Technical note: Issue with UKCP Local (2.2km) simulation data

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Headlines

- We have found an error within the UKCP Local 2.2km climate model in the computer code that determines how much of the solid precipitation falls as snow and how much as small ice pellets.
- No other UKCP product is affected by the error, and top-level messages from UKCP in terms of climate change in the UK are unchanged.
- The existing 2.2km data can still be used for many applications, but extra care is needed in the use of data for some variables and locations. The variables primarily affected are snow and winter temperature especially over Scotland, for which the existing 2.2km data should not be used. Also affected but to a lesser extent are winter precipitation, hourly precipitation extremes across the UK and wind extremes over the ocean and north-west coastal regions, and for these variables the existing 2.2km data should be used with caution. The variables unaffected are summer temperature including extremes and summer mean precipitation.
- New data with the error fixed will be issued, with a planned release for Spring 2021.
- On fixing the error, the simulation of lightning is considerably improved, allowing it to be potentially provided as a user diagnostic in the new release in 2021.
- This report is aimed at more technical users of the 2.2km data, providing guidance on when applications are likely unaffected by the error or where users should wait for the new 2.2km data.

Summary

An error has been found within the UKCP 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. Subsequent testing has shown that the UKCP Local (2.2km) projections (including for temperature, precipitation and wind) can still provide important information for many applications related to climate change but there is a need to update the user guidance on use of the UKCP 2.2km data, with additional caveats. Over the coming months, we will provide new additional simulations from the UKCP 2.2km climate model with the error fixed, which should ultimately be treated as the preferred dataset.

The graupel error emerged whilst having a detailed look at simulations performed with the same version of the model over the Colorado mountains. The error was in the code that controls the fraction of snow converted to graupel, rather than in the total snow/ice amount, 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 top-level messages from UKCP in terms of climate change in the UK (Lowe et al 2018) are not impacted.

Some rapid tests have been performed for one 2.2km ensemble member to look at the consequences of the graupel code error for the UKCP Local simulations. These show that for many variables and

locations the impact of the graupel code error is not significant compared to the spread across the UKCP Local simulations (i.e. the difference between the original and test runs is smaller than one standard deviation, which is a typical difference[1] between members of the original UKCP ensemble). We note that the test is performed for just one member, and differences on fixing the error could be larger or smaller in the other members (which we will only be able to assess once the new dataset is available). However, since different 2.2km members use the same model physics and only differ due to different large-scale conditions inherited from the driving models, we expect the members to respond similarly although with the impact of fixing the graupel code error potentially larger in cold members with more snow. Thus, whilst extra care should be taken using the 2.2km simulations users can still use the UKCP Local projections, alongside other UKCP tools, for many applications. This document provides the guidance to help users understand how to best continue in their use of the model results.

Fixing the graupel code error impacts winter temperature in some regions, due to more lying snow in the modified simulation. The impact on simulated temperature is judged to be significant[2] for cold winter days and nights over Scotland, with future increases in temperature by 2070s increased by 1°C or more for cold winter days locally over parts of Scotland and for cold winter nights more widely across the UK. This compares with 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 the original UKCP 2.2km model. For mean winter temperature change, the impact is not significant[2] with differences less than 0.5°C everywhere (with 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[2] impacts simulated present-day precipitation in winter, with the fixed-code run somewhat wetter although still not as wet as the 12km model (UK-wide bias in the 2.2km model increases from +16% to +22% on fixing the code error, compared to +31% bias in the 12km model). 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 2.2km and 12km model responses. Thus, the key finding that future increases in winter precipitation are greater in the Local (2.2km) compared to the Global and Regional projections (Kendon et al., 2019; Kendon et al., 2020) still holds. Key differences between the 2.2km and 12km model simulations in the frequency and mean intensity of hourly precipitation, and their future change, are unaffected by the graupel error.

The impact of the error is much smaller in summer, with no significant[2] impacts on summer mean precipitation and temperature. There is evidence that hourly precipitation extremes may change on fixing the graupel code error, even in summer (with a potential 20% reduction in present-day 5-year return levels for the one ensemble member analysed, compared to the spread across the original UKCP 2.2km ensemble of 10%). Future increases in hourly precipitation extremes are increased slightly, with the impact of the graupel code error on future changes significant[2] 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[2] 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 2.2km release. On fixing the

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[1] 68% of a normal distribution lies within one standard deviation of the mean.

[2] Significance is assessed by comparing the difference on fixing the graupel code error against the standard deviation for that metric across the original 12-member UKCP Local 2.2km ensemble.

graupel code error, the simulation of lightning is considerably improved, allowing it to be potentially provided as a user diagnostic in the new release; representing an enhancement for users.

The existing UKCP Local 2.2km data can be used for developing methods for application of the 2.2km data and for many applications, although extra care should be taken for applications using variables identified above as being affected by the graupel code error. This note will help users better understand when it is appropriate to use the UKCP 2.2km data in its current form. New data from the UKCP Local 2.2km model with the graupel code error fixed will be issued, with a planned release date of Spring 2021, and once available this should become the preferred dataset for all applications. Whilst many applications are unlikely to be strongly impacted by using the new data, we believe that issuing new data will provide the widest access to all UKCP products (i.e. ensuring the same quality of data for all locations and for all types of adaptation decision, consistent with our policy followed in earlier generations of climate projections). The new data will also come with the benefit of potentially providing additional climate metrics that are not available at present. We reiterate that the UKCP probabilistic, global and regional projections are unaffected by this issue, 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.

Part 1: Advice on use of UKCP Local data

The UKCP Local 2.2km projections consist of an ensemble of 12 simulations at 2.2km resolution run for 3 time periods (Kendon et al., 2019). The UKCP Local (2.2km) projections sit alongside a number of other UKCP18 tools to look at climate change (Murphy et al., 2018, Lowe 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 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 are aware of the other UKCP products and the advantages of each for their application, and also that users consider the sensitivity of their applications to uncertainty in the UKCP outputs. Further guidance on which UKCP product to choose is available from Fung et al. (2018a). The following advice is for those who have already used or are planning to use UKCP Local (2.2km) data, and covers the use of precipitation, temperature, snow, wind and lightning outputs.

The results reported in this technical note (see Part 2) show that fixing the graupel code error in the single-member test leads to some differences that exceed the standard deviation across the 12-member UKCP 2.2km ensemble. Under the assumption that the other 11 ensemble members are impacted similarly (although differences could be larger or smaller in other members that have the same model physics but sample different large-scale conditions), we judge the impact of the graupel code error to be significant compared to the ensemble spread, for some variables in some seasons, and especially in some locations. Although the current UKCP Local (2.2km) data remains suitable for many users dependent on application, to promote the widest access to all UKCP products in all regions of the UK, the decision has been taken to rerun the UKCP Local (2.2km) projections with the graupel code error fixed. These new data should be the preferred source for all new users. For current users of the existing UKCP 2.2km data, in many cases it is not necessary to rerun analysis with the new data, except for specific variables and seasons (as outlined below).

When and how can users apply the UKCP Local data?

The existing UKCP Local data, published in September 2019, can be used for method development (e.g. for developing methodologies to analyse an ensemble of climate model information or for writing code to work with the large volumes of data). It can also still be used for many applications, although it should be used with caution or not at all for some situations. Below we outline the use and decision cases where the original data are still appropriate for use (possibly with caution) and where we would recommend waiting for the new data.

Once the new data become available, this should become the preferred dataset for all new users. Any existing users of the UKCP 2.2km data who require items identified as "Do not use original UKCP 2.2km data for operational applications" (Table 1, Column 2) should wait for the new data and rerun their analysis if they have used the original data. Any existing users requiring items identified as "Original UKCP 2.2km data can be used" (Table 1, Column 4) do not need to rerun. For the "use with caution" category (Table 1, Column 3), we recommend that users should assess the sensitivity of their application to using different members from the UKCP 2.2km ensemble, and that where the analysis/decision is unaffected by the choice of ensemble member it is unlikely to be strongly impacted by the graupel code error and so it is likely safe to use the original data for the specific variables and seasons.

A summary of the size of the impact for future changes in key variables is given in Table 2, with further details on the impact of the graupel code error provided in Part 2.

✓ **Summer temperatures including extremes**

The original UKCP Local (2.2km) projections can be used for analysis of changes to summer temperatures, including extremes, as we have found the graupel code error has little impact on these variables. We are aware that some users have already considered using the UKCP 2.2km data, for example analysing the thermal performance of buildings, the impact on transport infrastructure and the health effects of heat, particularly in the summer. They should continue to use the original data.

✓ **Summer mean precipitation**

We advise that studies related to summer mean precipitation can continue to use the full suite of existing UKCP projections. The impact of the graupel code error on summer mean precipitation is small, and users that are already using or planning to use the UKCP 2.2km projections should continue to use the original data.

✗ **Winter temperature and snow**

Where users are already using or planning to use the UKCP 2.2km projections for winter temperature and snow, we recommend that users wait for the new data, or use the Regional (12km) data. There is a significant impact of the graupel code error on snow and temperature in winter. In particular, there is not enough snow in the original data in the present-day, which leads to an underestimation of future changes since almost all lying snow disappears by the 2070s under RCP8.5. Cold winter days and nights are too warm in the original data, and future temperature increases are underestimated by 1°C or more in some locations, especially over Scotland. Thus, winter temperature and snow data from the original UKCP 2.2km dataset should only be used for method development. This is likely to affect planning related to cold winter temperature and snow in future.

For winter temperature, there are biases in all the UKCP18 models, although different tools will offer different advantages and limitations (Fung et al 2018b). The new 2.2km results on fixing the graupel code error show much better agreement with historical observations than the original data and also lower biases than the Regional (12km) projections. The 12km regional climate model (RCM) is too cold over the northern UK, especially for cold winter nights. It is hoped that the new 2.2km simulations (with the graupel code error fixed), once available, will provide reduced model biases for cold winter days and nights and perform better than the 12km projections, but they will still provide a reduced sampling of uncertainties compared to the global and probabilistic projections. As general advice, users should be aware of the advantages and limitations of the different UKCP tools when choosing which tool or tools are best suited to their application.

? Winter precipitation

We advise that studies related to winter precipitation can continue to use the full suite of existing UKCP projections. Where the UKCP 2.2km data is being used, for example due to the need for higher spatial detail, the existing data should be used with caution. The impact of the graupel code error on future changes to winter precipitation is small and not significant compared to the CPM ensemble spread, at least for the single-member test, with winter precipitation increases still considerably larger in the CPM compared to the RCM. Thus, the key finding from the UKCP Convection-Permitting Model Projections Science report (Kendon et al., 2019) that future increases in winter precipitation may be underestimated in the global and regional projections still holds. Users should be aware that the original UKCP 2.2km CPM data underestimates winter precipitation for the present-day especially over high terrain and may slightly overestimate the future increases in winter precipitation, and once the new CPM dataset becomes available this should be used in preference to the original data for applications, for example risk assessments related to winter flooding.

? Hourly precipitation extremes

We advise that applications using data on high intensity rainfall events that cause summer flash flooding should use the existing UKCP 2.2km convection-permitting model (CPM) data with caution. Results from the single member test suggest that there is an impact on hourly (and, to a lesser extent, daily) precipitation extremes. For present-day return levels of hourly precipitation extremes, the original data overestimates values by about 20-25% (corresponding to a difference of about 3mm/h for the 5-year return level of 15mm/h) and users may wish to consider applying their own bias correction to the present-day data. The impact on future changes in hourly precipitation extremes is smaller but significant (differences in future changes are a similar magnitude to or larger than the CPM ensemble spread across much of the UK). If all ensemble members are impacted by the graupel code error in a similar way to the single-member test, there may be a systematic shift in the ensemble projected change that could be important for some applications; the single-member test estimates this at around +5-10%. For example, those sensitive to levels of surface water flooding should consider the sensitivity of their application to an additional 5-10% increase in extreme precipitation intensity. For other users, where rainfall is just one of multiple variables needed to inform their analysis/decision, for example building design, such a potential shift in extreme rainfall intensity may not be important.

Once new data from all 12 ensemble members becomes available, we will be able to make more confident statements regarding the impact of the error on precipitation extremes. We recommend that users carry out testing of the sensitivity of any analysis to the UKCP Local data and note that such sensitivity testing is already considered good practice in adaptation decision making with climate data. Once the new dataset becomes available this should become the preferred dataset for all new applications. We are aware that many users are awaiting results from the FUTURE-DRAINAGE project that are based on the UKCP 2.2km data. The project will provide new projections of change to surface water flooding, with updated guidance on precipitation uplifts that should be adopted in urban drainage design and flood risk assessment in the UK. We will work directly with the FUTURE-DRAINAGE project to ensure that results using the new UKCP Local simulations (with the graupel code error fixed) become available for that project as soon as possible.

? Surface winds

For surface winds, where users are already using or planning to use the UKCP 2.2km projections, we recommend that users can continue to use the existing data but with caution. There is some impact of the graupel code error on present-day surface winds, where the original data may underestimate wind speeds mainly over the ocean but also over Ireland, the Cairngorms and some north-western coastal regions. The impact on future changes in surface wind speeds is smaller and not significant compared to the CPM ensemble spread, except locally over the Cairngorms. Bias correction of the present day may be appropriate.

*** Lightning**

Due to concerns with the lightning results from the UKCP Local (2.2km) projections, lightning data was not released in the original launch in September 2019 (Kendon et al., 2019). The test simulation suggests that lightning occurrence will be much improved in the new simulations with the graupel code error fixed, allowing lightning data to be released in future. This will represent an enhancement for users not available in the original data release.

A summary of the advice on the use of the UKCP Local (2.2km) projections by impact sector is provided in Table 1. Any existing users of the UKCP Local (2.2km) projections using metrics identified in Column 2 should rerun their analysis using the new 2.2km data once available; those using metrics in Column 4 do not need to rerun; whilst for users of metrics in Column 3, initial conclusions based on the original data are unlikely to be radically changed, however, where possible this should be assessed with the new dataset when available. Further details on the impacts of the graupel code error are provided in Part 2 and summarised in Table 2.

