty.
Winter precipitation (e.g. winter flooding affecting multiple impact areas)	~ Original UKCP 2.2km data underestimate winter mean precipitation, but graupel code error has small impact on future changes. New 2.2km reruns should be preferred dataset for all new assessments.	~ Greater increases in UKCP 2.2km due to better representation of winter convective showers. Other UKCP18 products based on coarser models may underestimate "upper-end" responses.
Summer mean precipitation and soil moisture (e.g. water resources, drought affecting agriculture and natural ecosystems)	✔ Summer mean precipitation not significantly impacted by graupel code error, although new 2.2km reruns should be preferred dataset for all new assessments. ~ Soil moisture slightly higher in new 2.2km reruns.	UKCP 2.2km projections provide enhanced spatial detail and evidence of drier future soils than Regional 12km. Use alongside UKCP Probabilistic and Global projections due to wider sampling of uncertainty.
Hourly precipitation extremes (e.g. summer flash flooding affecting multiple impact areas)	✘ Original UKCP 2.2km data overestimate present-day return levels and underestimate future changes in hourly precipitation extremes.	* Use new 2.2km reruns only. Regional 12km projections considered unreliable.
Hot summer temperatures and heatwaves (e.g. transport, thermal building design and health)	✔ Results not significantly impacted by graupel code error, although new 2.2km reruns should be preferred dataset for all new assessments.	UKCP 2.2km projections provide more reliable local changes over cities and larger increases in hot spells over southern UK due to drier soils. Use alongside UKCP Regional and Global projections due to wider sampling of uncertainty.
Surface winds (e.g. infrastructure inc. transport, water, communications, energy, forestry/natural environment)	~ Original UKCP 2.2km data underestimate wind speeds mainly over the ocean. Significant impacts over land limited to localised regions over western Ireland and Scottish mountains. New 2.2km reruns should be preferred dataset for all new assessments.	Some added value from 2.2km expected over mountains and coastlines. UKCP Regional equally plausible. UKCP Global projections provide wider sampling of uncertainty.

Table 1. Summary of advice on use of new 2.2km reruns compared to original UKCP Local (2.2km) data and other UKCP18 products by impact sector. Red ✘ means 'no', green ✔ 'yes', purple ~ 'use new 2.2km runs in preference to original 2.2km runs and be aware of caveats indicated for other UKCP products' and blue * 'use new 2.2km runs only'.

1. Introduction

The UKCP Local (2.2km) projections consist of an ensemble of 12 simulations at 2.2km grid-spacing over the UK run for three periods 1981-2000, 2021-2040 and 2061-2080 for a high emission pathway (Kendon et al, 2019). They were published in September 2019 and were the first time, internationally, that national climate scenarios were provided at a resolution on a par with operational weather forecasting. The 2.2km "convection-permitting" model (CPM) represents a step forward in our ability to simulate small scale behaviour seen in the real atmosphere, in particular atmospheric convection that is a key process in many extreme weather events. It also better represents the influence of mountains, coastlines and urban areas than traditional climate models with coarser grid spacings (of the order 10-100km). As a result, the CPM provides a set of plausible projections of climate change for the UK on hourly and kilometre scales, allowing us to examine the risk of extreme weather events in local areas for the coming decades.

The UKCP Local (2.2km) projections sit alongside three other UKCP18 tools to look at climate change over land (Murphy et al, 2018, Lowe et al, 2018). These include probabilistic projections, a set of 28 global 60km climate simulations (including 15 versions of the Hadley Centre Global model HadGEM3-GC3.05 and 13 CMIP5 simulations) and a set of twelve regional 12km simulations. The UKCP Local (2.2km) projections are intended to be useful for impacts assessments that require enhanced spatial detail or information on changes in extreme weather at local and hourly timescales. However, they only downscale versions of the Hadley Centre climate model and the RCP8.5 scenario, and so sample a narrower uncertainty range than the global or probabilistic projections. It is important that users consider the potential advantages of each UKCP product for their application, and also the sensitivity of their applications to uncertainty in the UKCP outputs. Further guidance is available from Fung et al, (2018).

Subsequent to the release of the UKCP Local (2.2km) projections, an error was found in the 2.2km climate model in the scheme that represents graupel, which are soft small ice pellets with higher densities and fall speeds than snow. Graupel is typically smaller than hail and forms when supercooled water coats a snowflake. The error was in the code that controls the fraction of snow converted to graupel, and in general resulted in too much snow being converted to graupel. In the operational weather forecast model, graupel is included but the section of erroneous code is turned off, and thus operational weather forecasts are not impacted. No other UKCP product is affected by the error, and the top-level messages from UKCP in terms of climate change in the UK (Lowe et al, 2018) are not impacted.

Test simulations were performed for one 2.2km ensemble member to look at the consequences of the graupel code error for the UKCP Local simulations. These showed that the variables primarily affected are snow and winter temperature especially over Scotland, but to a lesser extent winter precipitation, hourly precipitation extremes across the UK and wind extremes over the ocean and north-west coastal regions. Many variables are unaffected, including summer temperature and summer mean precipitation, for which the existing UKCP Local (2.2km) data can still be used. On the basis of the test simulations, it was decided to rerun the UKCP Local (2.2km) projections fixing the graupel code error and also making some other science updates. Results from these reruns are presented here. In particular this report documents differences between the original UKCP Local (2.2km) projections (hereafter CPM_orig) and the new rerun projections (CPM_new), providing guidance to users on which applications are likely unaffected by the differences and where users should use the new data. The original Local (2.2km) and rerun projections are also presented alongside the UKCP Regional (12km) projections, allowing differences between CPM_orig and CPM_new to be viewed in the context of the differences seen on moving from a 12km regional climate model (RCM) to convection-permitting scale.

2. Description of Local (2.2km) model

2.1 Local 2.2km model and experimental design

The rerun projections follow an identical ensemble design to the original UKCP Local (2.2km) projections released in September 2019 (Kendon et al, 2019). They consist of 12 convection-permitting model (CPM) simulations spanning the UK at 2.2km resolution, driven by the 12 members of the UKCP Regional (12km) ensemble. The 12km regional climate model (HadREM3-GA705, hereafter RCM) spans Europe and is in turn driven by simulations of the 60km resolution Hadley Centre global climate model (HadGEM3-GC3.05, hereafter GCM). The RCM and GCM ensembles were created by perturbing parameters in the model physics, as described in Murphy et al, (2018). However, parameters were not perturbed in the CPM, due to structural differences (e.g. use of different parameterisation schemes) between the CPM and driving global and regional models, with the same version of the CPM used for each ensemble member. Thus, the CPM ensemble members inherit uncertainties from their driving simulations arising from different realisations of natural climate variability and different representations of parameterised physical processes. The 2.2km simulations add temporal and spatial detail through their representation of local processes and feedbacks, including important new functionality via their explicit representation of the dynamics of large convective storms. However, uncertainties in the representation of local processes (e.g. in relation to poorly constrained soil moisture parameters) are not included, as all 2.2km simulations use the same version of the CPM.

The 2.2km CPM is based on the Met Office operational UK weather forecast model (UKV). It shares many of the same model physics settings as the 12km RCM, but with some notable differences particularly in how convection is represented. The reruns have an almost identical model configuration as that used for the original UKCP Local (2.2km) projections (described in Kendon et al, 2019). Key points of the 2.2km model configuration are summarised below, with a description of the changes that have been implemented in the CPM_new reruns provided in the next sub-section.

The 2.2km model configuration is close to the Regional Atmosphere 1 mid-latitude configuration (Bush et al, 2019). It is termed "HadREM3-RA11M" and uses the Unified Model (UM) version 10.6. The model spans the UK at 2.2km grid-spacing, with a variable resolution outer rim where grid-spacing varies from 2.2km to 4km to help reduce boundary artefacts affecting the interior of the domain. It uses semi-implicit semi-Lagrangian ENDGame (Even Newer Dynamics for General atmospheric modelling of the environment, Wood et al, 2014) dynamics and an extensive set of parameterisations describing the boundary layer (Lock et al, 2000, Boutle et al, 2014), cloud (Smith, 1990), microphysics (Wilson and Ballard, 1999, with extensive modifications) and radiation (Edwards and Slingo, 1996). It includes a new mass conservation scheme (Zerroukat and Shipway, 2017). The Joint UK Land Environment Simulator (JULES, Best et al, 2011) is used to model processes at the land surface and in the sub-surface soil, with the topography-based rainfall-runoff model TOPMODEL (Beven and Kirkby, 1979). The new Met Office Reading Urban Surface Exchange Scheme (MORUSES, Porson et al, 2010) is used to represent processes over urban areas.

Key differences with respect to the 12km RCM are: (1) convective parameterisation (Gregory and Rowntree, 1990, with extensive modifications) is used in the RCM but switched off entirely in the CPM; (2) the RCM used the prognostic cloud scheme PC2 (Wilson et al, 2008) whilst the CPM uses the Smith (1990) scheme; (3) the CPM includes prognostic graupel, a second category of ice with higher densities and fall speeds found in convective cloud, but this is not included in the RCM; (4) the CPM includes the ice-based lightning flash rate prediction scheme (McCaul et al, 2009) which requires prognostic graupel; (5) the RCM uses the simpler one-tile urban scheme rather than MORUSES. For further details of the Local (2.2km) model configuration and differences with respect to the 12km RCM see Kendon et al, (2019).

The CPM simulations were run in three 21-year time slices (1980-2000, 2020-2040 and 2060-2080), with the latter two time slices using the high emissions RCP8.5 scenario. The first year of each CPM time slice is discarded as it corresponds to a period of spin-up, during which fine-scale circulations and land surface properties (particularly soil moisture at depth) transition to approximate equilibrium. Changes in greenhouse gas forcing are the same as in the driving GCM and RCM, and follow member-specific CO_2 concentration pathways (Murphy et al, 2018). Fully interactive aerosol modelling is computationally expensive and is only used in the GCM. Aerosol forcing in the CPM and RCM is described using "Easy Aerosol" (Stevens et al, 2017), in which time series of aerosol properties and cloud droplet number concentrations (CDNCs) are prescribed in order to replicate approximately the aerosol forcing simulated in the driving GCM. The approach uses monthly fields of optical properties and CDNCs saved from the relevant GCM ensemble member, thus smoothing out any daily variability in aerosols. Past and future changes in land use are represented by prescribing a time-varying component from the harmonised land-use LUH2 v2h dataset (at 0.5 degree resolution, Hurtt et al, 2011), consistent with the RCM and GCM (Murphy et al, 2018). Further details on present-day and future forcings are provided in Kendon et al, (2019).

An additional CPM_new simulation has been carried out using ERA-Interim reanalyses as the global driving data, with the standard (unperturbed) member of the RCM ensemble providing an intermediate nest (that accepts ERA-Interim data at its lateral boundaries and in turn provides boundary data for CPM_new). This pair of simulations allows the downscaling properties of the RCM and CPM to be assessed free from biases in the large-scale driving conditions from the GCM. The simulation was run from 1981-2002. Sea surface temperatures and sea-ice extents were prescribed from analyses of observations (Reynolds et al, 2002). Aerosol properties are prescribed using EasyAerosol (see above), but using a standard historical forcing dataset developed for CMIP6 (Stevens et al, 2017).

Subsequent to the UKCP 2.2km rerun simulations having started, a small 1 km offset in the East-West direction in the land-cover type ancillaries was identified compared to the operational UKV ancillaries. The offset is present in the vegetation fraction and urban morphology ancillaries, in both CPM_new and CPM_orig. This means there is a small displacement of cities relative to coastlines and topography. This will have no noticeable impact on results presented here, although may need to be considered by some users comparing present-day local climate with point observations. However, in general, we would recommend that users do not use projections from a single 2.2km grid box, but rather consider projections from a number of adjacent grid boxes, to give a more robust estimate – in which case the small 1 km offset will have negligible effect.

2.2 Changes implemented in new 2.2km reruns

The major difference between the reruns and the original UKCP Local (2.2km) projections is fixing the graupel code error. This error is present between UM versions 10.3 and 11.3 inclusive (operational between 2016 and 2020) and affects model runs where both of the following criteria are true: (1) prognostic graupel is in use; and (2) a temporary logical switch l_fix_mphys_diags_iter is switched on. Operational numerical weather prediction (NWP) configurations are thus unaffected by the error since global atmosphere (GA) model configurations do not use prognostic graupel, and regional atmosphere (RA) model configurations (including the UK forecast model, UKV) have l_fix_mphys_diags_iter switched off. However, this temporary logical was switched on in the original CPM_orig to be consistent with the driving 12km RCM and 60km GCM. This should have been a null change (l_fix_mphys_diags_iter temporary logical is only intended to affect models that use sub-stepping in the microphysics scheme, which is not used in the UKCP CPM) but unfortunately turning it on led to an erroneous section of the microphysics code being activated. In the CPM reruns (CPM_new) the short-term logical l_fix_mphys_diags_iter is switched from true to false. In this way, we avoid activating the erroneous auto-conversion calculation.

Other science changes implemented in the CPM reruns (CPM_new) include a more physical treatment of graupel. In the original runs (CPM_orig) graupel was not seen by JULES and so not included in the snowpack. This followed operational practice at the time and was recommended due to the tendency for the convection-permitting model to produce too much graupel, which if included in the snowpack would lead to an overestimation of lying snow. However, new science changes have subsequently been implemented operationally in the UKV that help to address this. In particular, basal melting of snow has been added, which allows melting of the snowpack from the base over warm ground (rather than just from the surface) and prevents thin layers of snow persisting. This is implemented in the UKCP reruns, along with inclusion of graupel reaching the surface in the snowpack. The multi-layer snow scheme (Best et al, 2011, refined in UM Global Land configuration GL7, Walters et al, 2019) was also activated. The original Local (2.2km) projections used the simpler zero-layer snow scheme (with no explicit model layers to represent snow) since at that time the newer multi-layer snow scheme has not been tested in convection-permitting climate simulations. However, the multi-layer snow-scheme has now been implemented operationally in the UKV and its use in the reruns achieves greater consistency with the driving RCM (which also uses the multi-layer scheme).

We note that snow albedo changes that are included with the multi-layer snow scheme in the GL7 UM configuration (Walters et al, 2019) are not turned on in the UKCP CPM rerun. This is not physically inconsistent (as the new albedo scheme is not an integral part of the multi-layer snow scheme), but the new albedo scheme is a feature that we will make use of in future 2.2km model configurations. The new albedo scheme computes snow albedo for the multi-layer vegetation canopy and includes the effect on albedo of snow being concentrated in valleys and the dependence of albedo on snow grain size. It represents an improvement compared to the original scheme (used in both CPM_new and CPM_orig) where snow albedo is determined by interpolating between a deep-snow and snow-free value using a function of the leaf area index (representing the masking of snow by vegetation). A 10-year test run (performed subsequent to the start of the rerun simulations) showed that including these albedo changes in the 2.2km model leads to winter temperatures being slightly warmer (consistent with more bare ground, due to snow not uniformly spread over a grid box, which reduces the effective albedo in mountainous regions). However, the impact is smaller than the spread across the 12-member UKCP 2.2km ensemble, and thus judged not significant.

The rerun of the CPM also gave the opportunity to fix two other code errors. These have relatively minor impacts on the model evolution (see below) and would not on their own have required a rerun of the CPM. The first involves a fix to the calculation of the true longitude/latitude used in the radiation scheme. This error affects variable resolution regional model configurations (such as the UKCP Local (2.2km) model), with the calculation incorrectly assuming all grid boxes are evenly spaced. Consequently, the incoming solar radiation has a symmetrical error with not enough incoming radiation in the north of the domain and too much in the south. The second error was in code used to generate the Easy Aerosol ancillaries used in both the CPM and RCM. It resulted in daylight hours weighting, which is used to calculate shortwave aerosol radiative effects, being set to the value for September for all months, instead of varying month-by-month.

This led to too much shortwave aerosol impact in summer and not enough in winter. In CPM_new, the Easy Aerosol ancillaries were regenerated with modified pre-processing code where this error is fixed. The UKCP RCM has not been rerun, and so still contains this error in the Easy Aerosol short-wave radiation effects. This introduces a small inconsistency in the aerosol forcing between the CPM and RCM, but Easy Aerosol only provides an approximation of the real aerosol forcing (e.g. it ignores cloud-aerosol interactions, Stevens et al, 2017) and the inconsistency is small compared with uncertainties in the magnitude of aerosol forcing.

2.3 Impact of individual science changes included in update

The list below summarises the key science changes implemented in the reruns discussed above. In this section, we briefly outline the impact of each of these changes when implemented individually, based on 10-year test simulations with the standard member. The impact of these changes is assessed as significant where the difference is larger than the standard deviation across the 12-member UKCP Local (2.2km) ensemble.

1. Fix to graupel code error. This code error is related to arrays not being initialised properly and results in too much graupel and not enough snow.

2. Inclusion of graupel in snowpack. Without this change graupel reaching the surface is neglected by JULES and not included in the snowpack, thereby breaking conservation of water at the surface.

3. Addition of basal melting of snow. This prevents thin layers of snow persisting on the ground, and is recommended with science change 2 above.

4. Activate the multi-layer snow scheme. This provides a more sophisticated treatment of snow.

5. Fix to the calculation of true longitudes and latitudes used in the radiation scheme. This corrects a code error that resulted in too little incoming solar radiation in the north and too much in the south of the UK.

6. Fix to daylight hours error in short-wave diagnostics calculation within the Easy Aerosol pre-processing code. This error resulted in too much shortwave aerosol impact in summer and not enough in winter.

The impact of fixing the graupel code error (1) is documented in detail in Kendon et al, (2020b). The largest impacts are seen in winter, with significant effects on snowfall, lying snow and temperature. There is a reduction in snowfall on fixing the code error, since in CPM_orig snowfall was mainly graupel. Unlike the snowfall diagnostic (which includes all forms of solid precipitation), lying snow does not include graupel (for model configurations that do not include science change 2 above). Fixing the graupel code error therefore has the opposite effect on lying snow, with a significant increase due to more of the solid precipitation being in the form of snow. This leads to a decrease in winter temperature in the present-day and greater future increases in temperature, which is significant for cold winter days and nights over Scotland. Future increases in temperature are increased by 1°C or more for cold winter days locally and for cold winter nights more widely, compared to an overall future increase in the temperature of cold winter days of about 3°C and cold winter nights of about 4°C for the 2070s over northern Scotland in CPM_orig. For mean winter change, the impact of fixing the graupel code error is not significant compared to the spread across the 12-member UKCP CPM ensemble (an average difference of 0.1°C on a temperature increase of 2.5°C for the British Isles as a whole).

Fixing the graupel code error also significantly impacts simulated present-day precipitation in winter, with the fixed-code run somewhat wetter although still not as wet as the 12km RCM (UK-wide bias in the CPM increases from +16% to +22% on fixing the code error, compared to +31% bias in the RCM). However, future increases in UK winter mean precipitation are not significantly different (25% increase becomes 22% increase in the fixed-code run), with this difference considerably smaller than the difference between the CPM and RCM responses. Key differences between the CPM and RCM in the frequency and mean intensity of hourly precipitation, and their future change, are unaffected by the graupel code error.

In summer, there is no significant impact of the graupel code error on temperature or mean precipitation. However, there is an impact on hourly precipitation extremes, with a 20% reduction in the present-day 5-year return levels for the one ensemble member analysed (compared to the spread across the UKCP CPM ensemble of 10%). Future increases in hourly precipitation extremes are slightly larger, with the impact of the graupel code error significant for the 5-year (and longer) return level over parts of the UK (29% increase becomes 36% increase in the fixed-code run). Fixing the graupel code error is found to have little impact on future changes in winds, but there is evidence of a significant impact in the present day mainly over the ocean but also over Ireland, the Cairngorms and some north-western coastal regions.

There is a considerable impact of the graupel error on lightning, which was not provided to users in the original UKCP Local (2.2km) release. On fixing the graupel code error, the simulation of lightning is considerably improved, allowing it to be provided as a user diagnostic in the new release. This represents an enhancement for users.

The inclusion of graupel in the snowpack (2) is expected to increase lying snow (see above). In particular any residual graupel after fixing the graupel code error (16% of frozen precipitation when averaged over Scotland) is now seen by the land surface scheme and added to the snowpack. The multi-layer snow scheme (4) is also expected to increase lying snow, since it captures the processes of melting and freezing better, which generally acts to delay the melting of the snowpack in winter with snow persisting more into spring. The combined effects of including graupel in the snowpack, the addition of basal melting and the multi-layer snow scheme (2 to 4 above) were assessed, showing increases in lying snow over high ground in the north (daily mean lying snow over Scotland is about 30% larger), but with these increases considerably smaller than the impact of fixing the graupel code error (lying snow is 840% larger). Looking at the distribution of daily mean lying snow amounts, the combined snowpack science changes lead to more values above 10mm and fewer below, with the latter likely reflecting the impact of basal melting. These changes impact surface temperature, with winter temperatures reduced. For daily mean temperature, the reduction is smaller than the decreases resulting from fixing the graupel code error, whilst for daily temperature extremes the combined snowpack science changes have a comparable impact to fixing the graupel code error. In terms of future changes, the combined snowpack science changes lead to larger future decreases in snow amounts over high ground reflecting the fact that there is more lying snow in the present-day and, consistent with this, larger future increases in winter temperatures. There is no significant impact on precipitation or surface winds.

Fixing the code error in the calculation of true longitude/latitude (5) in the radiation scheme only has a slight impact on surface variables. Differences in mean surface temperature are less than 0.1°C over the UK, being slightly warmer in the north and cooler in the south. There is no significant impact on future changes in temperature or precipitation. Overall, this individual code fix does not play a major role in the differences between the CPM_orig and CPM_new projections.

Fixing the daylight hours error (6) in the CPM leads to small differences in seasonal mean temperatures of up to 0.2°C locally, with temperatures generally warmer in the north and cooler in the southwest of the UK. Although fixing this error can lead to large local differences in daily temperature and precipitation, these are seldom both (i) larger than the spread across the UKCP CPM ensemble and (ii) statistically significant compared to natural year-to-year variability, and thus are judged not to be significant. There is a signal of less precipitation in central/eastern England in winter, but this may simply reflect noise due to the short (10 year) length of the test simulation. It should be noted that this fix to the daylight hours error has not been applied to the driving RCM since test simulations showed the impact to be small (maximum local impacts of 0.2-0.3°C over the UK and up to 1°C over central/eastern Europe). The impact is generally not significant compared to the spread across the 12-member RCM ensemble and so did not justify a rerun of the UKCP Regional (12km) projections.

The following sections look at the combined impact of these changes on present-day performance (Section 3) and future changes (Section 4) for all 12 ensemble members. Given the above results from the single member tests, we expect the fix to the graupel code error to dominate any differences, although the additional snowpack changes can have comparable sized impacts in some cases, for example for wintertime daily temperature extremes.

3. Present-day evaluation

3.1 Overview

This section assesses the present-day performance of the Local (2.2km) reruns (CPM_new) compared to the original UKCP Local (2.2km) projections released in September 2019 (CPM_orig). It follows a similar structure to the UKCP Convection-permitting Model Projections Science report (Kendon et al, 2019), except that here the figures show biases for the reruns (CPM_new) compared to both the Regional (12km) projections (RCM) and the CPM_orig simulations. The assessment focuses on selected metrics of precipitation and surface air temperature, from seasonal means to daily and hourly extremes. It also includes evaluation of soil moisture, snow, cloud, lightning and (as an addition to the original Science report) surface winds. The evaluation is primarily carried out at the 12km scale to allow comparison with the RCM, with the 2.2km CPM data averaged onto the RCM grid using area-weighted regridding, with land and sea points regridded separately.

We use several observational datasets, summarised in Table 3.1. The observational data is regridded to 12km for direct comparison with the models. We use the same 20-year baseline period (Dec 1980-Nov 2000) from the observations as the models where possible; otherwise we use 20 years of observational data that maximise the overlap with the model years; or where records are shorter than 20 years, we use all available observational data. For CEH-GEAR, we use all 25 years of the available hourly precipitation observations, since instances of missing data reduce the effective record length below 25 years. Note that we would not expect correspondence between the observations and the CPM or RCM simulations on a day-to-day or season-to-season basis. This is because the models produce simulated realisations of internal climate variability, rather than actual hindcasts of events: they are not initialised from observations, and use modelled rather than observed time series of lateral boundary conditions. However, their emergent climatological characteristics, such as 20-year averages or the typical intensity of selected types of extreme event, can be evaluated against corresponding observational metrics.

The ERA-Interim driven CPM and RCM simulations (hereafter ERAI-CPM and ERAI-RCM) are supplied with time series of information on the observed atmospheric state at the lateral boundaries of the European model, and are also driven by observed sea surface temperatures (SSTs). They can therefore be assessed in terms of their ability to reproduce specific historical events, as well as evaluated in a climatological sense. This is because these simulations (unlike the GCM driven 12-member ensemble projections) are expected to capture the observed sequence of large-scale weather patterns. However, the precise timing and location of related events of interest, such as occurrences of extreme regional precipitation, can still be expected to differ in detail. This is because the prescribed lateral boundary forcing does not fully constrain the generation of local variability within the RCM or CPM domains.

Significant differences between CPM_new and CPM_orig in their representation of the present day climate are assessed by comparison with the spread across the twelve member CPM_orig ensemble. Where differences are greater than the standard deviation across the ensemble these are assessed as significant. For testing differences in the ensemble mean (for an ensemble size of 12), this equates to testing at approximately the 95% confidence level.

Variable	Time scale	Dataset	Data span	Grid	Comments and Reference
Surface air temperature	Daily mean	NCIC	1960-present	5km	Based on meteorological station observations (Perry et al, 2009). The number of stations varies between 400 and 600, depending on the year.
Precipitation	Daily	NCIC	1958-present	5km	Gauge-based dataset (Perry et al, 2009). There are typically between 2500 and 5000 daily rain gauges, depending on the year, although with fewer stations before 1961. Rain gauge observations are affected by systematic measurement undercatch due to multiple factors including snow, wind blow losses and exposure of the gauge. Gauges may also miss localised events entirely and there is a tendency for gauges to be sited in valleys rather than at the tops of mountains. Biases vary with season and location, and are largest at high elevations. The systematic undercatch varies between 4% and 50%, with an average estimate of 20% (Kotlarski et al, 2014, Rajczak and Schar, 2017). No correction for this undercatch has been applied here.
Precipitation	Hourly	CEH-GEAR1hr	1990-2014	1km	Gauge-based dataset (Lewis et al, 2018). This is based on 1900 quality controlled hourly rain gauges (although the number used ranges from 295 to 1372 gauges on any given day, due to missing data or quality issues). The gridded hourly data is obtained by disaggregating the UK Centre for Ecology and Hydrology Gridded Estimates of Areal Rainfall (CEH-GEAR) daily gridded dataset using the hourly gauges. An average storm profile was used to disaggregate the daily dataset, where the nearest hourly gauge was >50km away. This process of disaggregation results in a discontinuity in the diurnal cycle at 09Z (when the daily data recording period starts). As for the daily gauges, the hourly gauges are expected to underestimate the intensity of heavy events, and the same caveats as for the daily dataset apply, with even greater sampling errors due to fewer hourly gauges. Additional error will also be introduced by the disaggregation step, associated with distance to the nearest gauge (low gauge density in Scotland and south-west England gives greater distances there).
Precipitation	Hourly	NIMROD RadarNet	2003-2017	5km	Radar dataset (Harrison et al, 2000). Precipitation is estimated from reflectivity measurements. There are known to be errors due to radar calibration, ground clutter, beam attenuation, and assumptions in the reflectivity-precipitation rate relationship. Heavy rainfall tends to be underestimated, and uncertainties are considerable for hail. The radar network provides good spatial coverage over the southern UK, but poorer coverage over northern UK. There are some spurious high totals and these have been removed here by setting all data >100mm/h averaged over a 12km box to missing (corresponding to 0.0004% of UK data; 63 mm/h is maximum value observed by gauges over UK). In general the radar data provide reliable information on the spatial patterns and temporal characteristics of rainfall, but we would have lower confidence in the absolute rainfall amounts especially for intense events.
Falling snow	Days of falling snow per month	NCIC	1971-2011	5km	Based on meteorological station observations (Perry et al 2005). A day is reported even if there is only one observation of snow (or sleet). There are typically 400 to 500 stations recording snow up to the 1990s, but with a subsequent fall. Gridding of snow data is problematic, and these gridded products are no longer updated operationally due to the diminishing network size.
Lying snow	Days of lying snow per month	NCIC	1961-2011	5km	Meteorological station observations (Perry et al 2005). Based on observer deciding that the ground is more than half covered in snow. There are typically 400 to 500 stations recording lying snow from 1961 to the 1990s, but a subsequent fall to approximately 100 stations currently. Gridding of snow data is problematic, and these gridded products are no longer updated operationally due to the diminishing network size.

Variable	Time scale	Dataset	Data span	Grid	Comments and Reference
Cloud and surface radiation	Monthly mean	CLARA-A2	1982-2015	0.25°	Based on Advanced Very High Resolution Radiometer (AVHRR) measurements from National Oceanic and Atmospheric Administration (NOAA) and European Organization for the Exploitation of Meteorological Satellites (EUMETSAT) polar-orbiting satellites (Karlsson et al 2017). Original visible radiances were inter-calibrated and homogenised using Moderate Resolution Imaging Spectroradiometer (MODIS) data. Prior to 1992 there was only one instrument available, leading to more missing data; it is more complete over Europe from 1992, and better again from 2002. Cloud detection biases for period October 2006-December 2009 are about 13% compared to Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO) Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP) observations.
Soil moisture	Daily mean	WFDEI-JULES	1979-2012	0.5°	Simulation of land-surface properties by JULES, forced by the WATCH Forcing Data methodology applied to ERA-Interim reanalysis (WFDEI, Weedon et al 2014) meteorological dataset. WFDEI is based on ERA-Interim reanalysis data, but includes bias correction using monthly gridded surface observations. This dataset is considered as a proxy for observed soil moisture.
Lightning	Flashes per day	ATDnet	2009-present	Point data	Met Office long-range very low-frequency lightning location system, Arrival Time Difference Network (ATDnet, Anderson and Klugmann, 2014). Relies on detection of electromagnetic fields produced by lightning, providing the location and time of every flash. ATDnet system mainly records cloud-to-ground (but not intra-cloud) lightning (Enno et al., 2016). ATDnet suffers from interference due to the height of the ionosphere, and so periods of nocturnal lightning are not detected (Bennett et al, 2011). The detection efficiency of ATDnet goes up every few years as the hardware is upgraded, so observations from the last few years (2010-2019) only are used here.
Surface winds	Hourly	ERA5	1979-2019	31km	Reanalysis dataset produced by the European Centre for Medium-range Forecasts (ECMWF) (Hersbach et al 2020). This is the fifth generation of reanalyses produced by ECMWF, and is an advance on ERA-Interim, with higher resolution and improved model physics. The reanalysis is based on the Integrated Forecasting System (IFS) Cy41r2, with assimilation of observations, including surface pressure, temperature, wind and humidity from near-surface and upper-air soundings.

Table 3.1. Observational UK datasets used in the evaluation of the RCM and CPM simulations

3.2 Seasonal mean performance

The performance of the RCM, CPM_new and CPM_orig standard members (RCM-STD, CPM-STD_new and CPM-STD_orig respectively) in representing seasonal mean temperature in winter and summer is shown in Figs 3.2.1-3.2.2. We focus on the standard member, which is the member driven by the unperturbed global and RCM simulations, since a corresponding ERA-Interim driven experiment is available, allowing an assessment of the extent to which biases are inherited from the driving GCM. We show results for both CPM_new and CPM_orig, and their differences, to assess the impact of the rerun on seasonal mean performance.

In winter, the root mean square (RMS) bias over the UK amounts to 0.5°C in both CPM_new and the RCM, although the relative performance varies across the country (Fig 3.2.1). The RCM is too cold in the north and too warm in the south (with local differences of up to 1°C), whilst CPM_new is too cold more widely in the north but has reduced biases in the south. CPM_new is considerably colder than CPM_orig, exacerbating cold biases in the north. Despite these increases in bias, however, we have greater confidence in the results from CPM_new than CPM_orig in terms of winter temperature. This is due to the improved physical representation of snow and graupel in the reruns (including fix to the graupel code error, Section 2), which leads to more lying snow in the present day (see Section 3.5) and consequently colder winter temperatures compared to CPM_orig (UK-average CPM_new minus CPM_orig RMS difference of 0.4°C, but with differences greater than 0.5°C over Scotland, compared to standard deviation across 12-member CPM_orig ensemble of 0.6°C). Thus, lower biases in CPM_orig likely reflect compensating errors. Comparison between the standard (STD) runs and those driven by ERA-Interim shows that biases are largely a feature of the 12km and 2.2km models, although there is some suggestion that cold biases over Scotland in RCM-STD and CPM-STD_new may be increased slightly by cold biases inherited from the driving GCM.

In summer, RCM-STD is too cold, but these biases are reduced or (in some areas) reversed in ERAI-RCM suggesting they are largely inherited from the driving GCM. CPM_new is generally warmer than the RCM except in the far north, with overall similar UK-average biases (UK RMS bias of 0.6°C in RCM and 0.5°C in CPM_new, Fig 3.2.2). As expected, the new 2.2km reruns have very little impact on the CPM performance in representing summer mean temperature, with little difference between CPM_new and CPM_orig (UK RMS difference of 0.1°C).

In winter, RCM-STD is too wet (UK RMS bias of 36.4%), although these biases are reduced in ERAI-RCM (24.0% bias) suggesting that they are in part inherited from the driving GCM (Fig 3.2.3). Biases in the RCM are greatest in south-east UK, where the RCM can be too wet by more than 40%, whilst over the mountains in the north and west the RCM tends to be too dry. These biases are considerably reduced in CPM_new, which is wetter than the RCM over the mountains but drier elsewhere. Code changes in the 2.2km reruns have some impact on biases in winter mean precipitation, with CPM_new wetter than CPM_orig across much of the UK but particularly over mountainous regions (UK RMS difference between CPM_new and CPM_orig of 12.0%; compared to standard deviation across CPM_orig ensemble of 9.8%, Kendon et al, 2020b). This leads to slightly greater biases (UK RMS bias of 25.7% in CPM_new and 20.1% in CPM_orig, reduced to 14.6% and 12.3% respectively in the ERAI driven runs), but these remain considerably smaller than biases in the RCM. Thus, the key improvement in the CPM in terms of the representation of winter mean precipitation compared to the RCM is not impacted by the rerun.

In summer, RCM-STD is too wet in the north of the UK, with biases only slightly reduced in ERAI-RCM-STD (Fig 3.2.4). As in winter, biases in summer mean precipitation are considerably reduced in the CPM compared to the RCM (UK RMS bias of 24.6% in RCM and 15.6% in CPM_new), with CPM_new being drier than the RCM in regions where it is too wet. The rerun of the 2.2km model, has little impact on these differences, with CPM_new and CPM_orig showing very similar results.

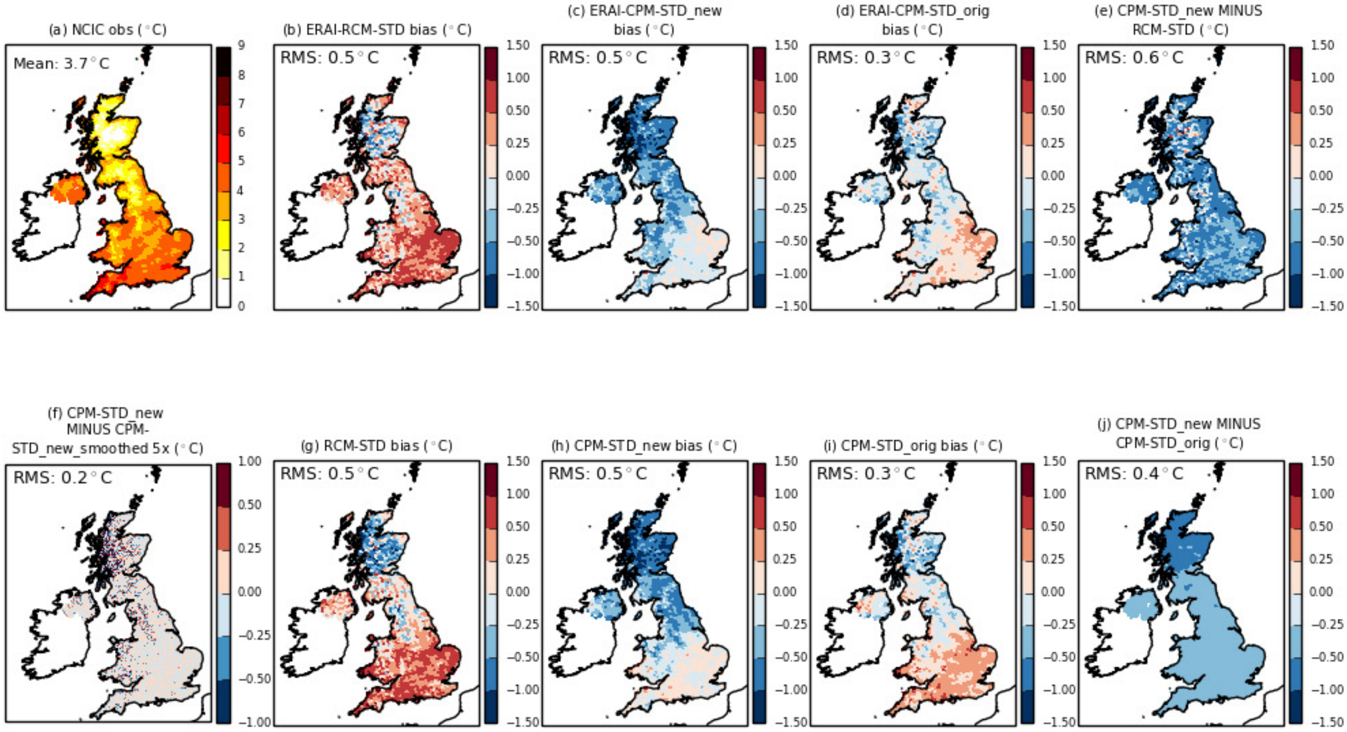

Figure 3.2.1. Observed and simulated winter mean surface air temperature. Mean temperature in winter in the (a) NCIC observations (1981-2000), and biases in the (b) ERAI-RCM-STD, (c) ERAI-CPM-STD_new (d) ERAI-CPM-STD_orig, (g) RCM-STD, (h) CPM-STD_new and (i) CPM-STD_orig, at the 12 scale. Model differences (e) CPM_new minus RCM and (j) CPM_new minus CPM_orig are shown for the STD member, and also (f) added spatial detail (2.2km minus 2.2km-smoothed-to-12km, which equates to averaging over 5x5 2.2km grid boxes) in CPM_new. The UK-averaged mean value or Root Mean Square (RMS) error is indicated.

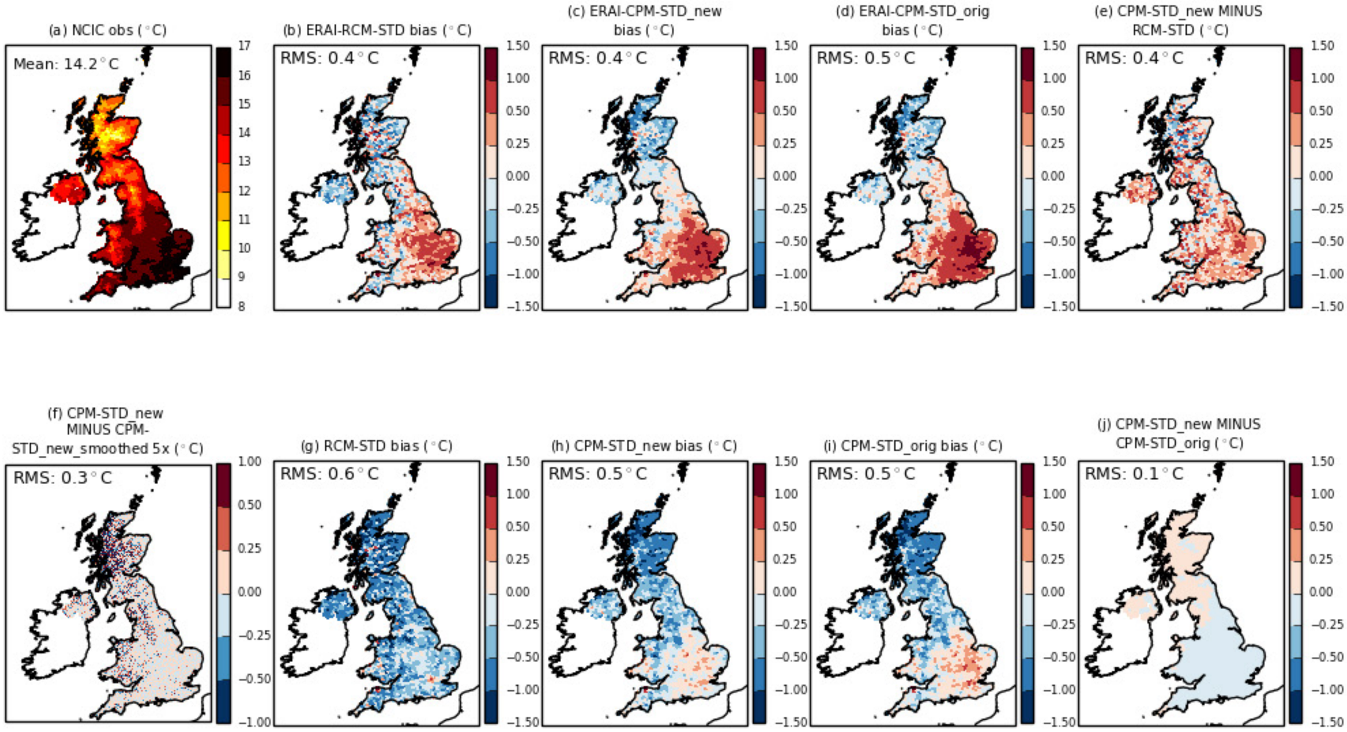

Figure 3.2.2. Observed and simulated summer mean surface air temperature. As Fig 3.2.1 but for mean temperature in summer.

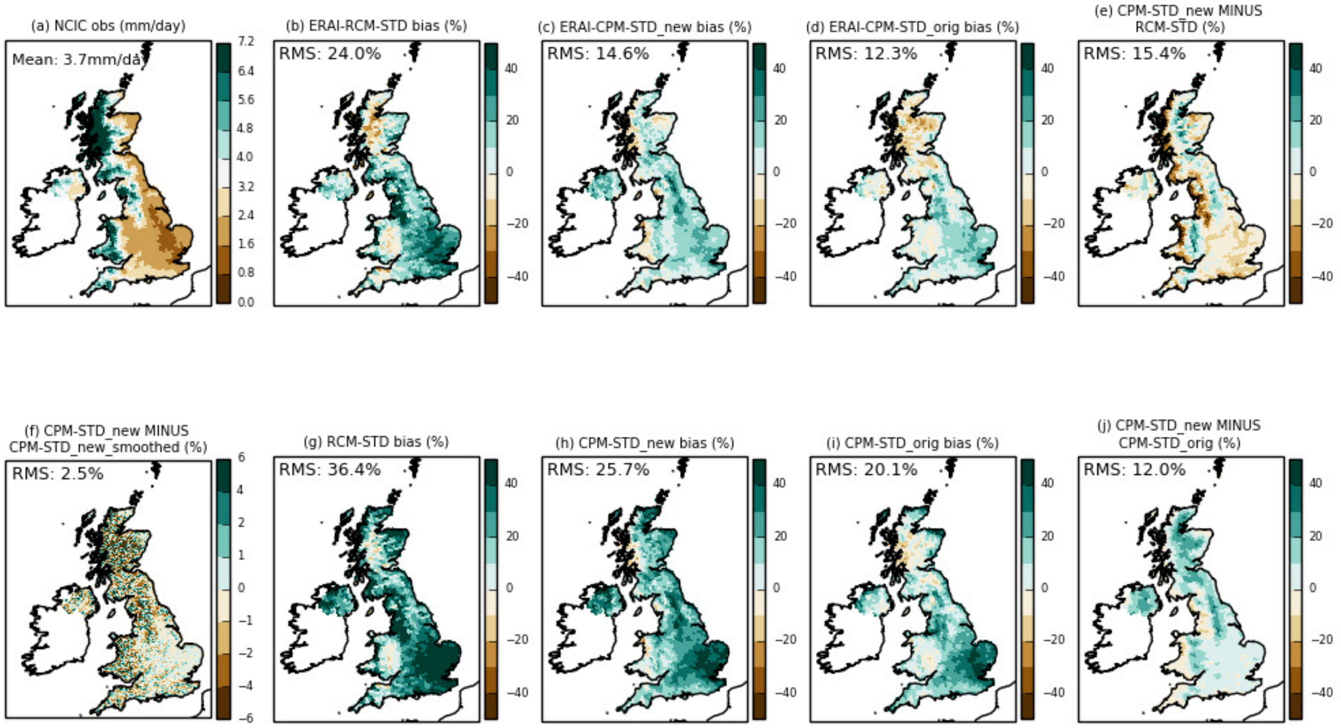

Figure 3.2.3. Observed and simulated winter mean precipitation. As Fig 3.2.1 but for mean precipitation in winter.