Impact metric (with some example impact areas)	**Do not use original UKCP 2.2km data for operational applications. Await new 2.2km data and/or use other UKCP18 products where appropriate.**	**Use original UKCP 2.2km data with caution. New 2.2km data should be preferred to original data once available.**	**Original UKCP 2.2km data can be used, alongside other UKCP18 products.**
Snow (e.g. infrastructure inc. transport and energy, natural environment/habitat)	**X** Original UKCP 2.2km data underestimate snow and its future change		
Lightning (e.g. infrastructure inc. transport, communications and energy)	**X** Lightning data not released from original UKCP 2.2km		
Cold winter temperatures (e.g. infrastructure inc. transport and energy, health, natural environment/habitat)	**X** Original UKCP 2.2km data underestimate future increases in winter temperature (especially for cold winter days and nights over Scotland)		
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.	
Summer precipitation (e.g. summer flash flooding affecting multiple impact areas)		? Original UKCP 2.2km data likely overestimate present-day return levels and underestimate future changes in hourly precipitation extremes in some regions. Revised surface water flooding estimates from FUTURE-DRAINAGE	
Wind extremes (e.g. infrastructure inc. transport, water, communications, energy, forestry/natural environment)		? Original UKCP 2.2km data underestimate wind speeds, mostly over ocean, but graupel code error has small impact on future changes.	
Hot summer temperatures and heatwaves (e.g. transport, thermal building design and health)			✓ Results not significantly impacted by graupel code error

Table 1. Summary of advice on use of original UKCP Local (2.2km) data by impact sector. Use "with caution" category implies the need for sensitivity testing of user-applications to the UKCP data.

Variable	**UK-average future change in CPM_UKCP**	**UK-average response difference (CPM_fix minus CPM_UKCP)**	**Approx. largest local response difference (CPM_fix minus CPM_UKCP)**	**UK-average standard deviation across CPM ensemble**	**Impact of graupel code error larger than CPM ensemble spread?**
Mean T, DJF	+2.5°C	+0.1°C	<0.5°C	0.6°C	No
Cold days, DJF	+3.0°C	+0.2°C	+2°C	0.8°C	Yes over parts of northern Scotland
Cold nights, DJF	+2.9°C	+0.6°C	+3°C	0.9°C	Yes locally
Mean T, JJA	+4.3°C	0.0°C	<0.2°C	0.5°C	No
Hot days, JJA	+5.7°C	0.1°C	+0.5°C	1.2°C	No
Mean P, DJF	+24.7%	-2.6%	-10%	11.0%	No
P_freq, DJF	+17.8%	-2.9%	-5%	7.5%	No
P_int, DJF	+6.1%	+0.3%	+/-5%	4.8%	No
Mean P, JJA	-23.7%	-1.3%	-10%	12.2%	No
P_freq, JJA	-30.5%	-1.0%	-5%	9.5%	No
P_int, JJA	+10.4%	-0.3%	+/-10% (local response differences are noisy)	8.3%	No (a few local grid points show large impact)
2yRL_hr, ALL	+28%	+5%	+10%	8%	No
5yRL_hr, ALL	+29%	+7%	+10-15%	8%	Yes for some regions
2yRL_dy, ALL	+13%	0%	+/-5%	7%	No
5yRL_dy, ALL	+14%	0%	+/-5%	8%	No

Table 2. Summary of impact of graupel code error on future changes for key surface temperature and precipitation metrics. Where T = surface temperature, P = precipitation, P_freq = frequency of wet hours (>0.1mm/h), P_int = mean intensity of wet hours, {n}yRL_hr = n-year return level of hourly precipitation extremes, {n}yRL_dy = n-year return level of daily precipitation extremes; for winter (DJF), summer (JJA) or all seasons (ALL). Where the impact of the graupel code error is smaller than the CPM ensemble spread, there could still be a systematic shift in the ensemble mean, if all ensemble members are impacted similarly to the single-member test.

Part 2: Technical description of graupel code error

An error was found within the UKCP 2.2km climate model in the microphysics code that represents graupel. Graupel is a second category of ice with higher densities and fall speeds found in convective cloud (Forbes and Halliwell, 2003). It is included in the 2.2km convection-permitting model (CPM), but not in the 12km regional model (where instead all ice precipitation is diagnosed uniquely as snow, with no graupel category). The error was in the graupel auto-conversion term, which controls *the fraction of snow converted to graupel*. In general, it has resulted in too much snow being converted to graupel.

Graupel is used to calculate lightning using the McCaul et al. (2009) lightning prediction scheme, and so this graupel error impacts the simulation of lightning. We note that lightning data was not issued from the original UKCP Local 2.2km projections, due to concerns over its verification, likely related to the graupel code error. Therefore, fixing the graupel code error creates the potential to now provide lightning data as a user diagnostic.

Graupel is in the snowfall output diagnostics, but since the error was in the term that converts between hydrometeor types rather than in the absolute amount of ice/snow, the impact on total precipitation is smaller. Following operational practice at the time, graupel was ignored by the land surface model JULES in the UKCP CPM, and so was not included in the snowpack (Kendon et al., 2019). This setting was recommended due to the tendency for the convection-permitting model to produce too much small graupel, which if included in the snowpack would lead to an overestimation of lying snow. The consequence of this is that, since the graupel error in general meant more snow was converted to graupel, its effect was to reduce the snowpack.

The error has been found to have been present between Unified Model (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 UKCP 2.2km CPM to be consistent with the driving 12km regional climate model (RCM) and 60km global climate model (GCM). This should have been a null change since the l_fix_mphys_diags_iter temporary logical is only intended to affect models that use sub-stepping in the microphysics scheme, which is not the case in regional models such as the UKCP CPM. Unfortunately, turning it on led to an erroneous section of the microphysics code being activated.

The error was detected following a detailed investigation of some simulations performed with the same version of the model over the Colorado mountains. It was not found in the UKCP simulations since much less precipitation falls as snow over the UK, and the impact on total precipitation is small. In the Colorado simulations, it was found that there was nearly as much graupel as snow, which does not agree with observations. As well as graupel amounts, the code error was found to impact lightning flash rates, some land surface diagnostics and does change the evolution of the model, albeit in a relatively minor way. These impacts over the Colorado mountains are expected to be reduced over the UK, due to the comparatively lower snowfall amounts, but need to be quantified and taken into account by users of UKCP 2.2km results.

We note that in addition to the graupel code error above, ongoing research is underway within the Met Office on improving the representation of graupel within the operational UKV model (Field et al., 2019). There is a tendency for too much small graupel and too little graupel with sizes greater than 2mm, and, as a consequence, unlike in observations we rarely see graupel at the surface in the summer or when the surface temperature is approximately 5°C or more in current models. The UKCP 2.2km CPM is similarly affected by this issue, which acts to lessen the effect of the graupel code error (discussed above), since it means that the excessive graupel aloft is expected to have little impact on surface parameters in the summer season (except for lightning activity which is strongly dependent on graupel).

Results from testing fix to graupel code

The current UKCP 2.2km product consists of an ensemble of 12 simulations run for 3 time periods. In order to assess the impact of the graupel code error in the UKCP Local (2.2km) projections, tests have been rapidly performed for one ensemble member (specifically the UKCP 2.2km standard reference member) where the graupel code error has been eliminated. The standard reference member is specifically the member where no parameter perturbations were applied to the driving model (Kendon et al., 2019). Here we present results looking at the impact of the graupel code error on the present-day biases and projected changes in surface temperature, precipitation, wind and lightning. 19 years of data are available from the test simulations to date and are reported here, and we also provide information on the convergence of results from adding more years of data. We also assess the significance of the impact of the graupel code error by comparing the difference between the fixed and erroneous runs against the standard deviation across the original UKCP 2.2km 12-member ensemble for each variable. Because all ensemble members are expected to be impacted similarly to the single-member test, we note that differences smaller than the CPM ensemble standard deviation could still lead to a systematic shift in the ensemble-mean projection. Here, we only have results from the single-member test, and use the original CPM ensemble standard deviation as a benchmark of whether the impact of the graupel code error is greater than differences we would expect between members. Where the impact of the graupel code error is less than the standard deviation, i.e. the fixed-code test simulation is within the original ensemble spread, we judge the impact of the graupel code error to not be significant.

The modified test suite is identical to the UKCP 2.2km CPM (described in Kendon et al., 2019), except 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, but do not actually fix the code itself (which has been done for later UM versions) although the effect is the same. Simulations were set off for time-slice 1 (1980-2000) and for time-slice 3 (2060-2080) and the results here are reported using the 19 years of data available to date (after the first year of the simulations are discarded as spin-up). Results here compare present-day performance and future changes for the test CPM with the graupel code error fixed (CPM_fix) with the original UKCP CPM (CPM_UKCP) and the UKCP RCM, for all data regridded to a common 12km grid. The same years of data are used from all model runs for a fair comparison.

A summary of the impact of the graupel code error on future changes for key surface temperature and precipitation metrics is provided in Table 2.

Impact on lying snow

Present-day performance:

- Lying snow is increased in the graupel fixed run (CPM_fix). For both mean values (Fig 1 top) and daily extremes (99th percentile of daily values, Fig 1 bottom), differences are larger than the standard deviation across the original UKCP CPM ensemble and thus are considered significant. This is true everywhere, but with differences being particularly large over high ground in Scotland where lying snow is greatest in the present-day.

Future changes:

- Future decreases in lying snow over land with warming are greater in the graupel fixed run (Fig 2), since the majority of present-day lying snow disappears by the 2070s under RCP8.5. Differences between the original and test runs are greatest over Scotland, especially over high ground, where the greatest present-day lying snow is found. The impact of fixing the graupel code error on future changes is greater than the original UKCP CPM ensemble spread across northern Scotland (both for the mean and daily extremes of lying snow amount), and thus here is considered significant.

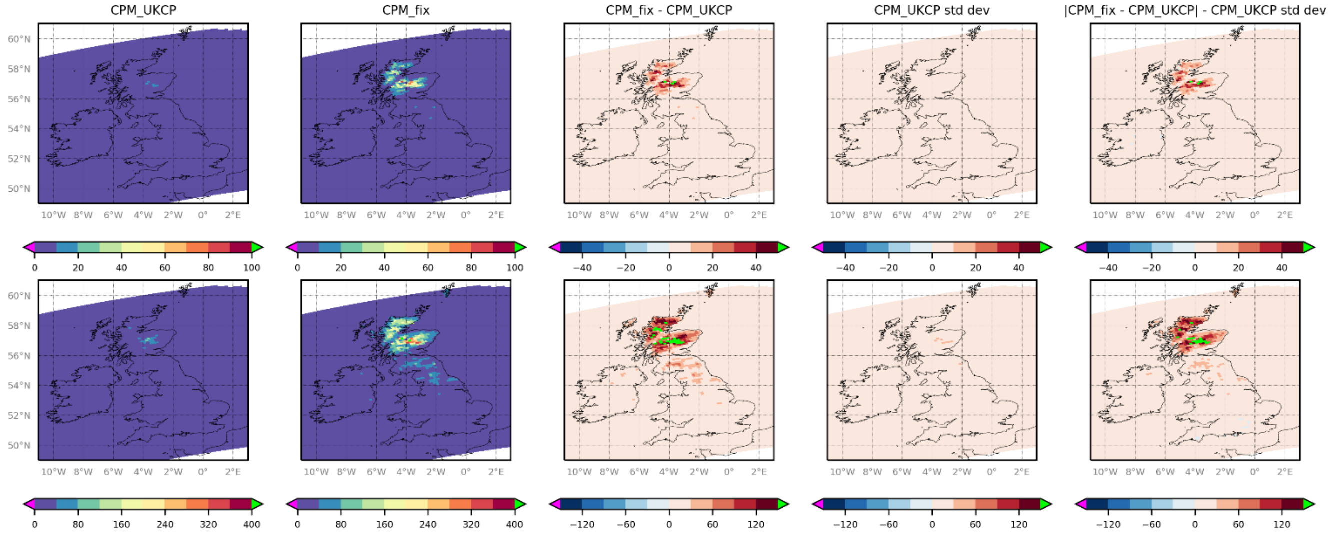

Fig 1. Impact of graupel code error on present-day lying snow amount (mm) for (top) the mean and (bottom) the 99th percentile of daily snow amount. Shown are results for (left) original UKCP CPM standard member, (left centre) CPM with graupel code error fixed (CPM_fix), (centre) the difference (CPM_fix minus CPM_UKCP), (centre right) the standard deviation across the original UKCP 12-member CPM ensemble and (right) the difference on fixing the error minus the ensemble standard deviation. 19 years of data are used corresponding to the period Dec 1980 to Nov 1999.

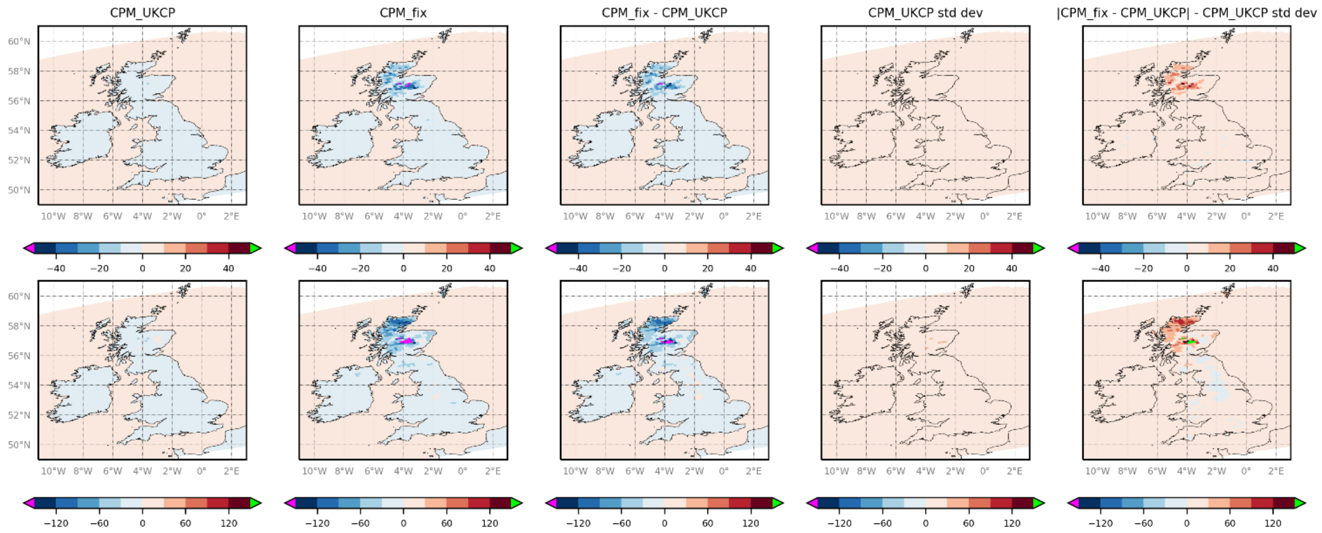

Fig 2. Future changes in lying snow amount (mm) for (top) the mean and (bottom) the 99th percentile of daily snow amount. Shown are responses for (left) original UKCP CPM and (centre left) CPM with graupel code error fixed (CPM_fix), for the standard unperturbed ensemble member. Also shown are (centre) differences between the CPM_fix and CPM_UKCP responses, (centre right) the standard deviation of responses across the original 12-member UKCP CPM ensemble and (right) the difference on fixing the error minus the ensemble standard deviation. 19 years of data for each of the future (Dec 2060 to Nov 2079) and present-day (Dec 1980 to Nov 1999) periods are used.

Impact on surface temperature

Present-day performance:

- In winter, daily average surface temperature is colder in the fixed-code run (CPM_fix), leading to increased biases from observations over the northern UK and reduced biases over the southern UK (Fig 3). Differences are greatest over northern Scotland, where CPM_fix is cooler by about 0.5°C, but these differences for winter mean temperature are smaller than the standard deviation across the original UKCP CPM ensemble and so are not considered significant.
- Looking at cold winter days, differences are larger, with CPM_fix having values that are colder by 1-2°C than the original CPM_UKCP run over northern Scotland. These differences are a similar magnitude or locally larger than the UKCP CPM ensemble standard deviation and thus are considered significant. They act to reduce overall biases, with the original model (CPM_UKCP) tending to have cold winter days that are too warm by 2-4°C over Scotland.
- The impact of the graupel code error is larger for night-time (daily minimum) temperature in winter (Fig 4). In CPM_fix, average winter nights are about 0.5-1°C colder and cold winter nights are about 2-4°C colder over northern Scotland compared to CPM_UKCP. These differences are significant compared to the original CPM ensemble spread (i.e. they are larger than the ensemble standard deviation locally). In general, fixing the graupel code error acts to reduce biases in the CPM, with night-time temperatures tending to be too warm compared to NCIC observations in the original UKCP run. In particular, cold winter

nights over Scotland are 4-7°C too warm in CPM_UKCP and are still 1-4°C too warm in CPM_fix, but by contrast are 5-8°C too cold in the UKCP RCM.

- These temperature differences in winter are consistent with more lying snow in the fixed-code run. There is also evidence of more cloud in the fixed-code run, particularly in winter.
- In summer, there is no significant impact of the graupel code error on daily surface temperatures, both for mean values and hot summer days (Fig 5).

Future changes (see summary Table 2):

- In winter, future increases in mean daily temperature are very similar between CPM_UKCP and CPM_fix (with differences in future changes less than 0.5°C everywhere, Fig 6). These differences are considerably smaller than the overall future temperature increase projected by the UKCP runs, with the UK-average impact of the graupel code error being only 0.1°C on an overall future projected temperature increase of 2.5°C, and are smaller than the UKCP CPM ensemble standard deviation everywhere and so are not considered significant.
- There is a more significant impact on future changes for cold winter days, with CPM_fix showing greater increases in temperature by 0.5-2°C locally over parts of northern Scotland (on an overall projected change of about 3°C in CPM_UKCP). Locally these differences can exceed the UKCP CPM ensemble standard deviation and so these differences are considered significant at some locations.
- Future increases in winter night-time temperature are also greater in CPM_fix over northern Scotland compared to the original CPM_UKCP (Fig 7). For average nights, future increases are increased by 0.2-0.6°C over northern Scotland, but for cold winter nights future increases are greater by up to 1-3°C locally over parts of the UK (with a mean response difference of 0.6°C across the British Isles on an overall projected change of 2.9°C in CPM_UKCP). Locally the impact of the graupel code error on future changes in cold winter nights can exceed the CPM ensemble standard deviation and so these differences are considered significant at some locations.
- The greater increases in winter temperature in CPM_fix, most apparent for cold winter days and cold winter nights, are likely due to the melting of more present-day lying snow.
- In summer, there is no significant impact of the graupel code error on future changes in daily mean temperature (Fig 8). For daily maximum temperature (not shown), there is some suggestion that future increases in temperature for hot daytime values (99th percentile of daily maximum temperature) may be increased on fixing the graupel code error by 0.5-1.5°C locally over parts of the south-east UK, but these differences are smaller than the UKCP CPM ensemble standard deviation (of 1.7°C averaged over the British Isles) and so not significant compared to the ensemble spread.

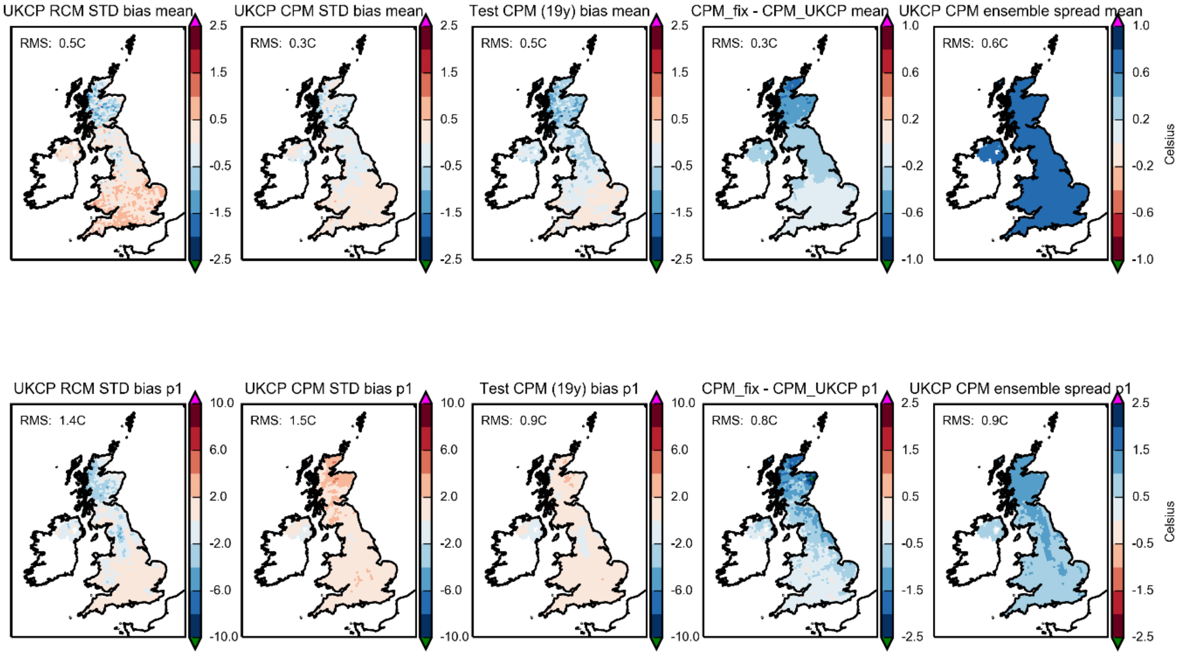

Fig 3. Present-day performance in representing the (top) mean daily temperature and (bottom) cold days (1st percentile of daily average surface temperature) in winter. Shown are (left) RCM model bias, (centre left) original UKCP CPM model bias and (centre) test CPM model bias with graupel code error fixed, for the standard unperturbed ensemble member compared to NCIC observations. Also shown (centre right) are differences between fixed-code (CPM_fix) and original CPM_UKCP and (right) the standard deviation across the original 12-member UKCP CPM ensemble. 19 years of data are used, corresponding to the period Dec 1980 to Nov 1999.

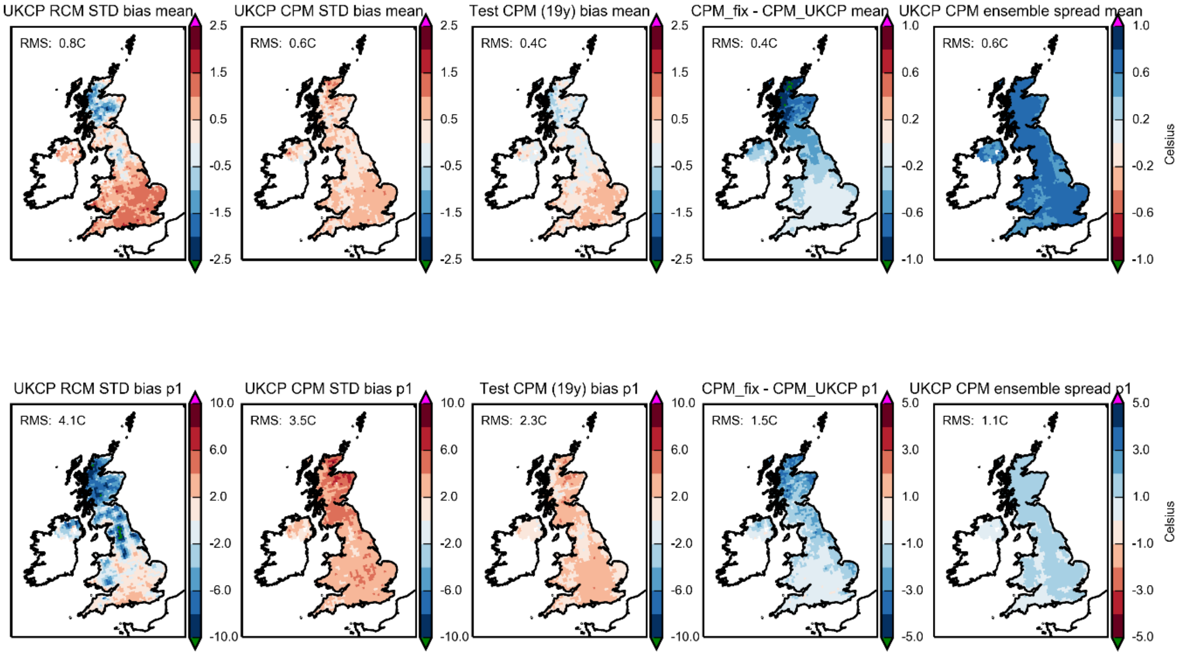

Fig 4. Present-day performance in representing the (top) mean daily minimum temperature and (bottom) cold nights (1st percentile of daily minimum surface temperature) in winter. As Fig 3, except for daily minimum surface temperature.

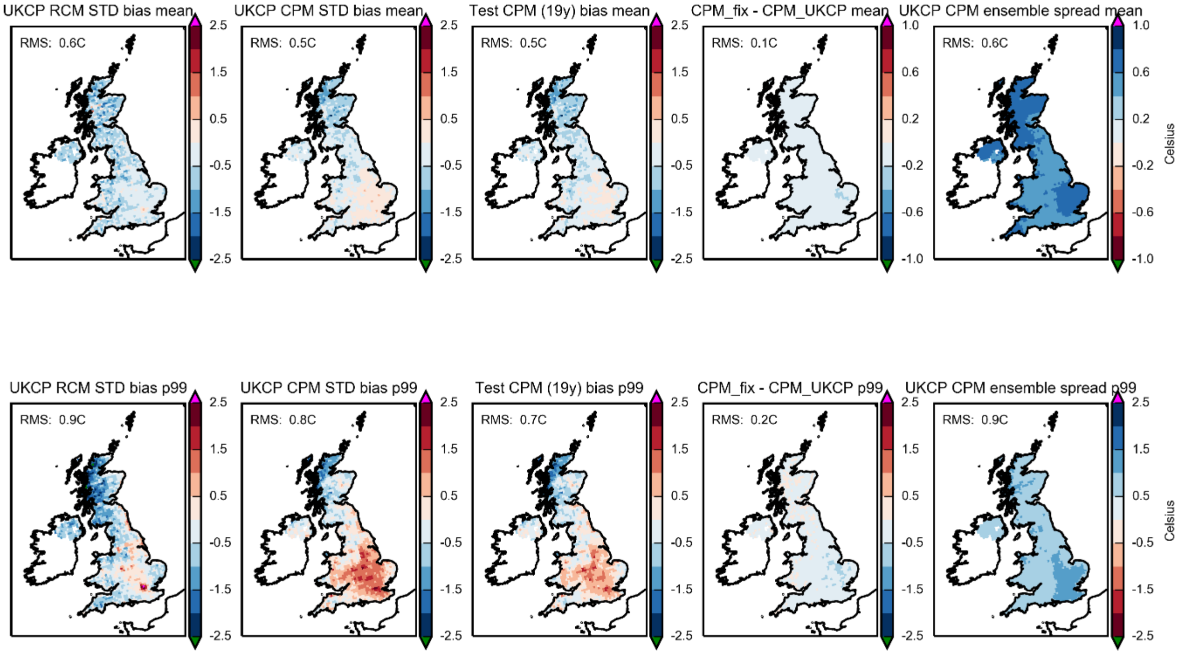

Fig 5. Present-day performance in representing the (top) mean daily temperature and (bottom) hot days (99th percentile of daily average surface temperature) in summer. As Fig 3, except for daily average surface temperature and hot days, in summer.