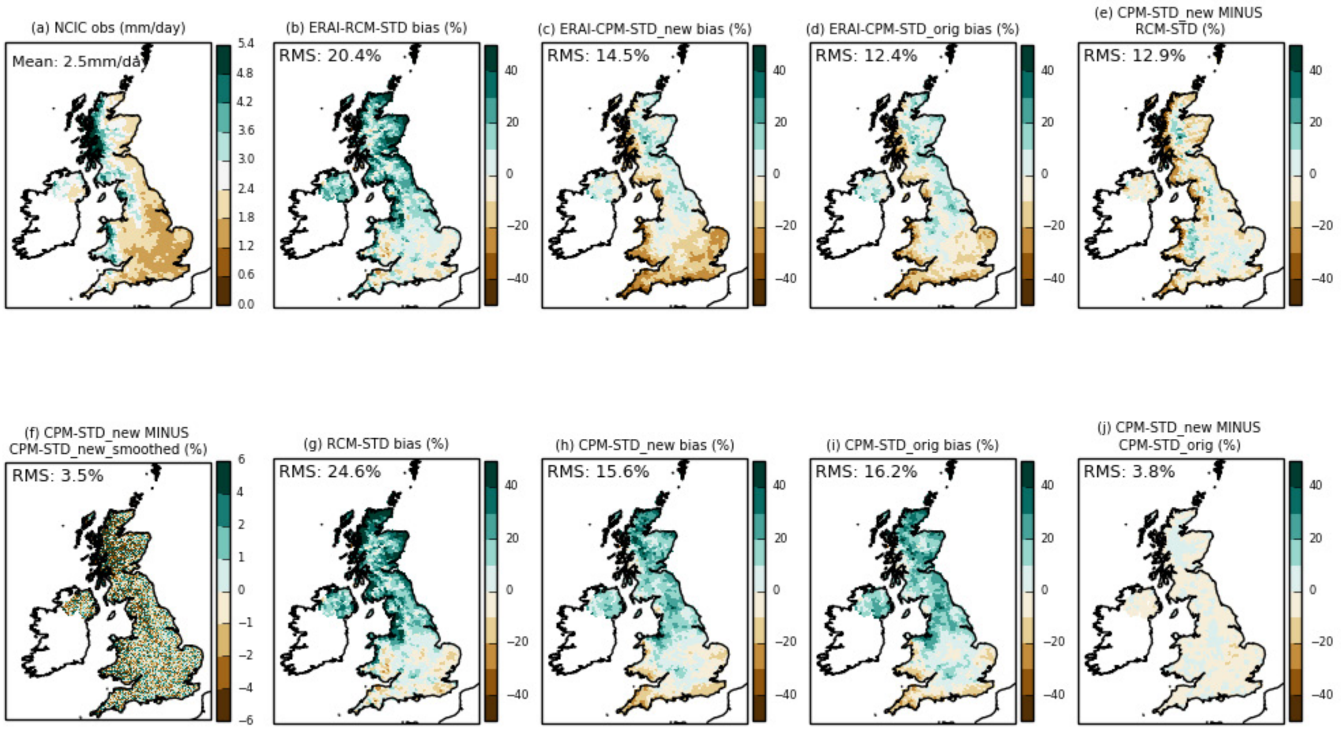

Figure 3.2.4. Observed and simulated summer mean precipitation. As Fig 3.2.1 but for mean precipitation in summer.

3.3 Daily variability

In this and subsequent sections, we move on to assess the performance of the CPM_new, CPM_orig and RCM ensemble means in capturing measures of daily and hourly variability and high impact events. We judge ensemble mean differences as being significant (at the ~95% level) where these are greater than the CPM ensemble standard deviation (Section 3.1).

Cold winter days are considerably colder in CPM_new than CPM_orig (UK RMS difference of 2°C) with this difference greater than the standard deviation across the CPM_orig ensemble (UK RMS of 0.9°C, Kendon et al, 2020b) and thus judged significant. This leads to an increase in cold biases in the north of the UK (Fig 3.3.1). However, cold winter days in the CPM are still warmer than the RCM in this region leading to reduced biases (UK RMS error of 1.7°C in RCM and 1.4°C in CPM_new). This contrasts with winter mean temperatures being lower in CPM_new compared to the RCM, at least for the standard (STD) member (Fig 3.2.1).

The impact of the code changes on daily temperature extremes is smaller in summer, with the difference between CPM_new and CPM_orig considerably smaller than the difference between CPM_new and the RCM. Overall CPM_new provides an improved representation of hot summer days compared to the RCM (UK RMS error of 0.8°C in RCM and 0.6°C in CPM_new), although values are slightly too warm in the south (local biases up to 1°C, Fig 3.3.1).

For daily precipitation in winter (Fig 3.3.2), CPM_new is wetter than CPM_orig, with the code changes leading to increases in wet day frequency, wet-day intensity and heavy daily precipitation. Increases in intensity are largest over mountainous regions. These differences lead to a small increase in biases for CPM_new compared to CPM_orig, but biases in CPM_new remain smaller than those in the RCM. Differences between CPM_new and CPM_orig are consistently smaller than the differences between CPM_new and the RCM, and thus key differences in the characteristics of daily precipitation between the CPM and RCM (with precipitation less frequent and more intense in the CPM, in better agreement with observations) are unaffected by the rerun.

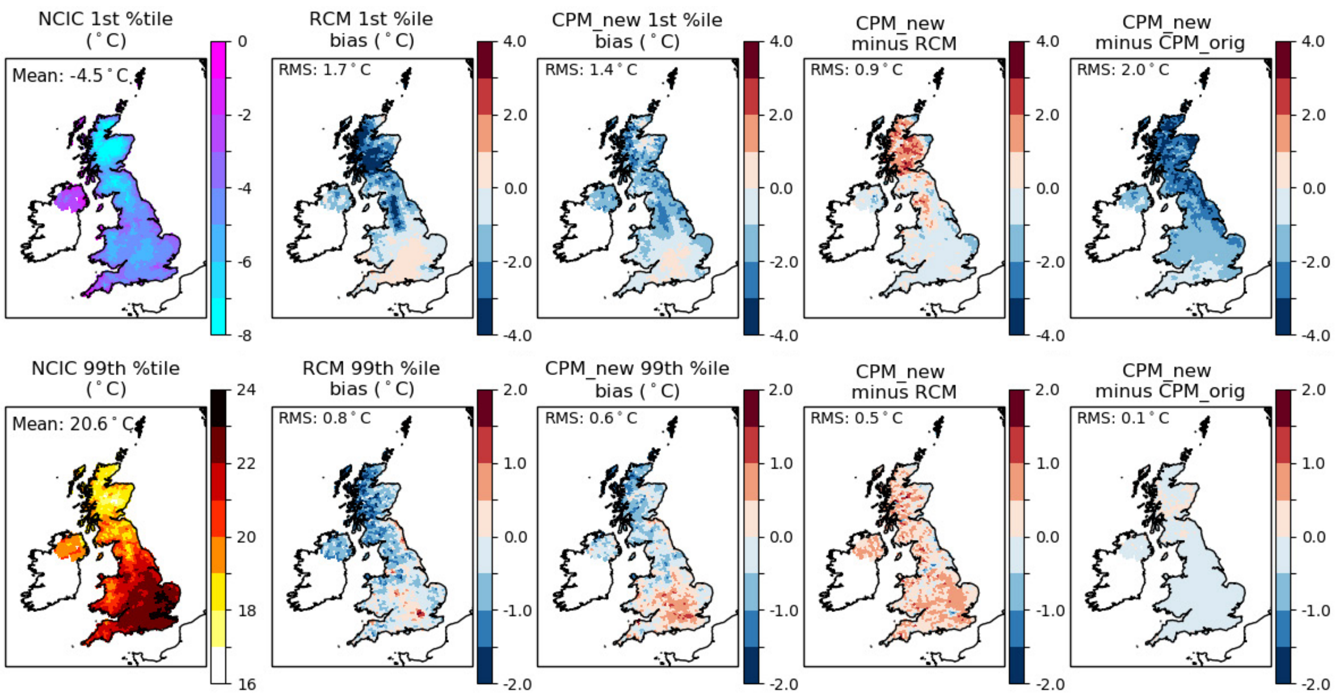

Figure 3.3.1. Observed and simulated daily temperature extremes in winter and summer. Left panels show the 1st percentile of daily average temperature in winter (cold days) and the 99th percentile in summer (hot days) in the NCIC observations during 1981-2000. Centre left and centre panels show biases (°C) in the ensemble-average from the 12-member RCM and CPM_new ensembles. Centre right shows differences between CPM_new minus RCM and right panel differences between CPM_new minus CPM_orig. Daily data was regridded to the 12km scale in all cases. The UK-averaged (left panels) mean value or Root Mean Square (RMS) error is indicated.

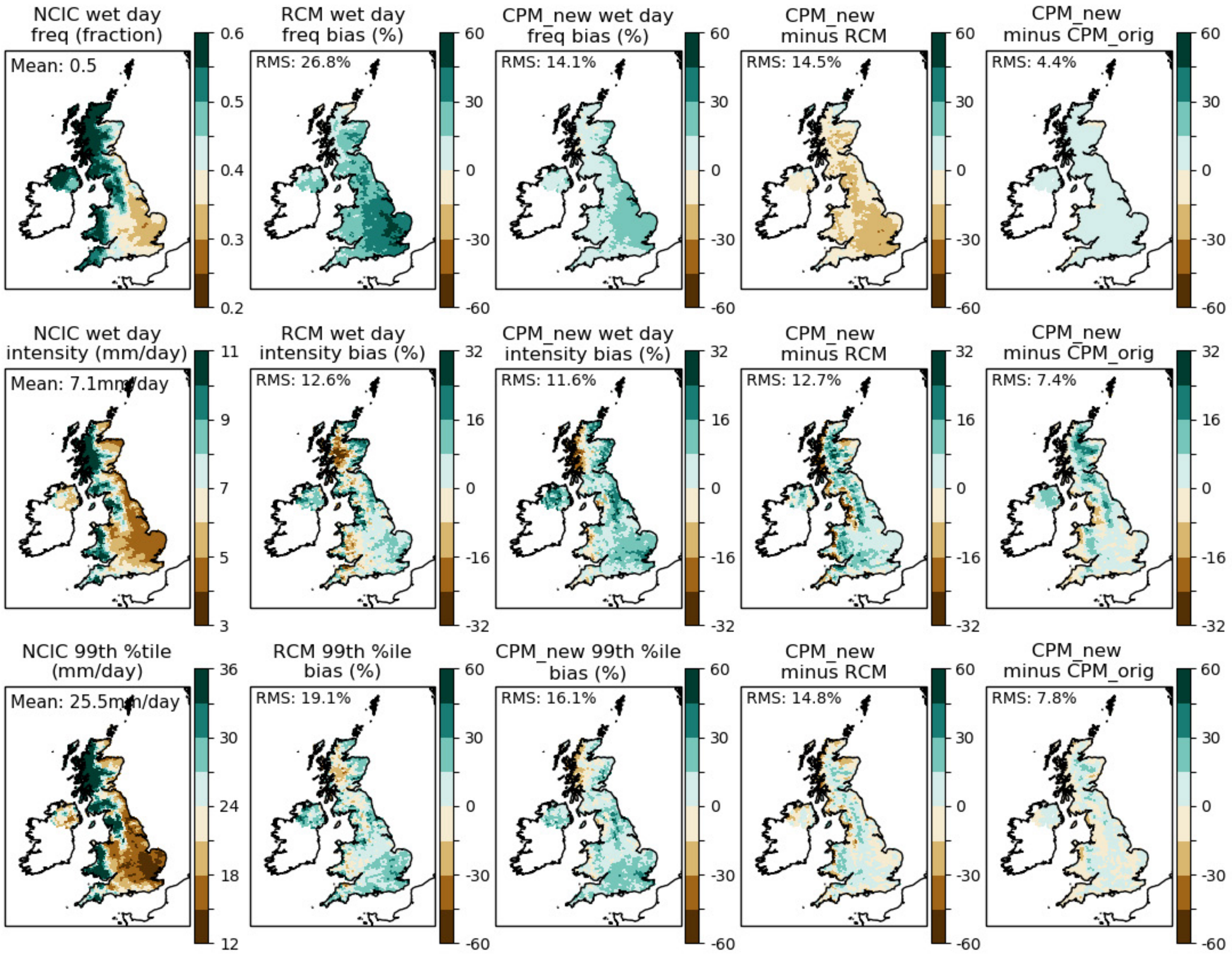

Figure 3.3.2. Observed and simulated daily precipitation in winter. Left panels show wet day frequency, mean wet day intensity and heavy daily precipitation (99th percentile of all days) in winter in the NCIC observations during 1981-2000. Centre left and centre panels show biases (%) in the ensemble-average from the 12-member RCM and CPM_new ensembles respectively. Centre right shows differences between CPM_new minus RCM and right panel differences between CPM_new minus CPM_orig. Wet days are days with greater than 1mm accumulation of precipitation, and daily precipitation data was regridded to the 12km scale in all cases. The UK-averaged (left panels) mean value or Root Mean Square (RMS) error is indicated.

In summer, the code changes lead to a reduction in daily precipitation intensity and heavy precipitation but have little impact on daily precipitation occurrence (Fig 3.3.3). These differences generally lead to smaller biases in CPM_new compared to CPM_orig, reducing the tendency for precipitation to be too intense in the CPM. As in winter, key differences in the characteristics of daily precipitation between the CPM and RCM are unaffected by the rerun. UK average biases are lower for CPM_new compared the RCM, for all daily precipitation metrics considered.

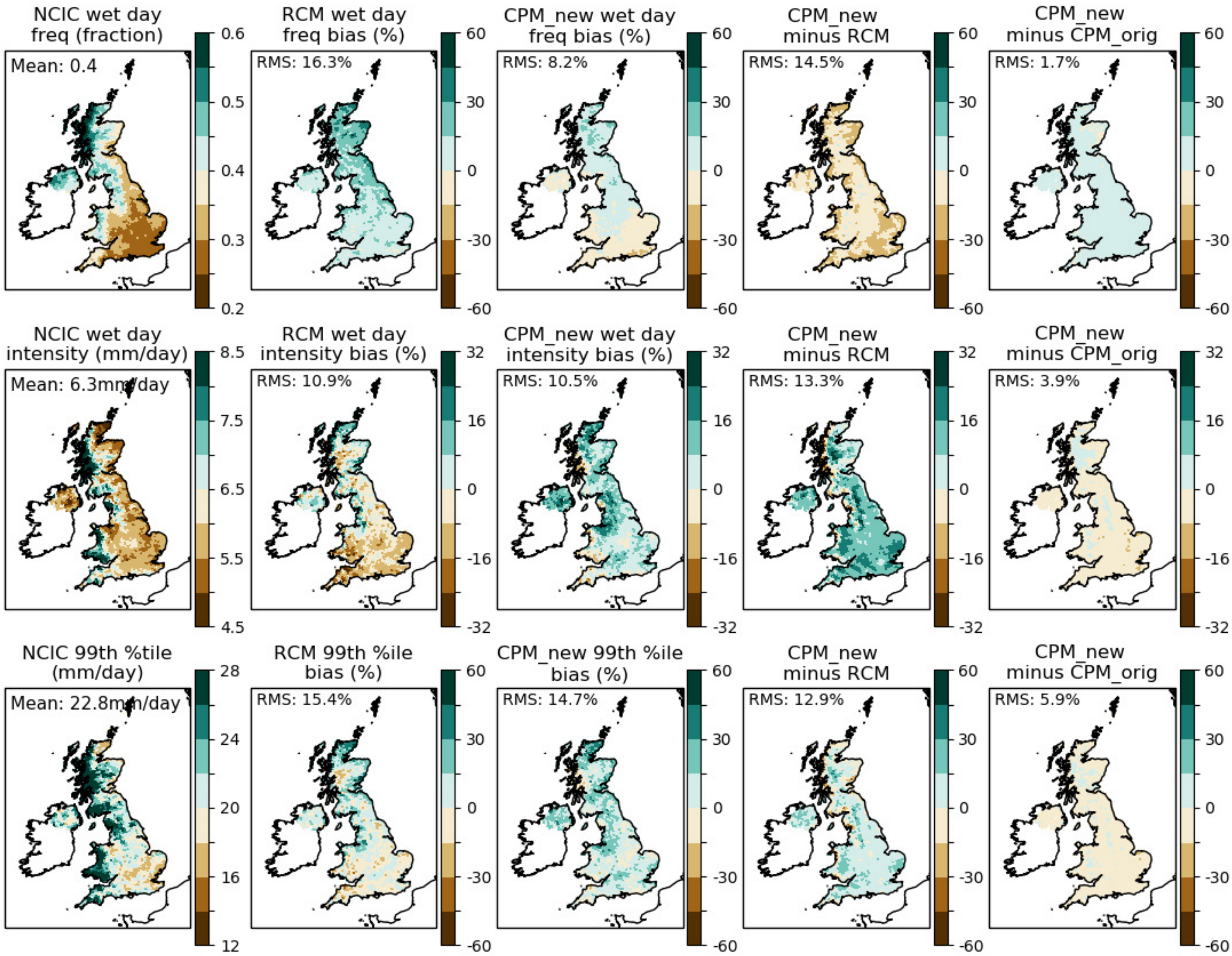

Figure 3.3.3. Observed and simulated daily precipitation in summer. As Fig 3.3.2 but for daily precipitation in summer.

3.4 Hourly precipitation frequency and intensity

In winter and summer, the 2.2km model changes from CPM_orig to CPM_new only have a small impact on hourly precipitation occurrence and intensity (Figs 3.4.1-3.4.2). In particular, the key improvements in the CPM compared to the RCM remain, with CPM biases considerably lower than RCM biases in terms of hourly precipitation occurrence in winter (UK RMS errors of 43% in RCM and 12% in CPM_new) and both occurrence and intensity in summer (38% and 25% RMS errors in RCM compared to 17% and 16% in CPM_new respectively). CPM_new in general represents an improvement compared to CPM_orig, with lower biases especially in summer.

For heavy hourly precipitation, the model changes have a small impact in winter, with heavy precipitation slightly reduced in CPM_new compared to CPM_orig leading to reduced biases across the UK overall (Fig 3.4.3). However there is a notable reduction in heavy rainfall in summer (consistent with the results of the single member test of fixing the graupel code error, Kendon et al, 2020b), which considerably reduces biases in the new compared to the original CPM (UK RMS errors decrease from 31% in CPM_orig to 14% in CPM_new for the 99.95th percentile of hourly precipitation, Fig 3.4.4). CPM_new generally performs better than both CPM_orig and the RCM, with the latter underestimating heavy hourly precipitation in both seasons.

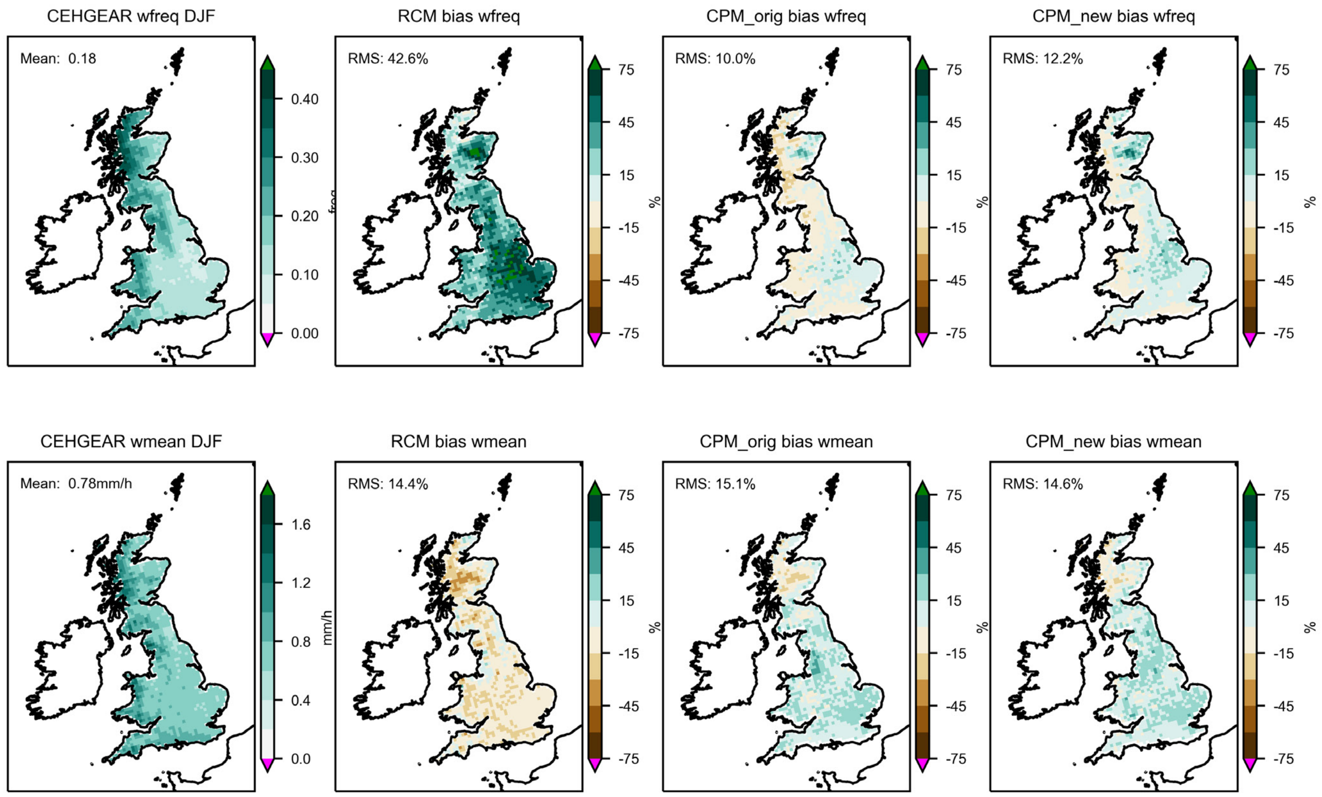

Figure 3.4.1. Observed and simulated hourly precipitation variability in winter. (Top) Wet hour frequency and (bottom) wet hour intensity in winter in the (left) CEHGEAR gauge observations and biases (%) in the ensemble-average for the (centre left) RCM, (centre right) CPM_orig and (right) CPM_new. The gauge observations correspond to 1990-2014, and the model results to 1981-2000. Wet hours are hours with greater than 0.1mm accumulation of precipitation, and hourly precipitation data was regridded to the 12km scale in all cases. The UK-averaged mean value (for gauge observations) or UK-Root Mean Square value (for biases) is indicated in each panel.

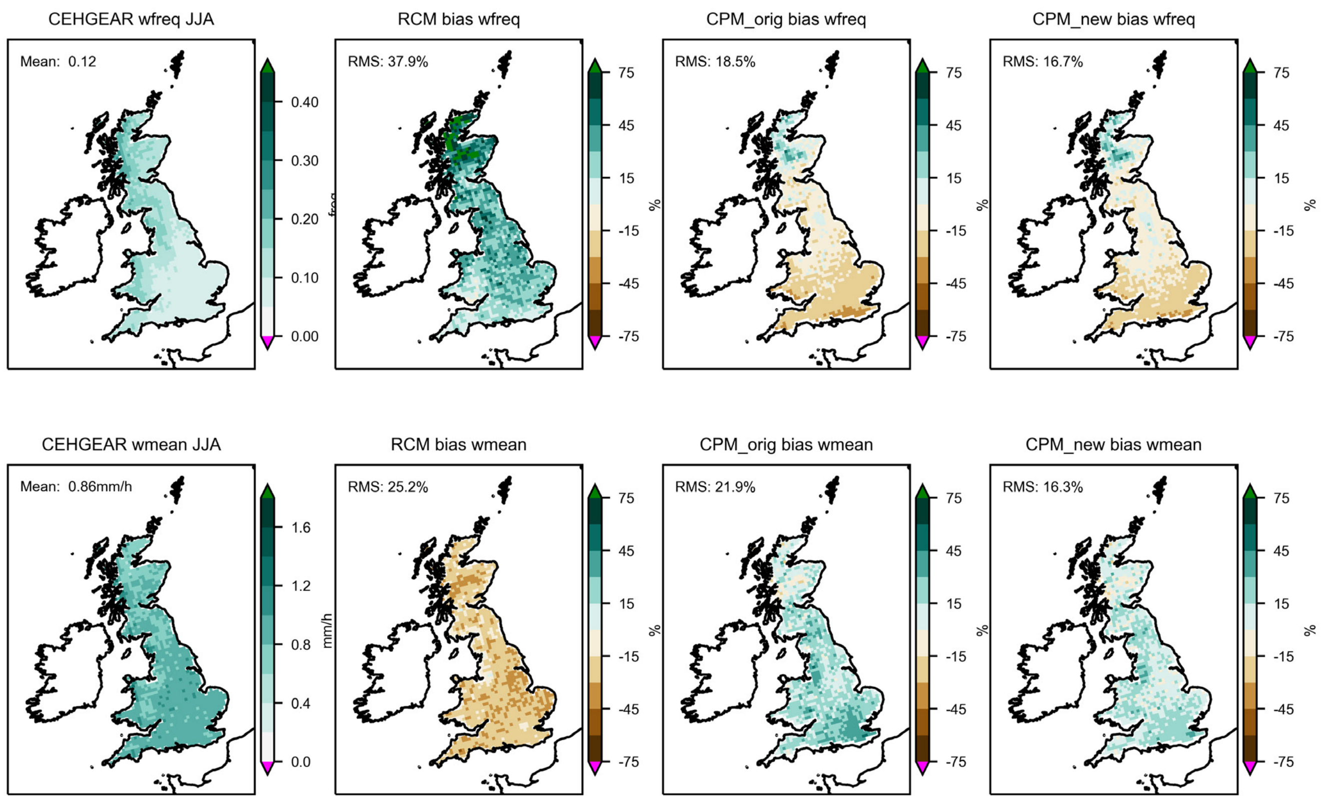

Figure 3.4.2. Observed and simulated hourly precipitation variability in summer. As Fig 3.4.1, but for hourly precipitation in summer.

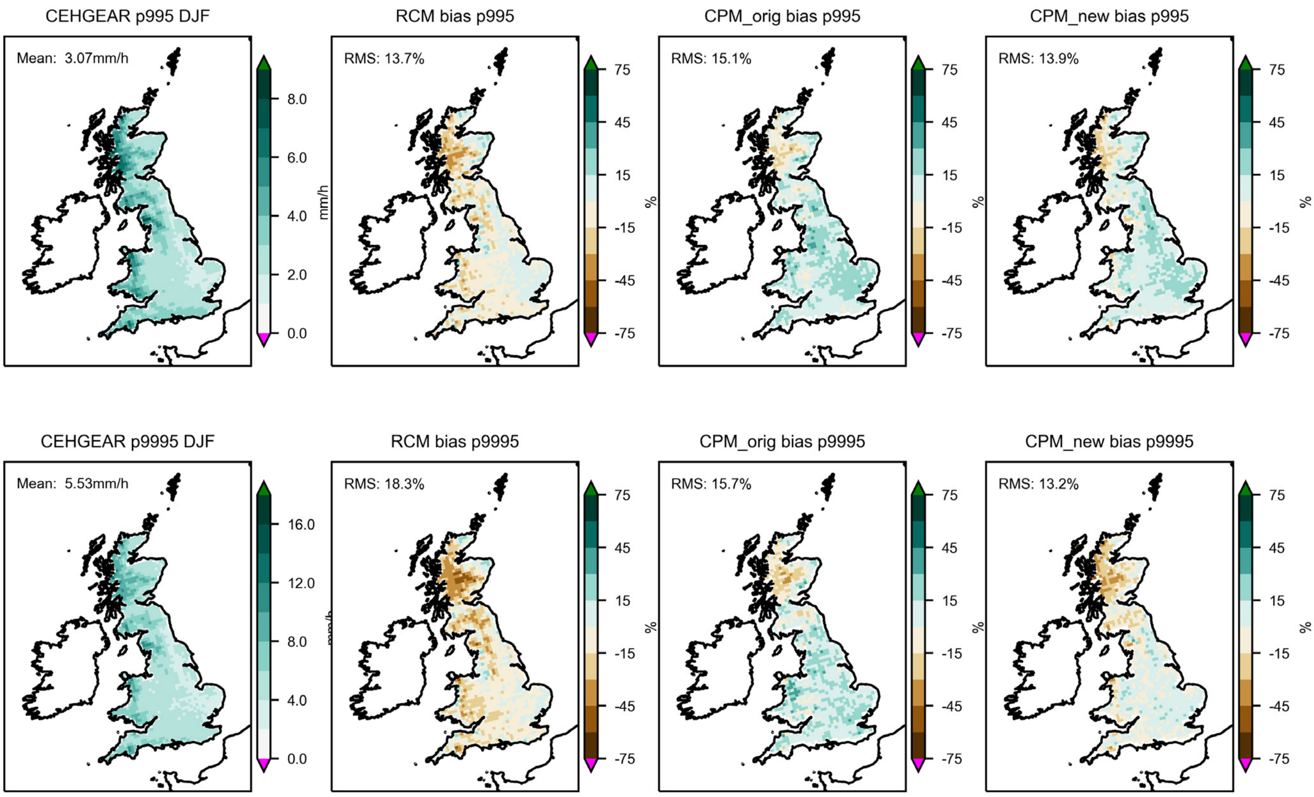

Figure 3.4.3. Observed and simulated heavy hourly precipitation in winter. As Fig 3.4.1, but for the (top) 99.5th and (bottom) 99.95th percentile of hourly precipitation (including all hours) in winter.

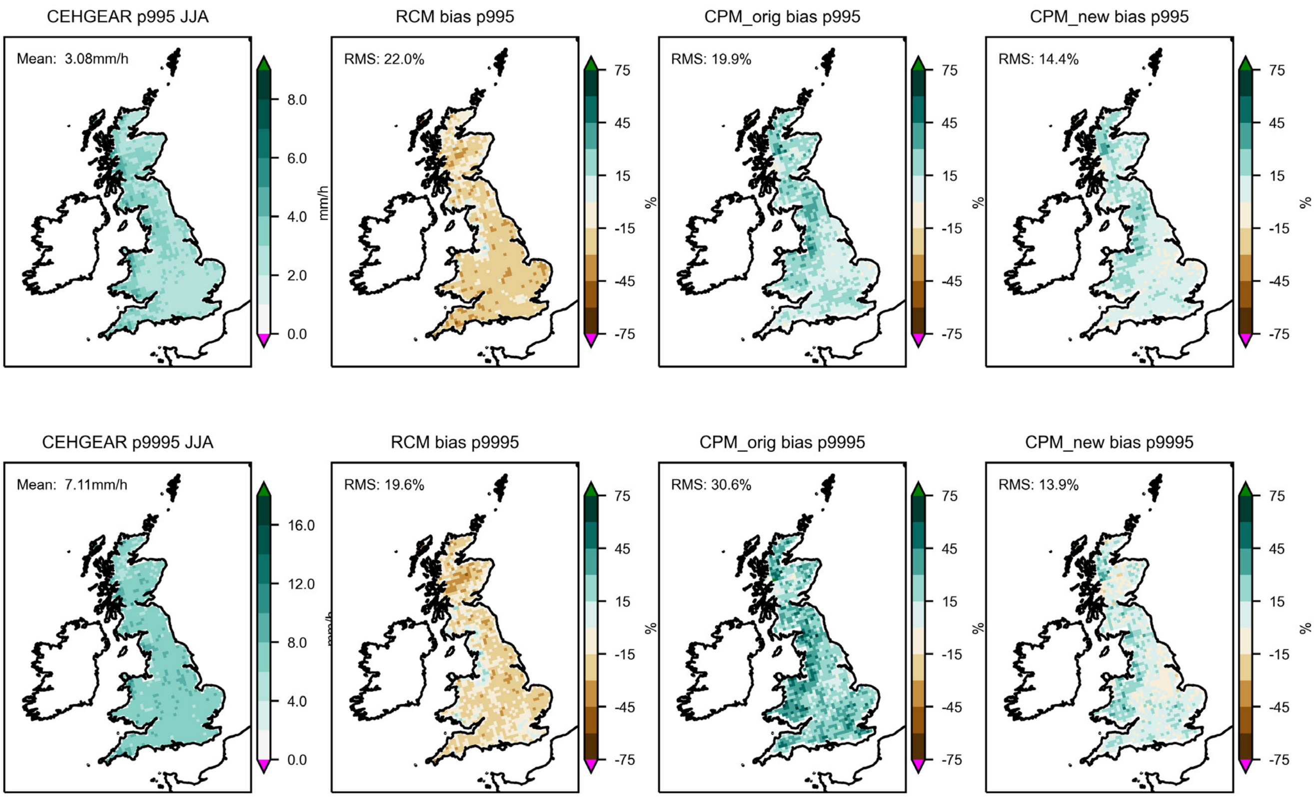

Figure 3.4.4. Observed and simulated heavy hourly precipitation in summer. As Fig 3.4.1, but for the (top) 99.5th and (bottom) 99.95th percentile of hourly precipitation (including all hours) in summer.

3.5 High impact events

Extreme hourly precipitation

To characterise the extreme tail of the hourly precipitation distribution, we fit a Generalised-Pareto Distribution (GPD) to extremes of daily maximum hourly precipitation selected using Peak-Over-Threshold (POT) methodology (Coles, 2001; Chan et al, 2014). In particular, extremes are values exceeding the 99.5th percentile of all daily-maximum hourly values for annual analysis or the 99.0th percentile for seasonal analysis. This corresponds to a sample size of almost 2 events per year, or almost 1 event per season, at each grid box. The use of daily maximum hourly values ensures only one event is selected on a given day, and is a simple method of accounting for time dependence in the data. In addition to the grid-point analysis, we also carry out a regional frequency analysis following Hosking and Wallis (1993) to allow a more robust calculation of return levels for longer return periods by effectively increasing the sample size through spatial pooling. For this we divide the UK into three sub-regions (NW, NE and S UK, see Fig 3.5.1), chosen as regions of similar size within which the precipitation climatology is approximately uniform. These approaches are the same as used in the analysis of the original Local 2.2km projections released in September 2019, with further details in Kendon et al, (2019).

The gauge and the radar datasets used for historical evaluation both have deficiencies in their representation of localised intense extremes. The gauges are expected to give an underestimate due to undercatch or the event being missed entirely; whilst the radar suffers from beam attenuation as well as spurious high values (Table 3.1). Given the deficiencies of the radar in measuring intense events, we primarily use the gauge observations here. However, we also note that the CPM has a known bias of too intense rainfall due to the model being unable to fully resolve convection at 2.2km grid spacing (Kendon et al, 2021).

2-year return levels of annual extremes are considerably reduced (by about 20%) in CPM_new compared to CPM_orig. This is consistent with results testing the impact of fixing the graupel code error (Kendon et al, 2020b) and significant compared to the spread across the original ensemble (difference of 2.5 mm/h, Fig 3.5.1, compared to standard deviation of 1.1 mm/h). This reduction leads to much better agreement with the observations and greater consistency with 2-year return levels in the RCM (Fig 3.5.1). Looking across a range of return periods, and for individual seasons, CPM_new gives a good representation of hourly precipitation extremes and how these increase with increasing return period over the southern UK (the observations typically lie within the 12-member ensemble spread, Figs 3.5.2). Over the northern regions, CPM_new generally underestimates return levels, especially in DJF (Fig 3.5.3-3.5.4). In general (although with some exceptions including the SUK and NE-UK in spring), there is good agreement between CPM-STD_new and ERAI-CPM-STD_new. This indicates that the representation of hourly precipitation extremes locally is largely controlled by the downscaled model physics. The tendency for the original model CPM_orig to overestimate extremes is considerably reduced (or even reversed in the northern regions) in the rerun, likely due to fixing the graupel code error.

Considerable differences in the shape of the return level curve between the CPM and RCM remain in the rerun. In the RCM, the rate at which extremes increase with return period (the "growth curve") is too steep compared to observations. Consequently the RCM tends to overestimate high return period events (particularly in JJA and SON, Figs 3.5.2-3.5.4), even though there may be good agreement with observations for modest return periods. In comparison, CPM_new captures the growth curve better. This is important since the growth curve is a measure of how precipitation extremes increase for more favourable conditions (e.g. favourable flow regimes with high moisture and instability). Thus, this provides an indication that the CPM captures the underlying processes behind the growth of extremes, with the hope that this extends to the future warmer climate (Kendon et al, 2021). The difference in behaviour at the extreme tail between the CPM and RCM has been found previously, and likely relates to unphysical "grid point storms" in the 12km model (Chan et al, 2014).

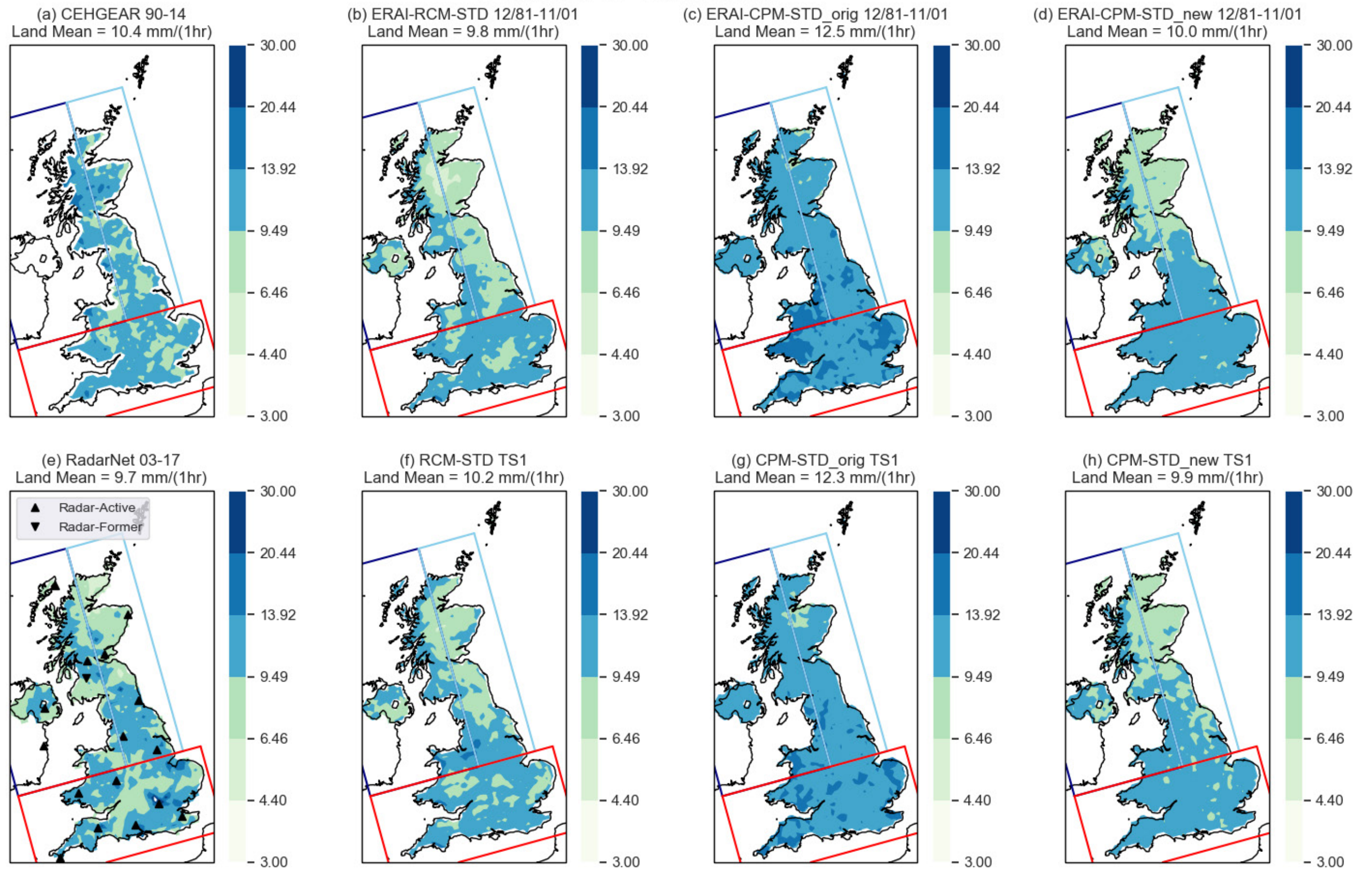

Figure 3.5.1. 2 year return level of daily maximum hourly precipitation. Shown are the return levels using data from all seasons for: observations from (a) CEHGEAR gauge dataset for 1990-2014 and (e) RadarNet radar dataset for 2003-2017; model estimates for (b) ERAI-RCM-STD, (c) ERAI-CPM-STD_orig and (d) ERAI-CPM-STD_new for Dec 1981 to Nov 2001; and (f) RCM-STD, (g) CPM-STD_orig and (h) CPM-STD_new and for TS1 (Time slice 1, Dec 1980 to Nov 2000). All hourly precipitation data has been regridded to a common 12km grid before calculation of return levels. The NW, NE and S UK regions for the regional frequency analysis are shown. Also indicated in (e) are the sites of radar stations that are currently operational (radar-active) and radar sites that are in the UK network but are no longer providing data (radar-former).

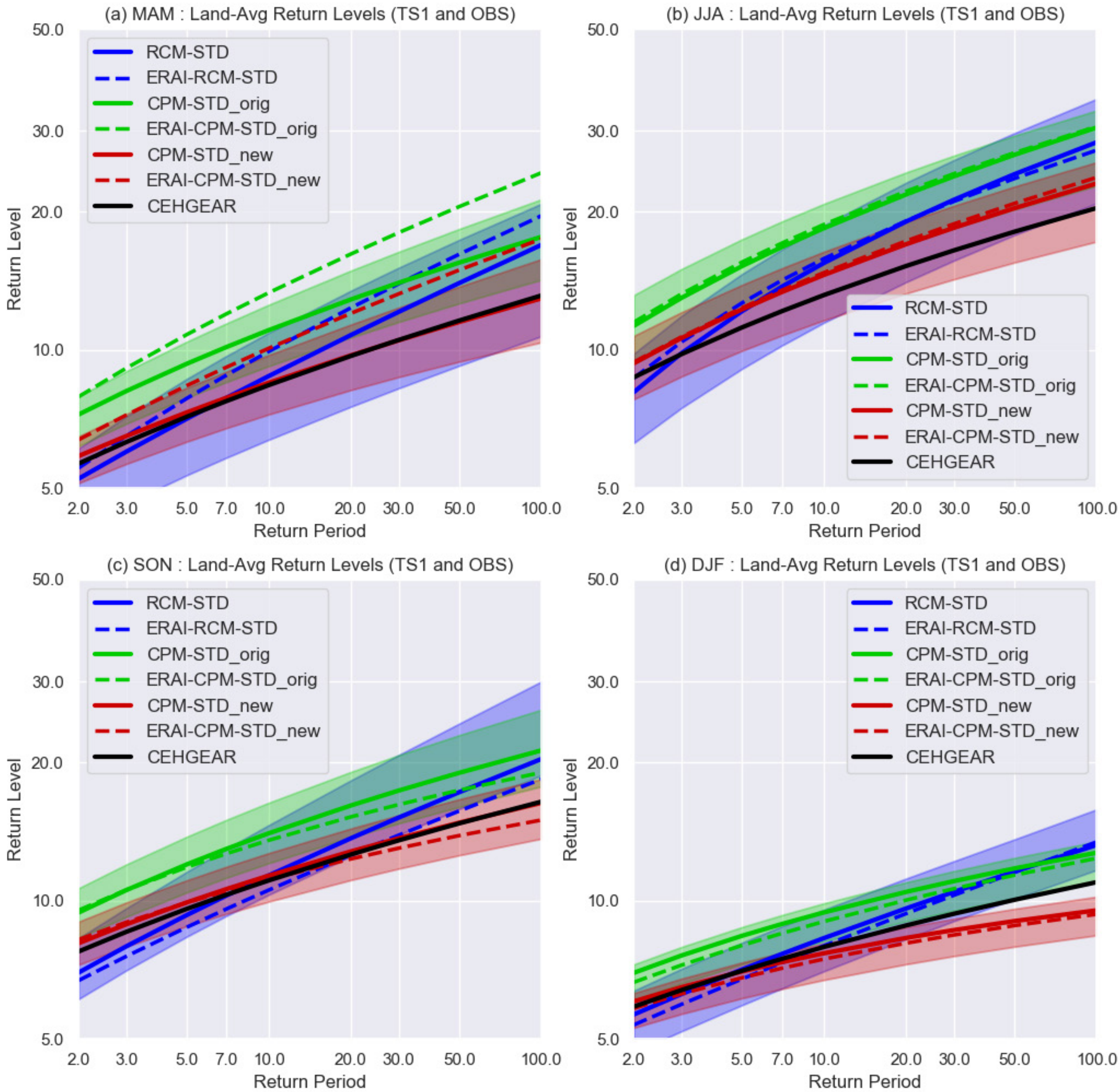

Figure 3.5.2. Southern UK average return level of hourly precipitation extremes. South UK average return level of daily maximum hourly precipitation as a function of return period, for individual seasons. Shown are the return levels (mm/h) for the CEHGEAR gauge observations (1990-2014, black); and the RCM (blue), CPM_orig (green) and CPM_new (red) model ensembles (1981-2000). The standard member (STD, solid line) and ERAI-driven run (ERAI, dashed) are shown, with the shaded region corresponding to the ensemble spread. The regional average values have been calculated using the regional frequency analysis method.