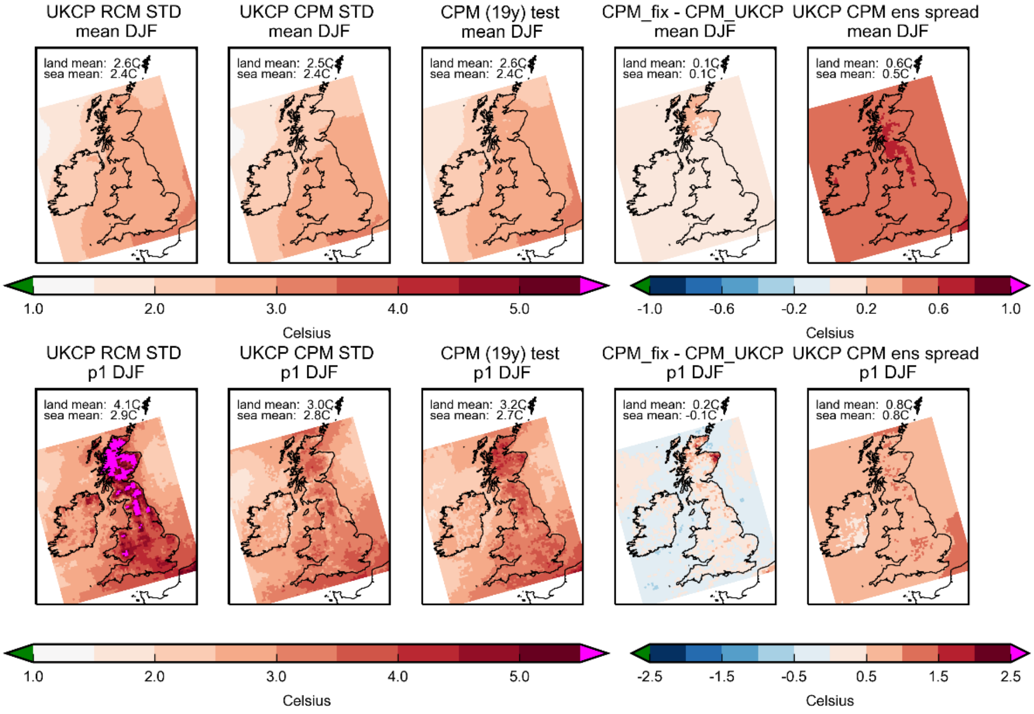

Fig 6. Future changes in (top) mean daily temperature and (bottom) cold days (1st percentile of daily average surface temperature) in winter. Shown are responses for (left) RCM, (centre left) original UKCP CPM and (centre) test CPM with graupel code error fixed, for the standard unperturbed ensemble member. Also shown are (centre right) differences between fixed-code (CPM_fix) and original CPM_UKCP responses and (right) the standard deviation of responses across the original 12-member UKCP CPM ensemble. 19 years of data for each of the future (Dec 2060 to Nov 2079) and present-day (Dec 1980 to Nov 1999) periods are used.

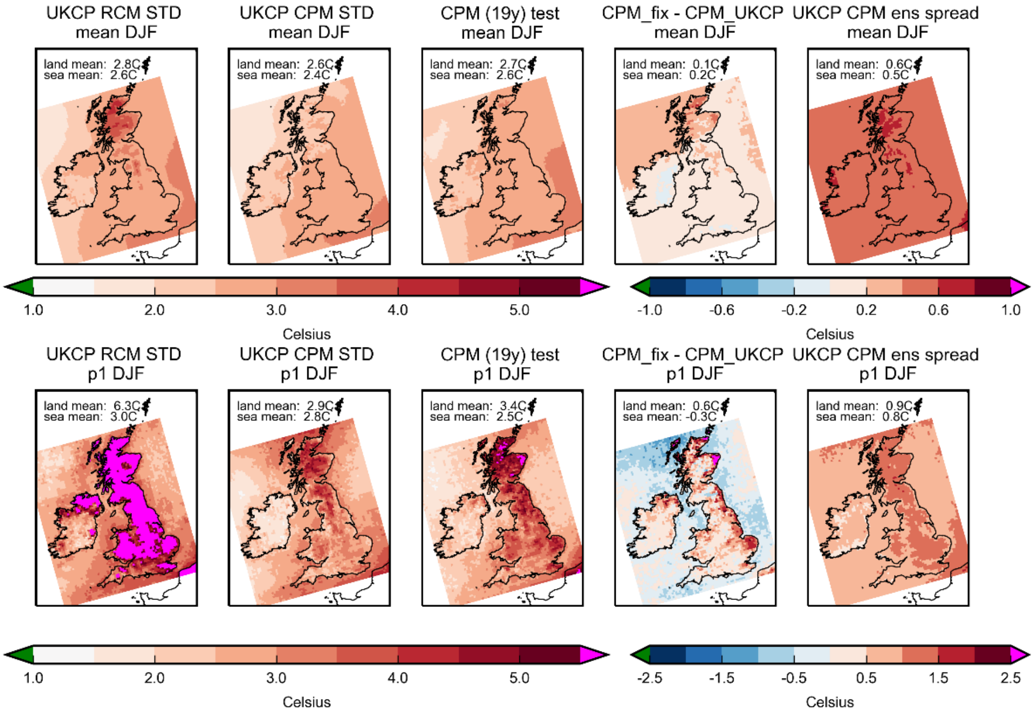

Fig 7. Future changes in (top) mean daily minimum temperature and (bottom) cold nights (1st percentile of daily minimum surface temperature) in winter. As Fig 6, except for daily minimum surface temperature.

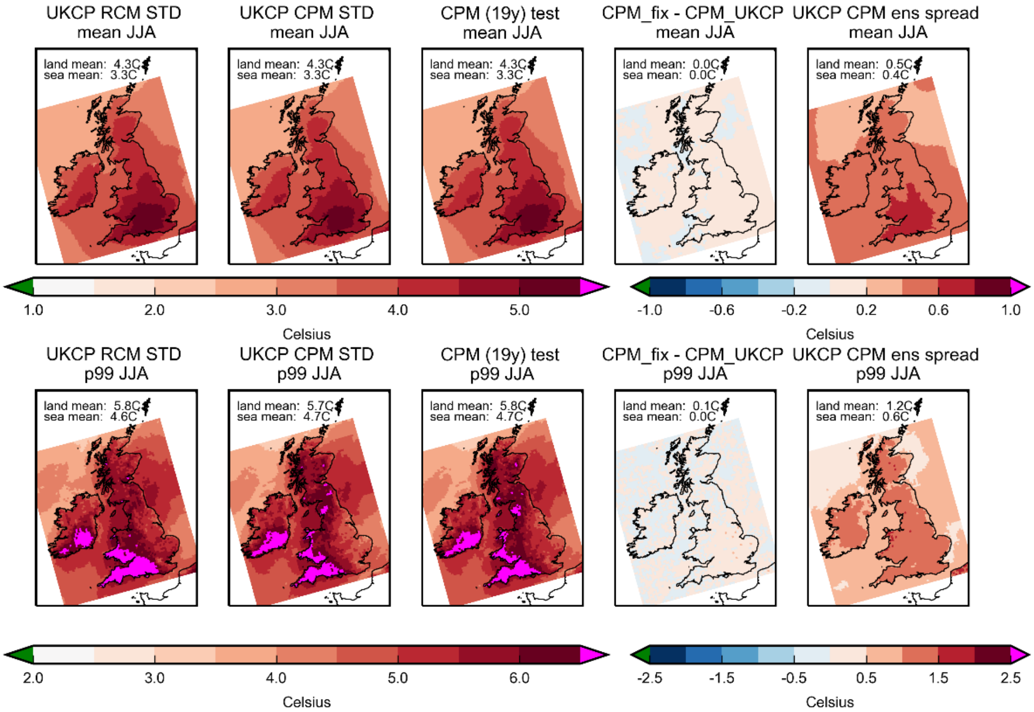

Fig 8. Future changes in (top) mean daily temperature and (bottom) hot days (99th percentile of daily average surface temperature) in summer. As Fig 6, except for daily average surface temperature and hot days, in summer.

Impact on hourly precipitation

Present-day performance:

- In winter, CPM_fix is wetter than CPM_UKCP especially over high terrain, resulting in increased biases in winter mean precipitation (22% versus 16%, Fig 9). Locally the impact of the graupel code error may be considerably larger than the standard deviation across the UKCP CPM ensemble and so significant at some locations. However, biases in the CPM are still substantially less than for the RCM (31%, Fig 9), and the big improvement in the representation of hourly precipitation occurrence going from RCM to CPM is still apparent for CPM_fix (40% bias in RCM versus 10-12% in CPM, Fig 10). Although the actual biases vary, the sense of these differences is robust to adding more years of data (Table 3), but it should be noted that the available data years differ between the model simulations and the observations (Fig 9). In general, root mean square differences across the UK on fixing the graupel code error are larger than the ensemble spread for the frequency, intensity and 99th percentile of hourly precipitation, but CPM_fix minus CPM_UKCP differences are considerably smaller than CPM minus RCM differences.
- In summer, differences between CPM_fix and CPM_UKCP are small for the mean, 99th percentile and frequency of hourly precipitation (Fig. 11 & 12). Differences are smaller than the standard deviation across the UKCP CPM ensemble everywhere, and so the effect of the graupel code error is not considered to be significant. There is some suggestion that the mean intensity of wet hours may be slightly lower in CPM_fix (leading to biases reduced from 23% to 17%, Fig 12) but there is still an overestimation of precipitation intensity in summer in the CPM (as discussed in Kendon et al., 2019), contrasting with a tendency for the RCM to underestimate precipitation intensity (biases of 25%). Locally differences in summer precipitation intensity on fixing the graupel can exceed the UKCP CPM ensemble spread, and so are significant at some locations. Again, these results are qualitatively consistent on adding more years of data.

3y-6y-9y-12y-16y-19y	**RCM**	**CPM_UKCP**	**CPM_fix**
DJF Mean RMS (%)	50-41-33-35-32-31	36-26-19-20-17-16	43-34-25-26-23-22
DJF Freq RMS (%)	50-48-41-43-40-40	13-11-10-10-10-10	19-17-11-13-12-12
DJF Intensity RMS (%)	13-14-15-15-15-15	26-20-20-19-18-17	24-20-19-18-18-17
JJA Mean RMS (%)	25-19-17-17-19-19	19-13-13-12-14-14	19-13-15-12-14-14
JJA Freq RMS (%)	45-38-31-38-41-40	17-20-25-19-18-19	17-19-24-18-17-18
JJA Intensity RMS (%)	24-22-25-24-25-25	25-28-24-24-23-23	21-22-18-19-17-17

Table 3: Convergence of results looking at present-day model performance for hourly precipitation metrics on adding more years of model data from 3 to 19 years. Performance is measured using the root mean square bias (RMS) over the UK, for the model compared to the CEHGEAR observations.

Future changes (see summary Table 2):

- With 19 years of data, future changes in mean winter precipitation are very similar between the original and fixed-code CPM runs (Fig 13). There is some suggestion that future increases may be slightly reduced in CPM_fix (25% increase over land in CPM_UKCP compared to 22% increase in CPM_fix). Individual model responses vary considerably on adding more years of data, due to the effects of internal climate variability, but CPM_fix consistently shows smaller future increases in mean winter precipitation than CPM_UKCP (Table 4). The differences between the CPM_fix and CPM_UKCP responses, however, are smaller than the standard deviation of UKCP CPM ensemble and thus are not significant in the context of the ensemble spread (Fig 13). They are also considerably smaller than the differences between the CPM and RCM responses, with the RCM showing a much smaller increase in mean winter precipitation over land (12% increase) compared to either CPM.
- Consistent with the results above, the graupel code error has only a small impact on future changes to the frequency and mean intensity of wet hours in winter (Fig 14). CPM_fix consistently shows smaller future increases in mean winter hourly precipitation occurrence than CPM_UKCP on adding more years of data (Table 4), but the difference in responses is considerably smaller than the standard deviation in responses across the UKCP CPM ensemble (Fig 14). The much greater increases in terrestrial winter precipitation occurrence in the CPM, compared to the RCM, are still apparent. Over land, winter precipitation frequency increases by 18% in the original CPM_UKCP, and 15% in the CPM_fix, compared to only 2% in the RCM.
- Future changes in summer precipitation are not significantly different between the original and fixed-code CPM runs, for the mean, intensity and frequency of hourly precipitation (with differences all smaller than the UKCP CPM ensemble spread, Figs 15 & 16). Future decreases in summer mean precipitation remain similar between the CPM and RCM (24% decrease in CPM_UKCP, 25% decrease in CPM_fix and 24% decrease in RCM). Future increases in the mean wet hour intensity in summer remain significantly larger in the CPM compared to the RCM (10% increase in the CPM compared to 4% increase in the RCM).

3y-6y-9y-12y-16y-19y	**RCM**	**CPM_UKCP**	**CPM_fix**
DJF Mean Change (%)	2-3-11-12-14-12	9-11-20-21-26-25	6-9-18-19-24-22
DJF Freq Change (%)	4-(-2)-4-4-4-2	12-9-16-17-20-18	7-6-13-15-17-15
DJF Inten Change (%)	(-2)-5-7-9-10-10	(-2)-2-4-4-5-6	(-1)-3-4-4-6-6
JJA Mean Change (%)	(-5)-(-19)-(-17)-(-27)-(-24)-(-24)	0-(-16)-(-15)-(-28)-(-24)-(-24)	(-2)-(-17)-(-16)-(-29)-(-25)-(-25)
JJA Freq Change (%)	(-11)-(-20)-(-20)-(-28)-(-27)-(-27)	(-10)-(-20)-(-20)-(-30)-(-30)-(-31)	(-11)-(-21)-(-21)-(-31)-(-31)-(-32)
JJA Inten Change (%)	7-1-2-0-4-4	11-5-6-3-10-10	10-5-6-4-10-10

Table 4: Convergence of results looking future changes in hourly precipitation metrics on adding more years of model data from 3 to 19 years. Shown are average changes (in %) over land regions.