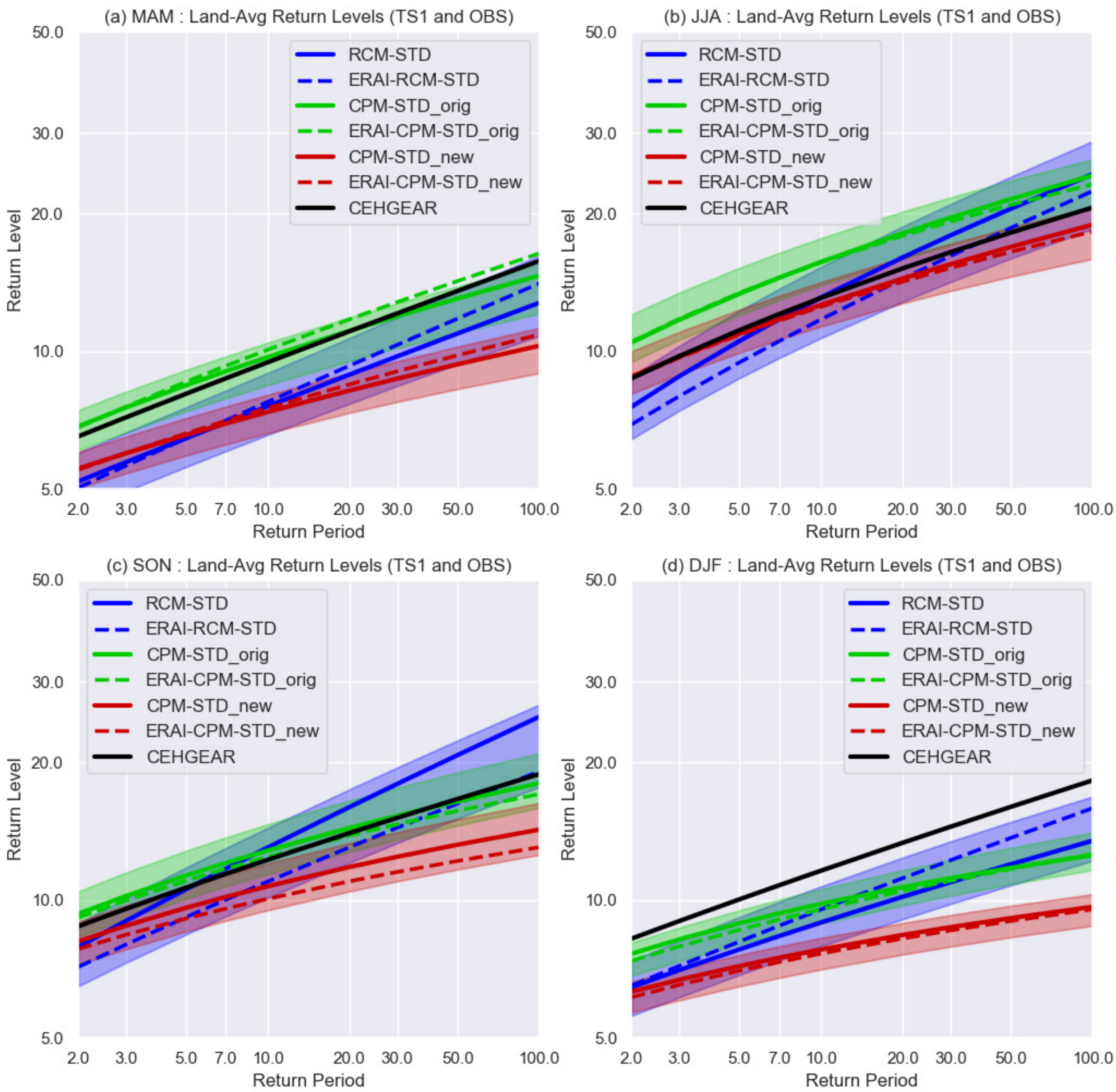

Figure 3.5.3. North-West UK average return level of hourly precipitation extremes. As Fig 3.5.2 but for NW region.

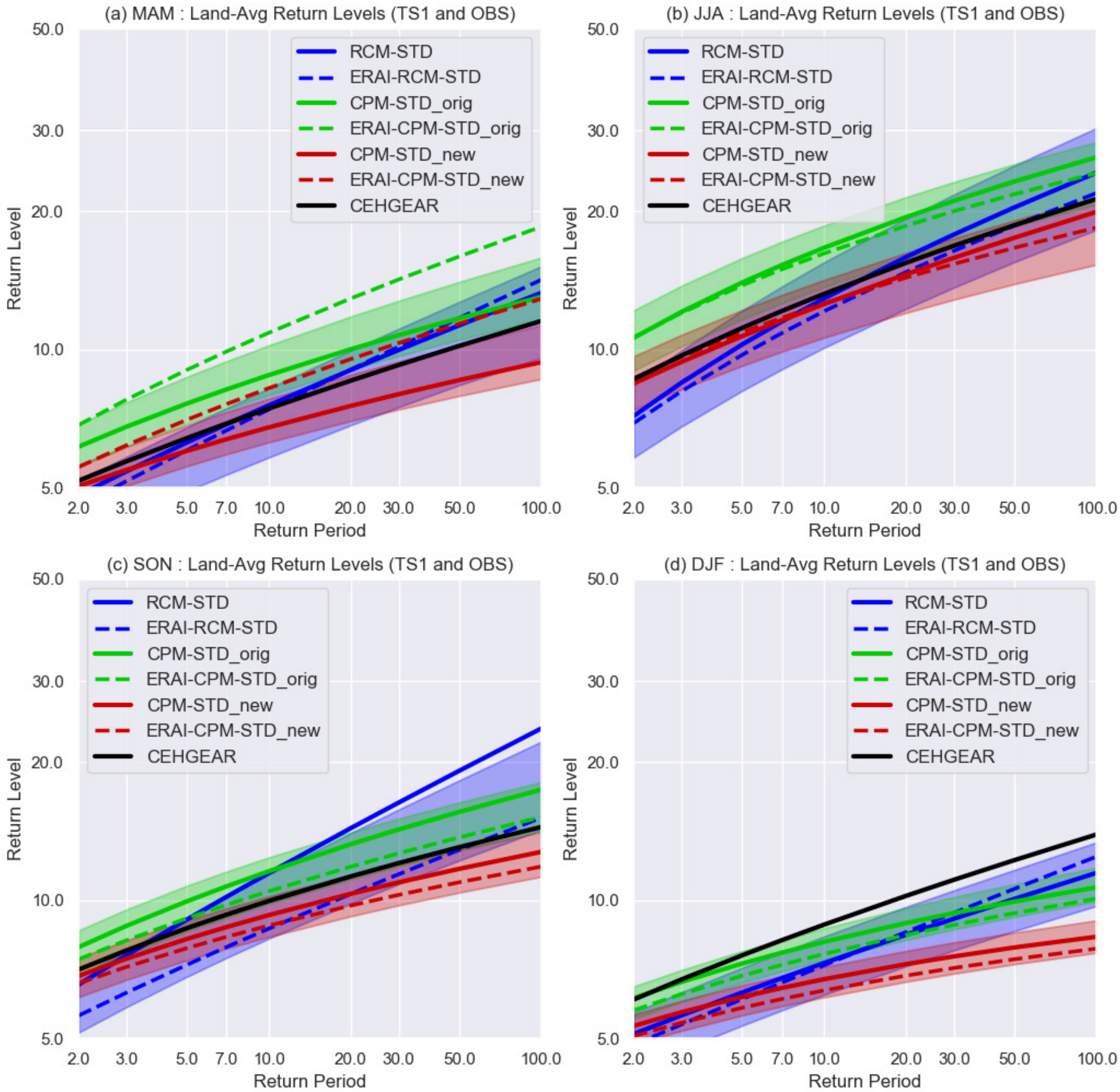

Figure 3.5.4. North-East UK average return level of hourly precipitation extremes. As Fig 3.5.2 but for NE region.

Hot and cold spells

The Met Office issues high temperature warnings based on multi-day temperatures; the threshold for public health is typically around 30°C for daily maximum surface temperature (Tmax). So here we define a hot spell as exceedance of this threshold for 2 or more days. Similarly for cold temperatures, the threshold is below +2°C for daily average surface temperature for 2 or more days. Here we assess this, along with a more severe threshold of -2°C to define "intense cold spells". We focus on cold spells over the northern UK, where they are relatively common (Figs 3.5.5-3.5.7); and hot spells over the southern UK, where they are largely confined but still relatively rare in the present-climate (Fig 3.5.8-3.5.9).

The new 2.2km reruns (CPM_new) have too many cold spells compared to the observations (Fig 3.5.5-3.5.7). These biases are worse than in CPM_orig, with more cold spells in CPM_new consistent with colder winter mean temperatures (Section 3.2) and more lying snow (see later in this Section). They are also generally worse than in the RCM, with the RCM actually having too few cold spells over high ground in northern Scotland (Fig 3.5.5) but too many intense cold spells (Fig 3.5.6). The tendency for more cold spells in CPM_new compared to the RCM is consistent with colder winter mean temperatures (Section 3.2) and slightly more lying snow in CPM_new (see below). However, we note that biases in the number of individual cold spells do not clearly correspond to biases in the intensity of cold winter days. In particular, cold winter days are actually warmer in CPM_new than the RCM, leading to reduced biases (Section 3.3). This is explained by different processes controlling the intensity of cold winter days and the frequency of cold spells (with the latter more closely tied to overall winter mean biases).

The new 2.2km reruns (CPM_new) show good agreement in the number of hot spells in the southern UK compared to observations (Fig 3.5.8, 3.5.9). Results are similar between CPM_new and CPM_orig, with slightly fewer hot spells in CPM_new in better agreement with observations. The code changes in the rerun have limited impact on hot spells in summer, as expected. The RCM tends to underestimate the frequency of hot spells over the southern UK, with fewer hot spells in the RCM compared to CPM_new. Model differences in the frequency of hot spells are consistent with model differences in the intensity of hot summer days, with hot summer days warmer in CPM_new compared to the RCM (Section 3.3).

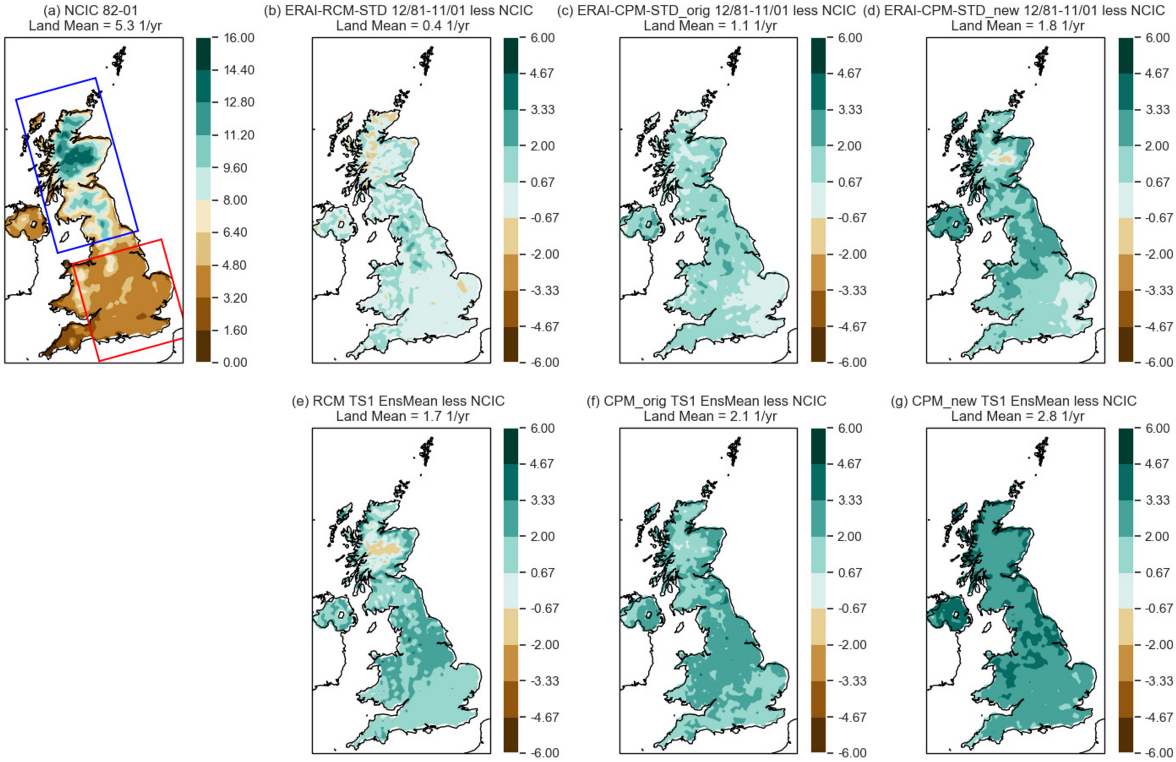

Figure 3.5.5. Observed and simulated cold spells. (a) Frequency of cold spells in NCIC observations (1982-2001) and model biases for (b) ERAI-RCM-STD, (c) ERAI-CPM-STD_orig, (d) ERAI-CPM-STD_new (Dec 1981-Nov 2001) and for (e) RCM, (f) CPM_orig and (g) CPM_new ensembles means (Dec 1980-Nov 2000). Cold spells are defined as two or more consecutive days with daily mean surface temperature below +2°C. The north and south regions are indicated.

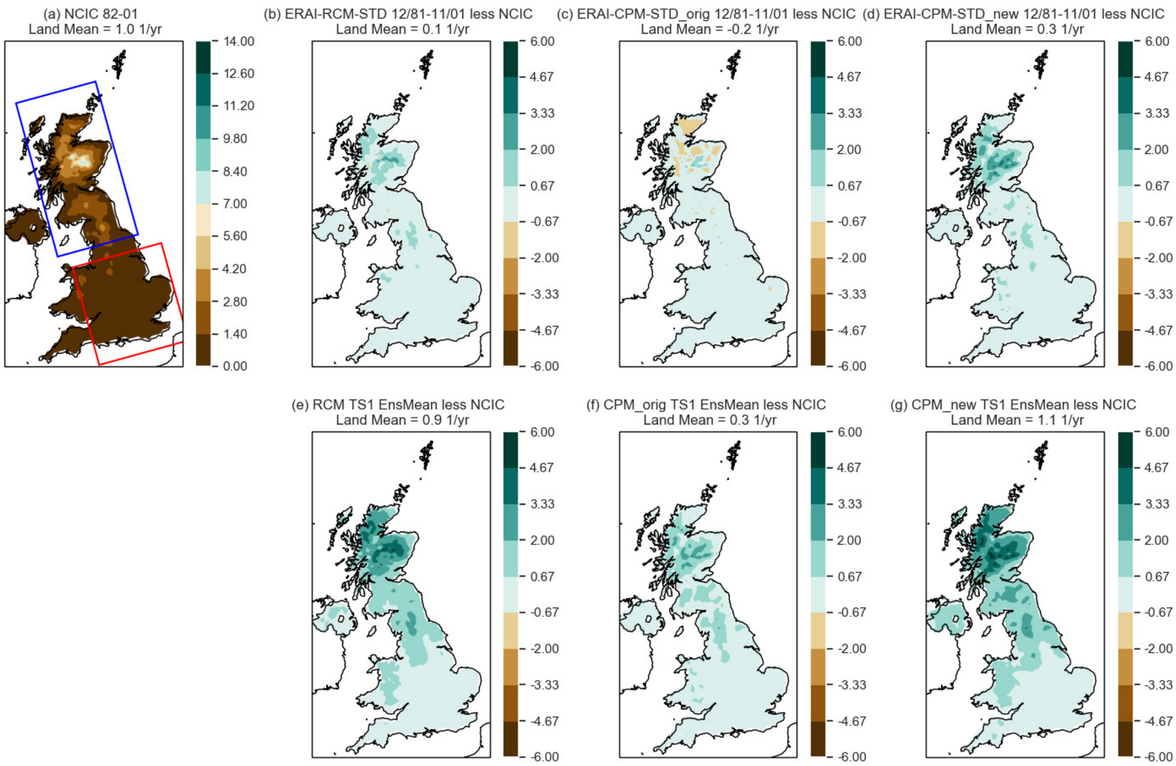

Figure 3.5.6. Observed and simulated intense cold spells. As Fig 3.5.5 but for intense cold spells defined as two or more consecutive days with daily mean surface temperature below -2°C.

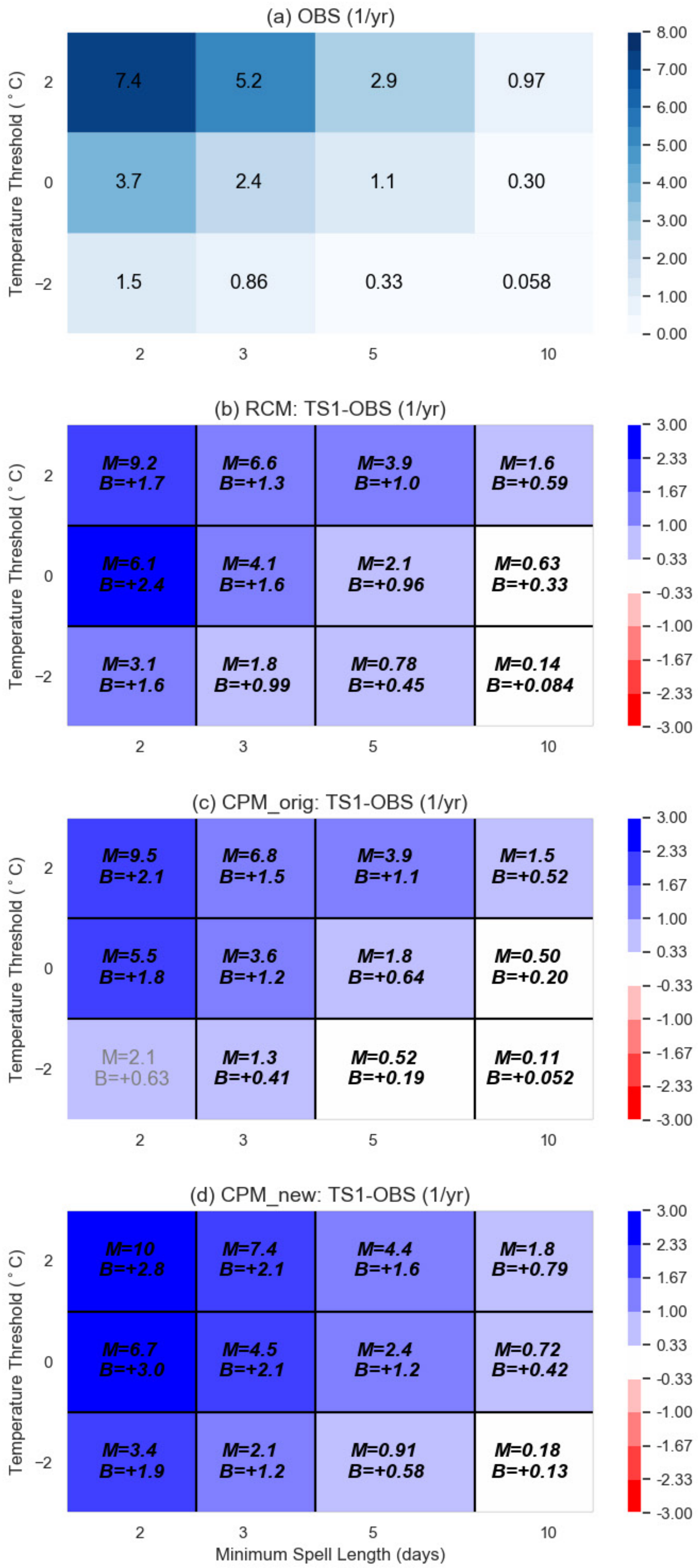

Figure 3.5.7. Frequency of cold spells over the northern UK. (a) Frequency of cold spells in NCIC observations (1982-2001) over the northern UK and (b,c,d) model biases for the RCM, CPM_orig and CPM_new ensemble means for Time Slice 1 (TS1, 1981-2000). Cold spells are defined using a range of daily mean surface temperature thresholds (-2°C, 0°C and +2°C) and minimum spell lengths (2, 3, 5, and 10 days). The mean frequency (M) in the model for the present-day is quoted, along with the bias (B). Differences significant compared to variability across the ensemble at the 5% level are indicated with a black border and bold black italic text. The northern UK region is as defined in Fig 3.5.5.

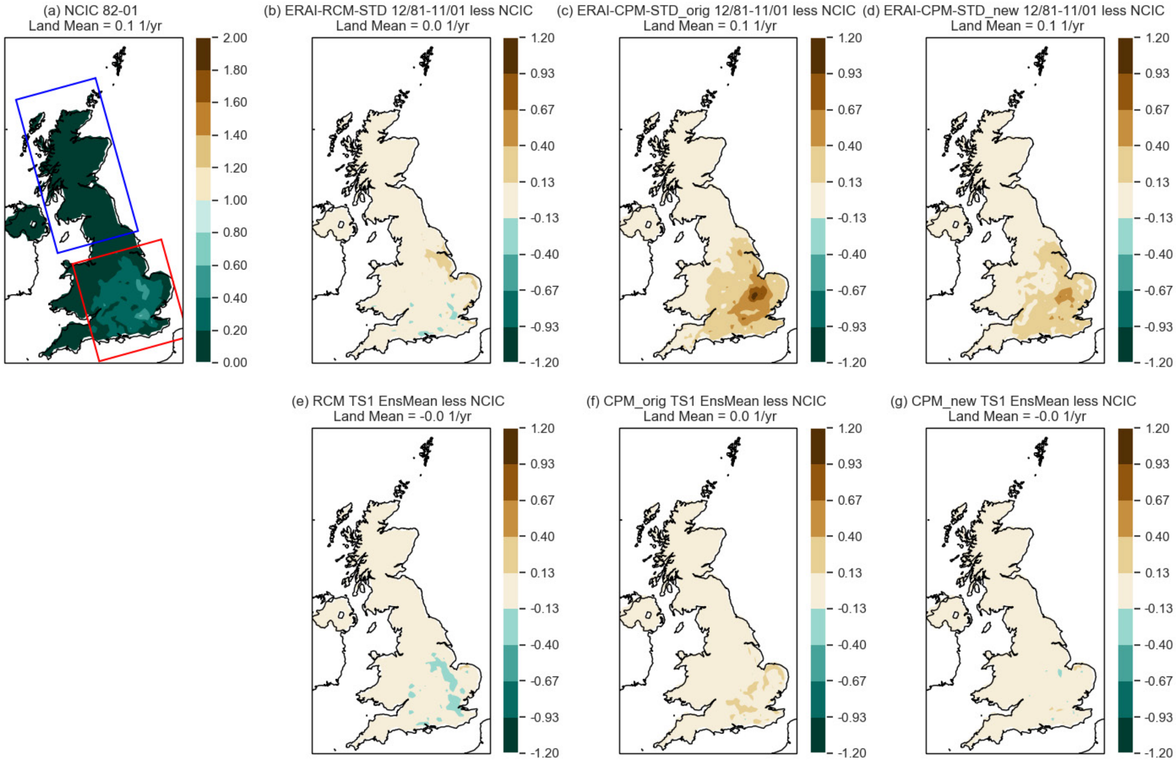

Figure 3.5.8. Observed and simulated hot spells. As Fig 3.5.5 but for hot spells defined as two or more consecutive days with daily maximum surface temperature above +30°C.

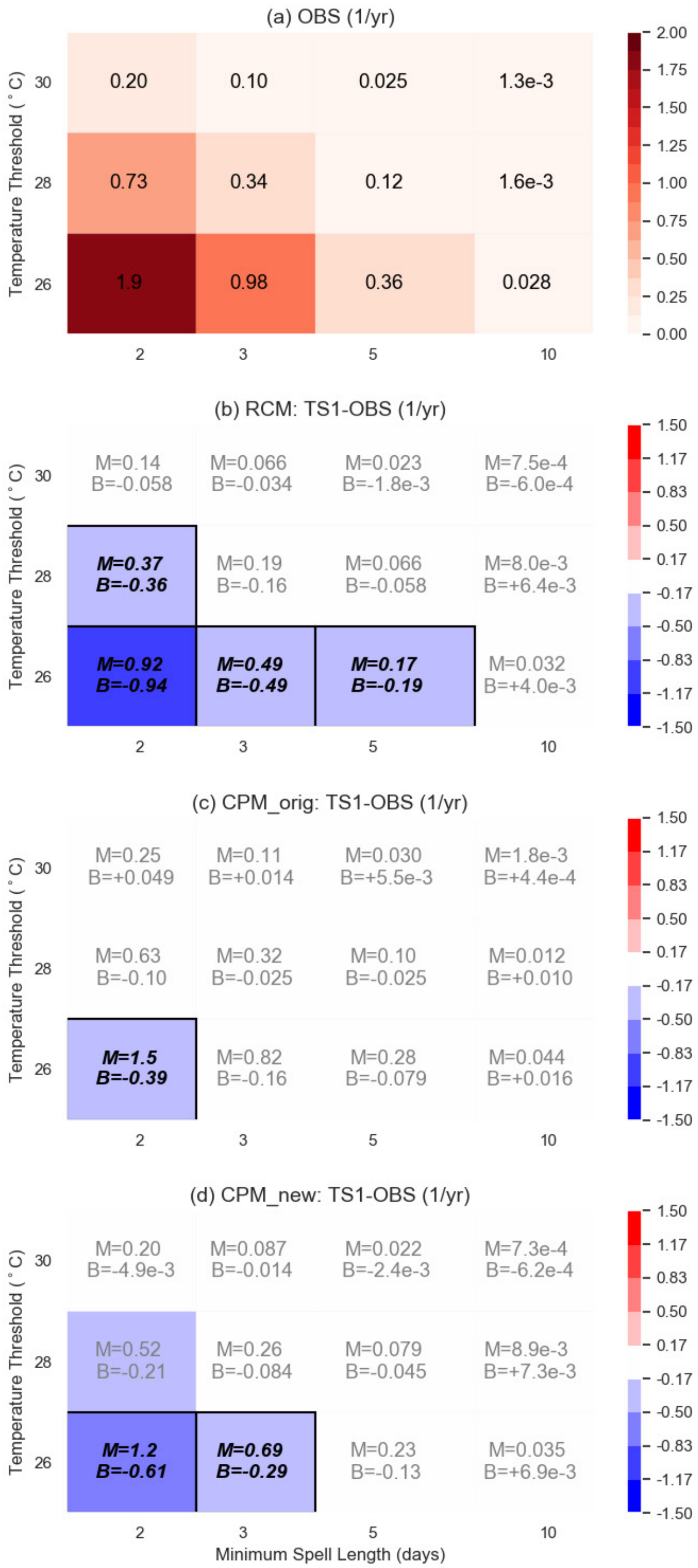

Figure 3.5.9. Frequency of hot spells over the southern UK. As Fig. 3.5.7 but for hot spells over the southern UK defined using a range of daily maximum surface temperature thresholds (26°C, 28°C and 30°C) and minimum spell lengths (2, 3, 5, and 10 days). The southern UK region is as defined in Fig 3.5.5.

Soil moisture

In this section we look at the annual cycle of soil moisture due to its relevance for temperature extremes including hot spells.

Soil moisture in CPM_new is similar to (and slightly higher than) CPM_orig (Fig 3.5.10 – 3.5.11). It remains lower than soil moisture in the majority of RCM ensemble members (noting perturbations are applied to soil moisture parameters in the RCM only, explaining the greater ensemble spread). An exception is the standard RCM member, which has the standard soil moisture parameter settings (as in CPM_new) and shows similar soil moisture values to CPM_new. CPM_new gives reasonable agreement with the WFDEI-JULES dataset (Table 3.1), with improved biases compared to CPM_orig and considerably so compared to the RCM ensemble (where soil moisture is too high in the majority of members).

Key differences in soil moisture between the CPM and RCM are unaffected by the rerun. In particular, evapotranspiration in the CPM is soil moisture limited in the southern UK during the summer months in all ensemble members, whereas this is not the case in the RCM with only 5 of the 12 members dropping below the critical point (Fig 3.5.11). These differences between the CPM and RCM are likely to be due to the different nature of rainfall in the CPM (which is more intermittent and intense), as well as the soil moisture parameter perturbations that are applied to the non-standard RCM members.

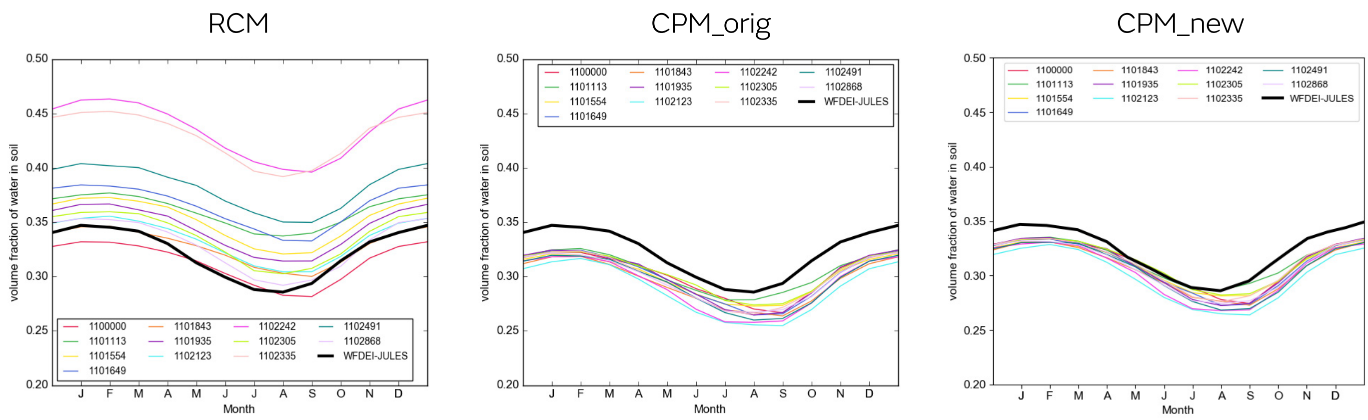

Figure 3.5.10. UK-average annual cycle of soil moisture in the top 1m of soil. Volume fraction of water in the soil (m^3/m^3) for (left) RCM, (centre) CPM_orig and (right) CPM_new ensemble members compared to WFDEI-JULES data, for the present-day (1981-2000). Colours correspond to the different ensemble members, with the STD member (1100000) shown in red.

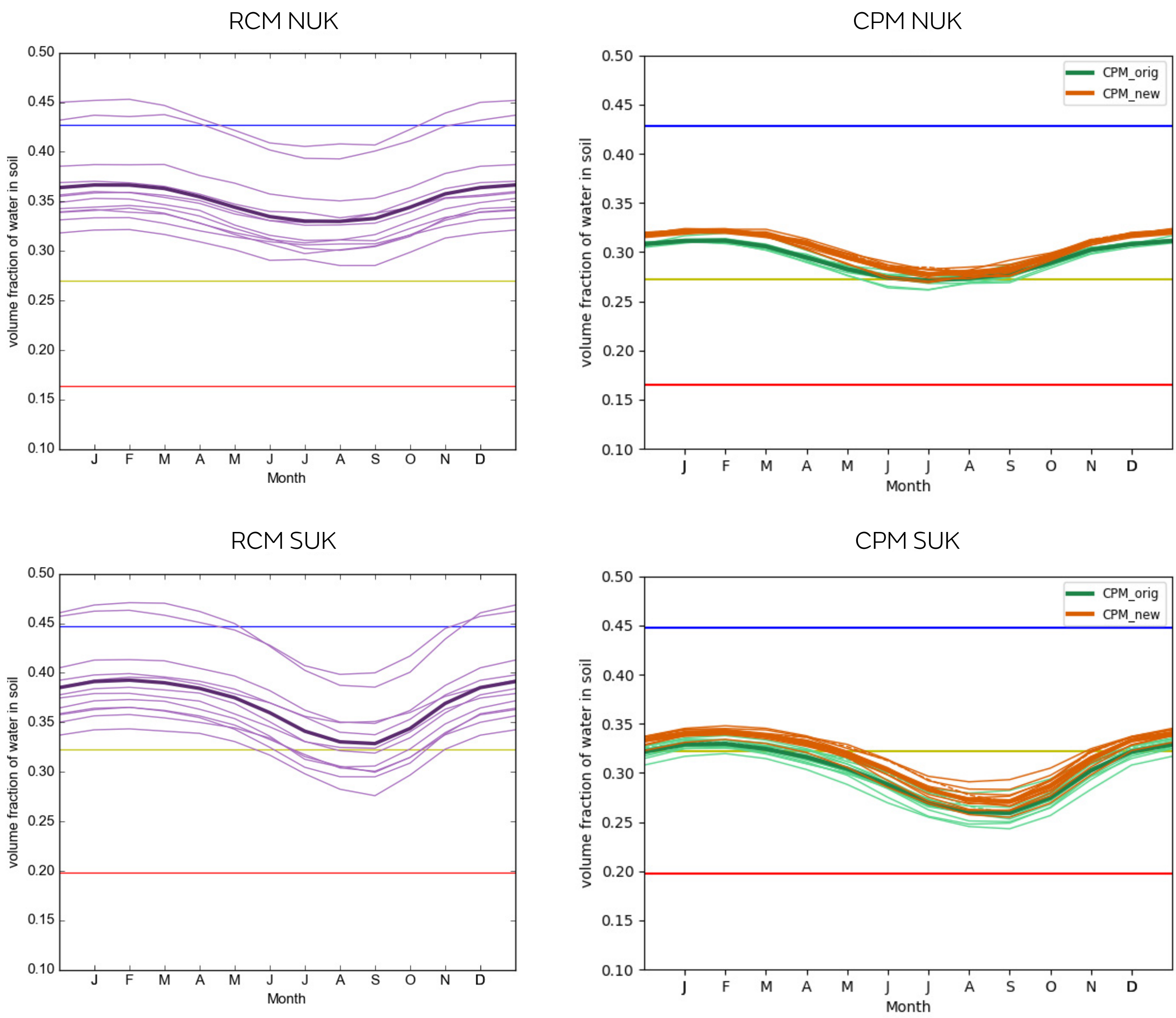

Figure 3.5.11. Annual cycle of soil moisture in the top 1m of soil, for the northern and southern UK. Volume fraction of water in the soil (m^3/m^3) for the (thin lines) individual ensembles members and (thick line) ensemble mean, for (left) RCM and (right) CPM_orig (green) and CPM_new (red), for the (top) northern-UK and (bottom) southern-UK. The horizontal blue line indicates soil moisture saturation; yellow line the critical point below which evapotranspiration becomes soil-moisture limited; and red line the wilting point.

Snow

Observations of the number of days of lying snow and the number of days of falling snow are available from NCIC (Table 3.1). To produce an equivalent metric for the models, a threshold needs to be applied to convert the daily model outputs of lying snow amount and snowfall rate to "yes/no" indicators of occurrence. This represents an uncertain choice, particularly in the case of lying snow, which is reported if the observer decides that the ground is more than half covered, rather than on the basis of a specific threshold in mm. A threshold of 0.02mm was used in UKCP09, and based on this choice, both CPM_new and the RCM substantially overestimate the number of days of lying snow and falling snow (Figs. 3.5.12-3.5.13). This threshold may be too low, although is used here to allow an initial comparison with observations. However, given the difficulty in assessing model performance, our focus is on model differences.

The number of days of falling snow is reduced in CPM_new compared to CPM_orig, leading to values closer to those in the RCM, and giving better agreement with the observations. Falling snow in CPM_orig was mainly graupel and a consequence of the graupel error (Section 2). By contrast, the number of days of lying snow is increased in CPM_new compared to CPM_orig, which again leads to values that are closer to those in the RCM. This increase in lying snow is a consequence of both fixing the graupel code error (such that more of the solid precipitation falls as snow), the inclusion of any residual graupel in the snowpack and the use of the multi-layer snow scheme in CPM_new (Section 2).

There are differences in the spatial distribution of snowfall between CPM_new and the RCM, in particular CPM_new produces more snowfall over the high peaks in the Cairngorms, and less in the vicinity of the northwest coastline of Scotland, which is more realistic (Fig 3.5.14). One possible reason is the different treatment of convection in the models; models that use a convection parameterization (like the RCM) often struggle to advect precipitation across coastlines (Kendon et al, 2020a). Another reason is that the higher resolution of the CPM means it is better able to represent the topography of the high ground in central Scotland. The total winter snowfall averaged over Scotland is actually very similar between CPM_new and RCM, with CPM_orig a clear outlier with considerably more falling snow.

In terms of lying snow, CPM_new is also much closer to the RCM than to CPM_orig. There is evidence of more lying snow in CPM_new compared to the RCM over high ground in Scotland (Fig 3.5.15). This is explained, at least in part, by higher resolution leading to mountains being substantially higher, allowing snow to persist more.

Overall, the greater consistency between CPM_new and the RCM for both falling and lying snow is reassuring given the improved physical representation of snow/graupel in CPM_new compared to CPM_orig.

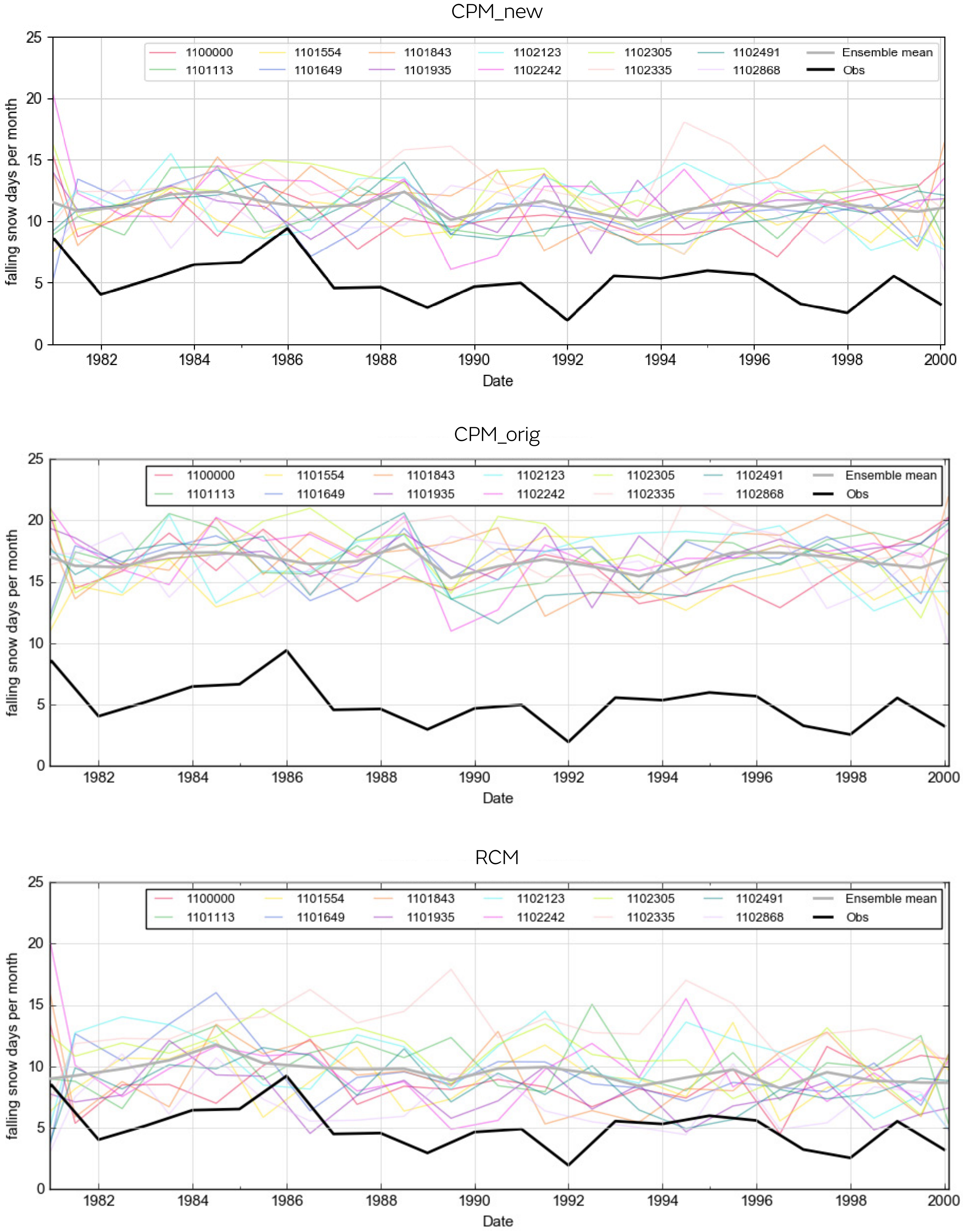

Figure 3.5.12. Observed and simulated UK-average number of days of falling snow. Yearly time-series are shown for NCIC observations, and for the individual ensemble members and ensemble-mean for the (top) CPM_new, (middle) CPM_orig and (bottom) RCM, for DJF. For the models a 0.02mm threshold in snowfall flux is used to define a day of falling snow.

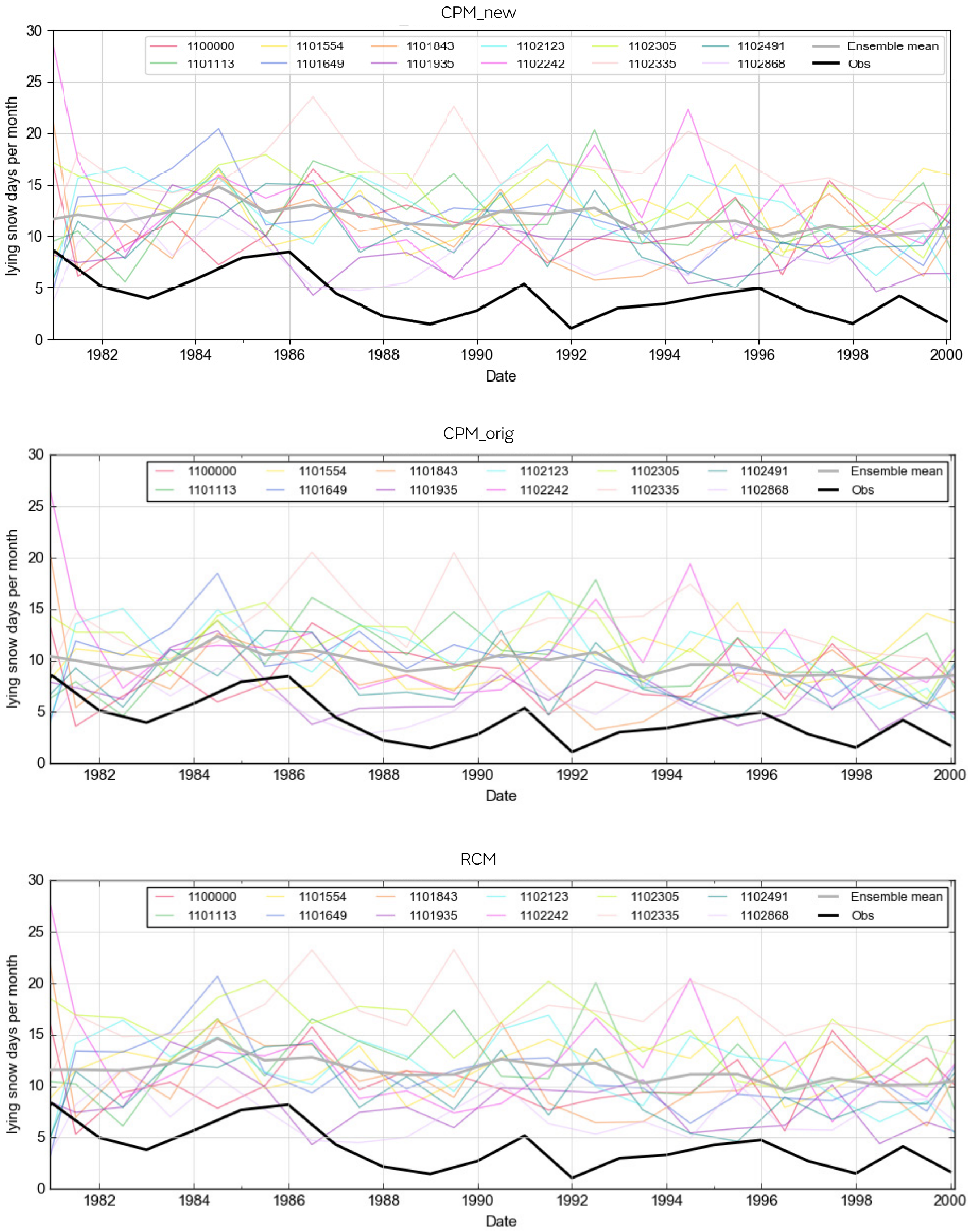

Figure 3.5.13. Observed and simulated UK-average number of days of lying snow. As Fig 3.5.12 but for lying snow. For the models a 0.02mm threshold in snow amount is used to define a day of lying snow.

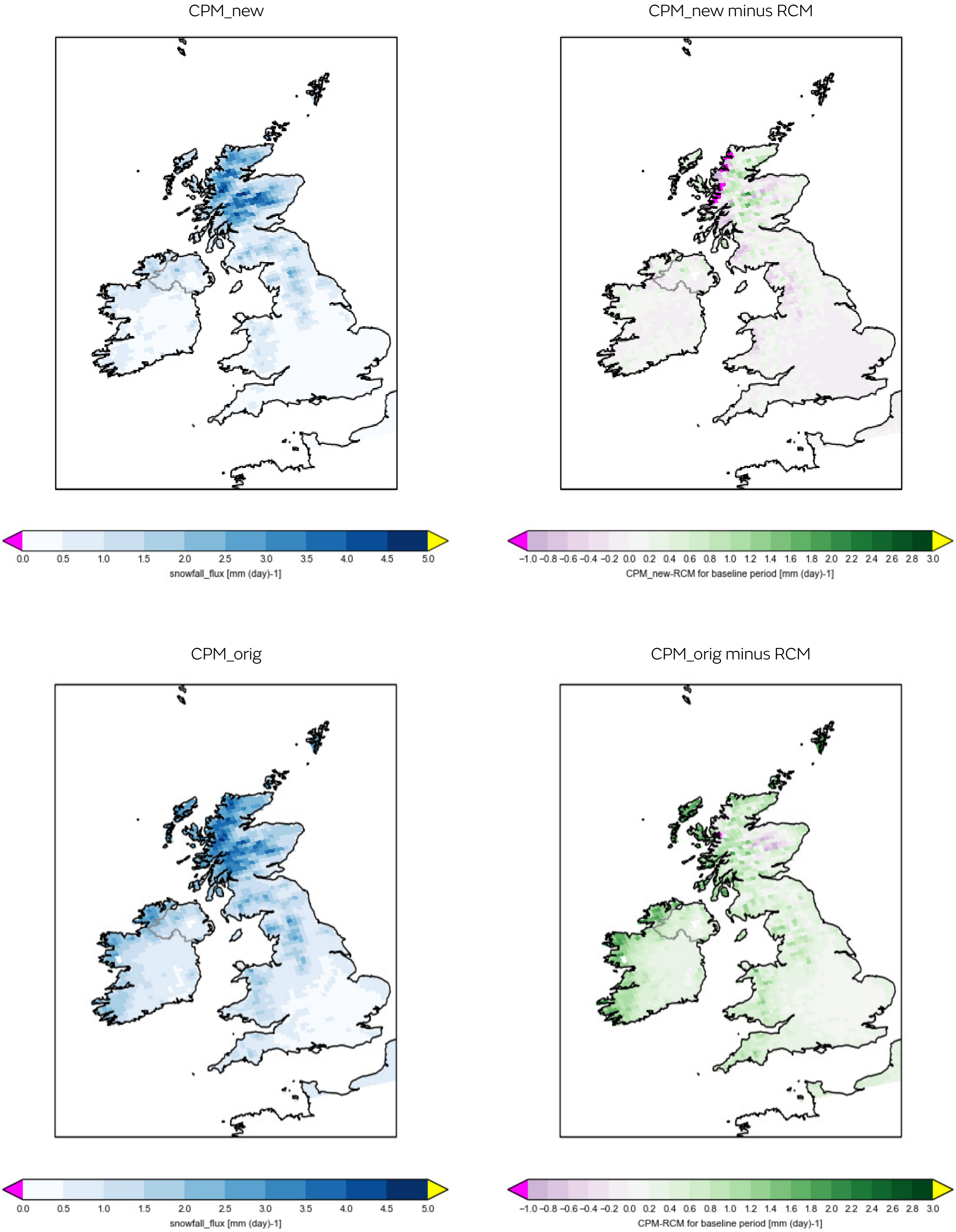

Figure 3.5.14. Mean snow fall in winter. Mean snowfall flux (mm/d) in (top) CPM_new and (bottom) CPM_orig, for (left) CPM ensemble-average and (right) the CPM-RCM difference, for DJF 1981-2000.

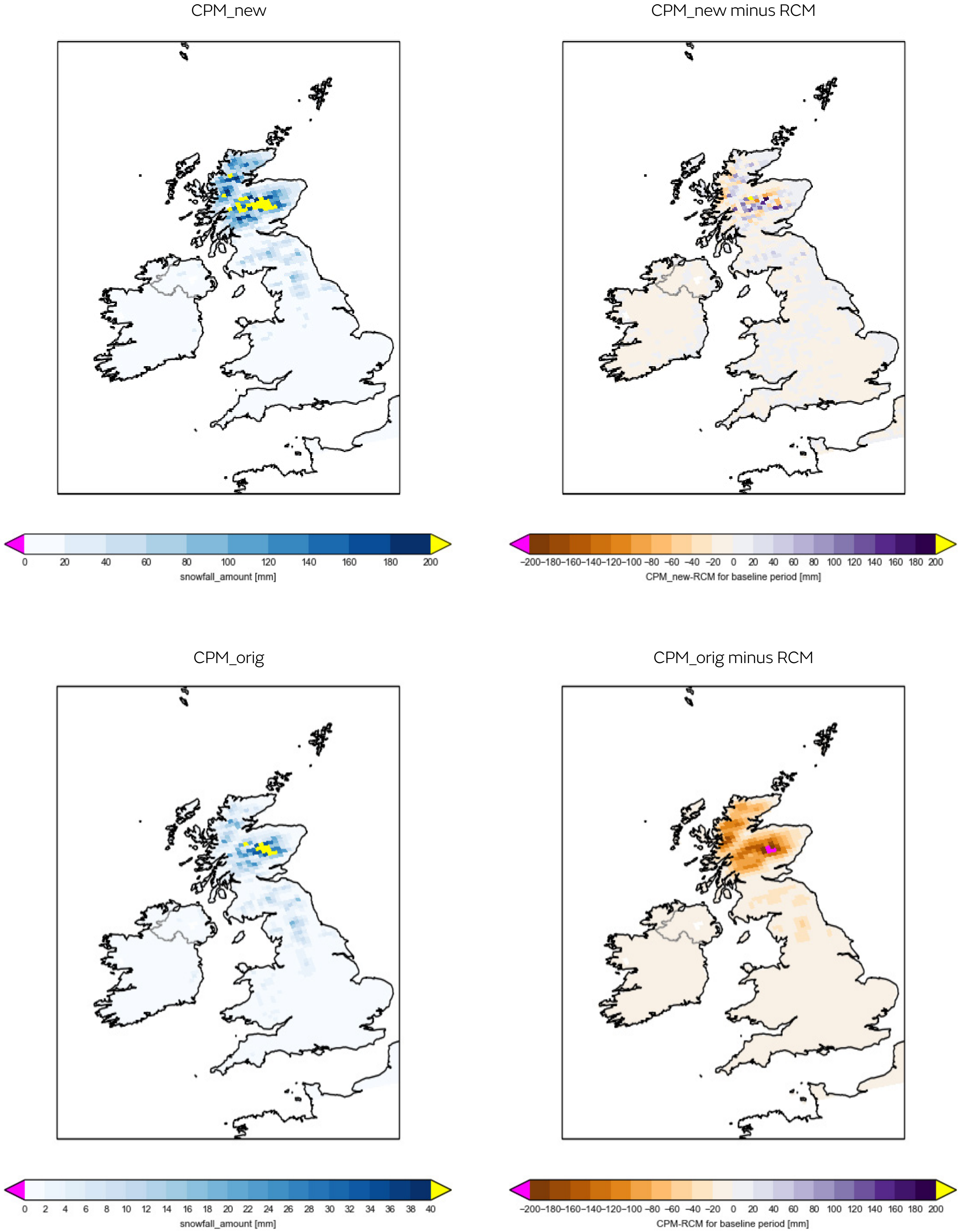

Figure 3.5.15. Mean lying snow amount in winter. Mean snow amount (mm) in (top) CPM_new and (bottom) CPM_orig, for (left) CPM ensemble-average and (right) the CPM-RCM difference, for DJF 1981-2000. Note difference in colour scale between top left and bottom left.

Cloud

In this section we evaluate seasonal mean cloud and associated surface radiative fluxes, which play a key role in the surface energy budget. This is important for understanding surface temperature differences, and thus is relevant to high impact temperature extremes.

There is consistently less cloud in CPM_new than the RCM in all seasons. In winter, CPM_new shows better agreement with the CLARA-A2 observations than the RCM both in terms of cloud cover and shortwave and longwave radiation (Fig 3.5.16). In this season, the RCM has too much cloud, and consistent with this, too little downward shortwave radiation at the surface and too much downward longwave radiation at the surface particularly over mountains. These biases are all reduced in CPM_new, but the differences are small, with the code changes in the local 2.2km reruns having little impact on these results. CPM_new tends to have slightly more cloud than CPM_orig (consistent with it being wetter in winter, Section 3.2), but these differences are much less than the CPM-RCM differences.

In summer, CPM_new has too little cloud cover compared to CLARA-A2 observations, with the RCM giving better agreement (Fig 3.5.17). However, CPM_new shows reduced biases in shortwave and longwave radiation, with the RCM having too much downward shortwave and too little downward longwave radiation at the surface. This is explained by the fact that the impact of clouds on the radiation fluxes is not just controlled by the cloud cover (clt), but also the optical properties of the cloud which will be influenced by the cloud thickness and its vertical distribution. So although the RCM has about the right amount of cloud cover in summer, the clouds may not be reflective enough and too high (and hence are too cold with less long wave radiation). Again, the code changes in the local 2.2km reruns have little impact on these results, with very similar biases seen in CPM_new and CPM_orig.

The differences in cloud between CPM_new and the RCM are likely related to the different cloud schemes used, with the CPM using the Smith (1990) scheme but the RCM using the prognostic cloud scheme PC2 (Section 2). The resulting radiation differences are consistent with the temperature differences in Section 3.2. In particular in winter CPM_new is colder than the RCM (consistent with less downward longwave at the surface) and in summer CPM_new is warmer than the RCM (consistent with more downward longwave).

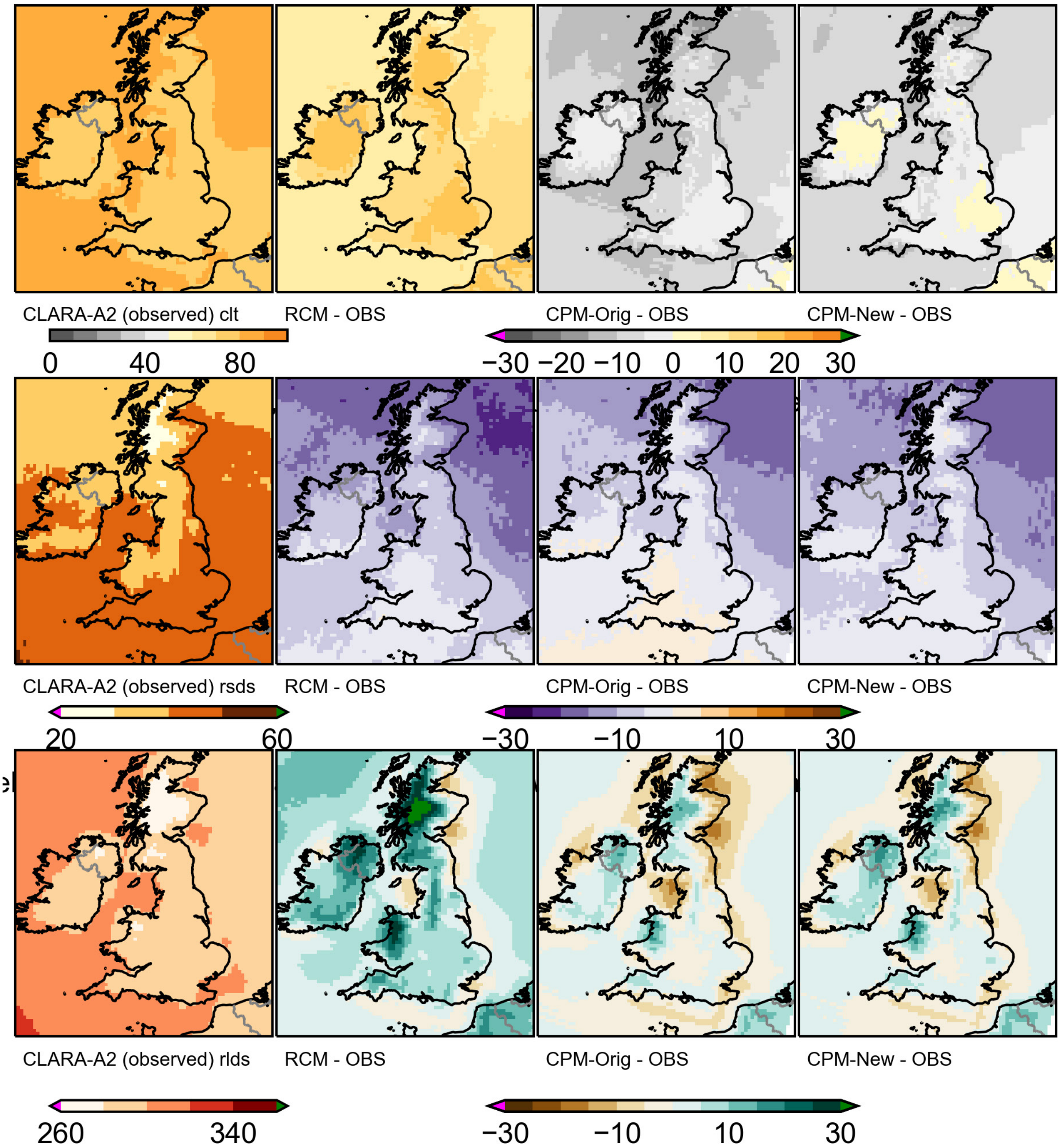

Figure 3.5.16. Observed and simulated cloud and radiative fluxes in winter. (Left) Observed cloud cover (top, clt, %), total downward shortwave radiation at the surface (middle, rsds, Wm^{-2}) and total downward longwave radiation at the surface (bottom, rlds, Wm^{-2}) from the CLARA-A2 observations. Biases compared to the observations for the ensemble-means of (centre left) RCM, (centre right) CPM_orig; and (right) CPM_new. The observational data corresponds to the 20-year period 1982-2002 and the model data to 1981-2000.

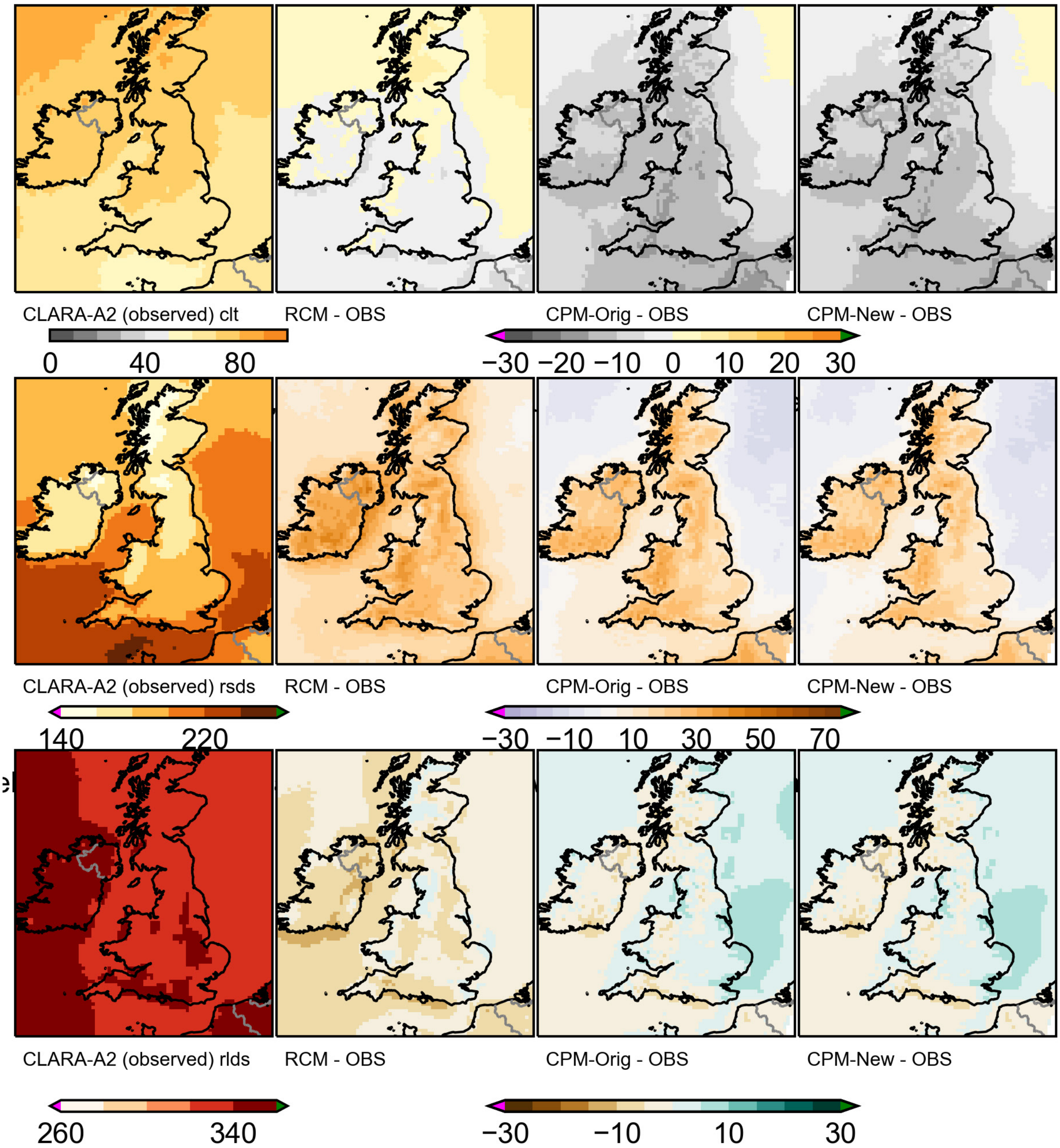

Figure 3.5.17. Observed and simulated cloud and radiative fluxes in summer. As Fig 3.5.16 but for summer.

Lightning

Lightning is predicted in the CPM using the McCaul et al, (2009) lightning prediction scheme, which requires a graupel prognostic that is included in the CPM but not the RCM. Lightning data was not issued from the original UKCP Local (2.2km) projections. This was due to concerns over its verification, likely related to the graupel code error (Kendon et al, 2019). On fixing the graupel code error in the 2.2km reruns (CPM_new), this creates the potential to now provide lightning as a user diagnostic subject to satisfactory evaluation.

Case studies of individual lightning events in the ERA-Interim driven runs show considerable improvements in the representation of lightning in the CPM_new compared to CPM_orig (Figure 3.5.18). For the case of the 10th June 1982, in CPM_orig there is lots of weak lightning everywhere with odd block-shaped structures across northern England; whilst in CPM_new lightning is confined to a few storm regions, with less blocky structure. The thunderstorms on this day were associated with a 'Spanish Plume' and southerly flow across the UK, which normally brings widespread and intense thunderstorms to the region. The larger, intense lightning structures produced in CPM_new are therefore considered more realistic than the weaker lightning in CPM_orig. On the 1st July 1991, again in CPM_orig there are odd block-like structures with some very high lightning values; whilst in CPM_new lightning features are smaller and much more realistic. This case was associated with lightning developing on the north-east flank of a high-pressure system which was centred to the south and west of the UK. Weather reports from the day suggest lightning was across northern England and southern Scotland, suggesting that CPM_new has managed to roughly predict the correct location of the lightning features.

Evaluation of the lightning flash rate output from the CPM is difficult because this includes both intra-cloud and cloud-to-ground lightning, whilst it is the latter component only that is typically of relevance to users and is measured by the ATDnet observations (Anderson and Klugmann, 2014; Table 3.1). Enno et al, (2016) suggest that the ATDnet observations capture ~90% of cloud-to-ground lightning over the south of France, but only ~25% of intra-cloud lightning, which tends to have weaker signals. A further problem is that ATDnet suffers from interference due to the height of the ionosphere, which is lower at night (Bennett et al, 2011). As a result, there will be periods of nocturnal lightning which are not being detected in the observations. For these reasons, only a subjective evaluation of lightning output from the CPM is possible.

A comparison of UK area total lightning flashes between CPM_new and ATDnet is shown in Fig 3.5.19. The CPM underestimates lightning activity in spring and summer, and to a lesser extent in autumn, compared to ATDnet. These differences may be partly explained by ATDnet giving false alarms even in high pressure. For example, in the hot summer of 2018, there were often 20 or more ATDnet flashes even when there was no cloud. In Fig 3.5.19, an attempt has been made to correct for this, using radar data to remove false alarms, but it is likely false alarms remain. In winter, CPM_new overestimates lightning flash rates compared to ATDnet (this is especially in the north and west of the domain, not shown). This discrepancy in winter is likely due in part to ATDnet being unable to pick up weak lightning activity (given the low detection efficiency of intracloud lightning).

Overall the above results show a considerable improvement in the realism of lightning in CPM_new compared to CPM_orig. There are differences compared to ATDnet, but these can be partially explained by the lack of detection of intra-cloud lightning and false alarms in the observational data.

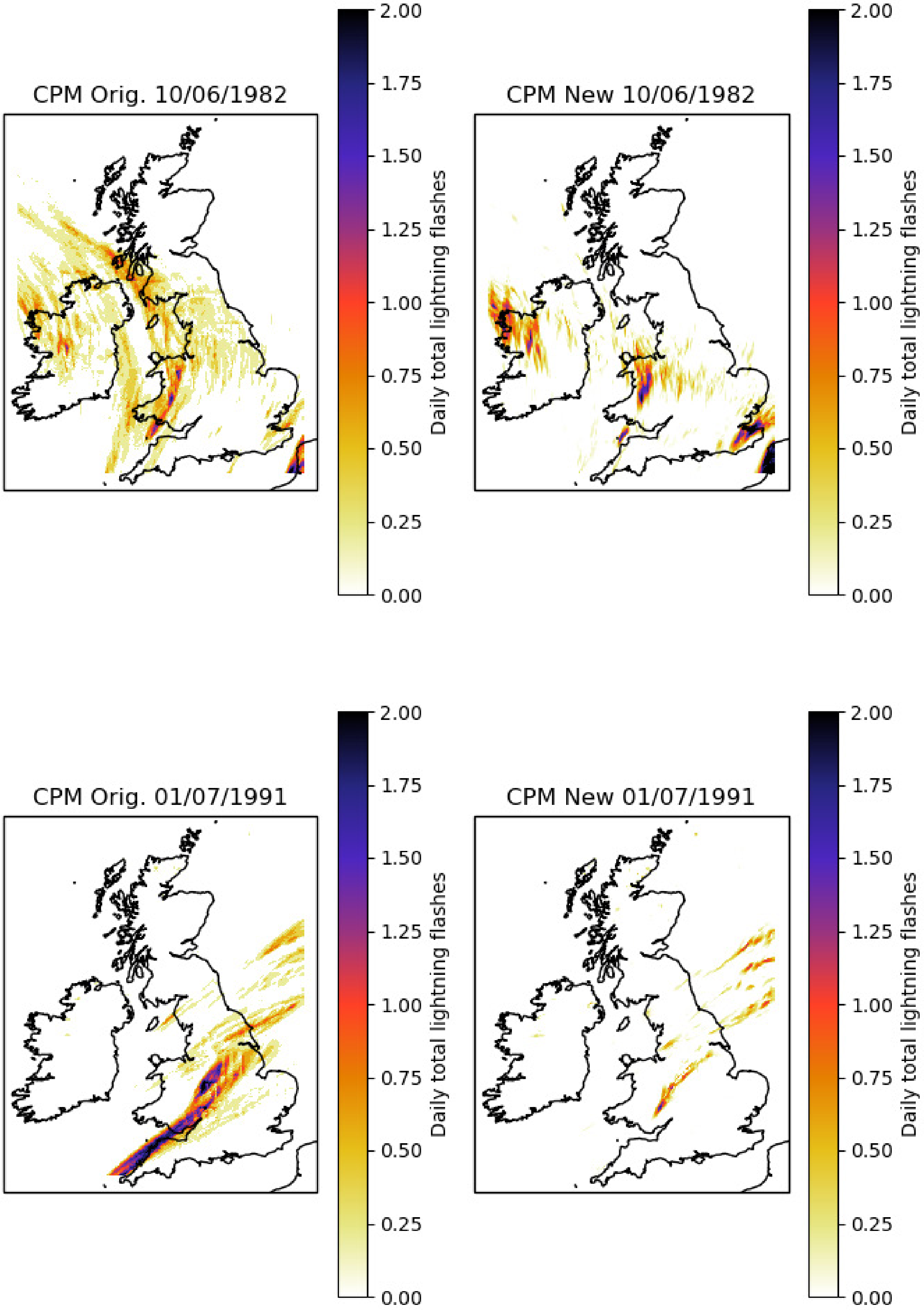

Figure 3.5.18. Lightning case studies. Lightning flashes in the ERAI driven runs of (left) CPM-STD_orig and (right) CPM-STD_new, on (top) 10th June 1982, (bottom) 1st July 1991.

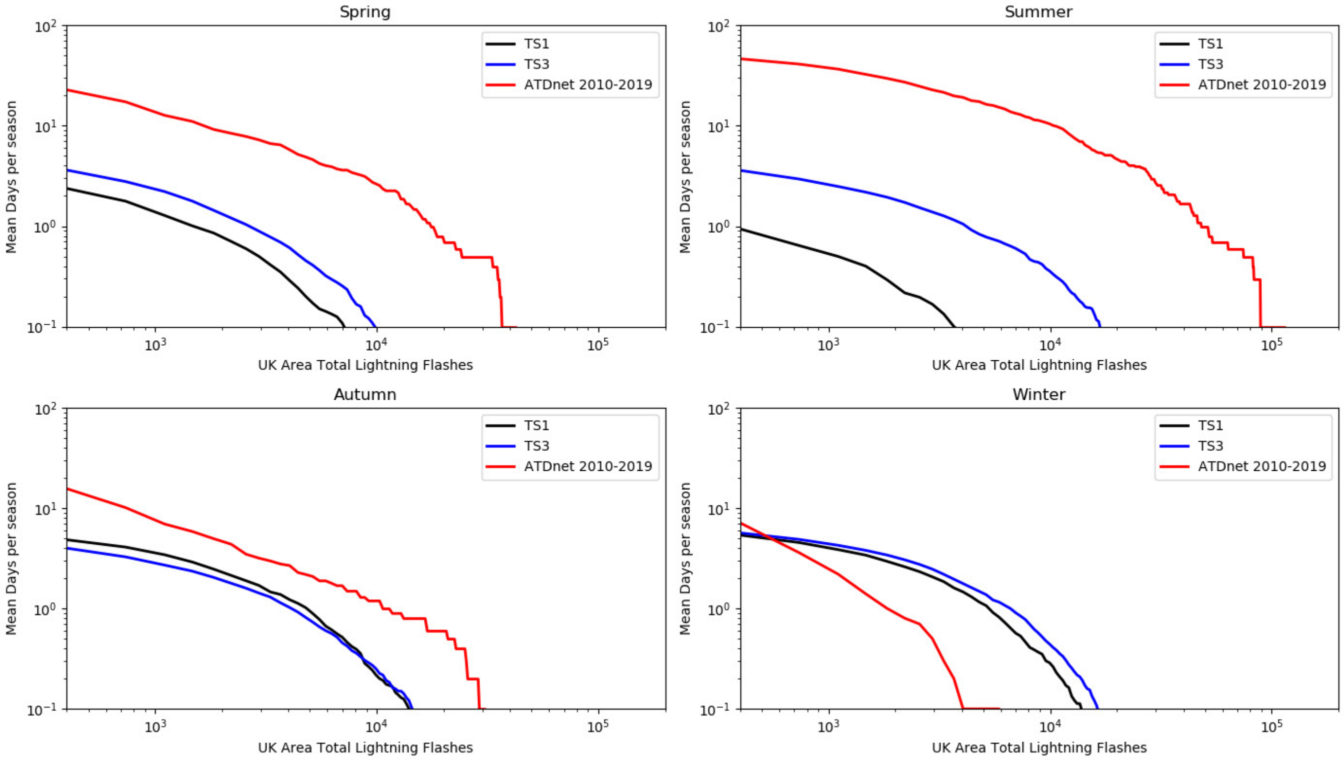

Figure 3.5.19. Simulated and observed UK-area total lightning flashes. Mean number of days per season, summed over all grid points in the UK model domain, where lightning flashes exceeds given threshold for (red) ATDnet observations (2010-2019) and CPM_new ensemble-average for (black) TS1 (1981-2000) and (blue) TS3 (2061-2080). Radar data have been used to remove ATDnet flashes when there is no cloud, to reduce the ATDnet false alarm rate.

Surface winds

Present-day mean and extreme surface wind speeds are shown in Figs 3.5.20 and 3.5.21. This is an addition compared to the original science report (Kendon et al, 2019) where present-day biases and future changes in wind speed were not assessed. They are included here as the single-member tests suggested that fixing the graupel code error has a significant impact on present-day surface winds mainly over the ocean but also over north-west coastal regions (Kendon et al, 2020b, summarised in Section 2.3). Here we use ERA5 reanalysis (Table 3.1) as an observational reference but this is on a coarser grid than the models (31km compared to 12km) and also daily maximum wind speeds are not output and so need to be constructed from hourly instantaneous values. This will lead to an underestimation of actual daily maximum wind speed, since it is unlikely that one of the 24 instantaneous samples will coincide with the actual time of maximum wind speeds each day. For the models sampling is done every timestep (which is every minute in the CPM and every 4 minutes in the RCM).

Daily maximum wind speed is greater in CPM_new than the RCM in both winter and summer, with differences greatest over high ground. In winter, when the strongest winds occur, differences can be up to 5m/s over the Scottish mountains. In general, the RCM shows good agreement with ERA5 over land, but stronger winds over the ocean, in both winter and summer; whilst daily maximum wind speeds are consistently higher in CPM_new. However, given the different sampling of data used to construct daily maximum wind speeds, we would expect higher values in the models (see above). Thus, it is difficult to establish which of the models is actually better. It is not surprising that CPM_new gives higher maximum wind speeds than the RCM since it is better able to resolve small-scale gusts as well as orography, and in addition has a lower roughness length specified in the model physics (0.01 in CPM_new compared to 0.15 in RCM) resulting is less orographic form drag.

Code changes in the local 2.2km reruns have a significant impact on present-day winds in some locations. Mean daily maximum wind speeds are higher in CPM_new compared to CPM_orig across the UK domain in winter, but particularly over the ocean and over isolated locations in western Ireland and over the Cairngorms where differences are more than 0.4 m/s (Fig 3.5.20). These differences are larger than the standard deviation across the CPM_orig ensemble (0.1-0.3 m/s dependent on location, Kendon et al, 2020b) and thus are judged significant locally. In summer, differences in mean daily maximum wind speed between CPM_new and CPM_orig are of mixed sign and not significant (<0.1m/s everywhere). Note that although the impact of the reruns is significant locally in winter, differences between CPM_new and CPM_orig are still considerably smaller (by about a factor of 10) than differences between CPM_new and the RCM. Thus, key differences between the CPM and RCM in terms of representation of present-day surface winds are unaffected by the rerun.

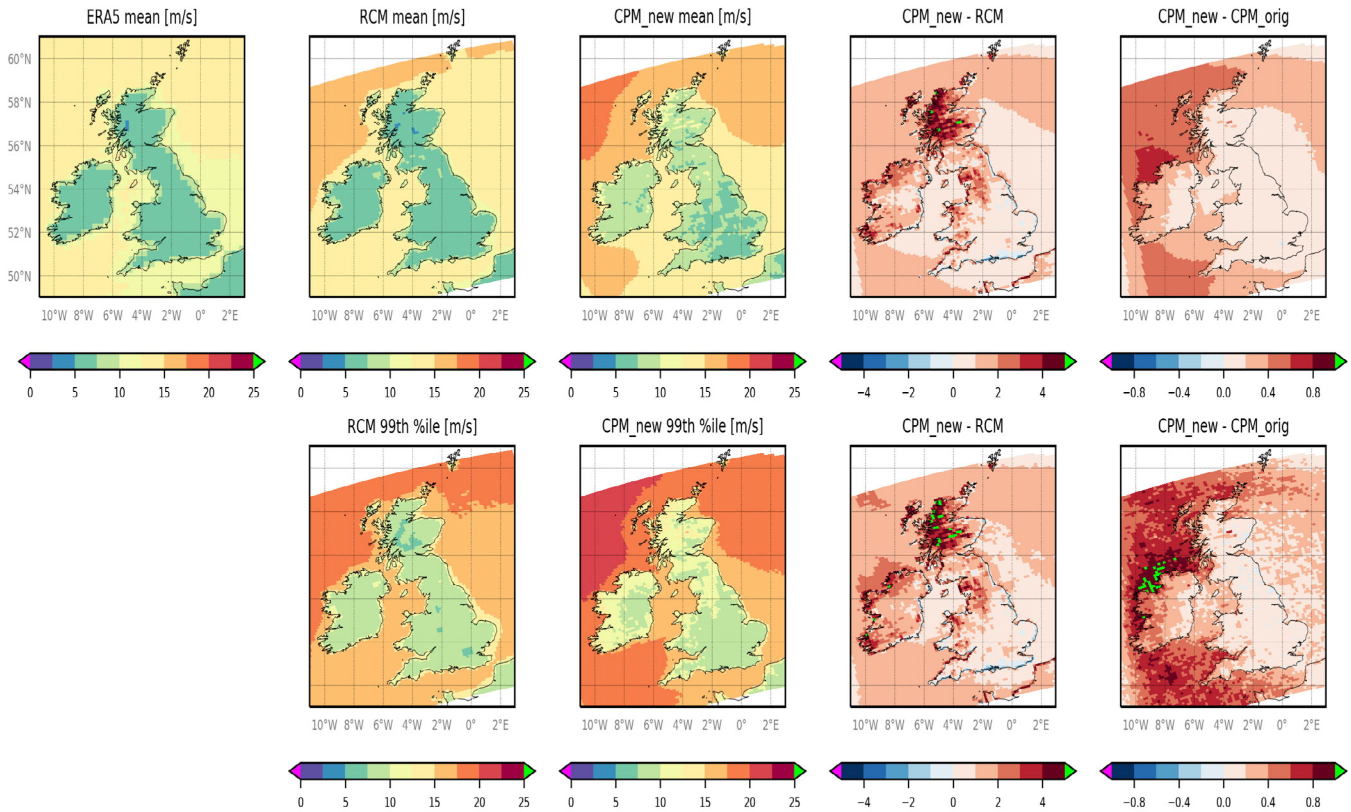

Figure 3.5.20. Present-day mean and extreme surface wind speeds (m/s) in winter. (top) Mean and (bottom) 99th percentile of daily max wind speeds, for (left) ERA5 reanalysis on 31km grid (shown for mean only) and ensemble-means of (centre left) the RCM and (centre) CPM_new at the 12km grid scale, for winters 1980-2000. Also shown are ensemble-mean differences between (centre right) CPM_new minus the RCM and (right) CPM_new minus CPM_orig. Daily maximum winds speeds for ERA5 are constructed from hourly instantaneous wind speeds, whilst for the models are from winds sampled every model timestep.

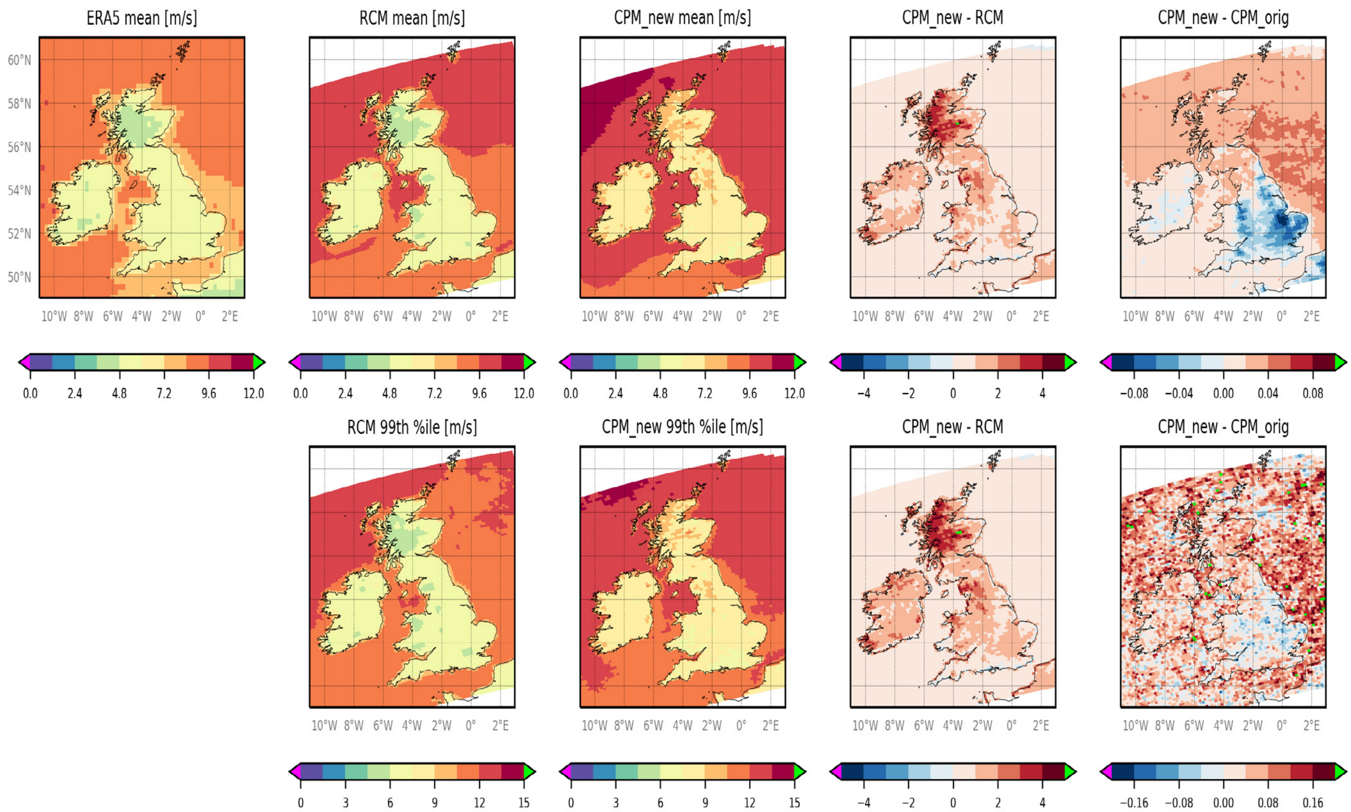

Figure 3.5.21. Present-day mean and extreme surface wind speeds (m/s) in summer. As Fig 3.5.20 but for summer.

3.6 Summary of present-day performance

We have assessed the performance of the UKCP Local (2.2km) reruns (CPM_new) compared to the original UKCP Local (2.2km) projections released in September 2019 (CPM_orig) and the driving 12km RCM in representing present-day temperature and precipitation. We have also briefly examined high impact events, including hourly precipitation extremes, hot and cold spells, snow, lightning and wind extremes, as well as soil moisture and cloud which play an important role in the surface energy budget. This provides the evidence base to establish the credibility of the CPM_new projections.

In general, the impact of the CPM_new model changes (including fix to the graupel code error and other science improvements) across all 12 ensemble members confirm results found in the single member tests (reported in Kendon et al, 2020b). The key differences compared to the original UKCP Local (2.2km) projections are:

1. CPM_new is significantly colder than CPM_orig in winter, exacerbating cold biases in the north of the UK, both for cold winter days and the number of cold spells. Mean winter temperature is also colder, particularly over northern Scotland, where differences may be locally significant compared to the CPM_orig ensemble spread.
2. CPM_new is significantly wetter in winter than CPM_orig, particularly over high terrain, leading to slightly increased biases for mean and heavy daily precipitation.
3. Summer-time precipitation intensity is reduced in CPM_new, leading to a reduction in biases in heavy summer precipitation on both daily and hourly timescales.
4. Extreme hourly precipitation is significantly reduced (the 2-y return level by about 20%) in CPM_new compared to CPM_orig, leading to reduced biases.
5. CPM_new has less snowfall but more lying snow compared to CPM_orig, which is a considerable improvement (biases are reduced and previous errors in the treatment of graupel are removed).
6. Unrealistic lightning features seen in CPM_orig are no longer found in CPM_new.
7. CPM_new has stronger surface winds in winter than CPM_orig, mainly over the ocean but also over western Ireland and the Cairngorms.

Biases in CPM_new are reduced compared to CPM_orig, for summer precipitation intensity, hourly precipitation extremes and lightning, due to fixing the graupel code error. We have increased confidence in the new projections for these variables, and lightning projections from CPM_new are sufficiently reliable to be provided to users for the first time. In winter, despite the increase in temperature and precipitation biases, we have much greater confidence in the results from CPM_new in terms of cold winter temperatures and snow. This is due to the corrected representation of snow and graupel in the reruns. For many other variables, including summer mean temperature and precipitation and hot summer days, there is no impact of the rerun code changes on present-day biases.

Some of these changes in the reruns have led to improved consistency between the CPM and RCM, but some key differences remain:

1. Cold winter days are warmer in CPM_new than the RCM, leading to reduced biases over the north of the UK; whilst there are more cold spells in CPM_new, generally increasing biases.

2. Hot summer days are warmer and hot spells over the south UK are more frequent in CPM_new than the RCM, leading to a slight improvement in biases.
3. CPM_new is wetter than the RCM over mountains but drier elsewhere, with reduced seasonal mean biases both in winter and summer.
4. CPM_new gives a better representation of daily precipitation, with precipitation being less frequent and more intense compared to the RCM, in both winter and summer.
5. CPM_new gives a much better representation of hourly precipitation intensity and occurrence.
6. CPM_new better represents the increase of extreme hourly precipitation with return period (or increasing rarity), with the RCM tending to overestimate high return period events over the southern UK in all seasons and over northern regions in summer and autumn.
7. Soil moisture is lower in CPM_new compared to the majority of RCM ensemble members, with a much smaller ensemble spread (due to the absence of soil moisture parameter perturbations in the CPM_new members) and better agreement with pseudo-observations.
8. There is more snowfall and lying snow over high ground in Scotland in CPM_new compared to the RCM, due to the better representation of topography.
9. There is less cloud in CPM_new than the RCM in all seasons, leading to improved biases in winter. In summer, cloud cover biases are worse in CPM_new, but downward shortwave and longwave radiation fluxes at the surface are improved compared to the RCM.
10. CPM_new has greater daily maximum wind speeds than the RCM particularly over high ground.

In general, for temperature, CPM_new shows similar or increased biases in winter temperature and cold spells in the north, but improved biases in summer temperatures and hot days compared to the RCM. Colder mean temperatures (and more cold spells) in winter in CPM_new compared to the RCM are explained by less cloud and also more lying snow, and thus are likely related to the different cloud schemes used in the CPM and RCM as well as the improved representation of high ground in the higher resolution model. The differences between CPM_new and the RCM in terms of summer temperatures are explained in part by reduced biases in radiation fluxes (relating to the differences in cloud radiative properties), although drier soils in the CPM may also contribute. The latter is likely due to the different nature of rainfall in the CPM, with rainfall tending to be more intense and intermittent in the explicit convection compared to the parameterised convection model.

For precipitation, CPM_new provides an improved representation of variability on daily and hourly timescales, leading to overall reduced biases in seasonal mean precipitation compared to the RCM. These improvements are due to the more realistic representation of convection, and in mountainous regions, the better resolution of topography.

A summary of present-day biases in CPM_new compared to the RCM, whether these have changed from the original 2.2km CPM runs, and the implications for the reliability of future projections, is given in Table 5.1.

4. Future changes

4.1 Overview

In this section we present projected changes for the UK under high emission scenario RCP8.5, comparing results from the 2.2km reruns (CPM_new), with the original UKCP Local (2.2km) projections (CPM_orig) and the driving 12km regional ensemble (RCM). The main focus is on surface air temperature and precipitation, with data from the CPM regridded to the 12km scale to allow comparison with the RCM. We show changes between the 2061-80 and baseline (1981-2000) periods, as these will be greater than the nearer-term changes during 2021-40, and therefore easier to discern above natural climate variability. We consider examples of high impact events, including precipitation extremes, hot and cold spells, soil moisture, snow, cloud, lightning and wind extremes.

The range of changes across each 12-member ensemble is represented by showing the 2nd lowest, central and 2nd highest member responses, calculated locally. These responses correspond approximately to the 10th, 50th and 90th percentiles of the ranked 12-member ensemble at each grid box (consistent with the approach used in Murphy et al, 2018). The maps should not be interpreted as examples of spatial patterns that may be simulated by an individual realisation (since the member selected at each grid point may differ). Instead, they give the best indication of uncertainty at each local grid point. The uncertainty sampled across the CPM_new and CPM_orig ensembles includes that arising from natural variability and parametric uncertainties in the physics of the driving models. However, uncertainty in the convective-scale model physics itself is not sampled (Section 2).

4.2 Seasonal mean changes

Mean temperature increases everywhere and in all seasons. The UK-average central estimate of temperature change in the 2.2km rerun (CPM_new) is 3.3°C in winter and 4.6°C in summer, with the greatest increases occurring in the south (Figs 4.2.1-4.2.2). Mean temperature changes are broadly consistent between CPM_new and the RCM, as expected. Differences reported previously, between CPM_orig and the RCM in winter mean temperature changes over Scotland (Kendon et al, 2019), are considerably reduced in CPM_new. In particular, future changes in winter mean temperature are slightly greater in CPM_new compared to CPM_orig (UK central estimate of +3.3°C increase compared to +3.1°C increase in CPM_orig and +3.1C increase in the RCM, Fig 4.2.1). These larger increases in winter temperature in CPM_new are consistent with more lying snow in the present day, which melts in the future and hence amplifies temperature increases.