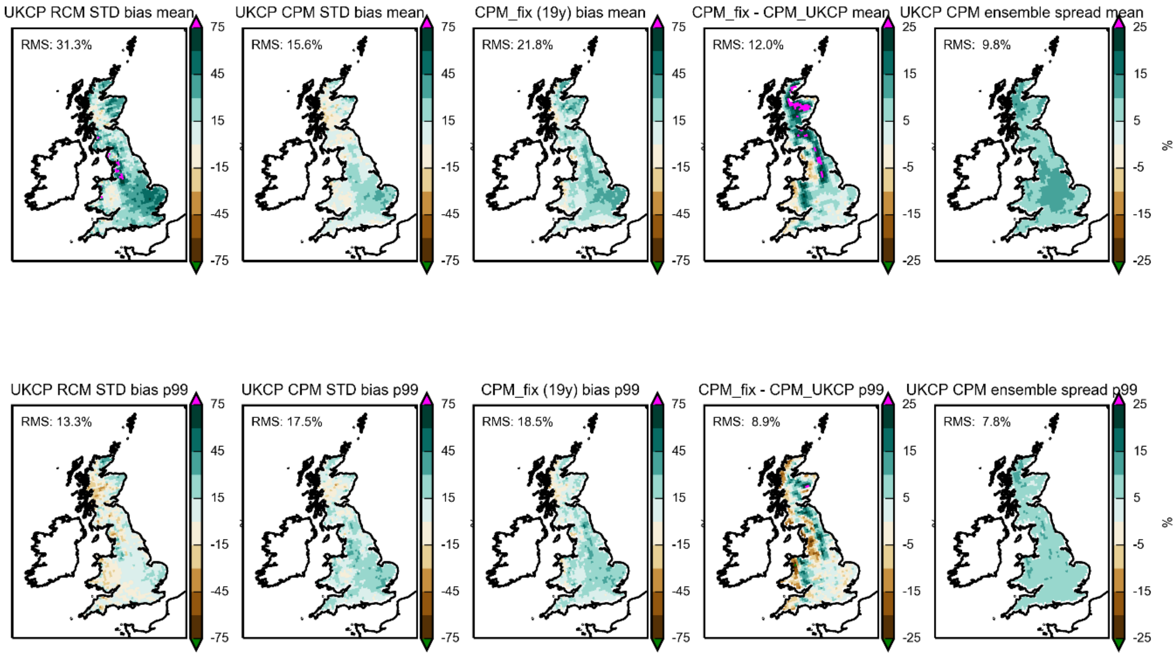

Fig 9. Present-day performance in representing the (top) mean and (bottom) 99th percentile of hourly precipitation in winter. Shown are (left) RCM model bias, (centre left) original UKCP CPM model bias and (centre) test CPM model bias with graupel code error fixed, for the standard unperturbed ensemble member compared to CEHGEAR observations. Also shown (centre right) are differences between the fixed-code (CPM_fix) and original CPM_UKCP and (right) the standard deviation across the original 12-member UKCP CPM ensemble. For all models 19 years of data are used corresponding to the period Dec 1980 to Nov 1999. For CEHGEAR, 15 years of data (1990-2014) are used.

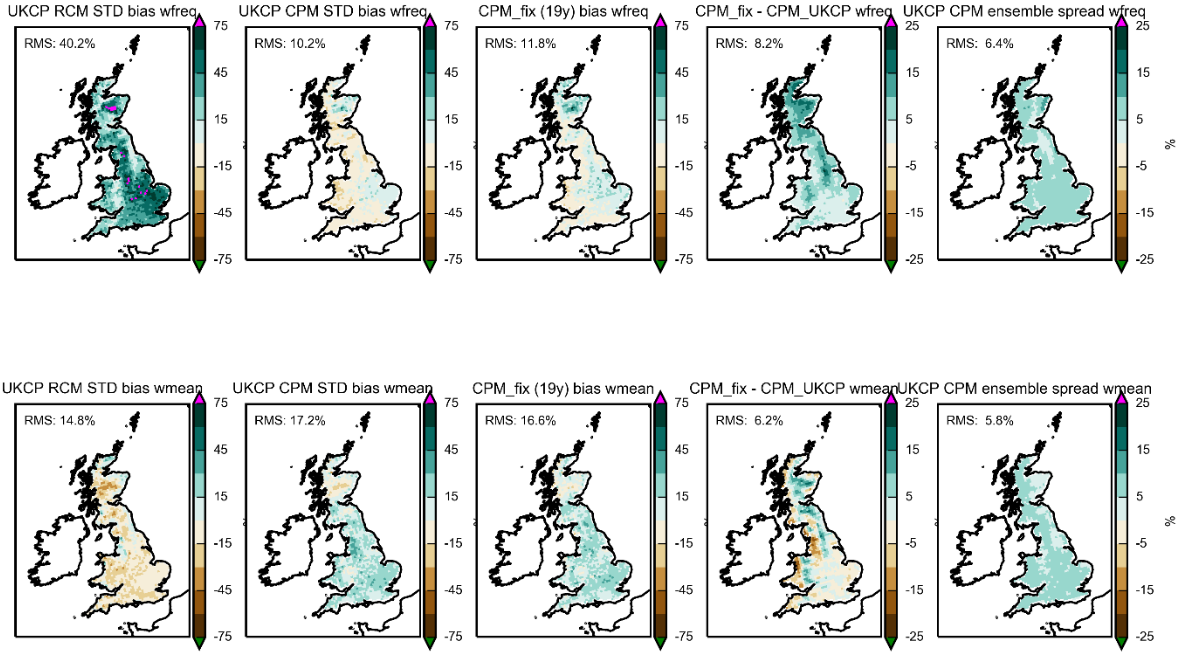

Fig 10. Present-day performance in representing the (top) frequency and (bottom) intensity of hourly precipitation in winter. As Fig 9, except for the frequency and mean intensity of wet hours, defined as hours with at least 0.1mm/h.

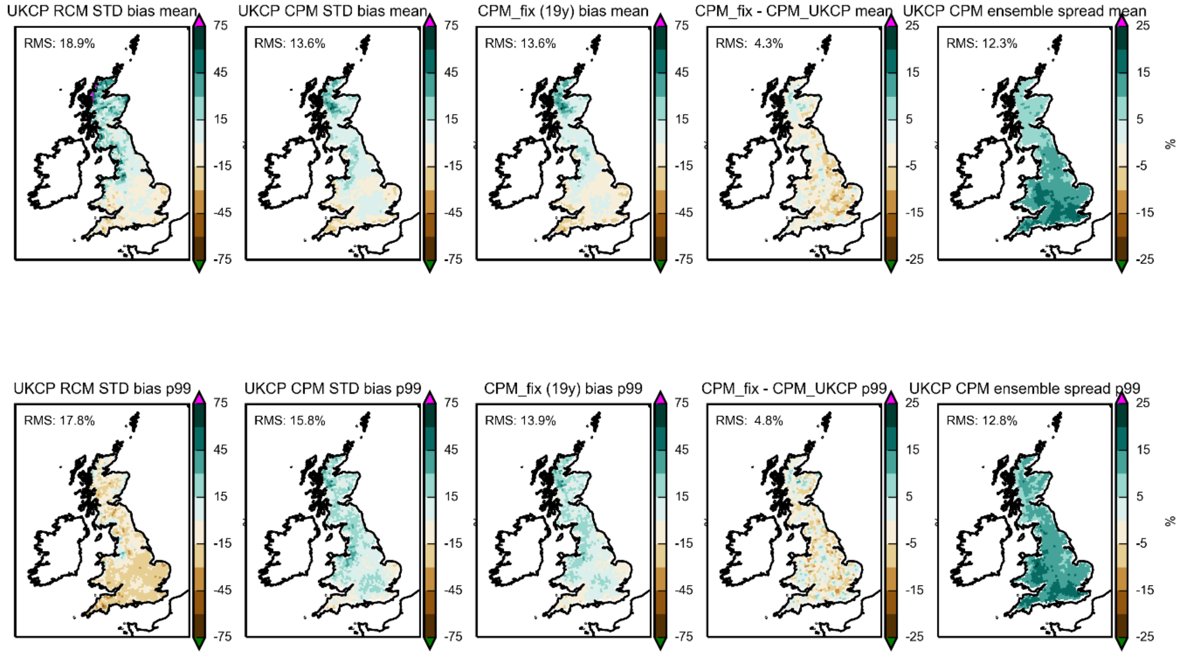

Fig 11. Present-day performance in representing the (top) mean and (bottom) 99th percentile of hourly precipitation in summer. As Fig 9, but for summer.

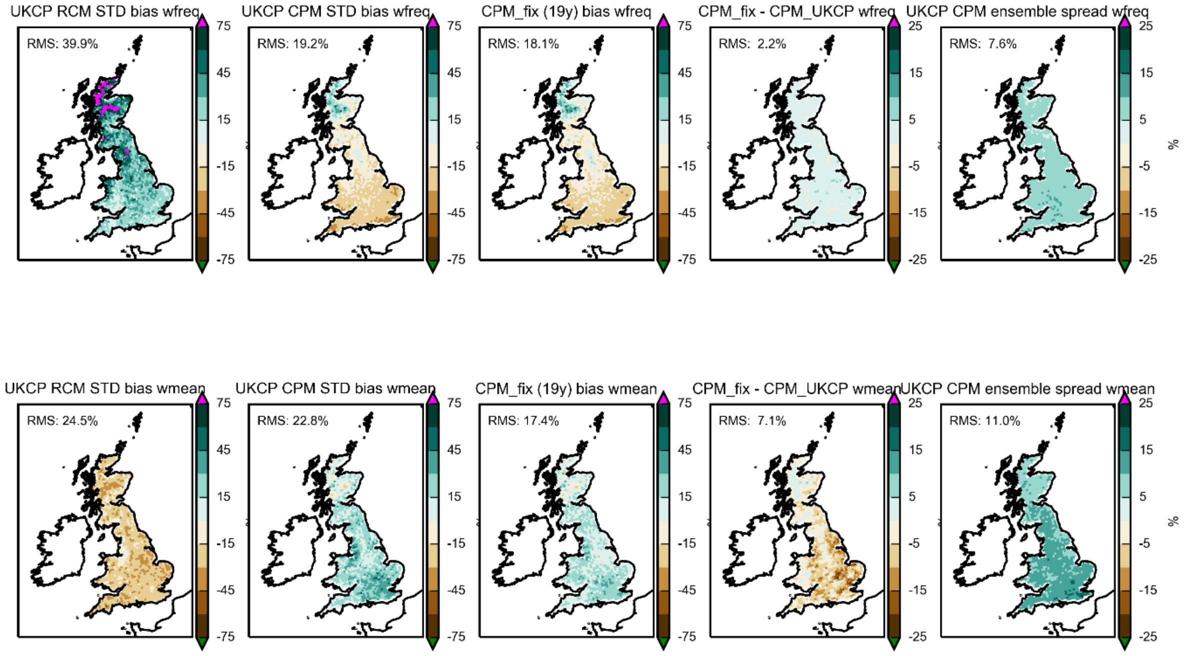

Fig 12. Present-day performance in representing the (top) frequency and (bottom) intensity of hourly precipitation in summer. As Fig 9, except for the frequency and mean intensity of wet hours, defined as hours with at least 0.1mm/h, in summer.

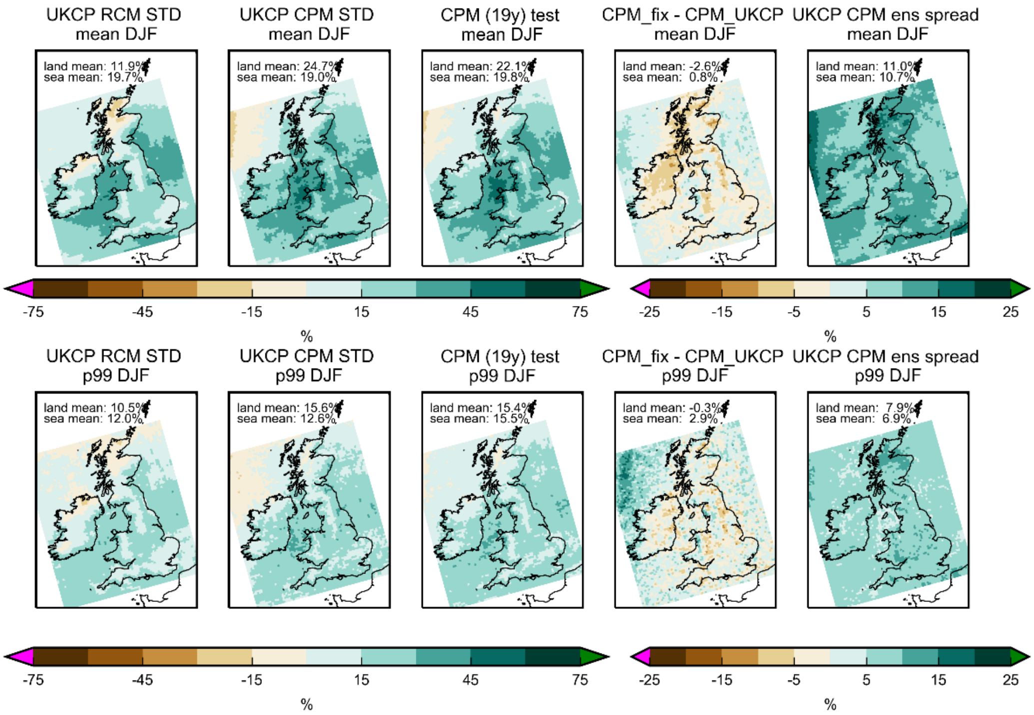

Fig 13. Future changes in (top) mean and (bottom) 99th percentile of hourly precipitation in winter. Shown are responses (%) for (left) RCM, (centre left) original UKCP CPM and (centre) test CPM with graupel code error fixed (CPM_fix), for the standard unperturbed ensemble member. Also shown are

(centre right) differences in responses between CPM_fix and CPM_UKCP and (right) the standard deviation of responses across the original 12-member UKCP CPM ensemble. 19 years of data for each of the future (Dec 2060 to Nov 2079) and present-day (Dec 1980 to Nov 1999) periods are used.