Future increases in temperature are greater in summer than winter. As expected, future changes in summer mean temperature are not significantly impacted by the code changes in the 2.2km reruns (i.e. differences are less than the CPM_orig ensemble standard deviation of 0.5°C, Kendon et al, 2020b) and are similar between CPM_new, CPM_orig and the RCM (UK-average central estimate of +4.6°C or +4.7°C, Fig 4.2.2). CPM_new shows upper estimate increases of +5.0°C as a UK-average, with the greatest increases in the south of up to +6.0°C.

The CPM_new ensemble projects increases of uncertain magnitude in winter mean precipitation across the UK, with the exception of northern Scotland where the low end of the range suggests that modest decreases are possible in places (Fig 4.2.3). Notably CPM_new shows greater increases in winter precipitation than the RCM (UK-average central estimate of +25.5% in CPM_new compared to +16.1% in the RCM at the 12km scale). Thus the key differences between the CPM and RCM in future changes in winter mean precipitation over the UK that were previously reported (Kendon et al, 2019, 2020a) are retained in the 2.2km reruns. Future changes in winter mean precipitation are not significantly impacted by the code changes in CPM_new, being similar to those in CPM_orig (UK-average central estimate of +25.5% and +27.0% respectively, Fig 4.2.3) and with differences less than the standard deviation across the CPM_orig ensemble (UK-average of 11%, Kendon et al, 2020b). The substantially greater increase in projections of winter precipitation in the CPM compared to the RCM is explored further in Sections 4.3 and 4.4 and has important implications for river flows and flood risk.

In summer, mean precipitation is projected to decrease in the future. Only over northern Scotland does the upper end of the ensemble range indicate the possibility of small increases (Fig 4.2.4). In general summer mean precipitation decreases are slightly greater in CPM_new compared to the RCM (UK-average central estimates of -29.1% in CPM_new and -25.9% in RCM at the 12km scale). These changes are not significantly impacted by the code changes in the 2.2km reruns, being similar in CPM_new to those in CPM_orig (-27.6%) and within the ensemble spread (standard deviation of 12%, Kendon et al, 2020b). Note that summer decreases in both the CPM and RCM ensembles are larger than those sampled by CMIP5 models, with little overlap between the ranges of changes from the perturbed parameter ensembles (PPEs) and 13 CMIP5 models for England (c.f. Fig 5.1).

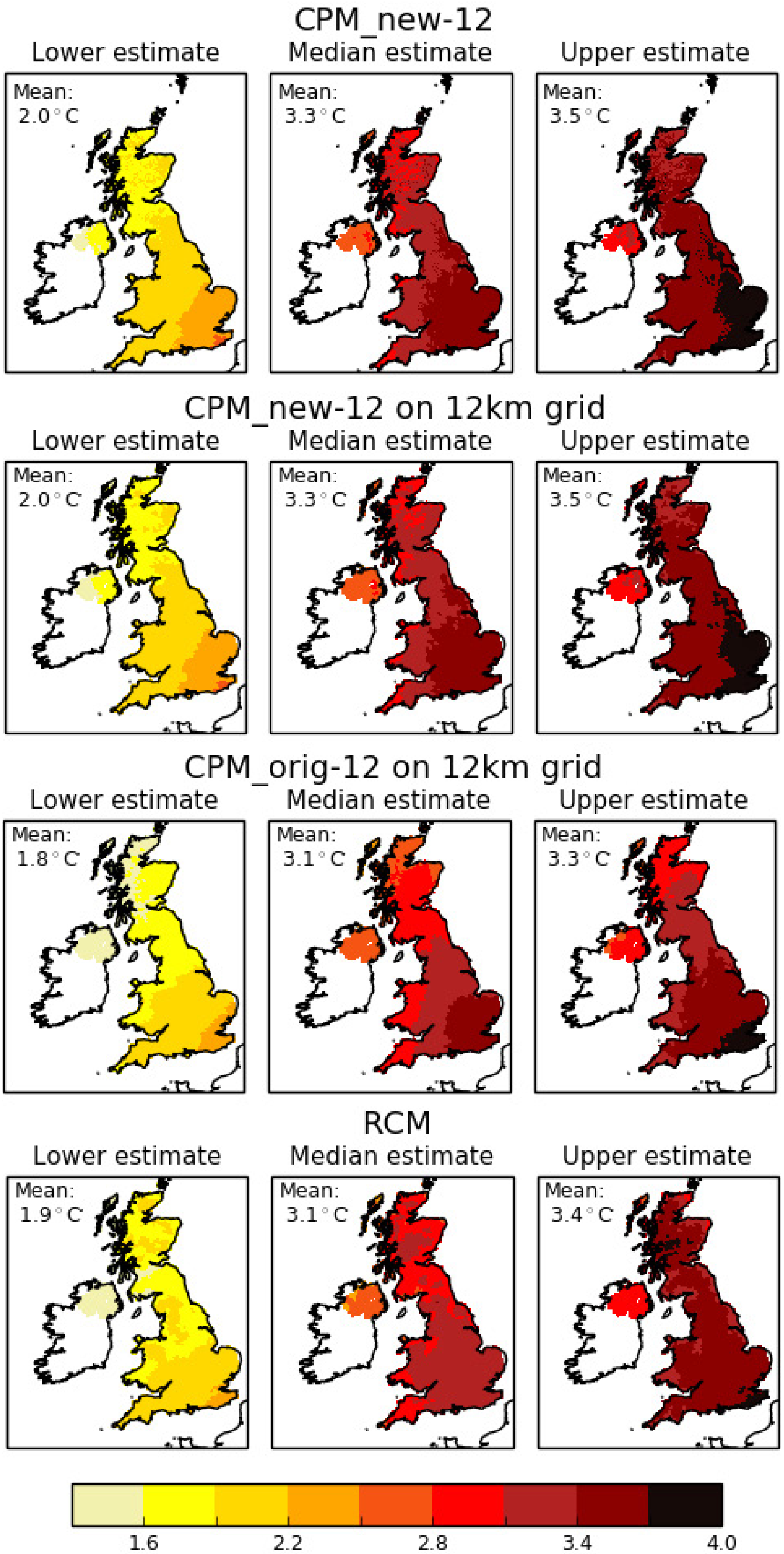

Figure 4.2.1. Future change in winter mean temperature. Changes for (left) 2nd lowest, (centre) central and (right) 2nd highest member locally, for (top) CPM_new at native 2.2km resolution, (2nd row) CPM_new regridded to 12km RCM grid, (3rd row) CPM_orig regridded to 12km and (bottom) RCM. Changes (in °C) correspond to the difference between the future (2061-2080) and baseline (1981-2000) periods. The regridding to 12km is done before calculation of responses and selection of low/high responses. The UK-averaged change is indicated in each panel.

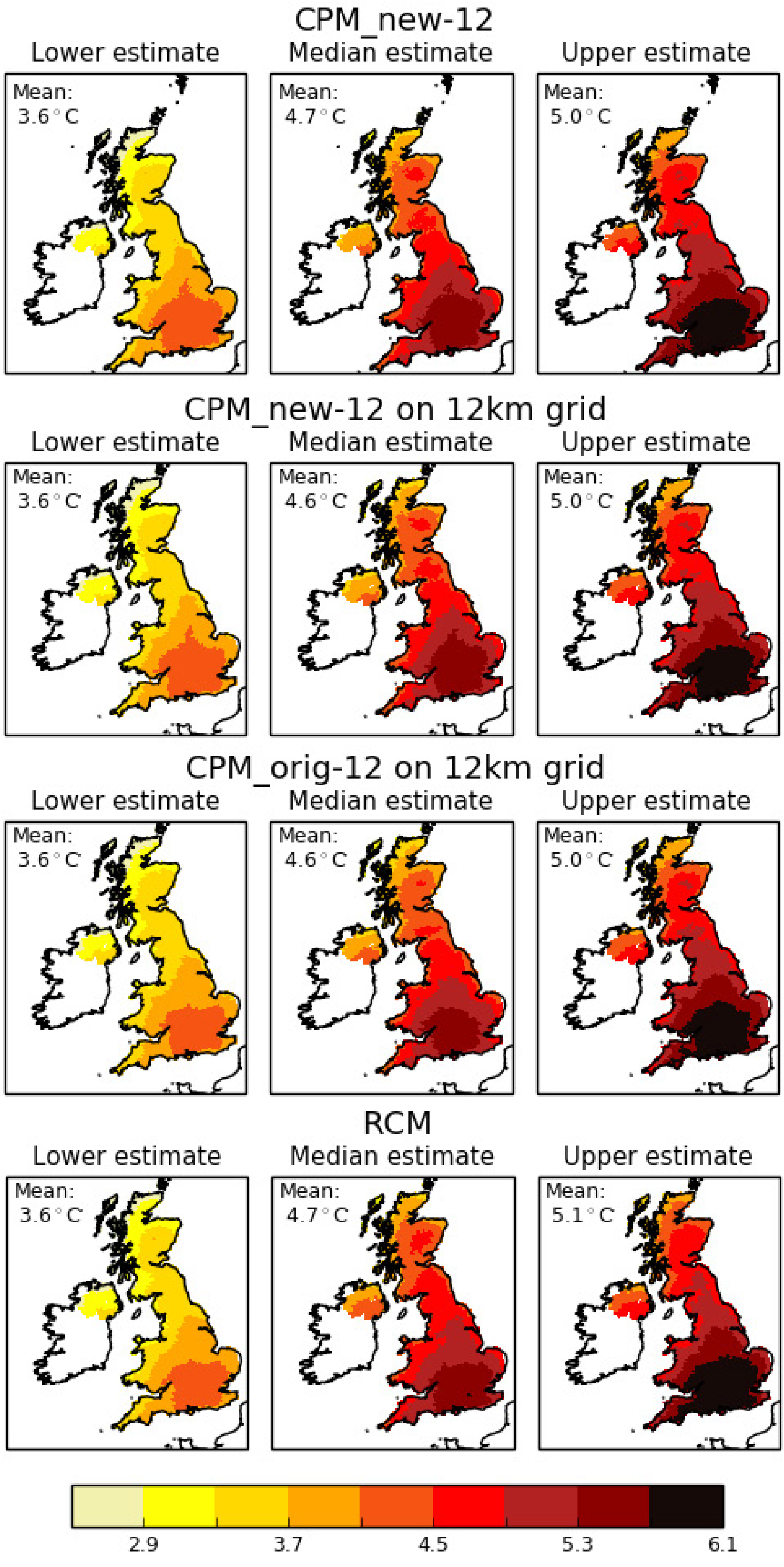

Figure 4.2.2. Future change in summer mean temperature. As Fig 4.2.1 but for summer mean temperature.

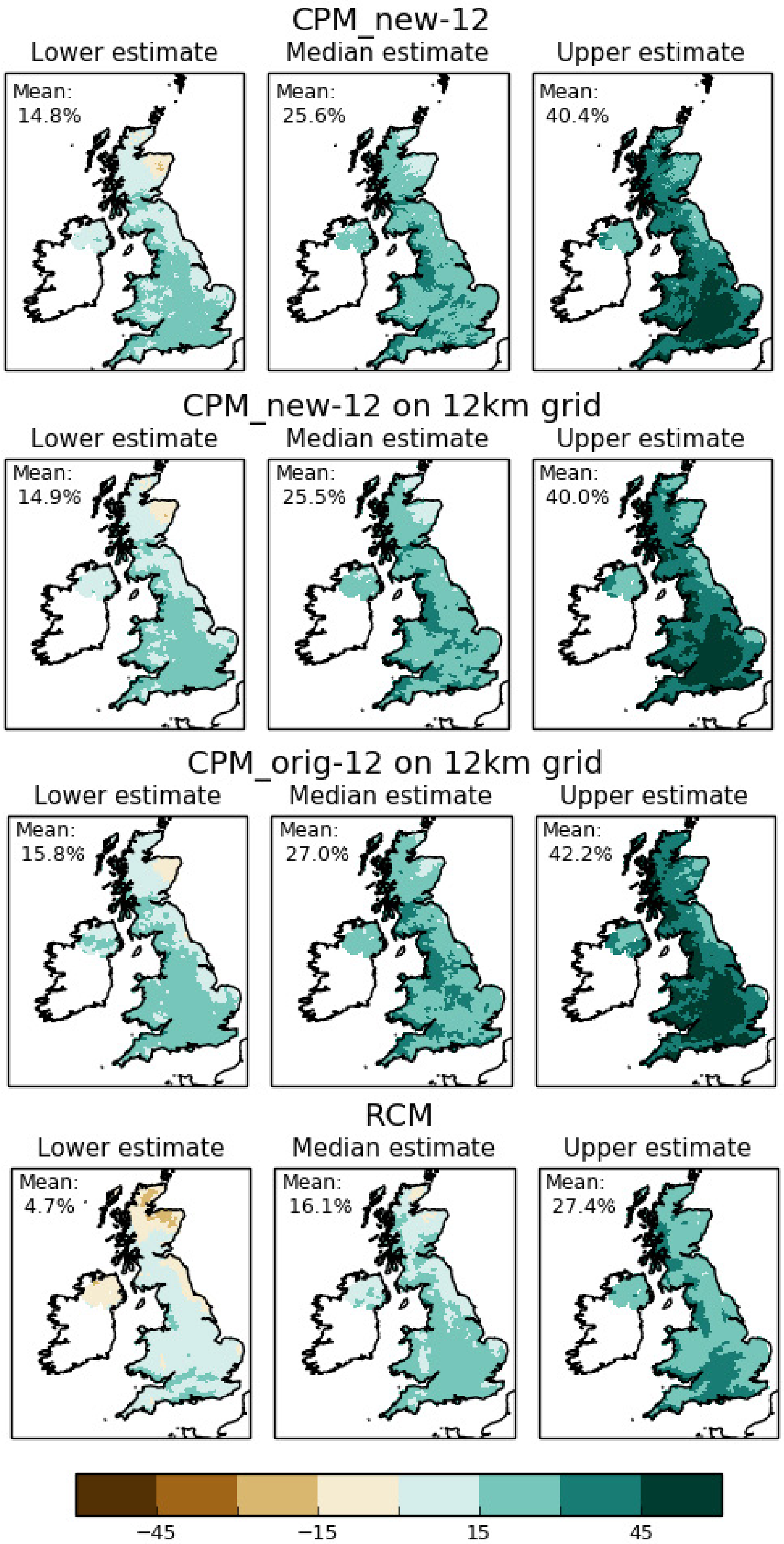

Figure 4.2.3. Future change in winter mean precipitation. As Fig 4.2.1 but for winter mean precipitation.

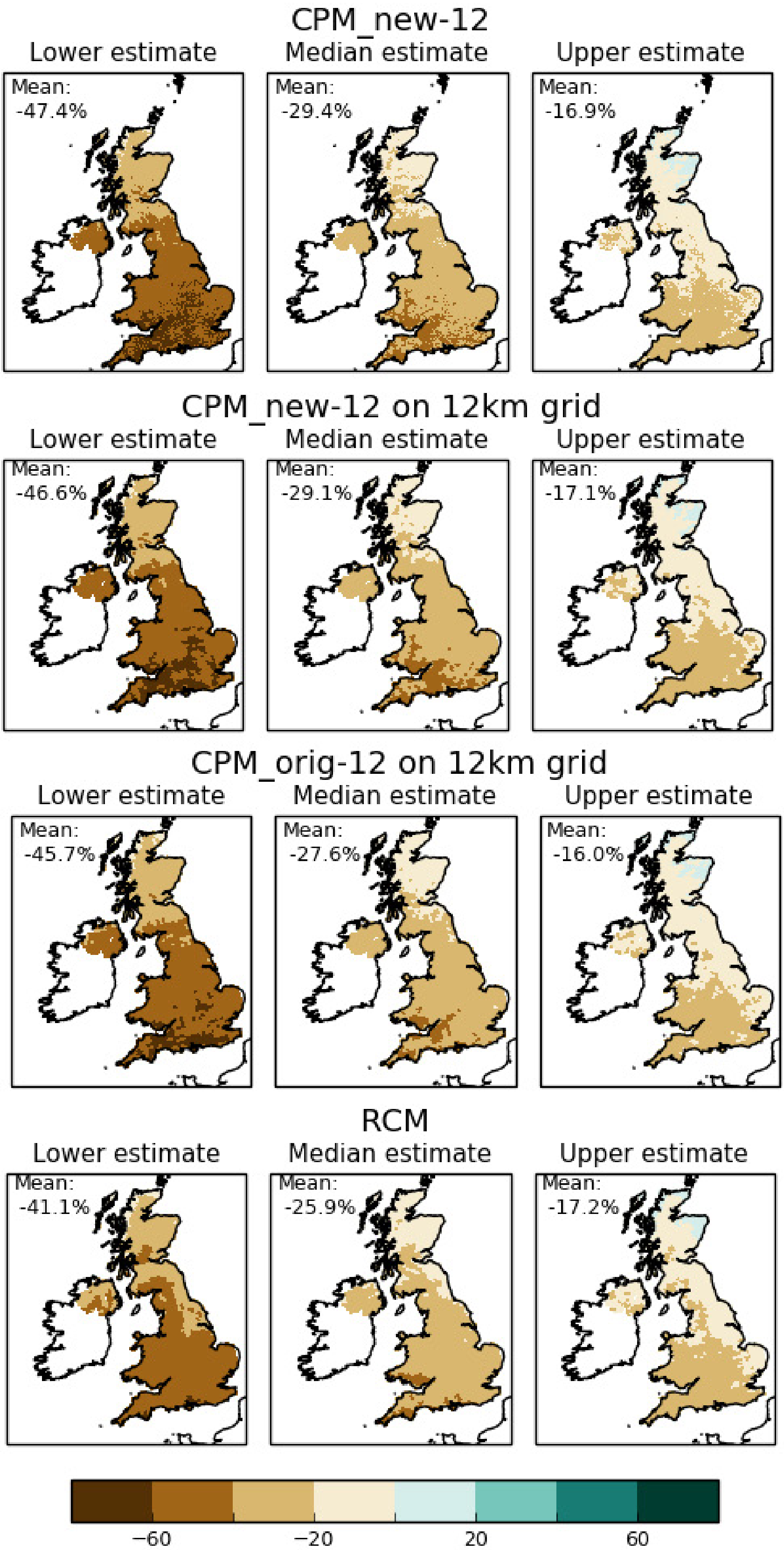

Figure 4.2.4. Future change in summer mean precipitation. As Fig 4.2.1 but for summer mean precipitation.

4.3 Changes at daily time scale

Future changes in the temperature of cold winter days are broadly consistent between CPM_new and the RCM (UK average central estimate of 5.3°C and 5.4°C increase, Fig 4.3.1). Differences in response between CPM_orig and the RCM, reported previously by Kendon et al, (2019), are considerably reduced in CPM_new. In particular, fixing the graupel code error and other science changes leads to significantly larger increases in temperature on cold winter days in CPM_new compared to CPM_orig (UK average central estimate of 5.3°C in CPM_new and 3.8°C in CPM_orig, with difference larger than the CPM_orig ensemble standard deviation of 1.2°C, Kendon et al, 202b). This is consistent with more lying snow in the present day, which melts in the future and amplifies temperature increases. Temperature increases are greatest in Scotland (low to high estimate of 5-9°C increase), with the UK-average low to high estimate being 3.6-6.4°C at 12km scale.

For hot summer days, CPM_new and the RCM again generally give consistent responses (UK average central estimate of 6.0°C in CPM_new and 5.9°C in RCM, Fig 4.3.2). As expected, future increases in hot summer days are not significantly impacted by the code changes in the 2.2km reruns, with very little difference in future changes between CPM_new and CPM_orig (and differences considerably smaller than the ensemble standard deviation of 1.2°C).

For daily precipitation, CPM_new shows an increase in wet day frequency in winter that is not seen in the RCM (UK average central estimate of 8.6% in CPM_new and 0.6% in RCM, for data at 12km scale, Fig 4.3.3). This key difference between the CPM and RCM, also reported previously (Kendon et al, 2019), is unaffected by the rerun. Increases in wet day frequency are slightly lower in CPM_new compared to CPM_orig (8.6% compared to 9.2% in CPM_orig), but this difference is much smaller than the CPM-RCM differences. The CPM_new projected changes are considered plausible given the much better representation of the baseline compared to the RCM and the better representation of convective showers and their advection inland in the CPM, which has been shown to be a major contributor to the difference (Kendon et al, 2020a). CPM_new projected changes are more reliable than those in CPM_orig due to the fix to the graupel code error and the improved modelling of the snowpack (Section 2).

Increases in wet day intensity in winter (central estimate of 16.9%, at 12km scale, Fig 4.3.4) are in good agreement between CPM_new and the RCM, which may be explained by the increases being driven by increasing atmospheric moisture with warming – a process well captured by coarse resolution climate models. Thus the greater increase in winter mean precipitation in CPM_new compared to the RCM (Section 4.2), is due to differences in precipitation occurrence. For heavy daily events in winter, increases in precipitation are slightly larger in CPM_new (central estimate of 23.1% compared to 19.8% in RCM, Fig 4.3.5). There is little impact of the new science changes and graupel code fix on future changes in wet day intensity and heavy daily precipitation in winter, with CPM_new showing similar projected changes to CPM_orig (Fig 4.3.4, 4.3.5).

In summer, there are large future decreases in the occurrence of wet days in CPM_new that exceed those found in the RCM ensemble (central estimate of -33.2% compared to -25.4% at the 12km scale, Fig 4.3.6). There are considerable differences between CPM_new and the RCM in terms of future changes in wet day intensity and heavy daily precipitation in summer, with the CPM tending to show greater increases or smaller decreases in precipitation intensity (central estimate of +4.7% compared to -2.7% for changes in wet day intensity and -1.5% compared to -6.3% for changes heavy daily precipitation at the 12km scale, Figs 4.3.7-4.3.8). Thus although changes in mean summer precipitation are similar between CPM_new and the RCM, there are quite different underlying changes in intensity and occurrence. Given present-day biases in rainfall occurrence in the RCM, and the improved representation of convective processes in the CPM, we have greater confidence in the daily precipitation changes in the CPM in summer. For precipitation intensity metrics in summer, changes in CPM_new at the native 2.2km scale show larger future increases (and smaller decreases) compared to when precipitation is aggregated to the 12km scale (Figs 4.3.7-4.3.8). This is consistent with rainfall being more localised in this season, with intensity increasing but fewer events. Future changes in summer wet day frequency and intensity are not notably impacted by the code changes in CPM_new, results being similar to CPM_orig. Future decreases in heavy summer daily precipitation are slightly larger in CPM_new than CPM_orig (-1.5% compared to -0.3%), but these differences are considerably smaller than CPM-RCM differences. Overall, key differences between the CPM and RCM in terms of future changes in precipitation on the daily timescale, both in summer and winter, are unaffected by the rerun.

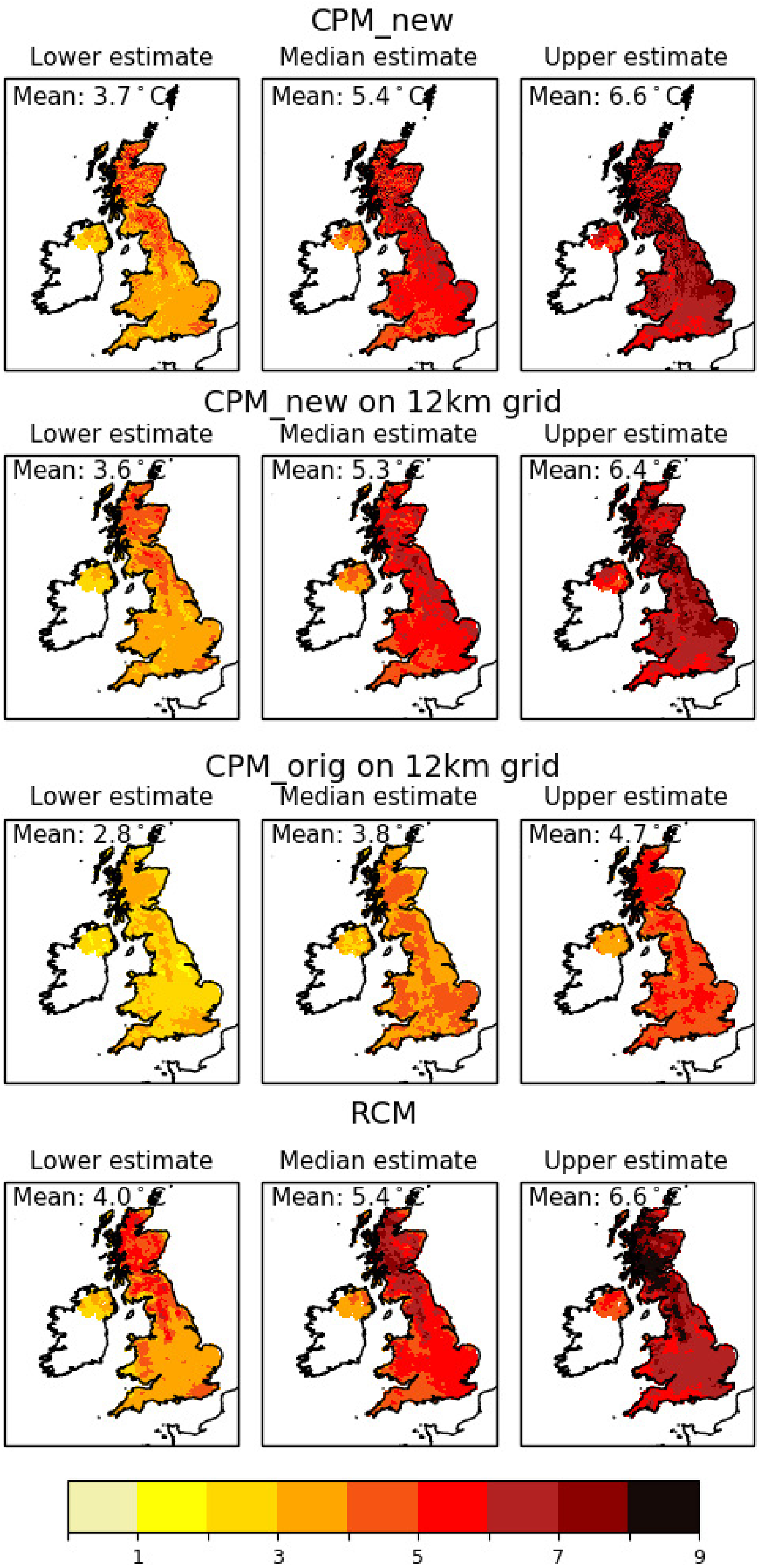

Figure 4.3.1. Future change in cold winter days. Changes for (left) 2nd lowest, (centre) central and (right) 2nd highest member locally, for (top) CPM_new at native 2.2km resolution, (2nd row) CPM_new regridded to 12km RCM grid, (3rd row) CPM_orig regridded to 12km and (bottom) RCM ensembles. Changes (in °C) correspond to the difference between the future (2061-2080) and baseline (1981-2000) periods. Cold winter days are defined as the 1st percentile of daily mean temperature in DJF. UK-average changes are indicated in each panel.

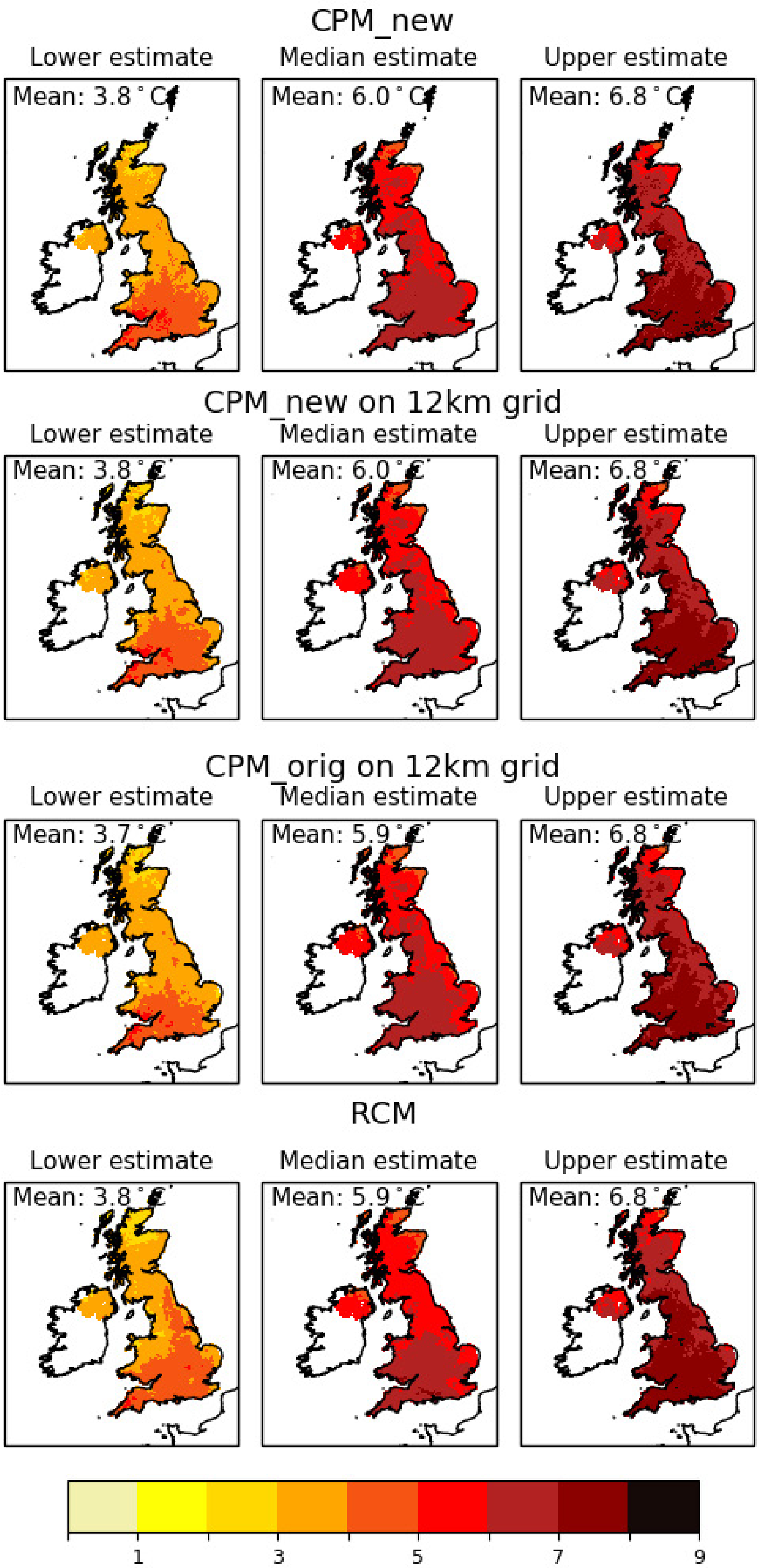

Figure 4.3.2. Future change in hot summer days. As Fig 4.3.1 but for future change in hot summer days. Hot summer days are defined as the 99th percentile of daily mean temperature in JJA.

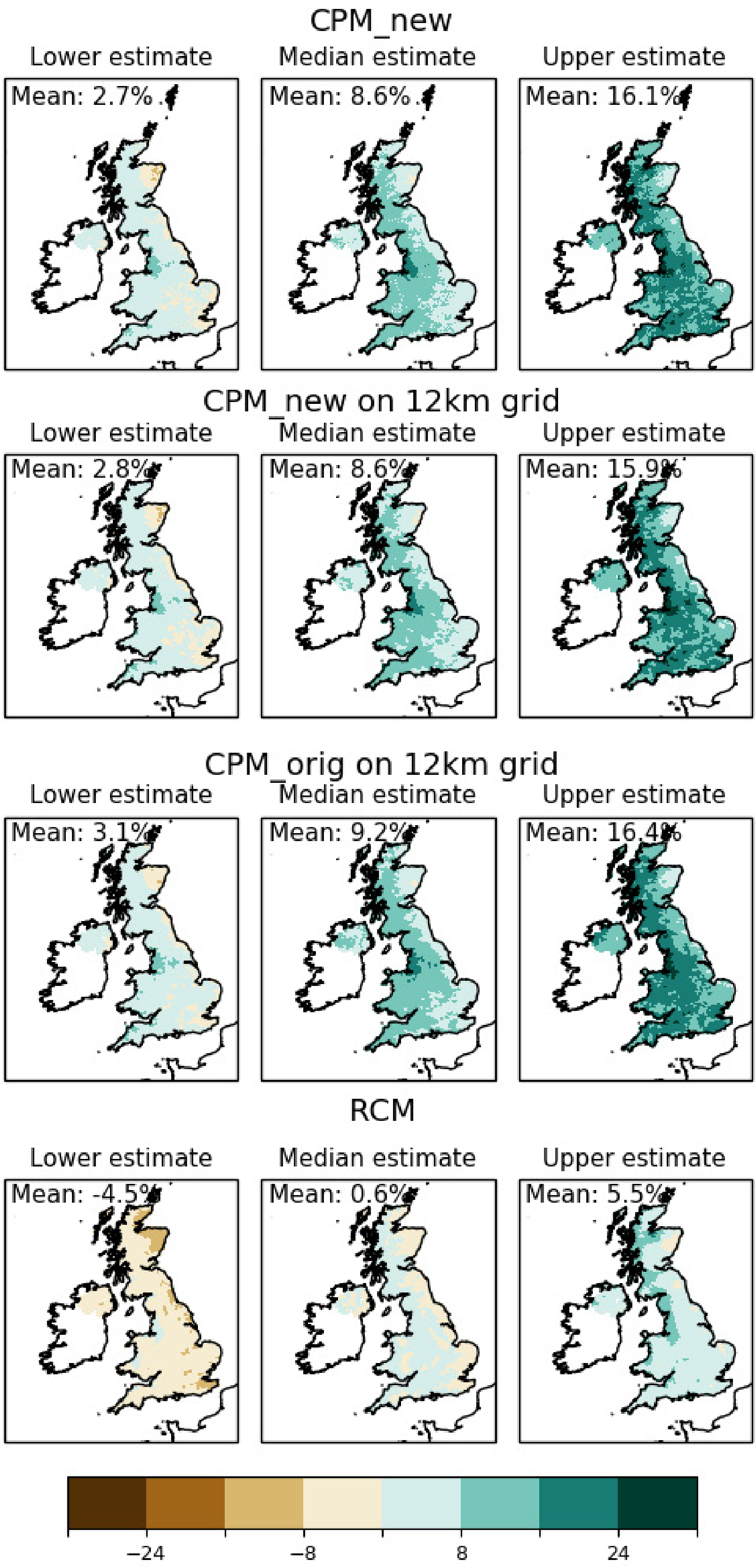

Figure 4.3.3. Future change in wet day frequency in winter. As Fig 4.3.1 but for future change in wet day frequency in winter. Wet days are defined as days with precipitation >1mm/d.

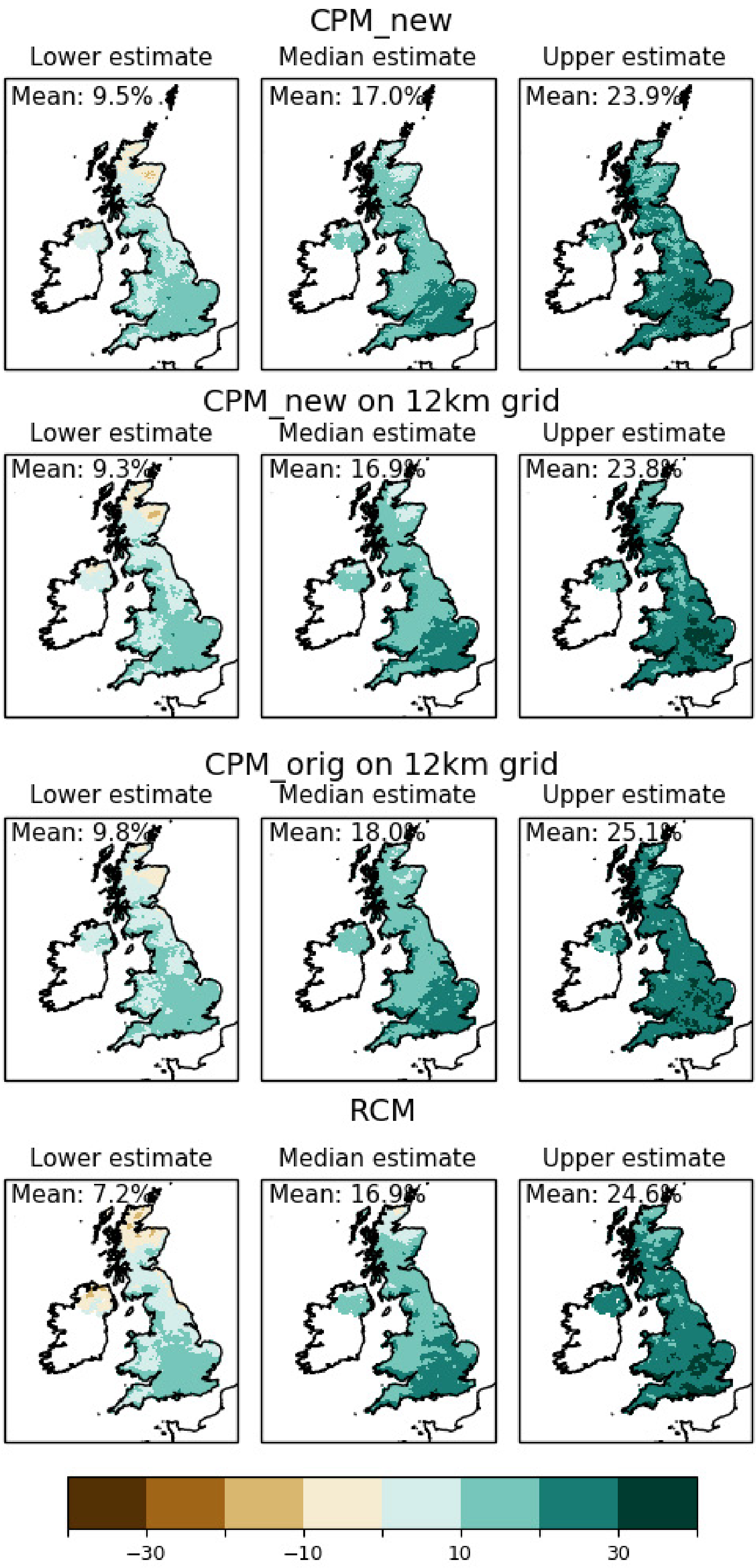

Figure 4.3.4. Future change in wet day intensity in winter. As Fig 4.3.1 but for future change in wet day intensity in winter. Wet days are defined as days with precipitation >1mm/d.

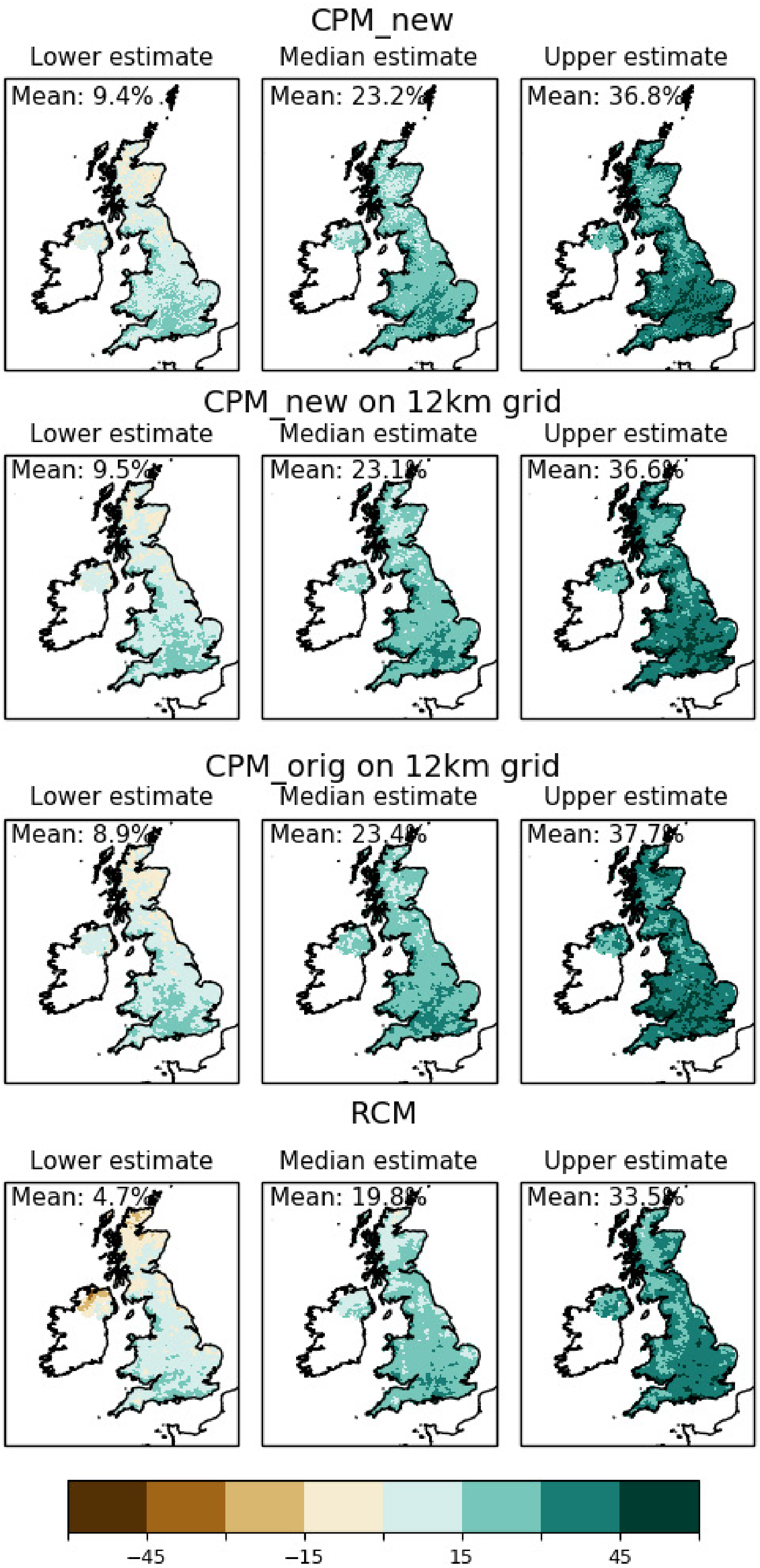

Figure 4.3.5. Future change in heavy daily events in winter. As Fig 4.3.1 but for future change in the 99th percentile of daily mean precipitation in DJF.

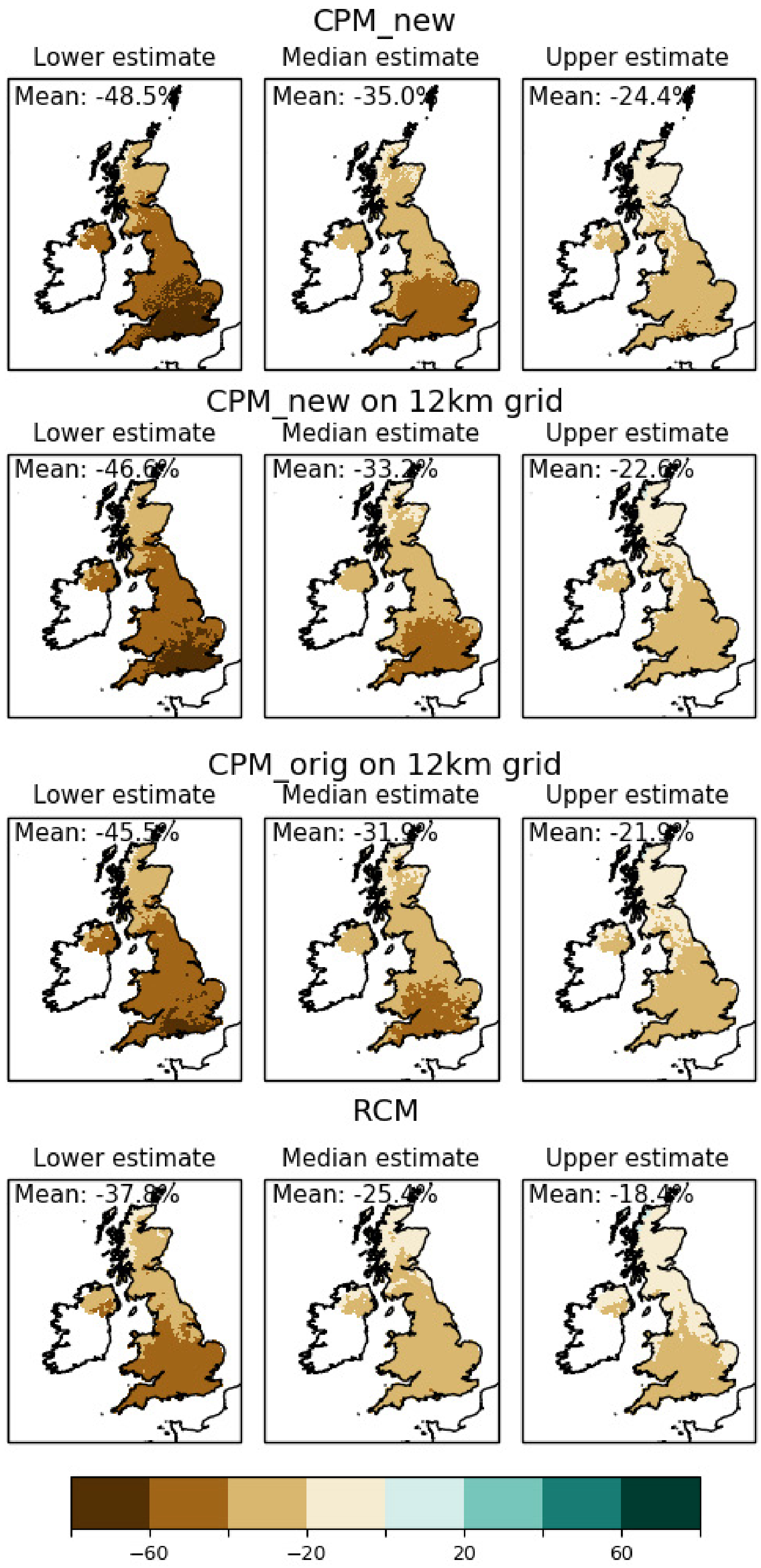

Figure 4.3.6. Future change in wet day frequency in summer As Fig 4.3.1 but for future change in wet day frequency in summer. Wet days are defined as days with precipitation >1mm/d.

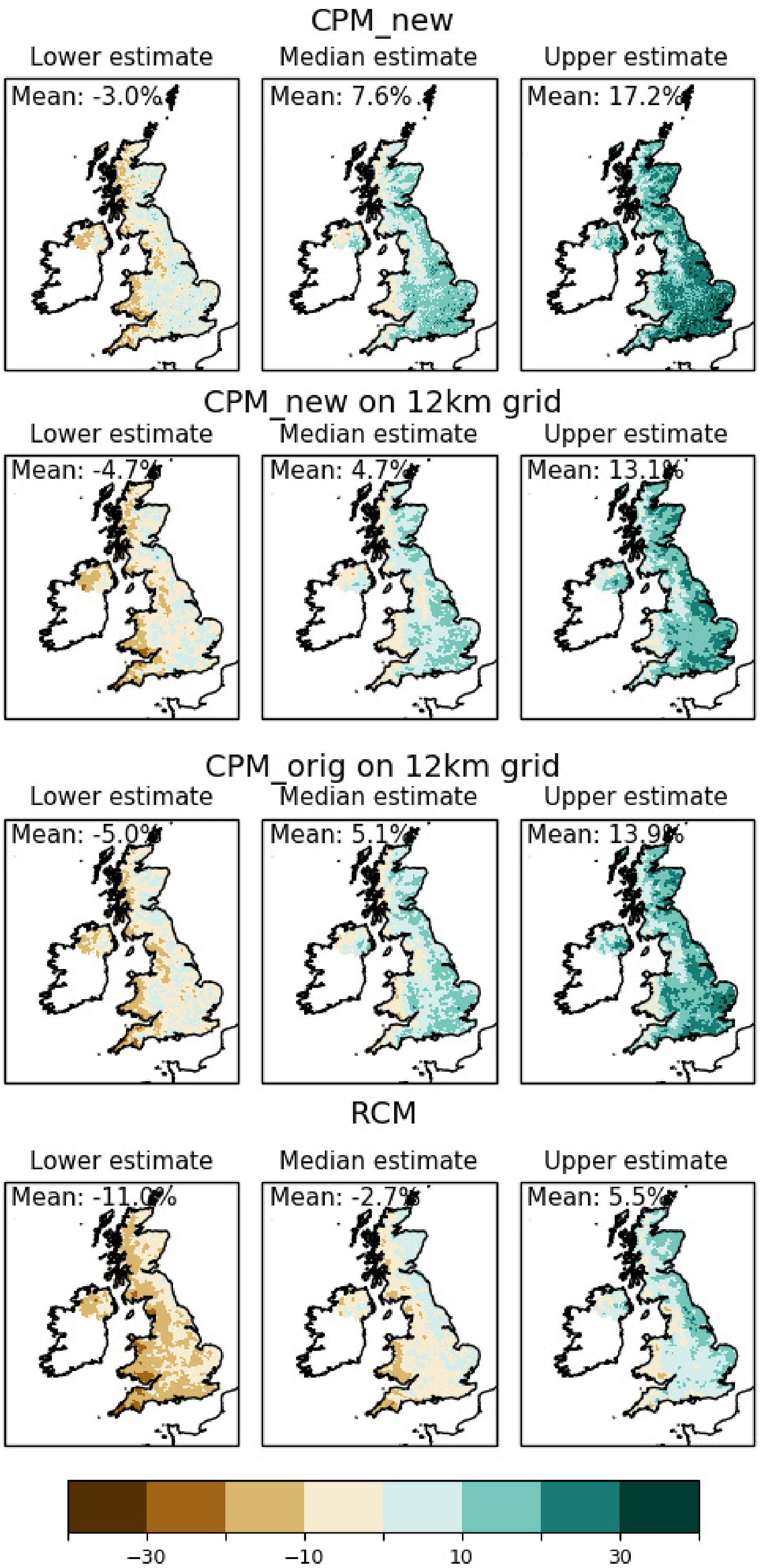

Figure 4.3.7. Future change in wet day intensity in summer. As Fig 4.3.1 but for future change in wet day intensity in summer. Wet days are defined as days with precipitation >1mm/d.

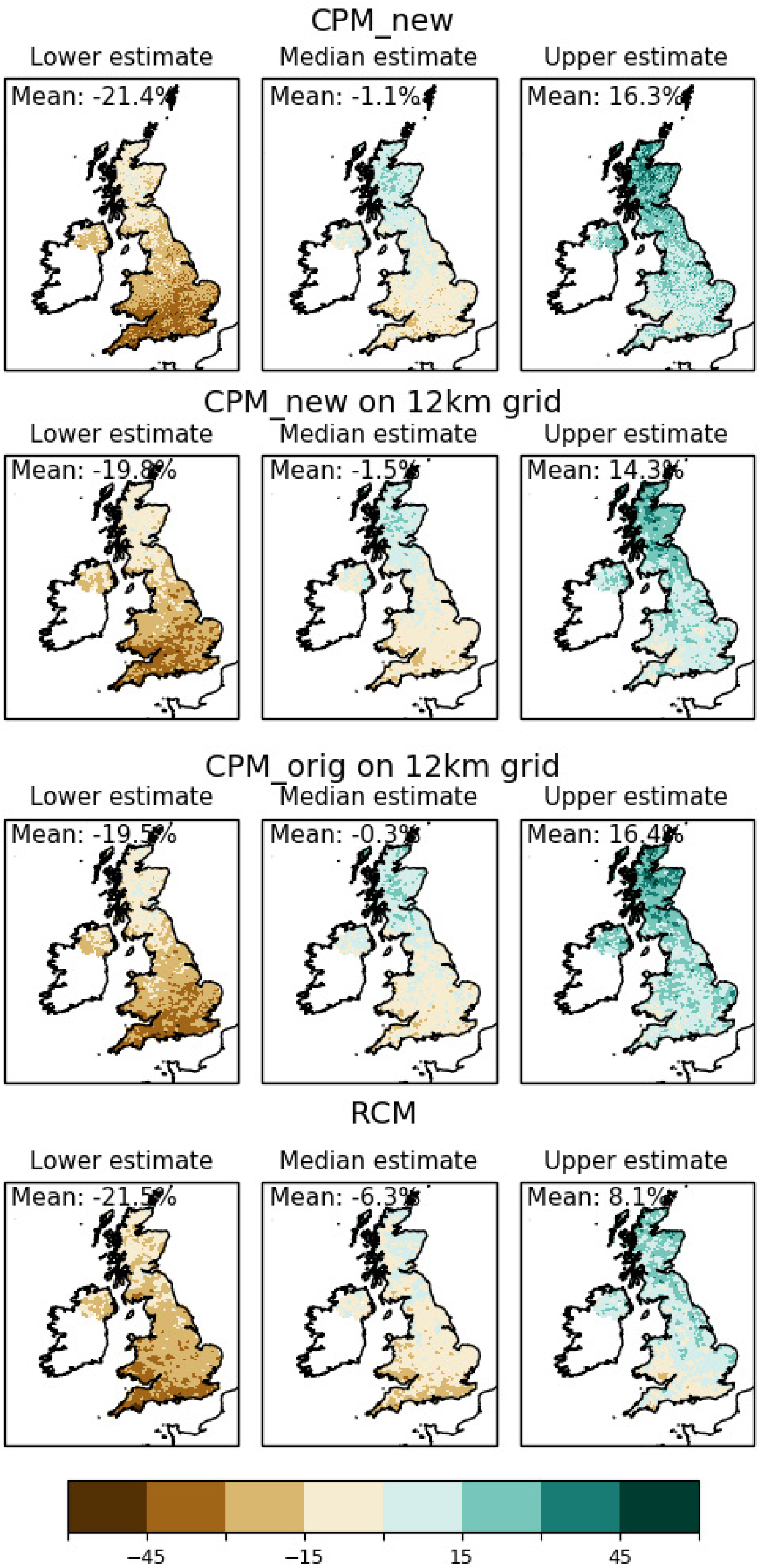

Figure 4.3.8. Future change in heavy daily events in summer. As Fig 4.3.1 but for future change in the 99th percentile of daily mean precipitation in JJA.

4.4 Changes in hourly precipitation frequency and intensity

Consistent with the results on the daily timescale (Section 4.3), key differences between the CPM and RCM in future changes in winter hourly precipitation occurrence are retained in the rerun (Fig 4.4.1). CPM_new shows a 15.4% increase (and CPM_orig a 16.9% increase) in winter precipitation occurrence compared to an increase of only 1.9% in the RCM. This difference is related to an increase in convective showers in the CPM, that are most likely triggered over the sea and advected inland with potentially further development (Kendon et al, 2020a). Such changes are not well captured in the RCM, due to limitations of the convection parameterisation scheme that acts locally without direct memory and so has no ability to advect diagnosed convection over the land. Thus we have greater confidence in the changes in the CPM than the RCM.

Increases in hourly precipitation intensity in winter are greater in the RCM (15.3% increase) compared to CPM_new (9.5% increase, Fig 4.4.2), with both models showing an increase in high percentiles of hourly precipitation in winter (23.1% and 20.4% increase respectively, Fig 4.4.3). These changes are not notably impacted by the 2.2km rerun, with similar increases in winter precipitation intensity and heavy hourly precipitation in CPM_new and CPM_orig.

In summer, CPM_new shows a slightly greater future decrease in hourly rainfall occurrence compared to the RCM (-33.8% in CPM_new and -28.0% in RCM, Fig 4.4.4) and a considerably greater future increase in hourly rainfall intensity (8.2% in CPM_new and 1.9% in RCM, Fig 4.4.5). These results are similar to those on daily timescales (Section 4.3). For the 99.95th percentile of hourly precipitation both models show an increase, although decreases are possible especially in the south (for low-end changes, Fig 4.4.6). Notably there are larger increases in high percentiles in CPM_new compared to the RCM (central estimate of 18.3% compared to 12.0% in the RCM). These differences between the CPM and RCM are slightly enhanced in the rerun, with CPM_new tending to show slightly greater increases in hourly precipitation intensity at high percentiles than CPM_orig. Given present-day biases in rainfall occurrence in the RCM, and the improved representation of convective processes in the CPM, we have greater confidence in hourly precipitation changes in the CPM in summer. This tendency for convection-permitting models to show a greater intensification of summertime rainfall has also been seen in other studies (Kendon et al, 2017, Pichelli et al, 2021). We also have greater confidence in the results from CPM_new compared to CPM_orig due to the graupel code error being fixed in the reruns, with graupel found in convective storms.

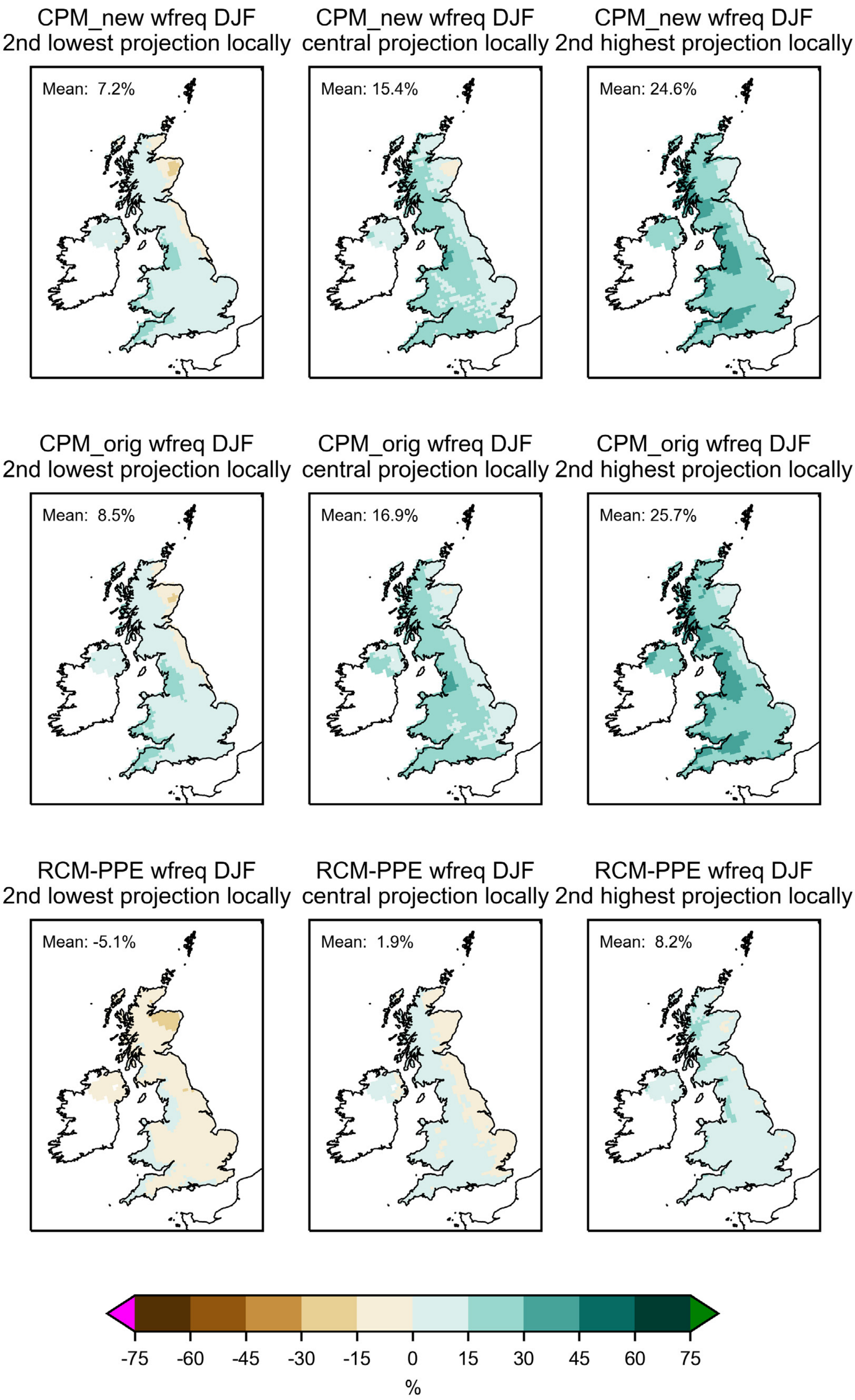

Figure 4.4.1. Future change in hourly precipitation occurrence in winter. Changes for (left) 2nd lowest, (centre) central and (right) 2nd highest member locally, for (top) CPM_new and (middle) CPM_orig regridded to 12km RCM grid and (bottom) UKCP18 RCM 12-member ensembles. Changes (in %) correspond to the difference between the future (2061-2080) and baseline (1981-2000) periods. Wet hours are defined as hours with precipitation > 0.1mm/h. UK-average changes are indicated in each panel.

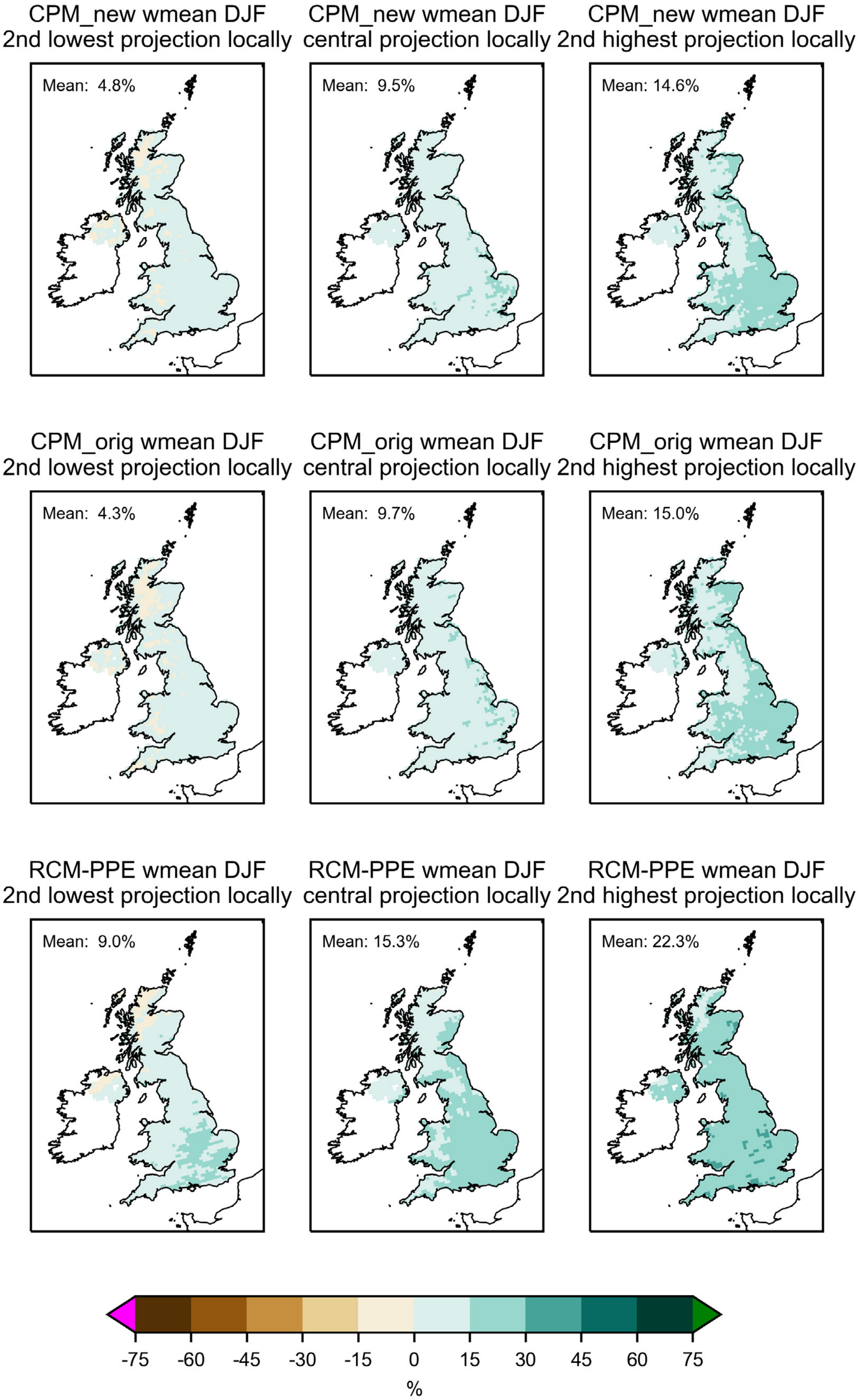

Figure 4.4.2. Future change in hourly precipitation intensity in winter. As Fig 4.4.1 but for hourly precipitation intensity, defined as the mean precipitation on wet hours.

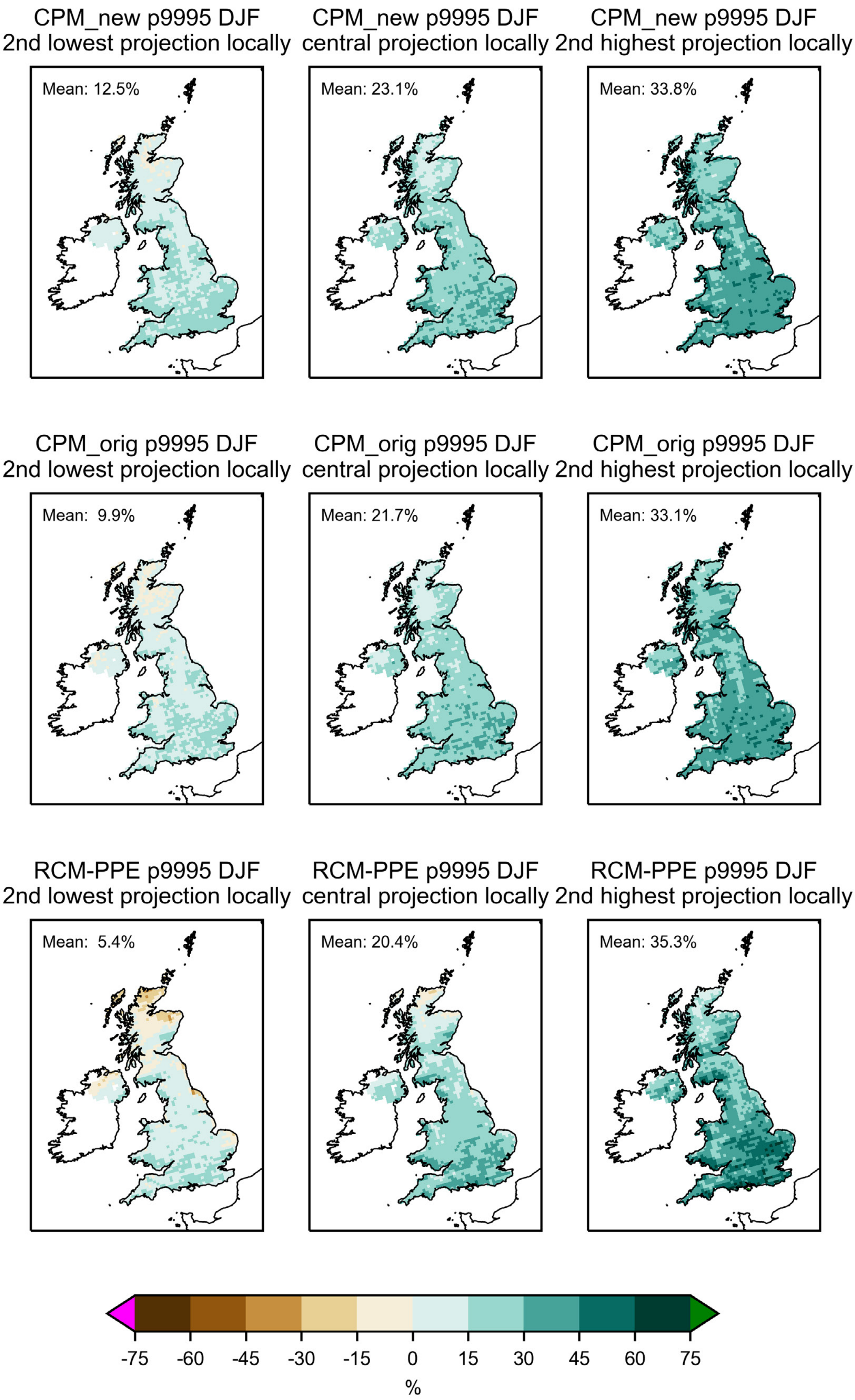

Figure 4.4.3. Future change in heavy hourly precipitation in winter. As Fig 4.4.1 but for heavy hourly precipitation defined as the 99.95th percentile of hourly precipitation (for all hours) in DJF.

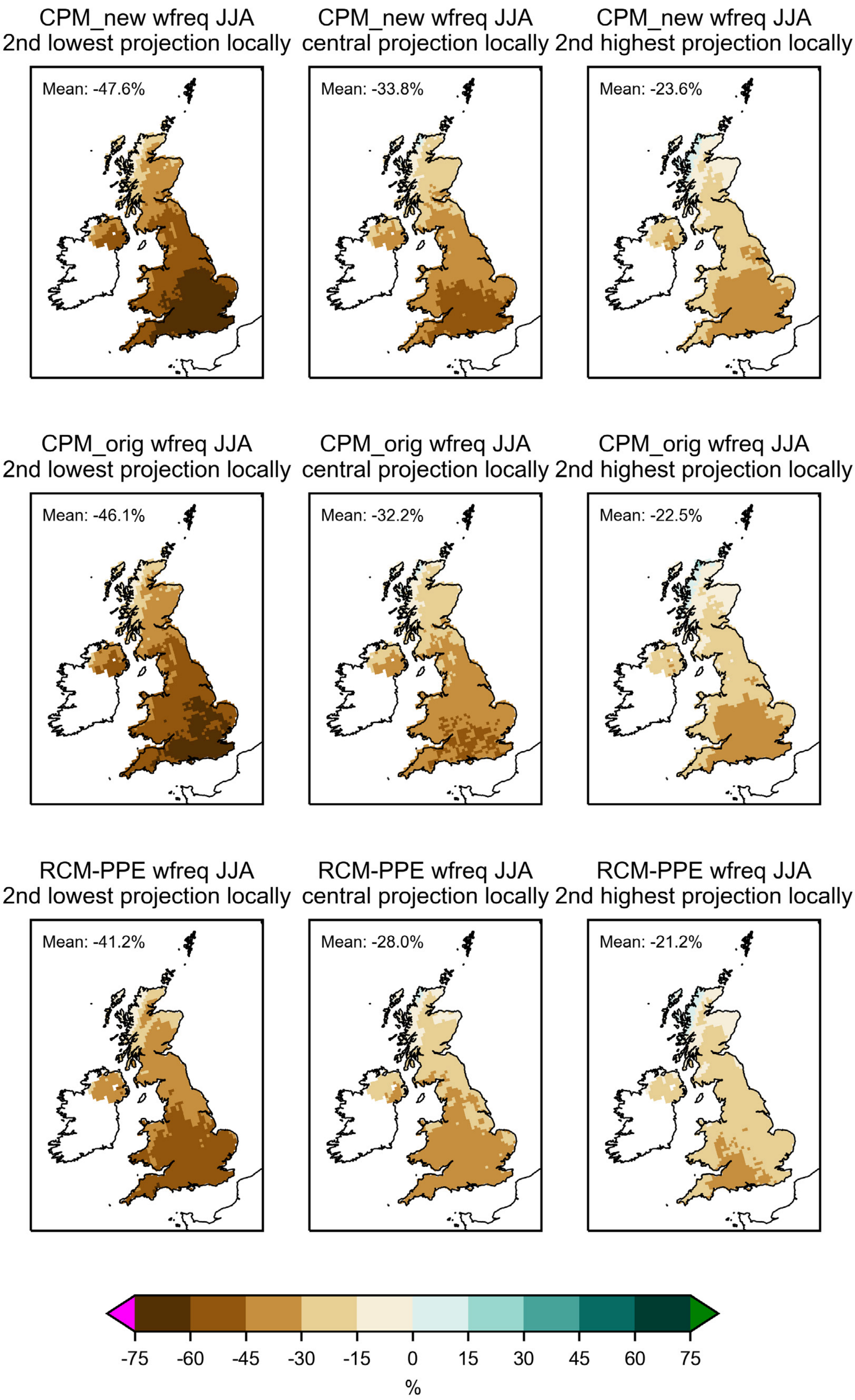

Figure 4.4.4. Future change in hourly precipitation occurrence in summer. As Fig 4.4.1 but for summer.

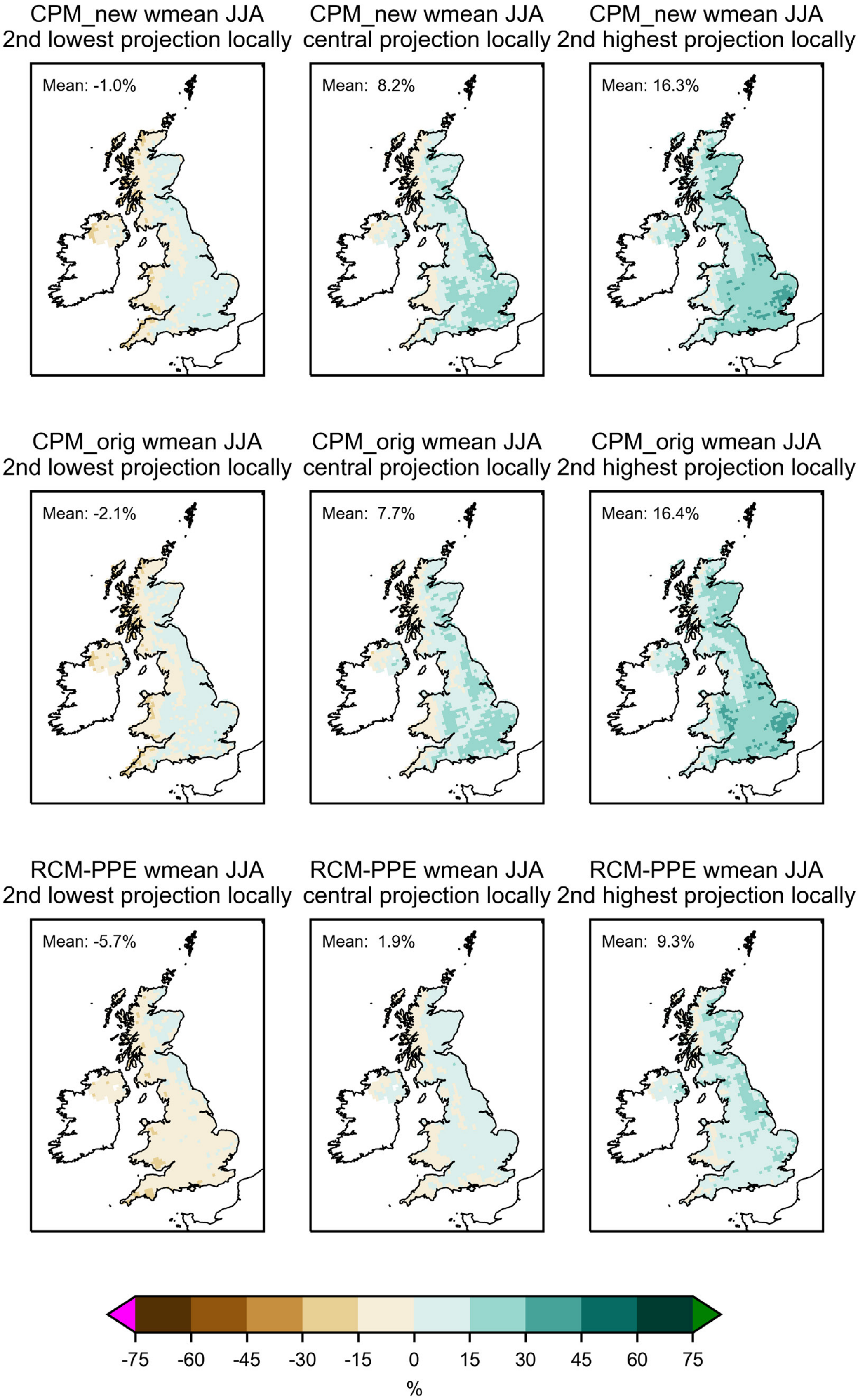

Figure 4.4.5. Future change in hourly precipitation intensity in summer. As Fig 4.4.1 but for hourly precipitation intensity, defined as the mean precipitation on wet hours, in summer.

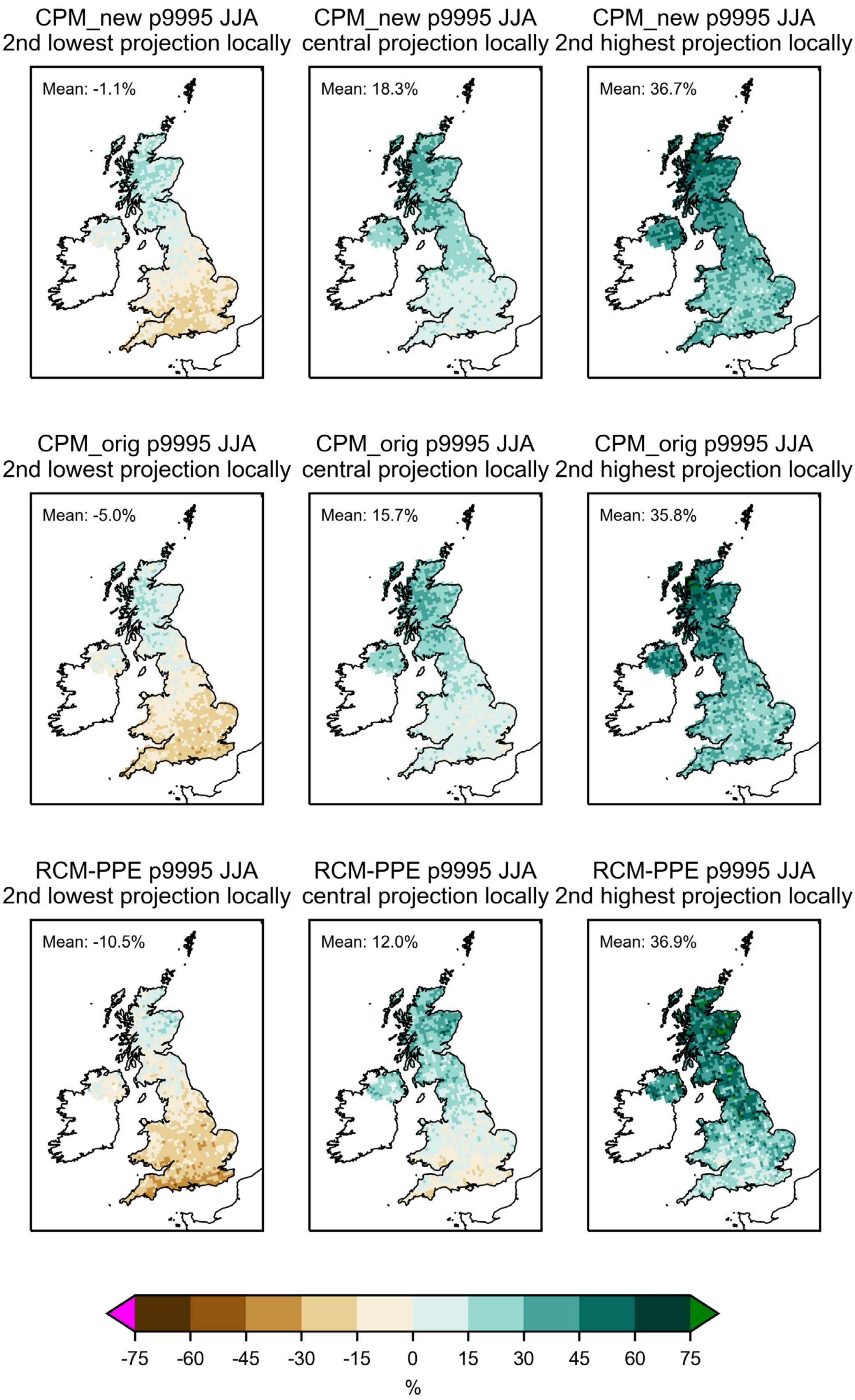

Figure 4.4.6. Future change in heavy hourly precipitation in summer. As Fig 4.4.1 but for heavy hourly precipitation defined as the 99.95th percentile of hourly precipitation (for all hours) in JJA.

4.5 Changes in high impact events

Extreme hourly precipitation

The 2-year return level of extreme hourly precipitation is projected to increase in future on an annual basis (Fig 4.5.1), and for all seasons, except for the southern UK (S-UK) in summer where some CPM_new members show a decrease in the 2-year return level (Figs 4.5.2-4.5.4). Changes in the 2-year return level reflect changes in both the intensity and frequency of precipitation, and decreases for the S-UK in summer are due to large decreases in rainfall occurrence (Fig. 4.4.4), which in this case override increases in rainfall intensity. The code changes in CPM_new have some impact on future changes in hourly extremes, with the UK-average central estimate showing a 29% increase compared to 25% increase in CPM_orig for the 2-year return level (Fig 4.5.1), however this difference is not significant compared to the ensemble spread (UK average standard deviation across CPM_orig ensemble of 8%). There is good agreement in the central estimate response between CPM_new and the RCM, however the ensemble spread is considerably lower in CPM_new (14 to 47% in CPM_new cf. 7% to 61% in RCM). Given that differences between CPM_new and CPM_orig in terms of future changes in extreme hourly precipitation are largely a result of fixing the graupel code error (Section 2), we have greater confidence in the projections from CPM_new.

Figs 4.5.2-4.5.4 show that future percentage changes in hourly precipitation extremes in CPM_new do not vary much with increasing return period. Differences between CPM_new and CPM_orig are also largely consistent, across return periods from 2 to 100 years. By contrast, differences in response between CPM_new and the RCM can vary considerably across return period (depending on ensemble member), with the RCM showing larger future increases for high return period events (especially for autumn and winter over the southern UK, and for the majority of seasons over the northern regions). Ensemble spread also increases with return period in the RCM. However, we have low confidence in these RCM results for rare (high return period) extremes, as they are likely due in some cases to unphysical grid point storms (Kendon et al, 2019).

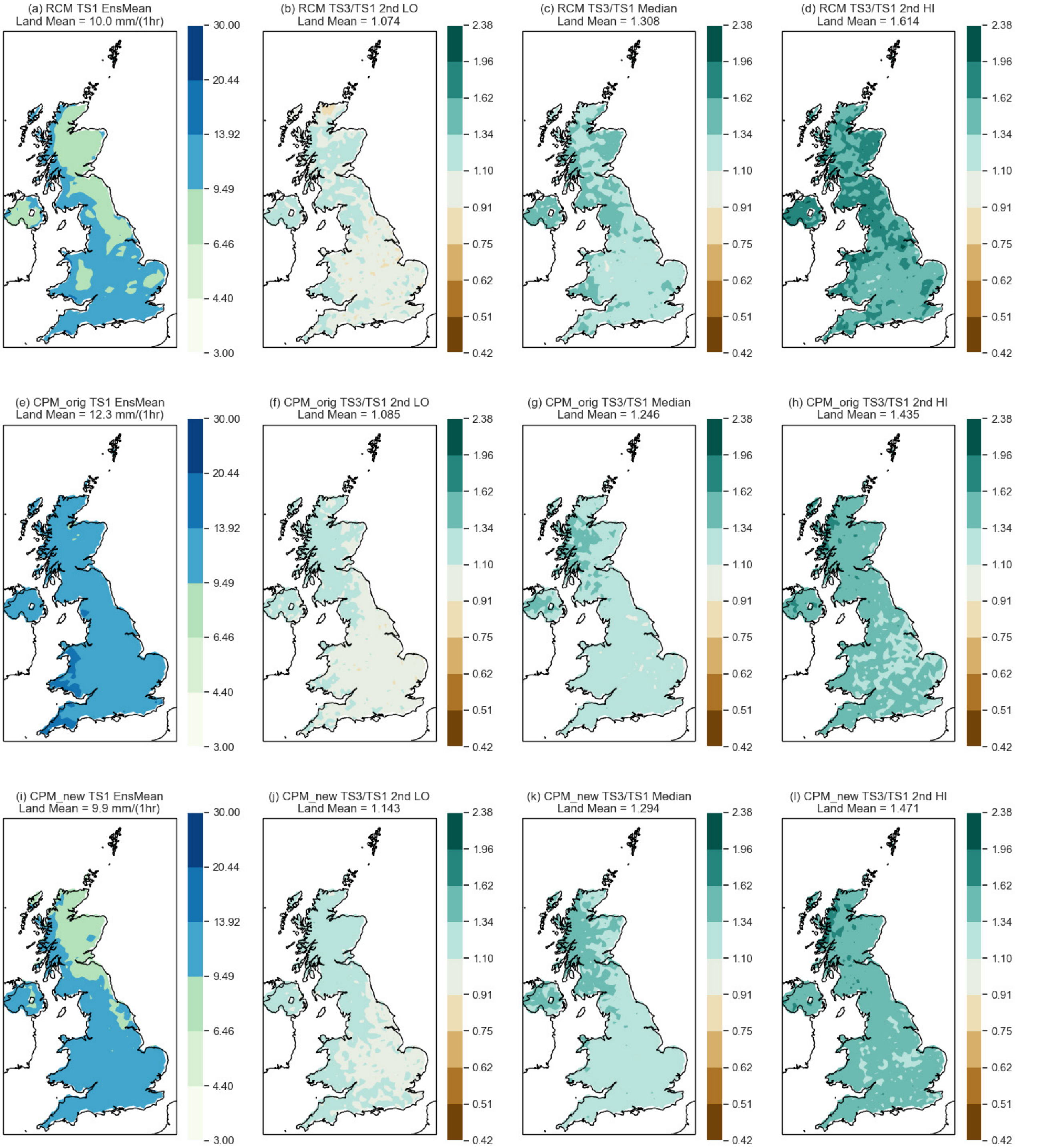

Figure 4.5.1. Future change in 2 year return level of daily maximum hourly precipitation. Shown are (a,e,i) ensemble-mean estimates of present-day return level (mm/h) for TS1 (Time slice 1, 1981-2000) and the ratio of future (TS3, 2061-80, RCP8.5) to present-day return levels for (b,f,j) 2nd lowest member locally, (c,g,k) central estimate and (d,h,l) 2nd highest member locally, for RCM, CPM_orig and CPM_new. This is for hourly precipitation data from all seasons, regridded to a common 12km grid before calculation of return levels.

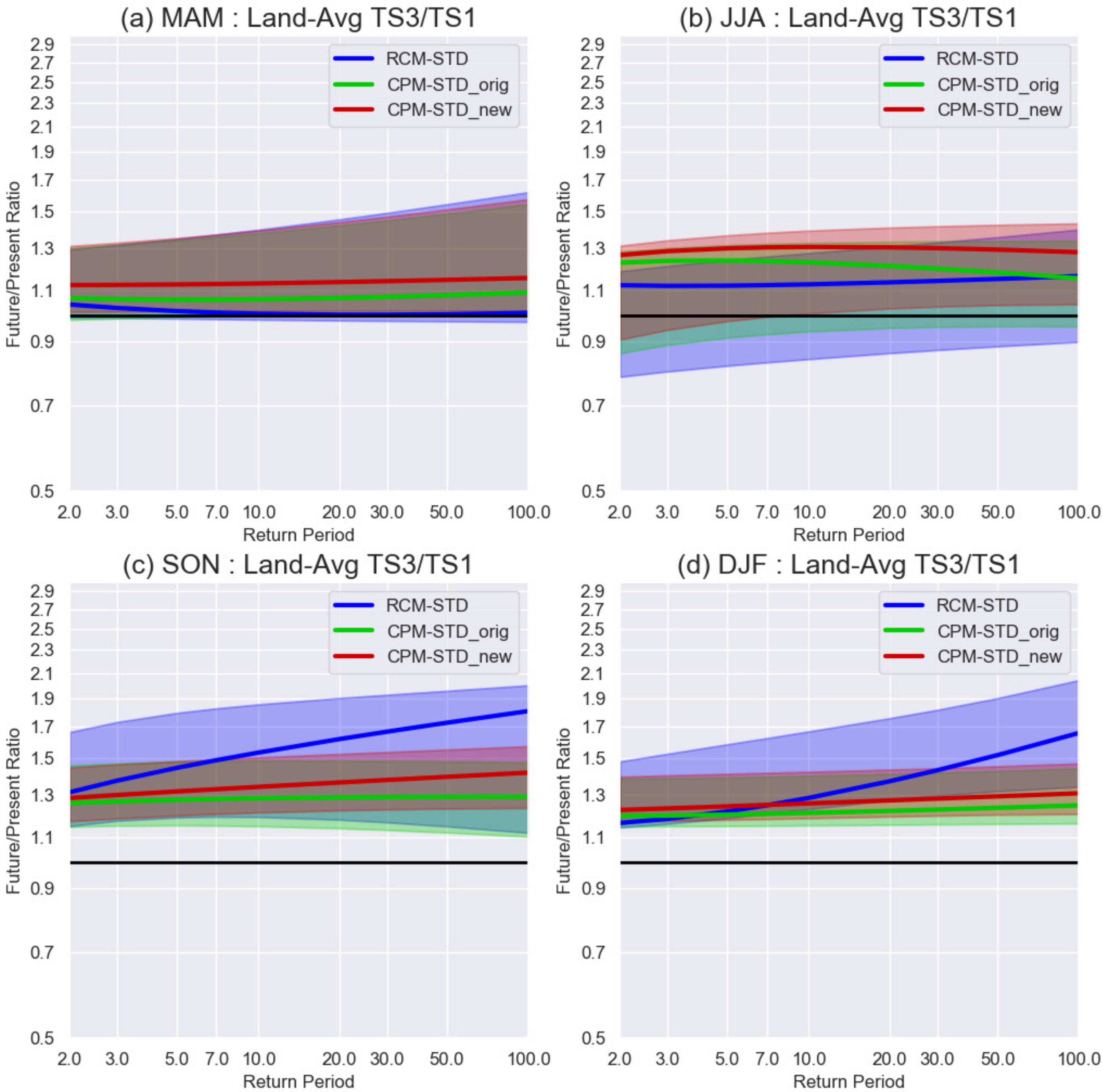

Figure 4.5.2. Future change in South UK return levels of daily maximum hourly precipitation as a function of return period, for individual seasons. Shown is the ratio of the return level for Time Slice 3 (TS3, 2061-2080) under RCP8.5 to that for the baseline period (TS1, 1981-2000) for CPM_new, CPM_orig and RCM. The South UK average return levels have been calculated using the regional frequency analysis method. The future changes for the standard member (STD) from each 12-member ensemble are shown (solid line), with the shaded region corresponding to the ensemble spread.