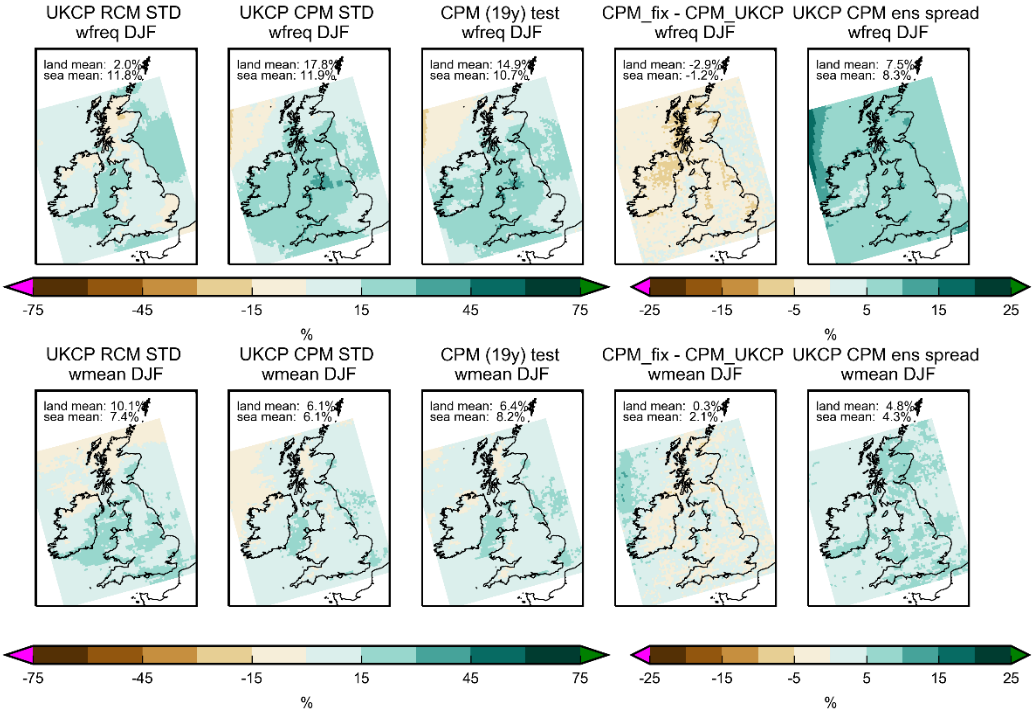

Fig 14. Future changes in (top) frequency and (bottom) intensity of hourly precipitation in winter. As Fig 13, but for frequency and intensity of hourly precipitation.

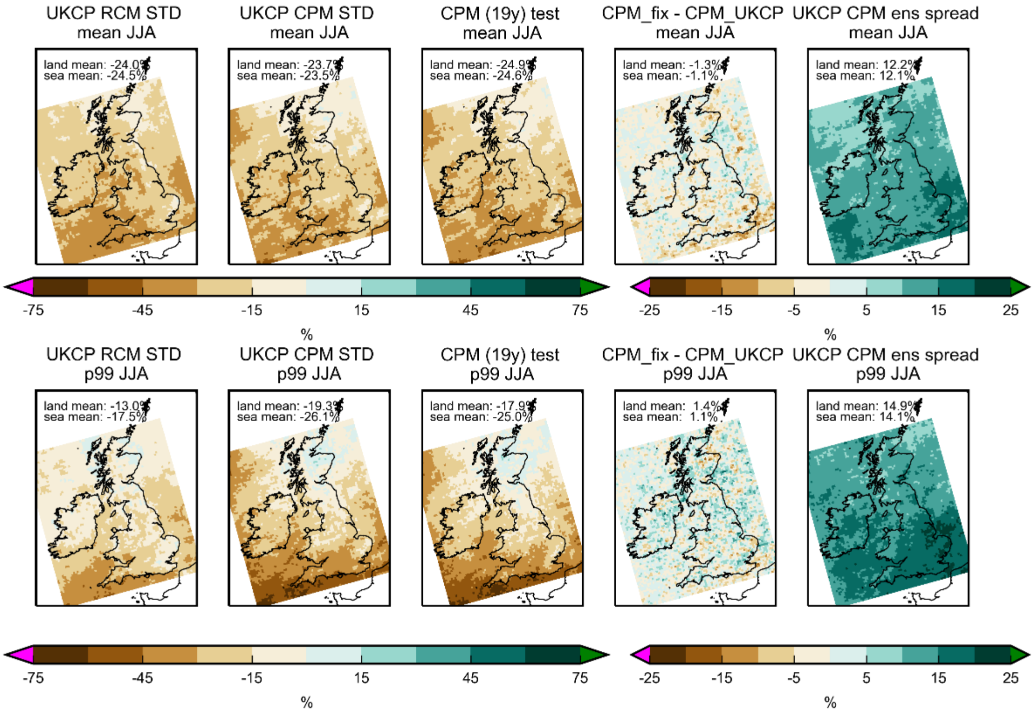

Fig 15. Future changes in (top) mean and (bottom) 99th percentile of hourly precipitation in summer. As Fig 13, but for summer.

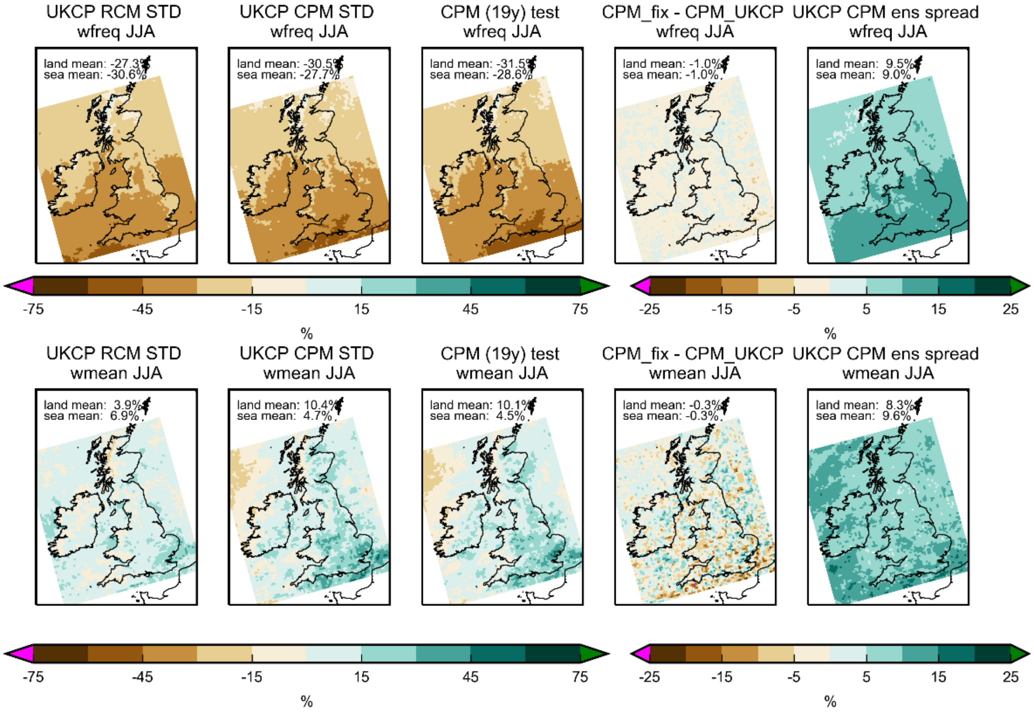

Fig 16. Future changes in (top) frequency and (bottom) intensity of hourly precipitation in summer. As Fig 13, but for frequency and intensity of hourly precipitation in summer.

Impact on precipitation extremes

As above, the results here are based on using 19 years of data from a single ensemble member, and so the estimation of return levels is subject to uncertainty. Therefore, we focus on relatively modest extremes, specifically the 2-year and 5-year return levels of hourly and daily precipitation. In order to assess whether the impact of the graupel code error is significant, we compare differences on fixing the graupel with the spread across the original 12-member CPM ensemble. The key results are as follows:

Hourly precipitation extremes:

- The graupel code error has a significant impact on present-day return levels of hourly precipitation extremes, even in summer, and a smaller but significant impact on future changes.
- Present-day 2-year and 5-year return levels are reduced by about 20% on average across the UK on fixing the graupel code error. This is the case on using data from all seasons and on using data just from summer (which for hourly extremes largely dominates the all-year result, Figs 17 & 18). The magnitude of the differences on fixing the graupel code error are larger than the original UKCP CPM ensemble spread across almost all of the UK (for the 5-year return level the UK-average difference on fixing the graupel is 3.3 mm/h compared to an ensemble standard deviation of 1.6 mm/h, Fig 17).
- Future increases in 2-year and 5-year return levels are slightly greater (29% increase becomes 36% increase for 5-year return level) on fixing the error (Fig 19). In the case of the 5-year return level, these differences are of a similar magnitude to the original UKCP ensemble spread in future changes (Fig 19). Similar results are seen for summer (Fig 20): in this case the ensemble spread is larger, but the impact of fixing the error can still exceed the ensemble standard deviation locally.
- Preliminary results looking at the 10-year return level of hourly precipitation extremes (not shown) suggest that the impact of the graupel code error on the 10-year return level is very similar to that for the 5-year return level with about a 20-25% reduction in the present-day value, an increase in the future change (from 28% to 36%), and the difference in uplifts of a similar magnitude to the ensemble standard deviation. With only 19-years of data from a single ensemble member, it is not possible to investigate the impact of the graupel code error on longer return period events.
- The above results indicate that there is a significant impact of the graupel code error on present-day return levels of hourly precipitation extremes and, although to a lesser extent, their future changes. If all ensemble members are impacted by the graupel code error in a similar way to this single-member test there may be a systematic shift in the ensemble projected change of about 5-10% which could be important for some applications.

Daily precipitation extremes:

- The impact of the graupel code error is less for daily precipitation extremes than hourly precipitation extremes. For daily extremes, the graupel code error has a small, but locally significant, impact on present-day return levels, but (in contrast to hourly extremes) does not have a significant impact on future changes.
- Present-day 2-year and 5-year return levels of daily precipitation extremes are reduced by about 5% on average across the UK on fixing the graupel code error (Fig 21). These differences are larger than the original UKCP CPM ensemble spread over western areas, and so are significant locally.

- Future increases in 2-year and 5-year return levels of daily precipitation are not significantly impacted on fixing the error, with differences smaller than the original UKCP CPM ensemble spread (Fig 22). In this case return levels in the present-day and future periods are impacted similarly by the graupel code error, and compensate each other to give a little impact on the future change.

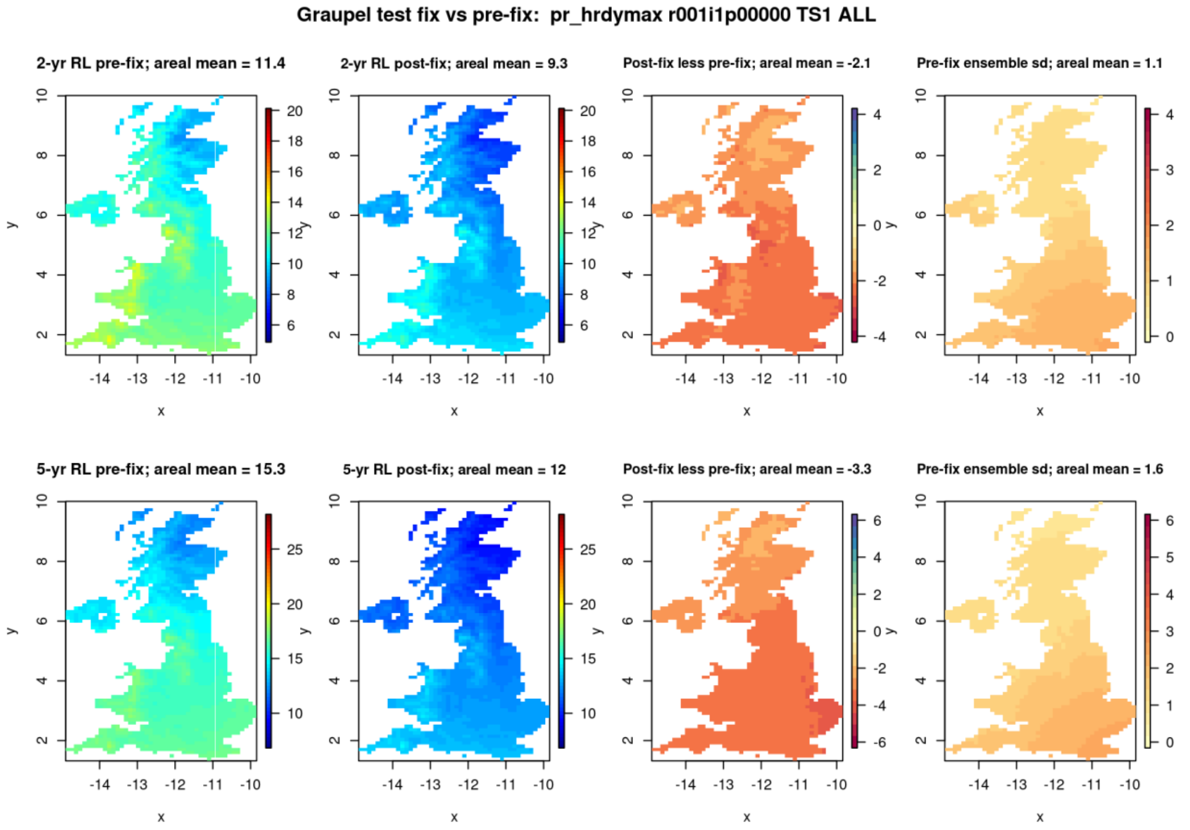

Fig 17. Present-day 2-year and 5-year return levels of annual hourly precipitation extremes. Shown are results for (left) original UKCP CPM standard member, (left centre) CPM with graupel code error fixed, (centre right) the difference (CPM_fix minus CPM_UKCP) and (right) the standard deviation across the original UKCP 12-member CPM ensemble. 19 years of data are used corresponding to the period Dec 1980 to Nov 1999. Extremes are calculated using daily maximum hourly precipitation data, from all seasons.