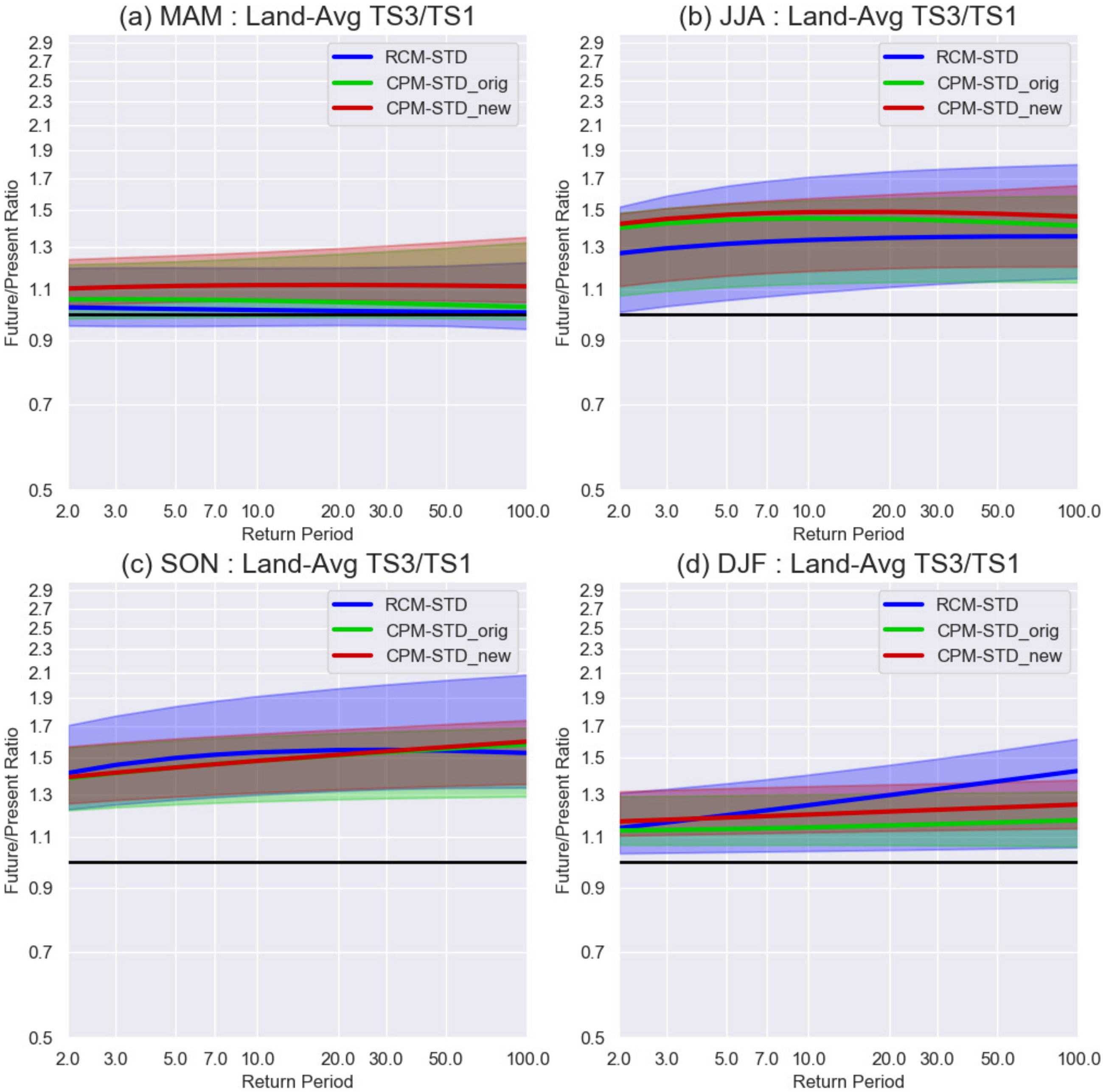

Figure 4.5.3. Future change in North West UK return levels of daily maximum hourly precipitation as a function of return period, for individual seasons. As Fig 4.5.2, but for NW region.

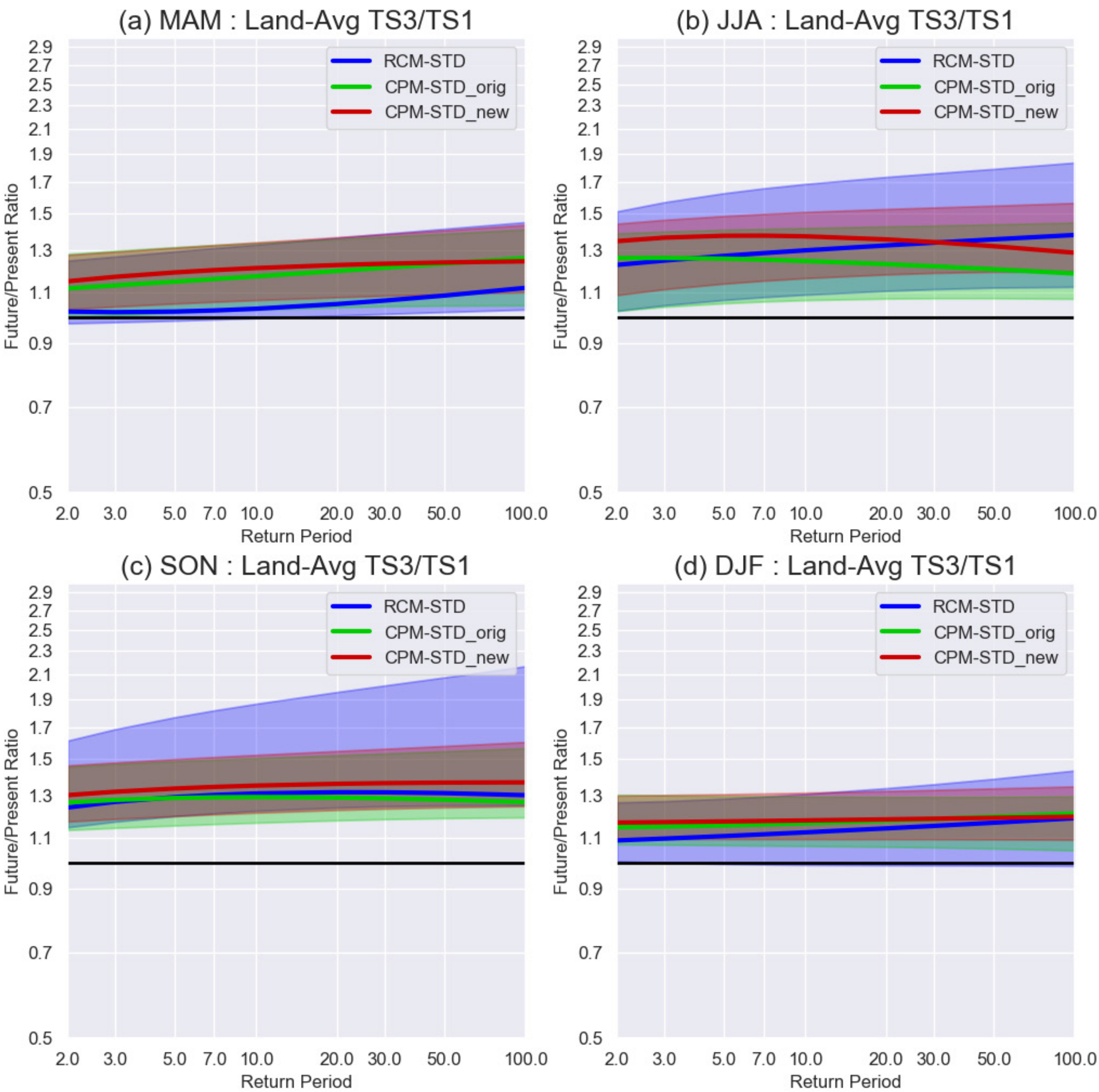

Figure 4.5.4. Future change in North East UK return levels of daily maximum hourly precipitation as a function of return period, for individual seasons. As Fig 4.5.2, but for NE region.

Hot and cold spells

Cold spells are projected to become less frequent in future in all models, as expected in a warming climate. CPM_new generally has larger future decreases in frequency than CPM_orig (Fig 4.5.5), but still has more cold spells in the future. This is because it simulates considerably more cold spells in the baseline period (Section 3.5). Over the northern UK on average, there are 0.33 intense cold events per year (less than -2°C for 2+ days) during 2061-2080 in CPM_new compared to 0.11 in CPM_orig, corresponding to a 3x difference.

Compared to the RCM, CPM_new has slightly larger future decreases in the frequency of cold spells (although differences are not significant at the 5% level, Fig 4.5.5). For intense cold spells, changes in CPM_new are closer to those in the RCM than those in CPM_orig, with CPM_orig showing notably smaller future decreases. This is likely due to the graupel code error and the fact that graupel is not included in the lying snow in CPM_orig.

Hot spells are projected to become more frequent in future in all models, consistent with increases in mean temperature and the intensity of hot days. As expected, the code changes in CPM_new have limited impact, with future increases in the number of hot spells being similar to those of CPM_orig (Fig 4.5.6). Future increases over the southern UK are larger in CPM_new compared to the RCM, and particularly so for the higher temperature thresholds. Future increases in hot spells will be driven by large-scale warming (seen by both models), but will also be influenced by other, regionally specific factors, such as changes in circulation or changes in soil moisture (see below).

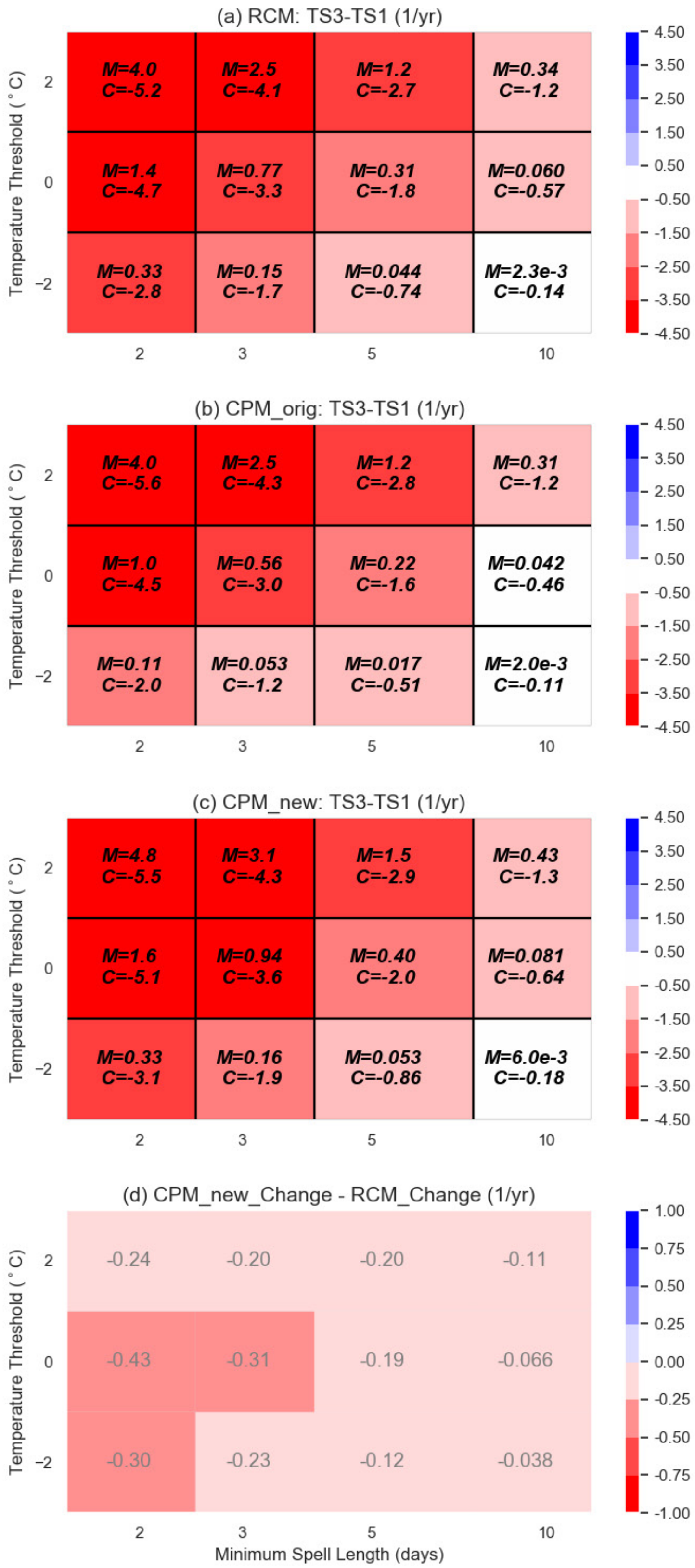

Figure 4.5.5. Future changes in the frequency of cold spells over the northern UK. Ensemble mean future changes in the frequency of cold spells over the northern UK for the (a) RCM, (b) CPM_orig and (c) CPM_new; and (d) CPM_new minus RCM difference in the future changes. TS1 refers to Time Slice 1 (1981-2000) and TS3 refers to Time Slice 3 (2061-2080) of the model simulations. Results are shown for cold spells defined using a range of daily mean surface temperature thresholds (-2°C, 0°C and +2°C) and minimum spell lengths (2, 3, 5, and 10 days). The northern UK region is as defined in Fig 3.5.5. The mean frequency (M) in the model for the future is quoted, along with future change (C). Differences that are significant compared to variability across the ensemble at the 5% level are indicated with a black border and bold black italic text.

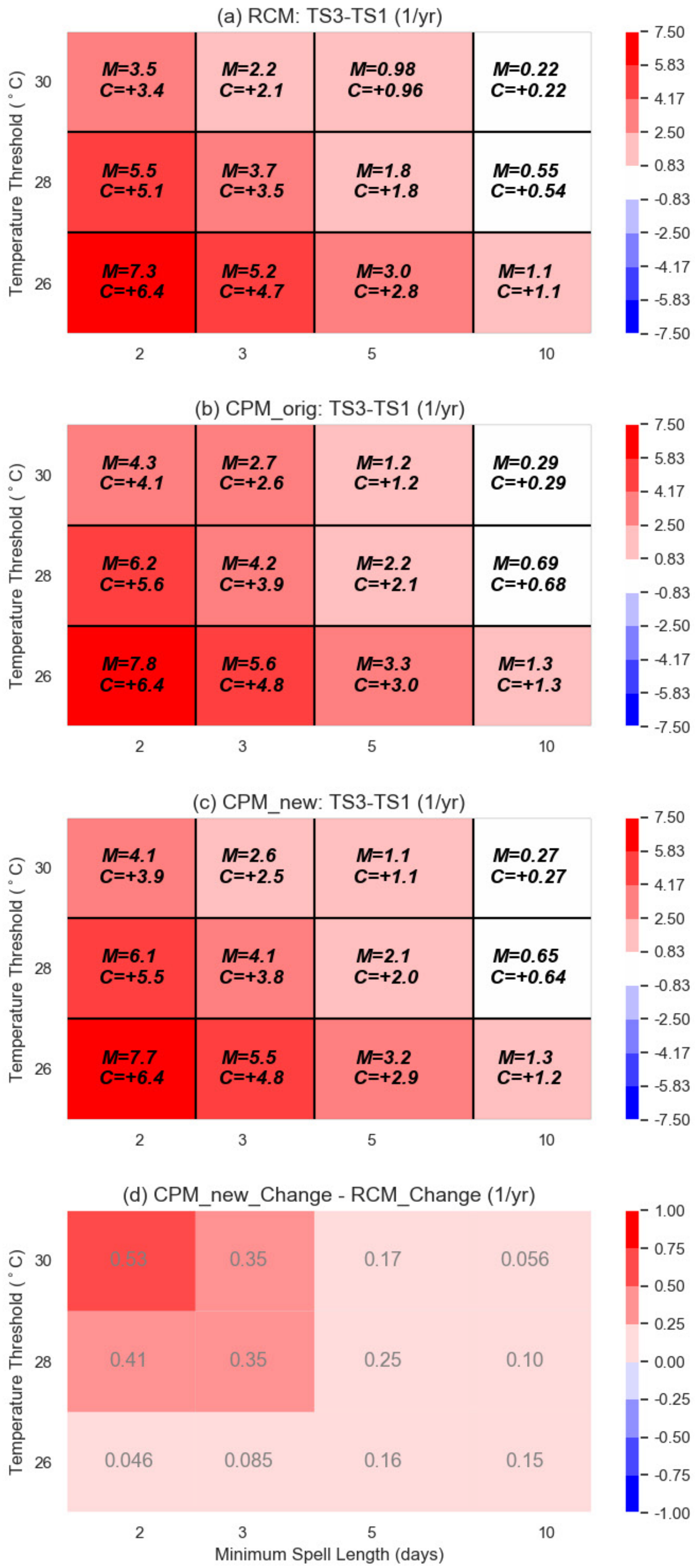

Figure 4.5.6. Future changes in the frequency of hot spells over the southern UK. As Fig. 4.5.5 but for hot spells over the southern UK defined using a range of daily maximum surface temperature thresholds (26°C, 28°C and 30°C) and minimum spell lengths (2, 3, 5, and 10 days). The southern UK region is as defined in Fig 3.5.5.

Soil moisture

In future there is a decrease in soil moisture during summer (Fig 4.5.7), consistent with the reduction in summer mean precipitation. This results in most members moving into a regime of restricted evapotranspiration over the southern UK in summer in the RCM, whereas the CPM ensemble is already in this regime in the baseline period. Evapotranspiration also becomes soil-moisture limited over the northern UK in summer in the CPM, but not in the RCM where it remains above the critical point in future. In general differences between CPM_new and CPM_orig are small, and thus key differences between the CPM and RCM in terms of soil moisture are unaffected by the rerun.

To what extent these differences in soil moisture drive greater increases in hot spells in the CPM than RCM (Fig 4.5.6) is not obvious. Over the S-UK, evaporation becomes limited in the future in the RCM in summer months, which would drive a positive feedback. In the CPM, evaporation becomes even more soil-moisture limited in summer and shifts into a limited regime earlier in spring, which could potentially lead to a greater positive feedback, although further analysis would be needed to confirm this.

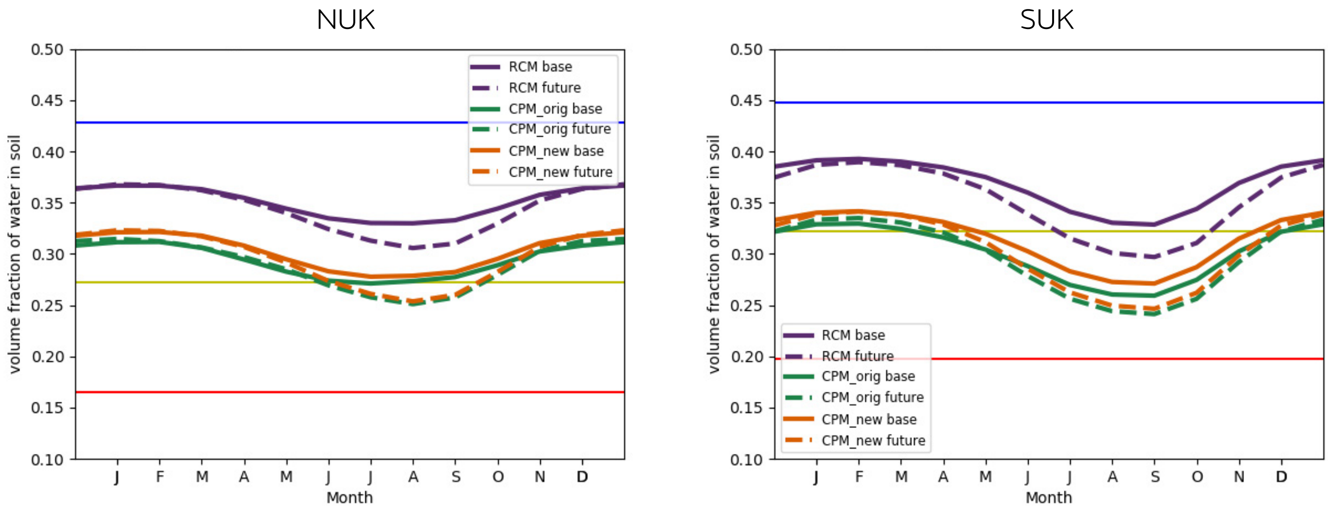

Figure 4.5.7. Future change in the annual cycle of soil moisture in the top 1m of soil. Ensemble-mean volume fraction of water in the soil (m^3/m^3) in the baseline (1981-2000) and future (2061-80) periods, in the (orange) CPM_new, (green) CPM_orig and (purple) RCM, for the (left) northern-UK and (right) southern-UK. The blue line indicates soil moisture saturation; yellow line the critical point below which evapotranspiration becomes soil-moisture limited; and red line the wilting point.

Snow

There is a decrease in falling snow in future winters, that is seen by all models. The decrease in falling snow is smaller in percentage terms in CPM_new compared to the RCM (Fig 4.5.8). This is consistent with there being a greater increase in precipitation in the CPM, some of which continues to fall as snow in future warmer winters. The decrease in falling snow is much smaller in CPM_orig, compared to both CPM_new and the RCM. This is likely explained by the majority of falling snow in CPM_orig being graupel (which falls faster than snow and thus is less prone to melting before reaching the ground), and thus is strongly impacted by the graupel code error.

In terms of lying snow cover, decreases are smaller in percentage terms in CPM_new compared to the RCM over Scotland, although similar elsewhere (Fig 4.5.9). This is consistent with smaller percentage decreases in falling snow in CPM_new, with snow still accumulating in the future over high ground in the northern UK. There are considerable differences between CPM_new and CPM_orig in terms of future changes in lying snow. The new science changes and fix to the graupel code error results in more lying snow in CPM_new compared to CPM_orig in the present-day (Section 3.5), and thus in absolute terms there is a greater reduction in lying snow in the future in CPM_new (since this approximately equates to its disappearance over much of the UK, with decreases in cover of almost 100%). Over Scotland, lying snow still persists into the future in winter (with decreases of less than 100%, Fig 4.5.9) and percentage decreases are actually smaller in CPM_new. Thus a greater proportion of the lying snow in winter in the present-day persists in the future in CPM_new compared to CPM_orig. This is likely to be due at least in part to the inclusion of the multi-layer snow scheme in the reruns.

We have greater confidence in the CPM_new projections in terms of both falling and lying snow compared to the RCM, since they can be linked to the improved representation of processes in the CPM. In particular, the improved representation of wintertime convective showers and their advection inland in the CPM appears to contribute differences in future changes in falling snow, and this in addition to the improved representation of the topography contributes to differences in future changes in lying snow over Scotland. Projections of snow from CPM_orig should not be used, since they are strongly impacted by the graupel code error.

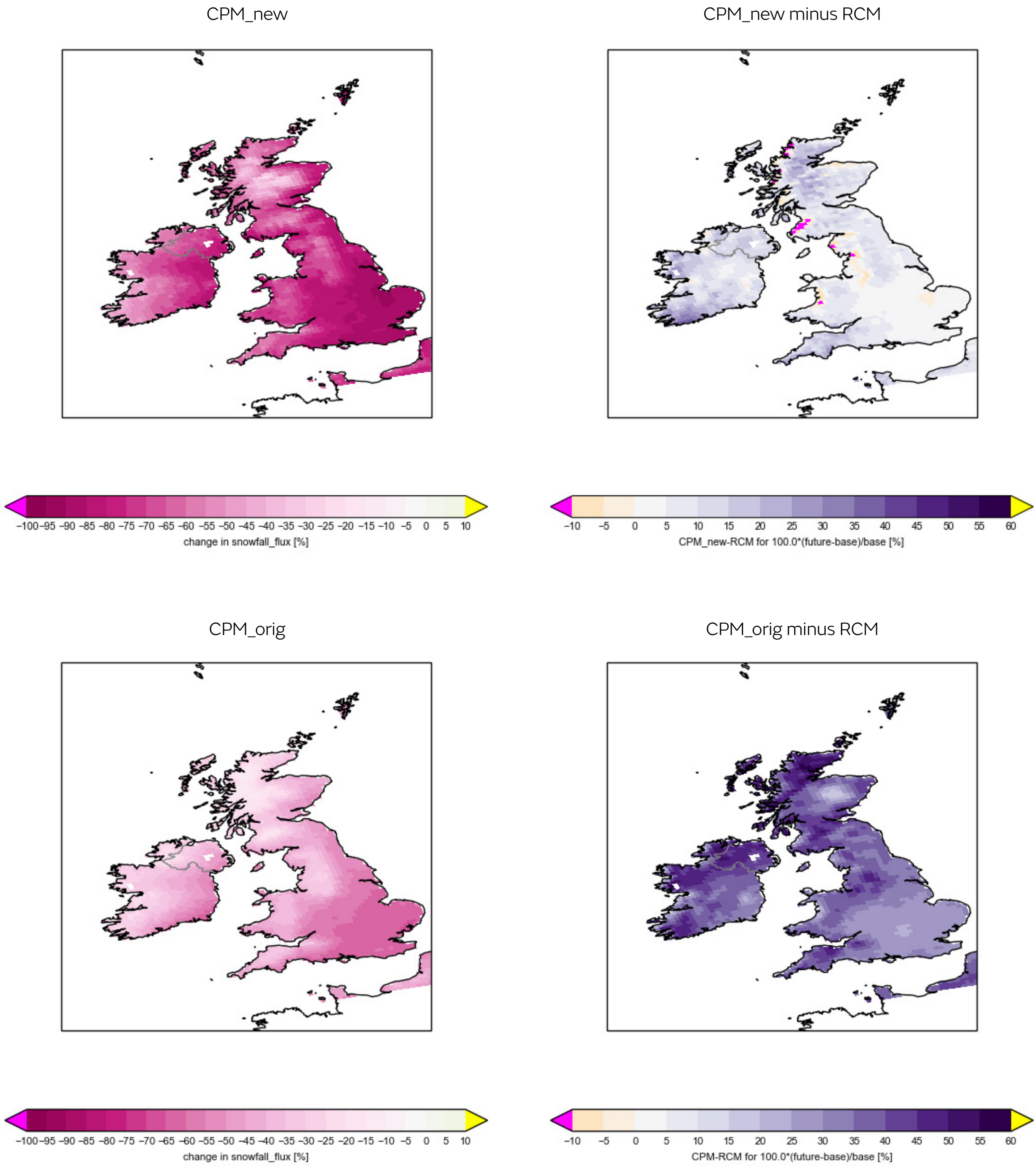

Figure 4.5.8. Future change in mean snow fall in winter. Future percentage change (%) in winter mean snowfall in (left) CPM ensemble mean and (right) CPM minus RCM difference, for (top) CPM_new and (bottom) CPM_orig The future change is the difference between 2061-80 and 1981-2000 periods.

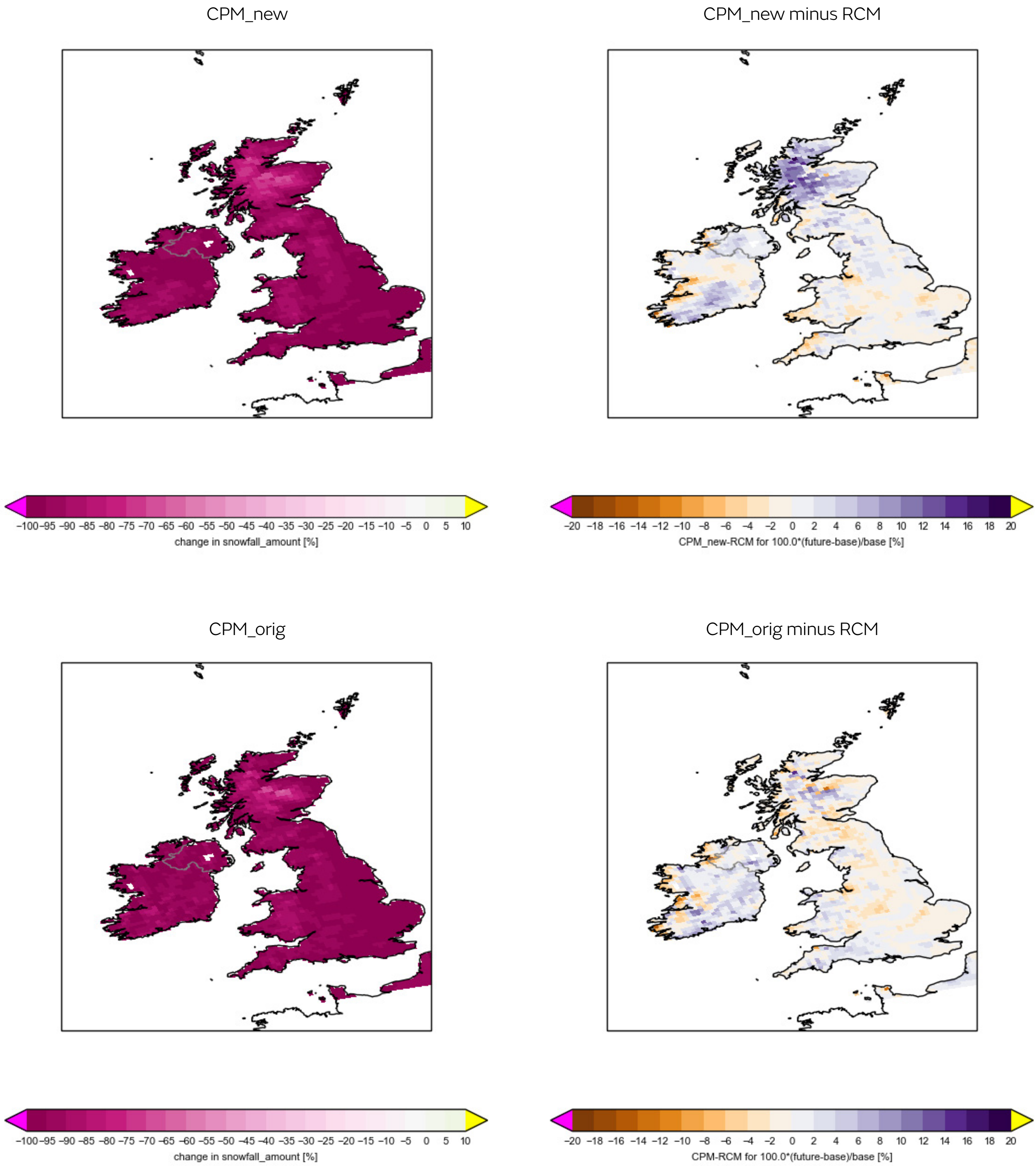

Figure 4.5.9. Future change in mean snow amount in winter. Future percentage change (%) in winter mean snow amount in (left) CPM ensemble mean and (right) CPM minus RCM difference, for (top) CPM_new and (bottom) CPM_orig The future change is the difference between 2061-80 and 1981-2000 periods.

Cloud

In winter, CPM_new shows future increases in cloud cover over the north and west UK and decreases over the south-east UK (Fig 4.5.10). By contrast, the RCM shows decreases everywhere, with a greater tendency for cloud to decrease over the south-east. These differences between CPM_new and the RCM are consistent with the greater increase in the number of wet days in winter in the CPM (Section 4.3). Furthermore, the spatial pattern of changes in cloud in CPM_new also follows the pattern of changes in wet day frequency, with underlying drivers of these changes likely to be changes in relative humidity and atmospheric stability, and circulation changes with warming. Cloud cover changes are similar between CPM_new and CPM_orig, with slightly greater decreases in the SE in CPM_new. However, these differences due to fixing the graupel code error in the 2.2km rerun are considerably less than the CPM-RCM cloud differences.

In summer, both CPM_new and the RCM show future decreases in cloud cover everywhere, with the largest decreases in the south (Fig 4.5.11). These decreases in cloud are consistent with the decreases in summer rainfall, seen in both models (Section 4.2). The decreases in cloud (absolute changes in a percentage cloud cover) are consistently smaller in CPM_new compared to the RCM. This appears to be inconsistent with the larger future decreases in the number of wet days in summer in the CPM (Section 4.3), but may simply reflect the fact that there is less cloud cover in the CPM in the present-day (Section 3.5). Again, the code changes in the 2.2km reruns have little impact on these future changes in the CPM. There is some evidence that cloud cover decreases in summer are slightly greater in CPM_new compared to CPM_orig, resulting in better agreement with the RCM.

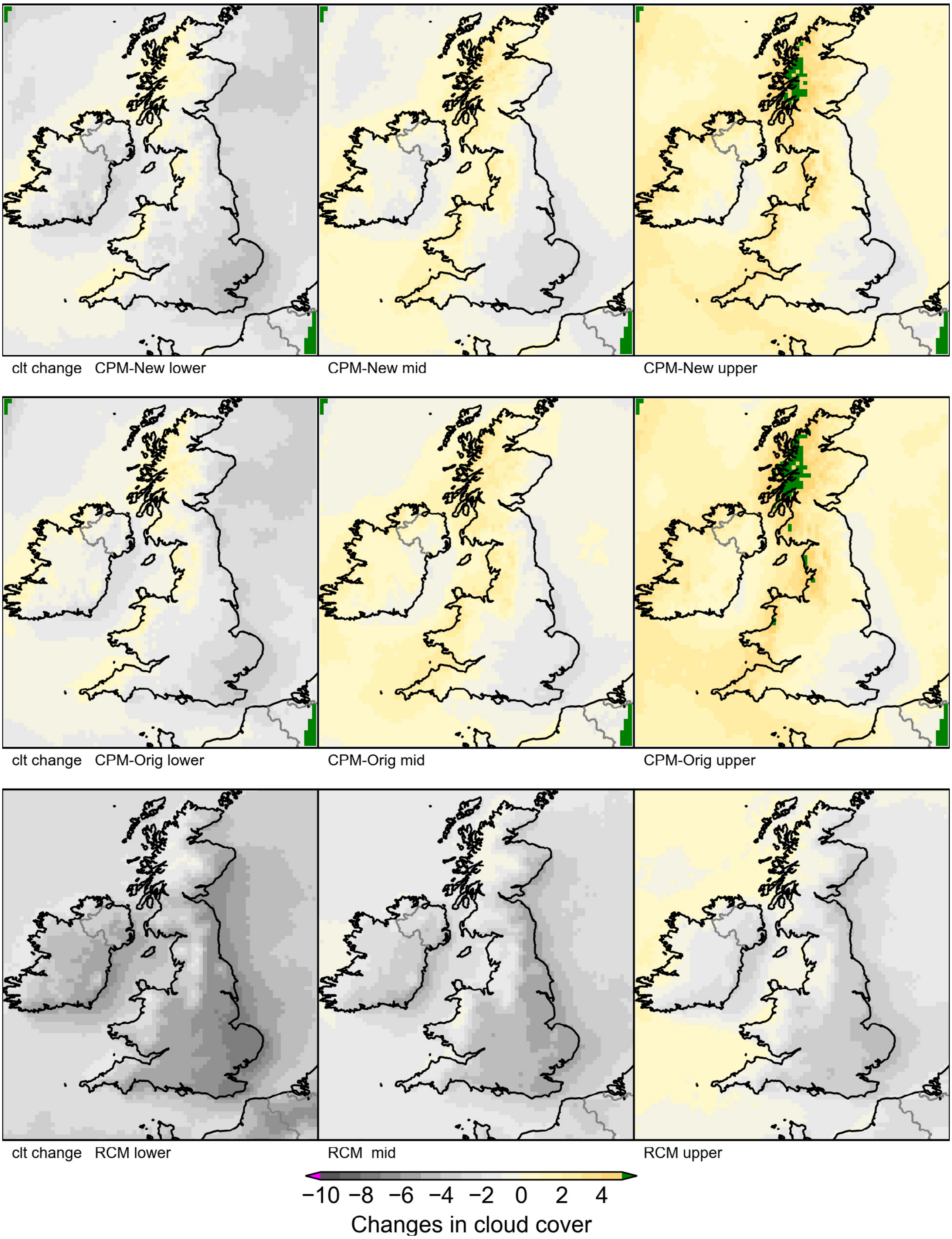

Figure 4.5.10. Future change in cloud cover in winter. Changes for (left) 2nd lowest, (centre) central and (right) 2nd highest member locally, for (top) CPM_new regridded to 12km RCM grid, (middle) CPM_orig regridded to 12km RCM grid and (bottom) RCM. Changes in cloud cover (absolute change in percentage cloud cover, %) correspond to the difference between the future (2061-2080) and baseline (1981-2000) periods.

Figure 4.5.11. Future change in cloud cover in summer. As Fig 4.5.10 but for summer.

Lightning

There a future increase in spatially averaged lightning frequency over the UK domain in summer and to a lesser extent in spring, little change in winter, and a decrease in autumn (Fig 3.5.19); although there is local variation in the sign of changes across the UK (Figs 4.5.12-4.5.15). In winter, future decreases in lightning are seen over the sea to the north and west of the UK, where high flash rates are seen in the present-day. This may be linked to the occurrence of deep low-pressure systems, which have been linked to strong lightning outbreaks in this season (Wilkinson and Neal, 2021). In summer there is a very different pattern of lightning, with a considerable future increase in lightning over the southern part of the domain. This is consistent with 'Spanish Plume' events, with warm and moist southerly flow being the predominant driver of thunderstorms in this season (Wilkinson and Neal, 2021). In autumn, future decreases in lightning are seen widely across the UK domain.

Most previous studies of the impacts of climate change on lightning have projected a future increase in flash rates, using simple parameterisations of lightning based on cloud heights and convective available potential energy (CAPE). For example, Boorman et al, (2010) found future increases in numbers of lightning days, in the RCM simulations carried out for UKCP09. However, these approaches neglect cloud ice fluxes that are fundamental to thunderstorm charging. Finney et al, (2018) projected a 15% decrease in flash rate globally when a parameterisation based on ice fluxes was used, although the simulated decreases over the UK are not significant. The UKCP Local (2.2km) model uses a similar ice-based lightning flash rate prediction scheme (McCaul et al, 2009) and results here suggest future increases in lightning across the UK in summer (consistent with Boorman et al, 2010), which are likely driven by deeper more intense storms. However, decreases in lightning are projected in autumn, despite increases in hourly precipitation extremes in this season (not shown), and can be explained by the role of ice fluxes in lightning generation (with cloud ice content decreasing in future).

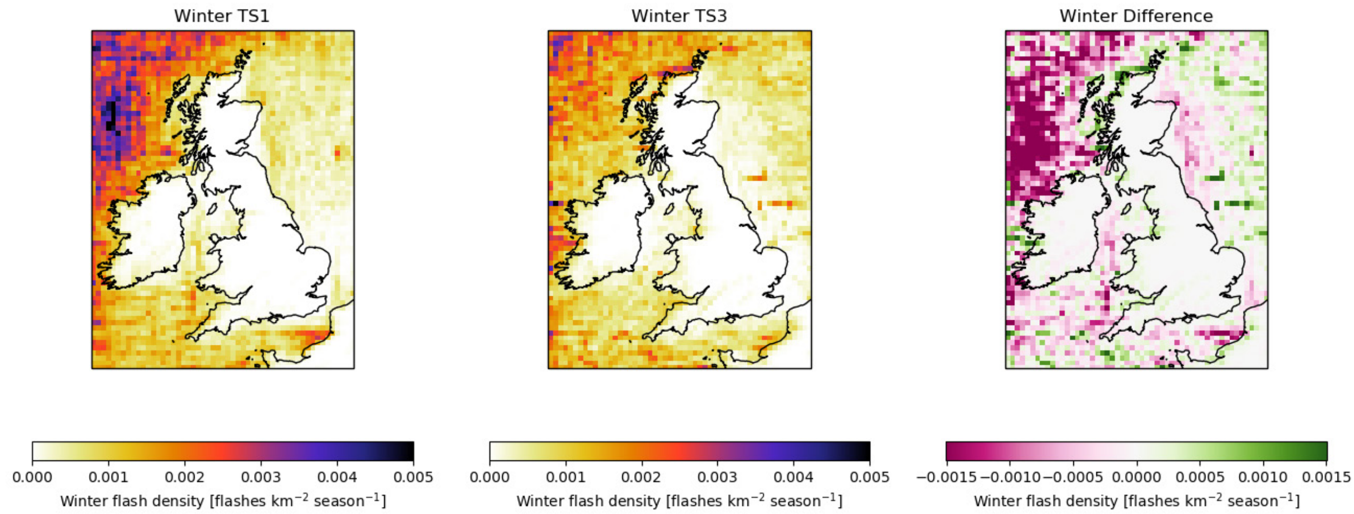

Figure 4.5.12. Lightning flashes in winter. Ensemble-average flashes per km^2 in CPM_new, for present-day (timeslice 1, TS1, left), future (timeslice 3, TS3, centre) and the difference (right) for winter. The data has been averaged over 8x8 boxes to improve the signal to noise.

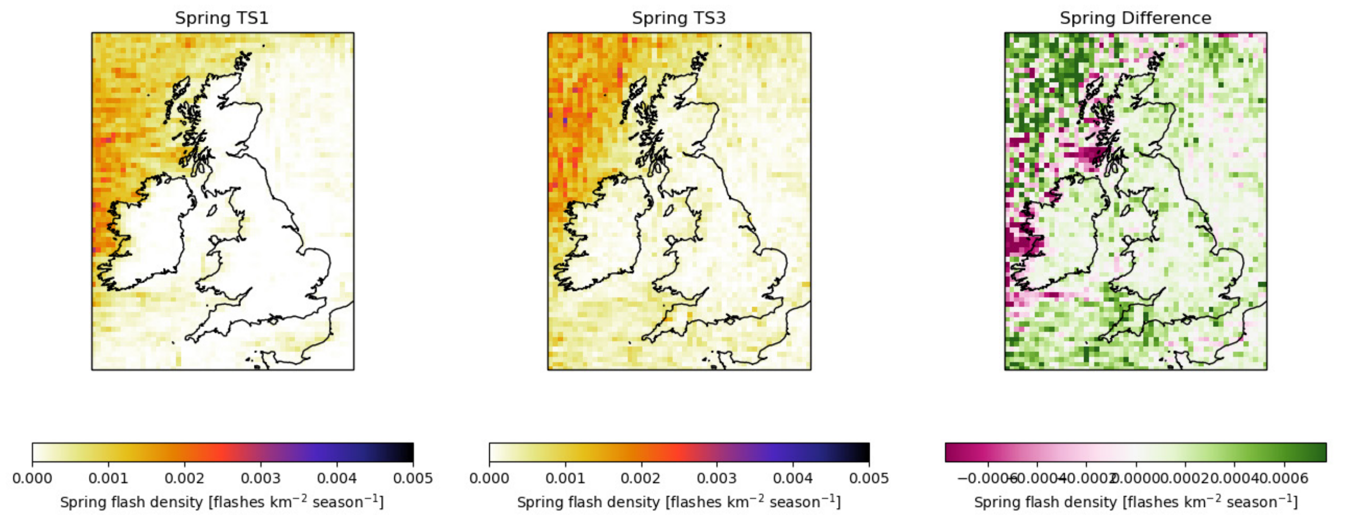

Figure 4.5.13. Lightning flashes in spring. As Fig 4.5.12 but for spring.

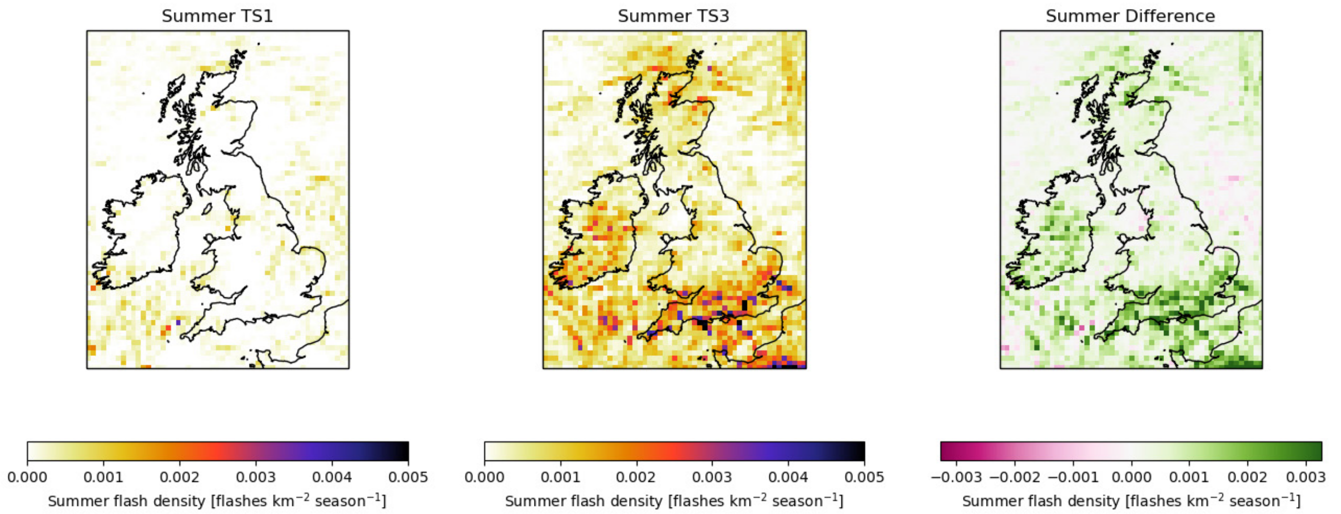

Figure 4.5.14. Lightning flashes in summer. As Fig 4.5.12 but for summer.

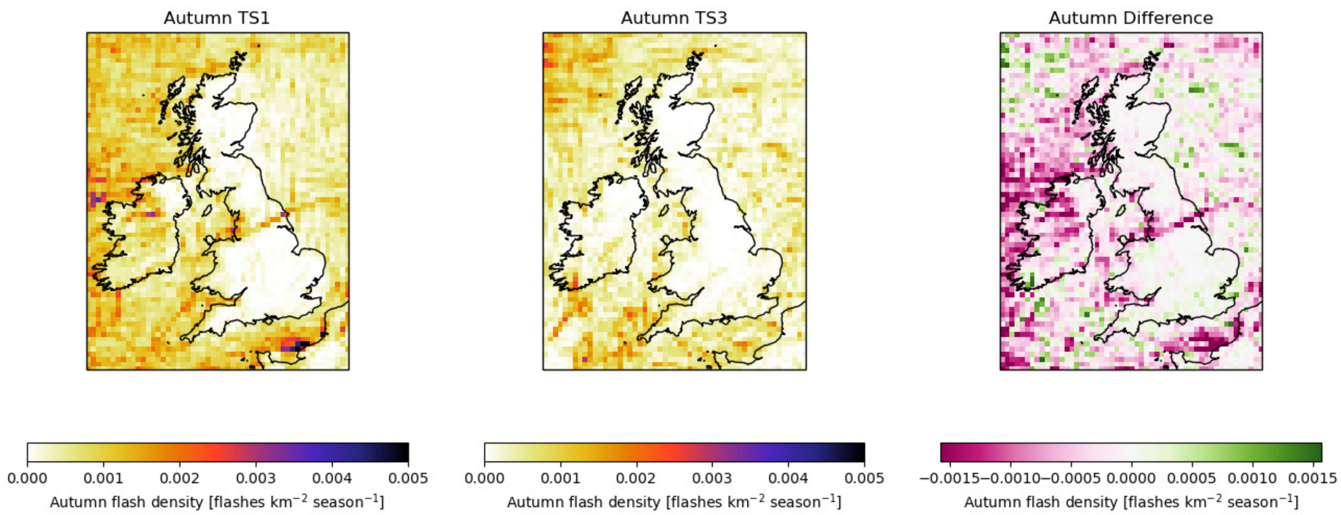

Figure 4.5.15. Lightning flashes in autumn. As Fig 4.5.12 but for autumn.

Surface winds

CPM_new shows a future increase in surface winds over western parts of the UK and over the ocean in winter (Fig 4.5.16). Future changes in the RCM are similar over the ocean, but CPM_new shows a greater tendency for decreasing wind speed over the south and east of the UK. Code changes in the 2.2km reruns lead to greater increases in wind speeds over the sea to the north of the UK and also over most land regions, except the Scottish mountains. Local differences in future changes in mean daily maximum wind speeds between CPM_new and CPM_orig can be up to 0.2 m/s, over the Cairngorms and over the sea to the NW of the UK, where they are significant compared to the spread across the CPM_orig ensemble (standard deviation of <0.12 m/s over land and <0.2 m/s over Scottish coastal waters, Kendon et al, 2020b).

In summer, there is a widespread decrease in wind speeds, with future decreases over the land greater in CPM_new compared to the RCM (Fig 4.5.17). Differences between CPM_new and CPM_orig are small (<0.1m/s everywhere for mean daily max wind speeds), with no significant impact of the rerun on CPM-RCM differences.

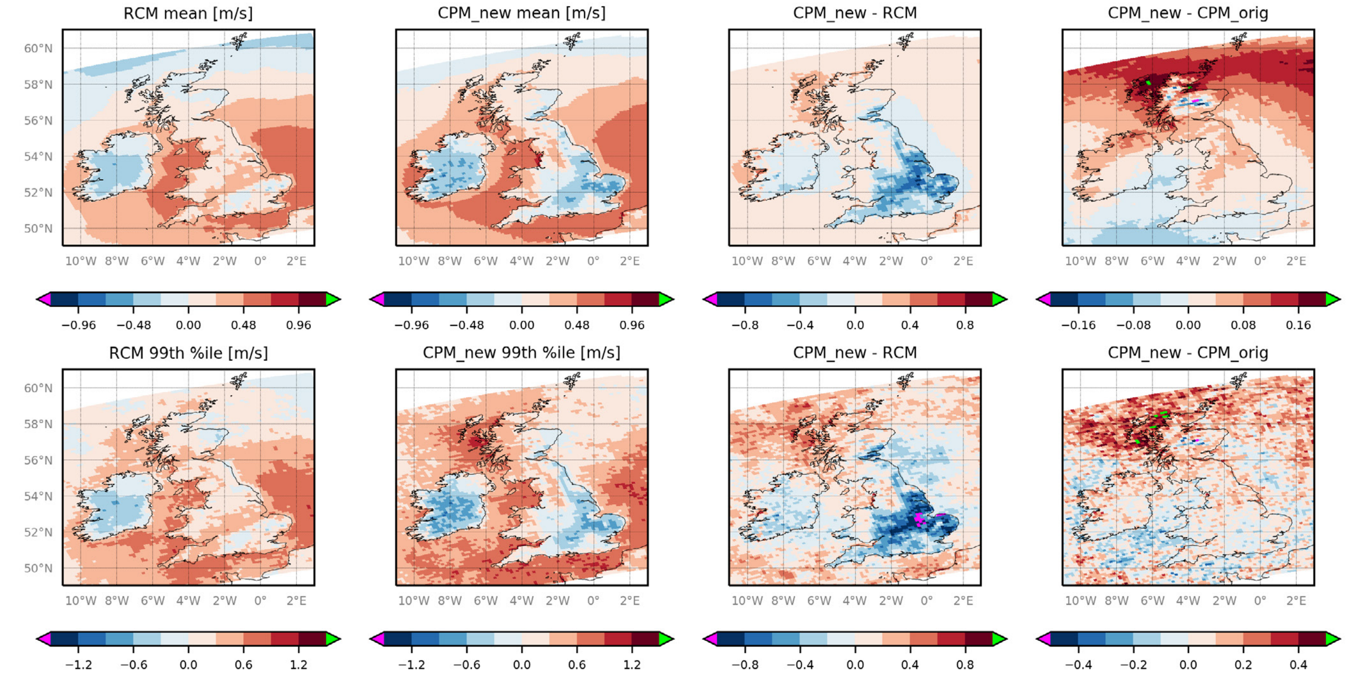

Figure 4.5.16. Future change (m/s) in surface winds in winter. Changes for (top) mean and (bottom) 99th percentile of daily maximum wind speeds for (left) RCM and (centre left) CPM_new ensemble means. Also shown are differences between changes for (centre right) CPM_new minus RCM and (right) CPM_new minus CPM_orig, for data regridded to 12km RCM grid. Future changes correspond to the difference between the future (2061-2080) and baseline (1981-2000) periods.

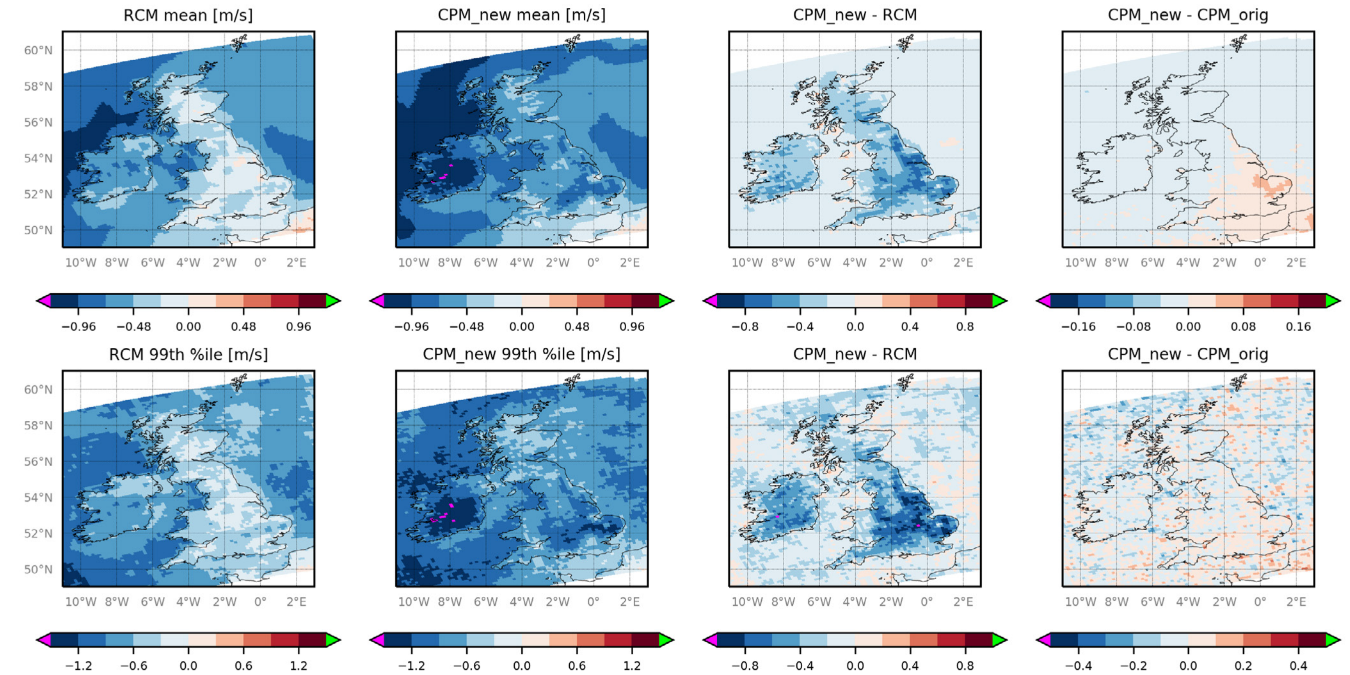

Figure 4.5.17. Future change (m/s) in surface winds in summer. As Fig 4.5.16 but for summer.

4.6 Summary of future changes

We have presented projected changes for the UK, for 2061-2080 compared to 1981-2000 under high emission scenario RCP8.5. We have mainly examined changes in temperature and precipitation, comparing projections from the Local (2.2km) reruns (CPM_new) with the original UKCP Local (2.2km) projections (CPM_orig) and the driving 12km RCM. We have also shown results for selected high-impact events, including hourly precipitation extremes, hot and cold spells, snow, lightning and surface winds, as well as related changes in soil moisture and cloud.

Mean temperature increases everywhere and in all seasons. The UK-average central estimate of temperature change is 3.3°C in winter and 4.6°C in summer in the new 2.2km reruns (Section 4.2), with the greatest increases occurring in the south. For hot summer days, the UK-average central estimate is a 6.0°C increase (Section 4.3). Precipitation increases in winter (UK-average central estimate of +26%) and decreases (-29%) in summer (Section 4.2), with the possible exception of northern Scotland where the uncertainty range spans decreases in winter and increases in summer in some parts. The intensity of heavy precipitation on hourly timescales increases in both seasons (+23% in winter and +18% in summer for the 99.95^{th} percentile, Section 4.4), with larger increases in hourly precipitation extremes (2-year return level shows a 29% increase in the 2.2km reruns, Section 4.5). Soil moisture decreases in summer, consistent with the reduction in summer mean precipitation, resulting in evapotranspiration being soil moisture limited in the northern and southern UK in future summers. Lying snow disappears almost entirely over low-elevation regions. There is also evidence of future increases in lightning in summer and spring and decreases in lightning in autumn in the new 2.2km reruns. The latter is not inconsistent with an increase in short-duration precipitation extremes due to the role of ice fluxes in lightning generation. Surface wind speeds increase over western parts of the UK and over the ocean in winter, and decrease across the UK in summer.

In general results here looking at the impact of the CPM rerun model changes (including the fix to the graupel code error and other science improvements) in all 12 ensemble members confirm results found in earlier single member tests (reported in Kendon et al, 2020b). The greatest impacts are on future changes in snow and temperature in winter, but there are also notable impacts on convective extremes including future changes in hourly precipitation extremes and lightning. The key differences compared to the original UKCP Local (2.2km) projections are:

1. There are significantly larger future increases in the temperature of cold winter days (+5.3°C compared to +3.8°C in CPM_orig) and larger decreases in the frequency of cold spells in the northern UK, although future changes in winter mean temperature are only slightly greater in CPM_new (+3.3°C compared to +3.1°C in CPM_orig). These differences are consistent with more lying snow in the present-day in CPM_new.

2. CPM_new has greater increases in hourly precipitation extremes (UK-average central estimate shows increase in 2-year return level of 29% compared to 25% in CPM_orig). These differences are likely related to the fix to the graupel code error, since graupel is mainly found in convective storms.

3. CPM_new shows considerably greater decreases in falling snow and lying snow compared to CPM_orig, consistent with the majority of falling snow being graupel and not being included in the snowpack in the original runs.

Future changes in summer temperature (mean and extremes) and summer mean precipitation are not significantly impacted by the 2.2km rerun code changes. For winter mean precipitation, despite differences in present-day biases, future increases are also not significantly impacted by the rerun. Again, this is consistent with results from the single member test (Kendon et al, 2020b). Key differences between the CPM and RCM in terms of future changes in precipitation on daily timescales, both in summer and winter, are unaffected by the rerun. For future changes in surface winds, significant impacts of the rerun changes are confined to localised regions over the Scottish mountains and off the coast of NW Scotland.

Changes in CPM_new are broadly consistent with the RCM, with the following key exceptions:

1. CPM_new shows considerably greater increases in winter precipitation than the RCM (UK-average central estimate of 26% increase in CPM_new compared to 16% in the RCM). This is due to a greater increase in occurrence of wintertime precipitation over the UK (seen on both the daily and hourly timescale), linked to the improved representation of convective showers and their advection inland in the CPM. There are also slightly greater increases in heavy daily events in winter (23% increase in CPM_new and 20% in RCM).

2. CPM_new shows slightly greater decreases in summer mean precipitation (UK-average central estimate of -29% compared to -26% in the RCM) and very different underlying changes in the frequency and intensity of precipitation in summer. On daily timescales, there are considerably greater decreases summer precipitation occurrence (-33% compared to -25% in the RCM) and increases in summer precipitation intensity (+5% compared to -3% in the RCM) in CPM_new. Similarly on hourly timescales, there are greater decreases in summer precipitation occurrence (-34% compared to -28% in the RCM) and greater increases in intensity (+8% compared to +2% in the RCM).

3. CPM_new shows different future changes in hourly precipitation extremes. Similar future increases are seen for the 2-year return level of annual extremes of hourly precipitation (29% and 31% increase respectively) but for rarer extremes, the RCM shows greater future increases, likely due to unphysical "grid point storms".

4. CPM_new projects larger future increases in the frequency of hot spells over the southern UK, which may reflect drier soils in the CPM.

5. Decreases in falling and lying snow are smaller in percentage terms in CPM_new compared to the RCM over Scotland. This is consistent with mean winter precipitation response differences, but the improved representation of topography in the CPM may also contribute. In particular, this may explain the greater persistence of lying snow in winter into the future over high ground in CPM_new.

6. For cloud, CPM_new shows increases in cloud cover in winter over the north and west UK, whilst the RCM shows decreases everywhere. Decreases in cloud (absolute changes in a percentage cloud cover) are consistently smaller in CPM_new compared to the RCM in summer. Factors driving these differences are likely to be the use of different cloud schemes in the two models and the greater increases in the number of wet days in winter found in CPM_new.

7. For surface winds, CPM_new shows a greater tendency for decreasing wind speed over the south and east of the UK.

Differences in precipitation projections between CPM_new and the RCM are largely attributable to the improved representation of convection in the CPM, including the advection and further triggering of showers in winter (Kendon et al, 2020a) and local dynamical feedbacks in storms which can amplify future increases in rainfall intensity in summer (Kendon et al, 2019). The improved representation of wintertime convective showers also contributes to differences in future changes in falling snow and potentially cloud cover, whilst the better resolution of topography likely also impacts future changes in lying snow. The different nature of rainfall in the CPM, which is more intense and intermittent, impacts soil moisture conditions that can in turn impact summertime daily temperature extremes and hot spells. Thus, for the majority of differences summarised above, we have greater confidence in the projections from CPM_new since these can largely be traced to an improved representation of processes compared to the RCM (see Section 5).

The summaries above of future changes in CPM_new compared to CPM_orig and the RCM, along with our assessment of the reliability of future projections, are consolidated in Table 5.1.

5. Advice on use of data

In this section we provide advice on use of the new 2.2km reruns compared to the original UKCP Local (2.2km) projections, and also compared to the Regional (12km) projections. This is based on our understanding of the representation of underlying processes (from differences in model physics, Section 2) and draws on the assessment of present-day model performance (Section 3). We also consider use of the new 2.2km reruns in the context of wider UKCP18 information. This has implications for deciding which UKCP18 data products may be most appropriate to use for a given application.

Table 5.1 summarises the extent to which code changes in the 2.2km rerun (CPM_new) have impacted present-day biases or future changes for various metrics considered here. It also examines whether present-day biases are reduced in CPM_new compared to the RCM, whether future changes are different between the models, and our assessment of the relative reliability of the future changes given our understanding of the key processes responsible for any differences. In this we are primarily considering differences in the central estimates of future change. However, although the central estimates may be similar, the different models may provide somewhat different estimates of the uncertainty in future changes. Later in this section we compare the sampling of uncertainty across the different UKCP18 products, for some key variables, and discuss this in the context of user requirements.

Phenomenon	1. Significant impact of code changes in rerun?	2. CPM_new improved present-day biases compared to RCM?	3. CPM_new different future changes compared to RCM?	4. Comment on reliability for projecting future change
Temperature				
Winter mean temperature	~ CPM_new colder in present-day, with slightly greater future increases.	~ Similar biases in CPM_new and RCM	~ Similar future increases	CPM_new and RCM projections equally plausible. CPM_new more reliable than CPM_orig especially over northern Scotland.
Summer mean temperature	**No**	~ CPM_new is warmer than RCM, but similar UK-mean biases	~ Similar future increases	CPM_new and RCM projections equally plausible.
Cold winter days	**Yes** – CPM_new significantly colder in present-day, with considerably larger future increases	**Yes** – cold winter days in the north are too cold in the RCM, with reduced biases in CPM_new	~ Similar future increases in temperature	CPM_new and RCM projections both plausible, although improved representation of topography in CPM may have influence on local projections over mountains. CPM_orig should not be used.
Hot summer days	**No**	~ Slightly reduced biases in CPM_new	~ Similar future increases	CPM_new and RCM projections equally plausible.
Cold spells over north UK	**Yes** – more cold spells in CPM_new in present-day, and larger future decreases in the frequency of cold spells	**No** – CPM_new has too many cold spells	~ Similar future decreases in frequency	CPM_new and RCM projections equally plausible. CPM_orig should not be used.
Hot spells over south UK	**No**	~ Slightly reduced biases in CPM_new	+ Larger future increases in frequency	CPM_new and RCM projections both plausible. Some improvement in biases in CPM_new possibly related to drier soils in CPM.

Phenomenon	1. Significant impact of code changes in rerun?	2. CPM_new improved present-day biases compared to RCM?	3. CPM_new different future changes compared to RCM?	4. Comment on reliability for projecting future change
Precipitation				
Winter mean precipitation	**Yes** – CPM_new significantly wetter over mountains in present-day. Little impact on future changes.	**Yes** – reduced biases in CPM_new	+ Substantially greater increase in CPM_new compared to RCM	CPM_new most reliable, with considerably reduced biases compared to RCM and better representation of wintertime convective showers
Summer mean precipitation	**No**	**Yes** – reduced biases in CPM_new	~ Slightly greater decrease in CPM_new compared to RCM	CPM_new most reliable, with considerably reduced biases compared to RCM and better representation of convection
Heavy daily precipitation events in winter	~ CPM_new wetter in present-day. Little impact on future changes.	**Yes** – considerably reduced biases in daily variability in CPM_new	~ Increases slightly greater in CPM_new compared to RCM	CPM_new most reliable, with considerably reduced biases compared to RCM and better representation of wintertime convective showers
Heavy daily precipitation events in summer	~ CPM_new has reduced summer precipitation intensity in present-day, and future decreases in heavy daily precipitation are slightly larger	**Yes** – considerably reduced biases in daily variability in CPM_new	+ Greater tendency for increase in summer precipitation intensity in CPM_new compared to RCM	CPM_new most reliable, with considerably reduced biases compared to RCM and better representation of convection.
Hourly precipitation variability (all seasons)	~ CPM_new has reduced precipitation intensity especially in summer in present-day, and tendency for slightly greater future increases in summer hourly precipitation intensity	**Yes** – considerably reduced biases in CPM_new	+ Significant increase in hourly precipitation occurance in winter in CPM_new not seen in the RCM + Greater increase in summer rainfall intensity in CPM_new	CPM_new most reliable, with considerably reduced biases compared to RCM and better representation of convective processes.
Hourly precipitation extremes (all seasons)	**Yes** – hourly extremes significantly reduced in CPM_new in present-day, and future increases are greater	**Yes** – CPM_new better represents the rate at which extremes increase with increasing rarity	- Similar increases in 2-year return level, but smaller increases for 10-year (and longer) return levels for some regions/seasons	Use CPM_new only. RCM projections of hourly precipitation extremes considered unreliable. CPM_orig should not be used.

Phenomenon	1. Significant impact of code changes in rerun?	2. CPM_new improved present-day biases compared to RCM?	3. CPM_new different future changes compared to RCM?	4. Comment on reliability for projecting future change
Other				
Soil moisture	~ Soil moisture slightly higher in CPM_new in present-day and future climate	**Yes** – soils are drier in CPM_new for most members	~ Similar decreases in soil moisture in summer, with soils remaining drier in CPM_new	CPM_new most plausible, due to improved present-day biases related to more realistic hourly and daily precipitation variability
Falling snow	**Yes** – less days of falling snow in CPM_new in present-day, and greater future decrease in falling snow	~ Similar UK biases, but more realistic snowfall over NW Scotland in CPM_new	- Smaller percentage decrease in falling snow in CPM_new	CPM_new most plausible due to improved representation of wintertime convective showers compared to RCM. CPM_orig should not be used.
Lying snow	**Yes** – more days of lying snow in CPM_new in present-day, and greater future decrease in lying snow in absolute terms	~ Similar biases, but more lying snow over high ground in Scotland	- Smaller percentage decrease in lying snow in CPM_new	CPM_new most plausible due to improved representation of wintertime convective showers and better representation of mountains over Scotland compared to RCM. CPM_orig should not be used.
Cloud	**No** – slightly more cloud in winter in CPM_new in present-day. Little impact on future changes	**Yes** – reduced cloud cover biases in winter, and reduced shortwave and longwave surface radiation biases in summer and winter in CPM_new	- Smaller decreases in cloud cover (or greater tendency for increases in winter) in CPM_new	CPM_new and RCM projections both plausible. Greater tendency for cloud increases in winter in CPM_new may reflect improved representation of wintertime convective showers.
Lightning	**Yes** – unrealistic features no longer seen in CPM_new	Lightning output not available for RCM	Lightning output not available for RCM	Use CPM_new only.
Surface winds	**Yes** locally – stronger winds in CPM_new in present-day over the ocean, western Ireland and the Cairngorms. Significant impacts on future changes confined to isolated regions.	Not possible to assess.	+ Greater future decreases in wind speed over south-east UK in winter and across UK in summer in CPM_new	CPM_new and RCM projections equally plausible, although added value of CPM over mountains. CPM_orig should not be used for projections over the Scottish mountains and over the sea to the NW of the UK.

Table 5.1. Summary of present-day biases and future changes in CPM_new compared to the RCM, whether these have changed significantly from the original 2.2km CPM runs, and the implications for the reliability of future projections. (1) Significant impact of rerun, with red indicating '**yes**', grey '**no**,' and purple '~' indicating impact but significance not assessed (differences are judged significant if they are greater than the standard deviation across the CPM ensemble); (2) Improved present-day biases in CPM_new compared to RCM, with green indicating '**yes**', red '**no**' and grey '~' similar biases; (3) Future changes in CPM_new compared to RCM, with orange '**+**' indicating greater and blue '**-**' smaller magnitude of change in CPM_new, and grey '~' similar changes; and (4) Comment on reliability of future projections.

5.1 Use of new 2.2km reruns compared to original data

The new UKCP 2.2km data (CPM_new) should be the preferred dataset for all new users of the Local 2.2km projections. The model physics has been improved, and key known code errors in the original 2.2km model have been fixed. Thus, even for those variables where no significant impact of the rerun has been identified (summer temperature including extremes, summer mean precipitation, and cloud, Table 5.1), we advise using the new 2.2km data for new assessments.

For existing users of the original UKCP Local (2.2km) projections, in many cases the analysis will be unaffected by the changes implemented in the new reruns, and the original data can still be used. However, there are applications where the original data should be used with caution or not at all. Below we outline the use and decision cases where the original data are still appropriate for use and where we would recommend using the new data.

The original UKCP Local (2.2km) projections should not be used for the following variables:

- Cold winter days
- Frequency of cold spells
- Hourly precipitation extremes (all seasons)
- Falling snow
- Lying snow
- Lightning
- Surface winds over the Scottish mountains and over the sea to the NW of the UK

For these variables, the code changes implemented in the reruns significantly impact both present-day values and future changes (Table 5.1). Thus, if users require local scale information (high spatial resolution or local projections over mountains) on cold winter temperatures or surface winds, they should use the new 2.2km rerun data. For these variables more generally, the 12km Regional projections provide an alternative source of data (see Section 5.2). For falling snow and lying snow, we would recommend using the new 2.2km rerun data in preference to the 12km Regional projections (Section 5.2). For hourly precipitation extremes and lightning, users should use the new 2.2km rerun data only.

The original UKCP Local (2.2km) projections should be used with caution for the following variables:

- Winter mean temperature
- Winter mean precipitation
- Heavy daily precipitation events (all seasons)
- Summer hourly precipitation intensity

For winter mean temperature, the original 2.2km data may overestimate present-day temperatures particularly over northern Scotland and underestimate future increases. For winter mean precipitation and heavy daily precipitation events in winter, the original 2.2km data may underestimate present-day values but future changes are not significantly impacted by the rerun. For heavy daily precipitation events and hourly precipitation intensity in summer, the original 2.2km data may overestimate present-day values but any impact of the rerun on future changes is small. For these variables, the new 2.2km reruns provide the most reliable projections and should be used for any new assessments, but we do not anticipate that decisions made using the original 2.2km projections will be strongly impacted by the rerun. For the precipitation metrics above, we would also recommend use of the new 2.2km rerun data in preference to the 12km Regional projections, although the less comprehensive sampling of uncertainty by the 2.2km projections is a consideration (e.g. the sampling of uncertainty in soil moisture parameters in the 12km Regional projections may be important in some cases).

We emphasize that the UKCP Probabilistic, Global (60km) and Regional (12km) projections are unaffected by the 2.2km rerun, with no change to their use guidance. Furthermore, we continue to recommend that UKCP products are used together, rather than in isolation, in order to give the most complete picture of future climate.

5.2 Use of new 2.2km reruns compared to 12km RCM projections

For temperature, both for seasonal means and daily variability, there is no evidence to suggest that the CPM_new projections are more or less plausible than those from the RCM (Table 5.1). In some cases there are differences in the projections between the models locally, most notably for future changes in hot spells over the southern UK. In this case, these differences may relate to drier soils in the CPM. We also anticipate some local differences over mountains and coastlines, where the improved representation of complex topography in the 2.2km model may be important for some users. Also, over cities, CPM_new is expected to better represent changes due to the higher spatial resolution and the use of the more sophisticated urban scheme (MORUSES, Section 2). A further consideration is the relative sampling of uncertainty, with the RCM providing a slightly broader uncertainty range (although still limited compared to Strands 1 and 2[3], see Section 5.3) than CPM_new. In particular the 12-member RCM ensemble samples parameter uncertainty in the regional model and uncertainty in the large-scale driving conditions, whilst the CPM ensemble samples local conditions given uncertainty in the large-scale driving conditions only (with no parameter perturbations applied to the CPM itself).

For precipitation, there is more evidence of added value from CPM_new (Table 5.1). In winter, mean precipitation changes are different between CPM_new and the RCM. These differences mainly arise from wet day frequency changes and are largely attributable to the improved representation of wintertime convective showers and their advection inland in the CPM (Kendon et al, 2020a). Since CPM_new has considerably reduced biases in wet day frequency in the present-day, and better represents convective processes which are playing a key role in future changes, we have greater confidence in the CPM_new projections. Although we may have greater confidence in the central estimate of the change, however, this is not true for the uncertainty range. The uncertainty range is likely to be underestimated in both CPM_new and the RCM due to the small ensemble size and the lack of information from other international climate models. The implications of the CPM results from our confidence in winter mean precipitation changes from Strands 1 and 2 are discussed below.

For summer mean precipitation, CPM_new and the RCM provide similar central estimates of the projected change. Thus in this season the improved representation of daily variability in the CPM does not impact

[3] The UKCP18 land projections (Murphy et al, 2018) are made up of three Strands. Strand 1 is the Probabilistic projections; Strand 2 the Global (60km) projections, consisting of the 15 member HadGEM3-GC3.05 PPE and 13 CMIP5 models; and Strand 3 the downscaled projections including the Regional (12km) and Local (2.2km) projections

future changes in the mean, with the latter instead driven by large scale change. This agreement with the CPM provides additional evidence that the RCM projections of decreasing summer mean precipitation over the UK, which follow the driving HadGEM3-GC3.05 perturbed parameter ensemble (PPE), are plausible. However, as noted above, locally there may be added value from the CPM, especially in regions of high spatial heterogeneity such as cities, mountains and coastlines.

For heavy daily precipitation events, we have greater confidence in projections of change from CPM_new due to considerably reduced biases in the present-day in both winter and summer. In winter CPM_new and the RCM provide similar central estimates of the change, since these are largely driven by large-scale changes (specifically increasing atmospheric moisture with warming) captured by both models. This agreement with the CPM, supports increases in heavy precipitation in winter seen in the RCM. In summer, CPM_new shows a greater tendency for increases, likely due to the improved representation of convective processes, with local dynamical feedbacks in storms acting to amplify future increases in rainfall intensity. Again although we have greater confidence in the central estimate of the change from CPM_new, the new 2.2km rerun projections underestimate the uncertainty range.

For hourly precipitation variability and extremes in all seasons, we have greater confidence in the CPM_new projections of future change. This is based on the much more realistic representation of convective processes and present-day hourly precipitation characteristics, compared to the convection-parameterised model. The CPM still tends to overestimate the intensity of hourly precipitation, which is due to convective plumes and smaller convective showers not being well resolved at the 2.2km grid scale. Nevertheless, the CPM provides a step change in our ability to represent convective processes and local storm feedbacks, to the extent that it can provide plausible projections of future changes in hourly rainfall and convective extremes. Due to inherent limitations of the convection parameterisation scheme, RCM projections of hourly precipitation extremes are considered unreliable, and for high return periods may differ from CPM_new projections by up to a factor of 2. We note that in the case of hourly precipitation extremes, the RCM projections span a greater range than CPM_new. However, this is not “real” uncertainty but instead likely reflects unphysical grid point storms in the RCM.

For soil moisture, CPM_new and the RCM provide similar central estimates of the projected change, consistent with similar decreases in summer mean precipitation. Thus the fact that soils are drier in the CPM, in better agreement with pseudo-observations, does not impact future changes. Drier soils in both the present-day and future climates in CPM_new reflects the more intense and intermittent nature of rainfall compared to the convection-parameterised model. This is more realistic, however there remain deficiencies in the correct partitioning of rainfall at the surface, in terms of how much is intercepted by the canopy, infiltrates the soils and runs off. Agreement between CPM_new and the RCM in projected changes provides additional evidence that these are plausible. It should be noted however that the uncertainty range is likely to be underestimated due to the lack of information from other international climate models (which can give quite different summer precipitation changes, see below), and in CPM_new due to the lack of any perturbations to the land-surface parameters.

For snow, including falling and lying snow, we have greater confidence in projections of change from CPM_new due to the improved representation of wintertime convective showers which contributes to future changes in winter precipitation (see above) and the improved representation of mountains on the 2.2km model grid.

For cloud, we suggest that CPM_new and RCM projections are both plausible (Table 5.1). There are differences between the models, likely due to the different cloud schemes used, but it is difficult to establish which is more reliable. In winter, CPM_new shows reduced present-day biases, and the greater tendency for increases in cloud cover may reflect the improved representation of wintertime convective showers but, unlike the RCM, it does not use the prognostic cloud scheme.

For lightning, projections are only available from CPM_new, since the ice-based lightning prediction scheme requires prognostic graupel with is not included in the RCM.

For surface winds, including mean and extremes, there is no evidence to suggest that the CPM_new projections are more or less plausible than those from the RCM (Table 5.1). There are some differences in the projections, but it is difficult to establish which is more reliable. We anticipate some local differences over mountains and coastlines, where the improved representation of complex topography in the 2.2km model may be important.

5.3 Use of 2.2km projections in context of wider UKCP18 information

Finally, we now move on to consider the use of the downscaled regional projections (from the RCM or CPM) in the context of the wider sampling of uncertainty from Strands 1 and 2.

The Strand 1 (UKCP Probabilistic) projections are designed to provide a broad view of uncertainties, for a set of key variables. They can be interpreted as probabilistic estimates, conditional upon the climate modelling information and methodological choices used. The Strand 2 GCM projections provide a more flexible dataset, for spatially coherent, multi-variate impacts studies. They are plausible climate outcomes that include multi-model ensemble information (13 CMIP5 models) alongside perturbed parameter ensemble (PPE) results (HadGEM3-GC3.05-PPE), and also support understanding of mechanisms driving future changes, for Europe and other worldwide regions (Murphy et al, 2018). These Strands offer alternative sources of information for UK impacts, useful in applications where the higher horizontal resolution of Strand 3 products is not required, or to provide context relating to uncertainty and/or understanding that may inform the interpretation of studies based mainly on Strand 3.

The Strand 3 (CPM and RCM ensemble) projections are driven exclusively by variants of the Met Office Hadley Centre model (HadGEM3-GC3.05-PPE) and currently lack information from other international climate models. This results in relatively high temperature changes in the downscaled Local (2.2km) and Regional (12km) projections. In particular, they sample few outcomes cooler than the median of the UKCP Probabilistic projections in winter and none in summer (Fig 5.1). Changes in summer precipitation show a considerable drying in the Local (2.2km) and Regional (12km) projections (following the driving HadGEM3-GC3.05-PPE), whereas the 13 CMIP5 simulations and the UKCP Probabilistic projections indicate that outcomes with more modest reductions or small increases should also be considered.

In winter, the two ensembles in Strand 2 (HadGEM3-GC3.05-PPE and CMIP5-13) show considerable overlap in their responses, and in the case of temperature changes the downscaled Strand 3 projections span a similar range to the driving global PPE. There is a notable difference in the CPM_orig responses, however, with these lower than global and regional driving models over Scotland in winter. Temperature changes over Scotland are higher in CPM_new than CPM_orig, resulting in better agreement with the driving RCM and GCM. This is an expected consequence of fixing the graupel code error, which leads to more lying snow in the present-day and greater positive albedo-feedbacks on future winter temperature increases (Section 4.2).

In terms of winter precipitation changes, the range from the CPM (CPM_new and similarly CPM_orig) is shifted higher compared to the range in the Regional (12km), and includes a few outcomes that are higher than any in the Global (60km) projections (Fig 5.1). As explained earlier (see Section 4.4), this difference is related to an increase in convective showers in the CPM, triggered over the sea and advected inland (Kendon et al, 2020a). As a result, we have greater confidence in the CPM projections for mean winter precipitation.

In general, with the exception of winter mean precipitation change, the Strand 3 (RCM and CPM) projections show a similar range of changes to the driving GCM PPE for seasonal mean changes at national scales. For these, we find no evidence to suggest that the CPM projections are more or less plausible than those from the RCM or driving GCM. Thus, for these changes, we suggest Strand 1 and Strand 2 should be the primary source of information, as these provide a more comprehensive view of uncertainties. For winter mean precipitation change, however, results here suggest that projections based on convection parameterised models may underestimate "upper-end" responses.

For applications focussing on extremes, or requiring information on fine spatial scales, the RCM and CPM_new products are expected to be the primary source of information. For daily precipitation extremes, CPM_new projections are more reliable especially in summer, and for hourly precipitation including extremes, projections from models using parameterised convection are unreliable and so users should use the CPM_new projections. However, the Strand 3 projections do not support a probabilistic interpretation and provide a narrower sampling of uncertainty compared to Strands 1 and 2. The importance of including structural modelling uncertainty, sampled by multi-model ensemble information, is highlighted above especially for changes in summer. For applications using Strand 3 projections, we would recommend augmenting with multi-model information. At the 12km scale, this could include RCM results from EURO-CORDEX simulations (Jacob et al, 2014), which consists of a partly-filled matrix of RCM simulations contributed by several European regional modelling groups, driven by a selection of CMIP5 global models. At the 2.2km scale, multi-model CPM simulations are available from the CORDEX-FPS (Coppola et al, 2018) and Horizon 2020 EUCP (Hewitt and Lowe, 2018) projects. It should also be noted that simulations of RCM-STD and CPM-STD downscaling selected members of the CMIP5-13 ensemble are planned for future UKCP updates (see Section 5.4). Adding these Regional (12km) and Local (2.2km) simulations driven by other international climate models will likely broaden the range of downscaled projections available for detailed UK impacts studies.

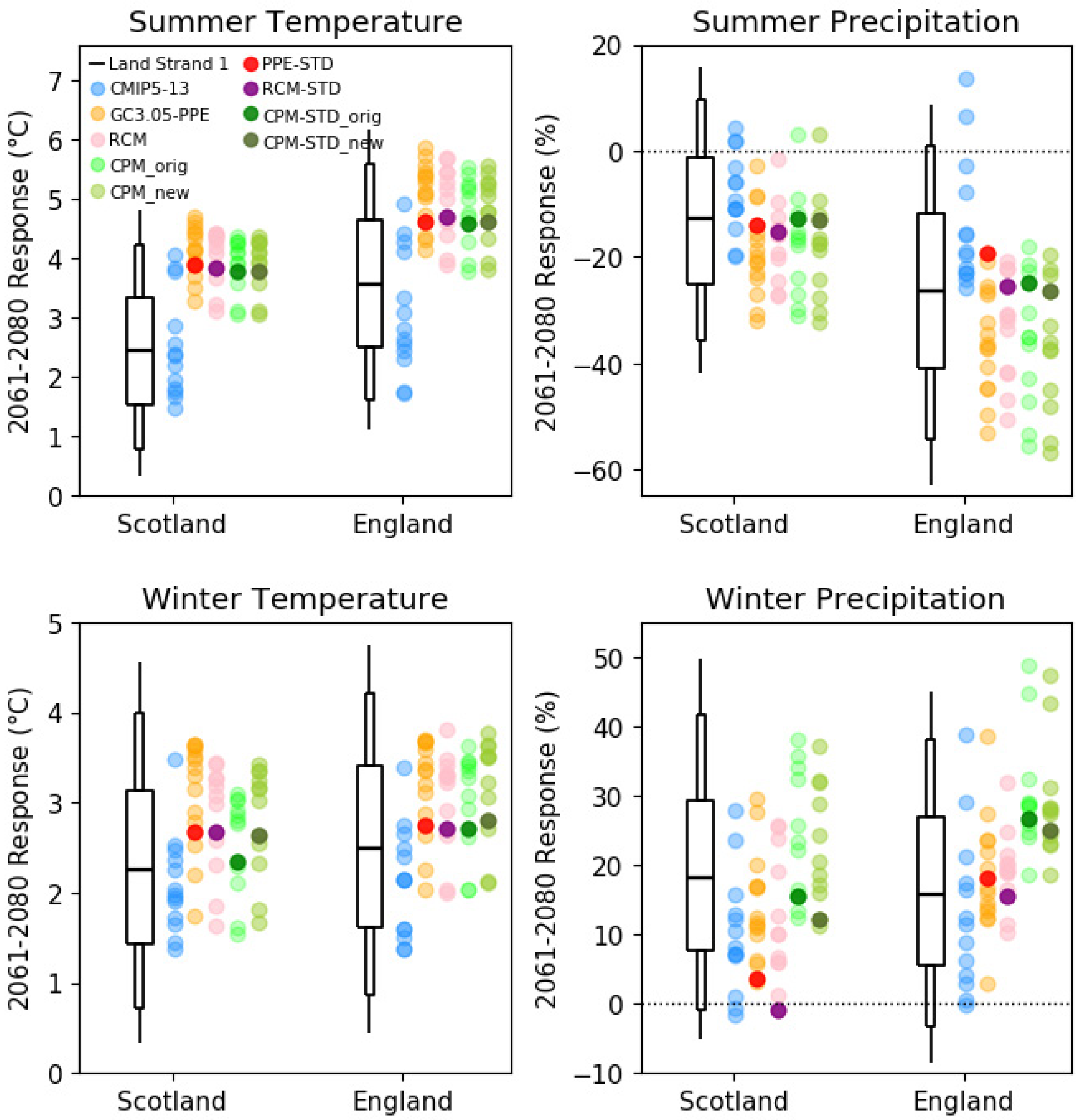

Figure 5.1. Comparison of seasonal mean changes across UKCP18 products. Projected changes for 2061-2080 relative to 1981-2000 for Scotland and England in (top) JJA and (bottom) DJF, under RCP8.5 emissions. Results are shown for surface air temperature (left, °C) and precipitation (right, %). Box and whiskers denote the 5, 10, 25, 50, 75, 90 and 95% probability levels of the UKCP probabilistic projections (Strand 1). Orange dots (with STD in red) denote members of GC3.05-PPE and blue dots those of CMIP5-13, which together comprise the UKCP Global (60km) projections (Strand 2). Pink dots (with STD in purple) show the Regional (12km) projections and green dots (with STD in dark green) those of the Local (2.2km) projections (with CPM_orig in fluoro-green and CPM_new in olive-green, Strand 3).

5.4 Future planned updates and data availability

It is planned that, at least initially, the original UKCP Local (2.2km) data will be retained in the CEDA archive and on the user interface, with the new 2.2km CPM data appearing as an additional product. In consultation with users, we will consider eventually removing the original data, once it is no longer being used, as the new data should become the preferred dataset for all new users.

In terms of future updates, the inclusion of multi-model information within the Strand 3 projections is planned. This will involve a selected subset of CMIP5 global models being downscaled with the standard variant (STD) of the RCM and CPM, which would add some sampling of structural uncertainty in the global driving model. The effects of structural uncertainty in the downscaling model could potentially be added by using data from the EURO-CORDEX archive of multi-model RCM simulations and EUCP multi-model CPM simulations, for domains which overlap the UK, available for RCP8.5 (as noted above). These simulations could be screened based on historic performance to identify which are appropriate for inclusion. Augmenting the available regional modelling information could be particularly helpful for assessments of future risks relating to extremes, as the influence of the downscaling is a major source of uncertainty in the projected changes.

As a further enhancement for users, not available in the original UKCP 2.2km release, additional simulations for the intervening time periods (2001-2020 and 2041-2060) are currently underway and will be provided to users in a future release, alongside the CMIP5 downscaled 12km and 2.2km simulations. This represents a key advance, providing for the first time continuous 100-year timeseries of 2.2km data from 1980 to 2080. This will improve the ability of users to analyse the changing contributions of forced climate change and internal variability through the 21st century and improve sampling of extreme events for studies of climate impacts.

Parameter perturbations in the CPM were not implemented here as it was not possible to mirror the full set of RCM parameter perturbations, given structural differences between the models. However, the possibility of sampling parametric uncertainties in the CPM will be explored in future work and could be made available for future UKCP releases. Work underway at the Met Office to develop a scale-aware convection scheme will facilitate this, as it will allow the same convection scheme to be used across all model resolutions. It is also expected to alleviate many deficiencies in the explicit convection model due to convection not being fully resolved at kilometre scales, including the overestimation of intense precipitation events. Research on the next 5-10 year timescale will focus on determining the optimal design for any CPM perturbed parameter ensemble experiments, which would allow an estimate of uncertainties in projections due to the convective-scale model physics. Other research will focus on assessing new developments in the model physics, potentially including scale-aware convection, and also exploring new Regional Environmental Prediction (REP) capability (Lewis et al, 2019). This includes ocean and wave models coupled to the km-scale atmospheric and land models to allow an assessment of combined hazards (for example storm surges and heavy precipitation events) at the coast, in addition to potentially impacting model performance through explicit representation of atmosphere-ocean feedbacks. These new developments and capability will initially be explored through research programmes, such as the Met Office Hadley Centre Climate Programme, but will also become available for consideration for inclusion in potential future UKCP releases when the research is sufficiently mature.

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