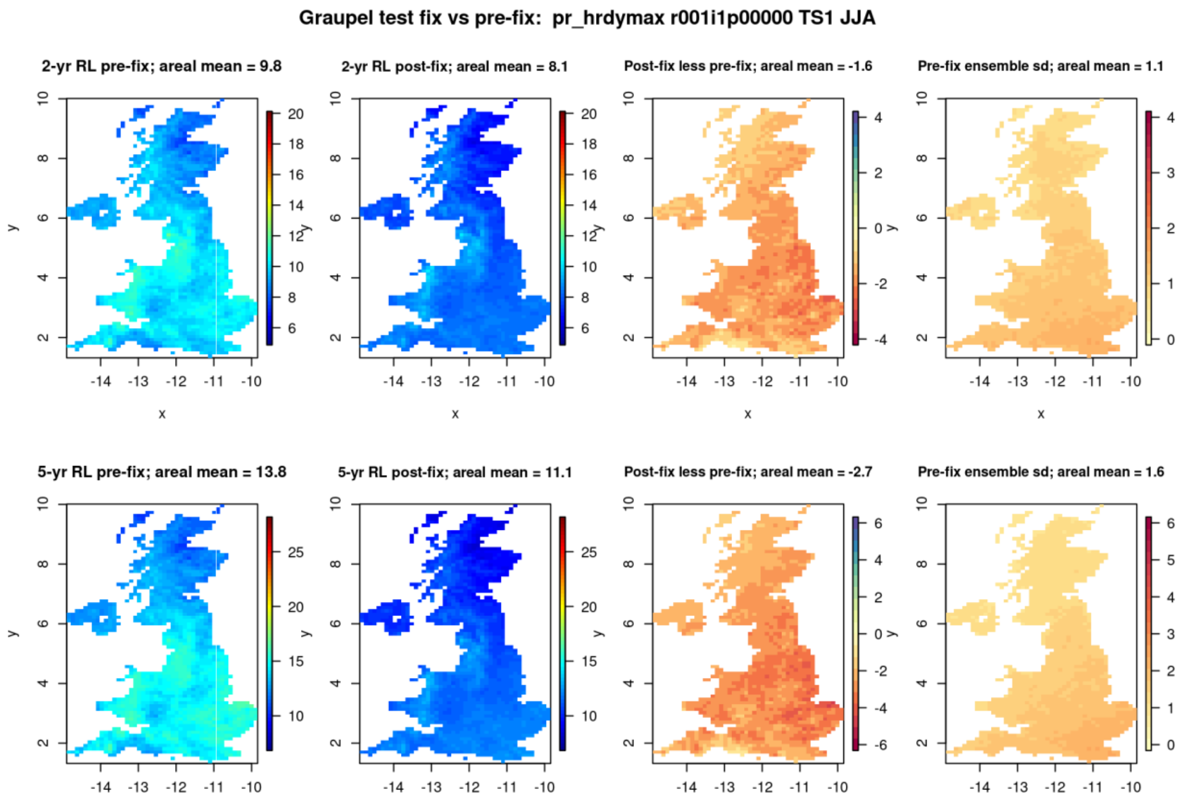

Fig 18. Present-day 2-year and 5-year return levels of summer hourly precipitation extremes. As Fig 17, but extremes are calculated using daily maximum hourly precipitation data, from summer only.

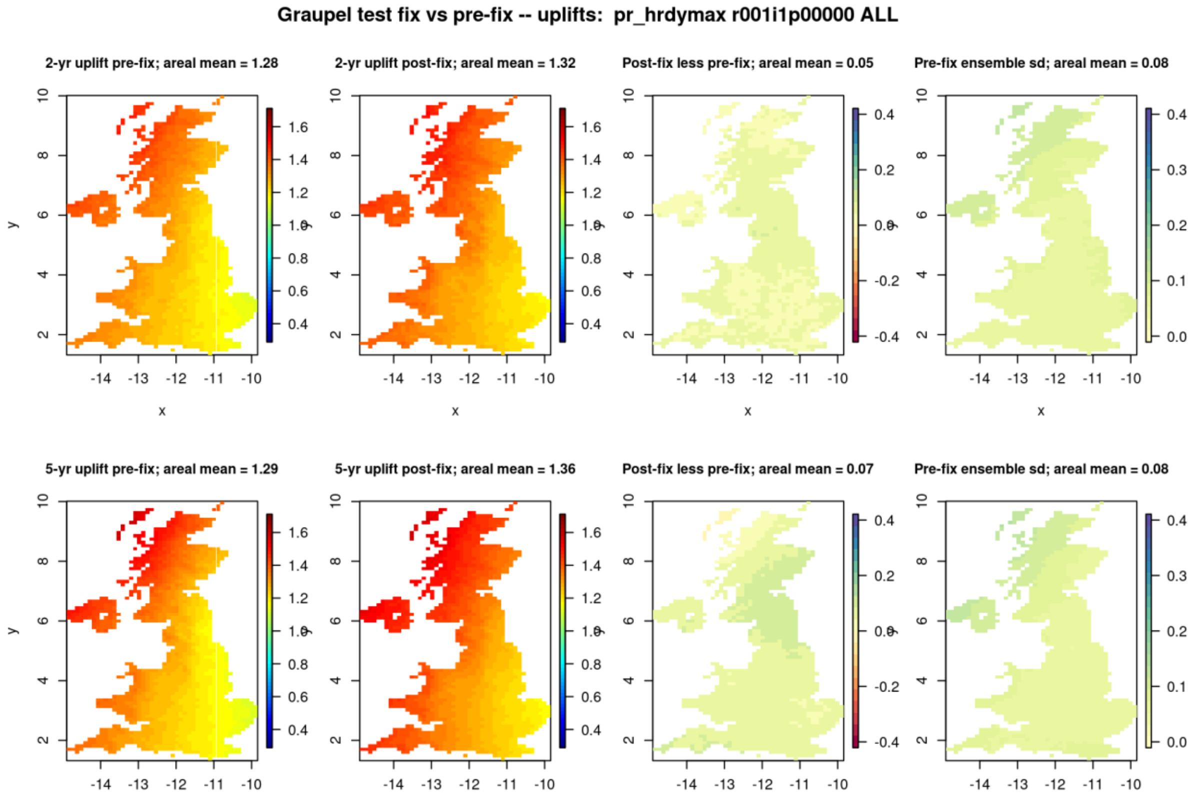

Fig 19. Future changes in 2-year and 5-year return levels of annual hourly precipitation extremes. Shown is the ratio of future to present-day return levels (RL uplift) for (left) original UKCP CPM standard member, (centre left) CPM with graupel code error fixed, (centre right) the difference

(CPM_fix uplift minus CPM_UKCP uplift) and (right) the standard deviation of RL uplifts across the original UKCP 12-member CPM ensemble. 19 years of data are used corresponding to the period Dec 1980 to Nov 1999 for present-day and Dec 2060 to Nov 2079 for future. Extremes are calculated using daily maximum hourly precipitation data, from all seasons.

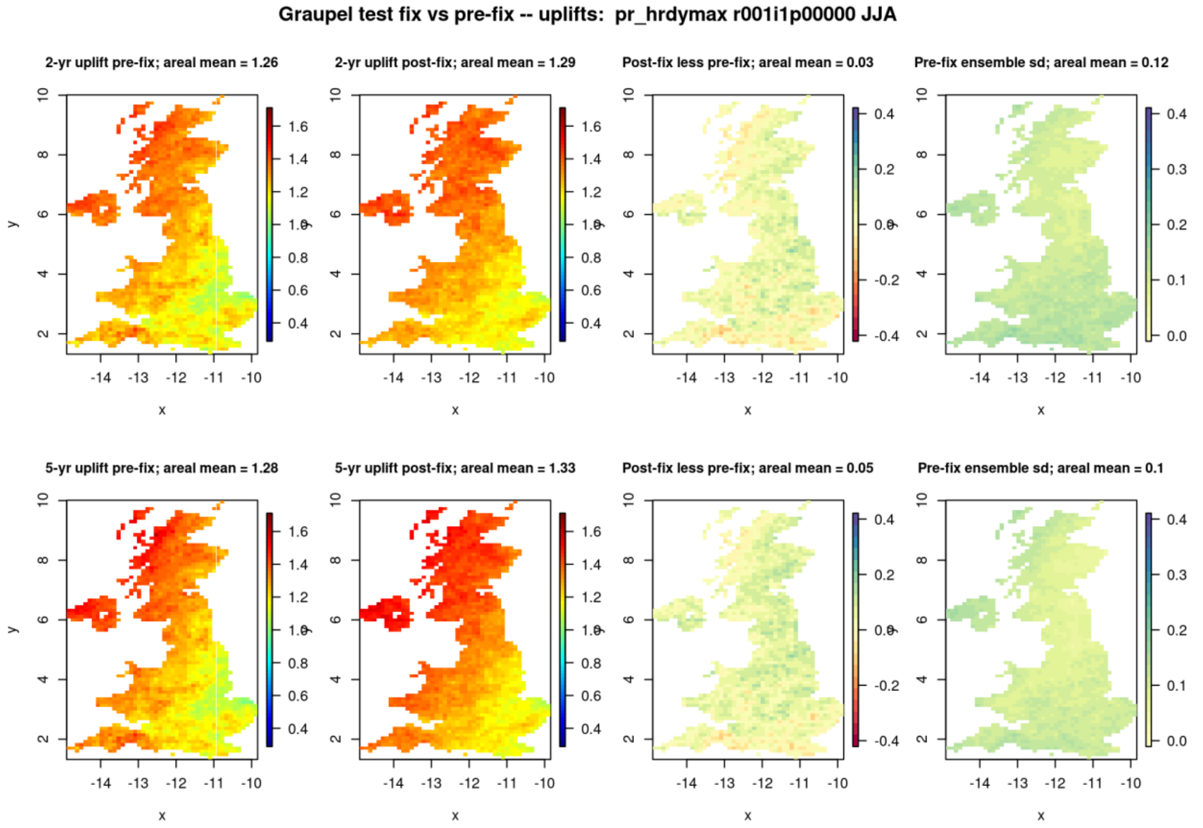

Fig 20. Future changes in 2-year and 5-year return levels of summer hourly precipitation extremes. As Fig 19, but using daily maximum hourly precipitation data from summer only.

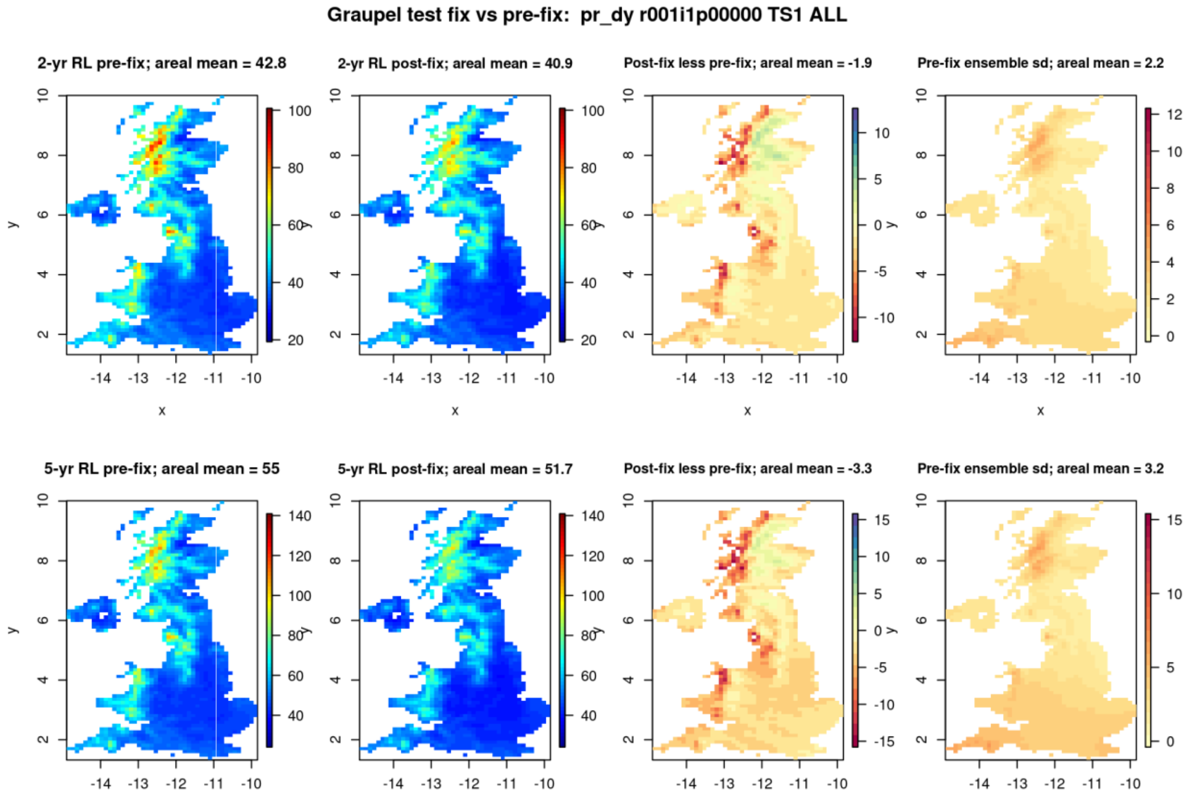

Fig 21. Present-day 2-year and 5-year return levels of annual daily precipitation extremes. As Fig 17, but for daily precipitation extremes. Extremes are calculated using daily mean precipitation data, from all seasons.

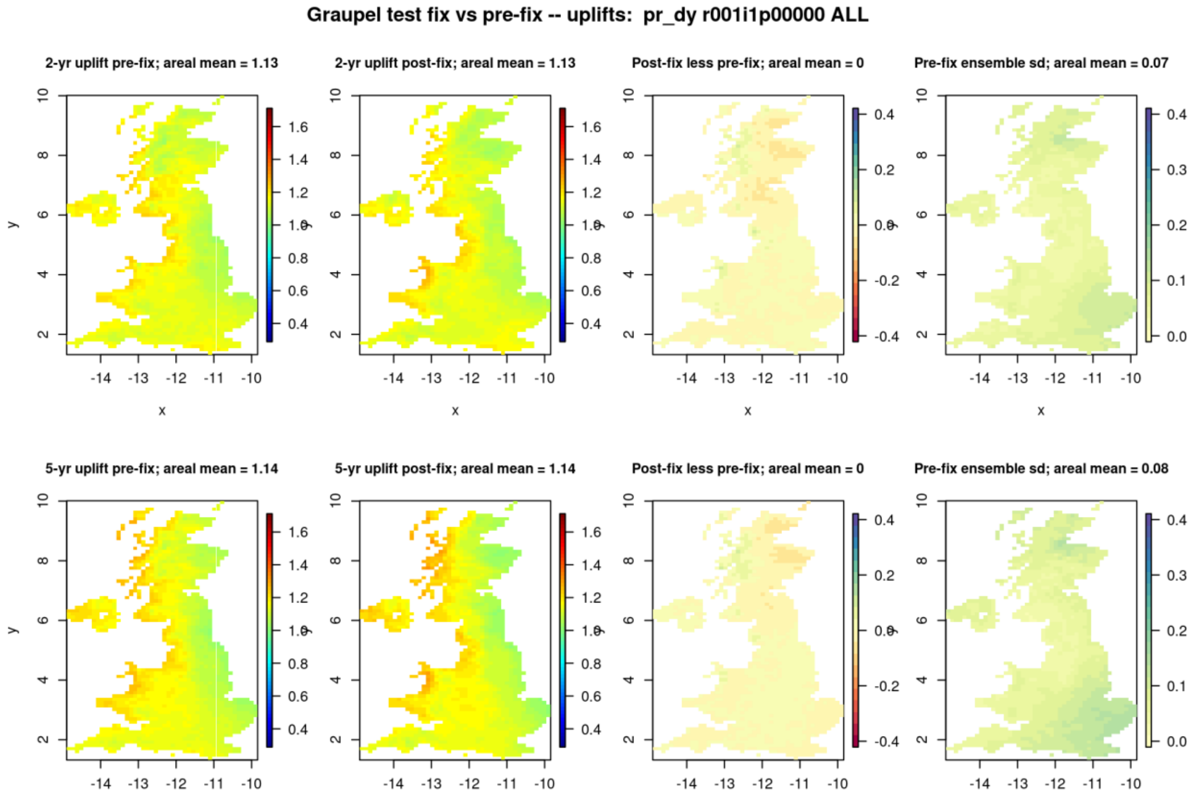

Fig 22. Future changes in 2-year and 5-year return levels of annual daily precipitation extremes. As Fig 19, but for daily precipitation extremes. Extremes are calculated using daily mean precipitation data, from all seasons.

Impact on surface winds

Present-day performance:

- Daily maximum wind speeds are increased in the graupel fixed run (CPM_fix). For mean values (Fig 23 top), differences are larger than the standard deviation across the original UKCP CPM ensemble over the sea to the north-west of the UK but only for a few points over land (e.g. Cairngorms, some coastal regions in the west of Ireland, Fig 23). Elsewhere differences are smaller than the ensemble spread.
- For present-day wind extremes (99th percentile of daily max wind speeds, Fig 23 bottom), on fixing the graupel code error differences are larger than the ensemble spread over Ireland and over most of the ocean in the western half of the domain. Over Scotland, England and Wales, the differences are generally similar to or smaller than the ensemble spread and so the effect of the fix is not significant, apart from local regions such as the Outer Hebrides.

Future changes:

- In general, there is no significant impact of fixing the graupel code error on future changes in surface wind speed. For mean daily maximum wind speeds (Fig 24 top), the differences in changes in the mean daily max wind speed are less than the original UKCP CPM ensemble spread across the domain, except for a few points over the Cairngorms.
- For future changes in wind extremes (Fig 24 bottom), differences on fixing the graupel code error are also less than the ensemble spread, apart from the odd cluster of grid points mainly located over the sea.
- Although fixing the graupel code error can have a significant impact on daily maximum wind speeds in the present day, impacts are largely consistent in the present-day and future periods, resulting in future changes being largely unaffected.

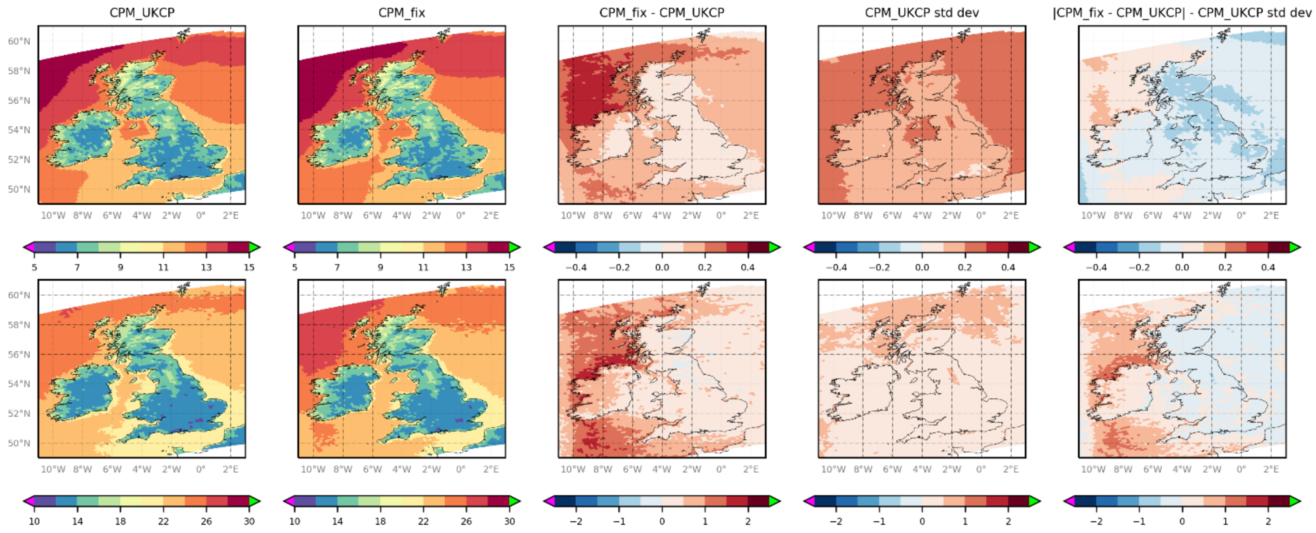

Fig 23. Impact of graupel code error on present-day surface wind speed for (top) the mean and (bottom) the 99th percentile of daily maximum wind speed. Shown are results for (left) original UKCP CPM standard member, (left centre) CPM with graupel code error fixed (CPM_fix), (centre) the difference (CPM_fix minus CPM_UKCP), (centre right) the standard deviation across the original UKCP 12-member CPM ensemble and (right) the difference on fixing the error minus the ensemble standard deviation. 19 years of data are used corresponding to the period Dec 1980 to Nov 1999.

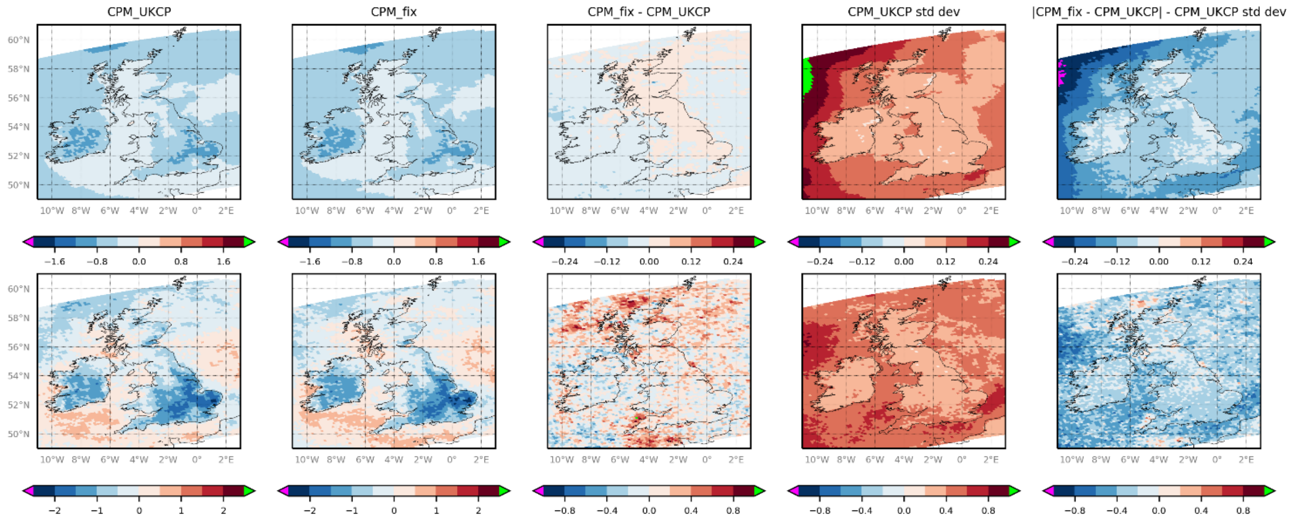

Fig 24. Future changes in surface wind speed for (top) the mean and (bottom) the 99th percentile of daily maximum wind speed. Shown are responses for (left) original UKCP CPM and (centre left) CPM with graupel code error fixed (CPM_fix), for the standard unperturbed ensemble member. Also shown are (centre) differences between the CPM_fix and CPM_UKCP responses, (centre right) the standard deviation of responses across the original 12-member UKCP CPM ensemble and (right) the difference on fixing the error minus the ensemble standard deviation. 19 years of data for each of the future (Dec 2060 to Nov 2079) and present-day (Dec 1980 to Nov 1999) periods are used.

Impact on lighting

Lightning data was not released to users in the original UKCP Local (2.2km) projections launched in September 2019. This was due to issues around the verification of lightning in the CPM compared to Arrival Time Difference Network (ATDnet) observations. Therefore, only a subjective evaluation of lightning output from the CPM was possible, as discussed in the UKCP CPM science report (Kendon et al., 2019). Initial results suggested that the UKCP CPM overestimates lightning in winter but performs better in summer in terms of representing the UK-average occurrence rate, but with potential deficiencies in the spatial distribution of lightning. It is likely that these deficiencies were at least in part due to the graupel code error in the original UKCP CPM.

Overall, we find that lightning occurrence is reduced in the run with the graupel code error fixed (CPM_fix), consistent with a reduction in excessive graupel. Here we present results from a case study looking at graupel, lightning and precipitation on the 6th July 1983 (Fig 25). The graupel amounts are considerably reduced in CPM_fix, and some unrealistic features present in CPM_UKCP, such as an unusual linear feature near the western boundary of the simulation domain and rectangular-shaped features in Ireland (which are clear indications of the graupel code error), are not apparent in CPM_fix. Consistent with these graupel differences, lightning occurrence is also reduced in CPM_fix, along with the removal of similar unrealistic features. It is notable that despite significant differences in graupel amounts and lightning, away from the simulation domain boundary, precipitation rates are very similar between the original and fixed-code runs.

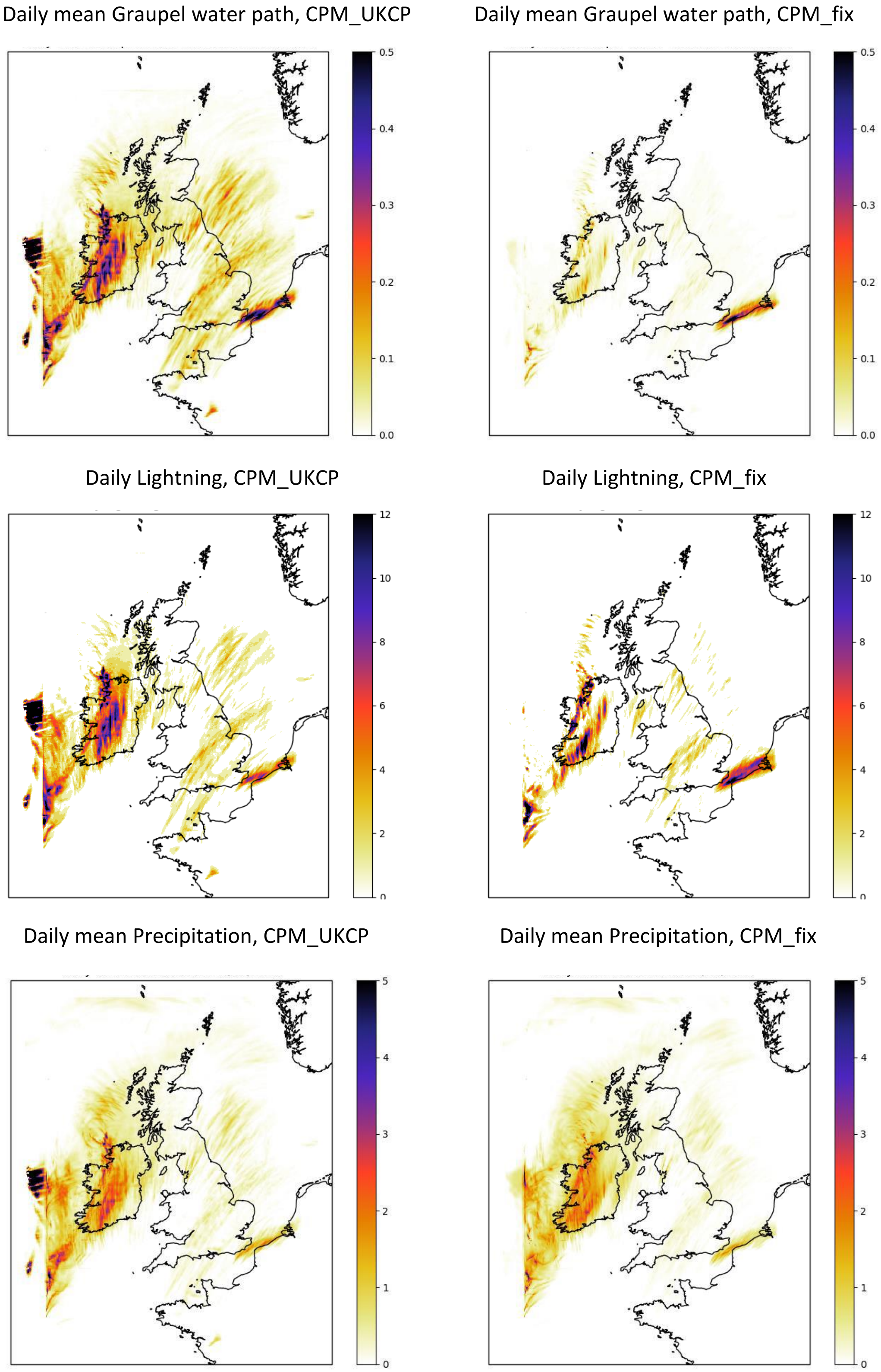

Fig 25. (top) Daily mean graupel water path, (middle) total lightning flash counts per day and (bottom) daily mean precipitation in mm/h, for the case of 6th July 1983, with the original CPM_UKCP on the left and the fixed-code model run (CPM_fix) on the right.

Additional changes and timeline for new runs

In addition to the graupel code error, a couple of other issues have been recently found that effect the UKCP Local (2.2km) projections. Firstly, an error has been found in the calculation of grid box latitude and longitude coordinates provided to the radiation scheme. In the case of variable resolution configurations like the UKCP CPM, the calculation was performed as if all grid boxes are evenly spaced. Consequently, the incoming solar radiation has a largely symmetrical error with not enough incoming radiation in the North of the domain and too much in the South. The magnitude of the error is largest in winter where it reaches 3.5 W m^{-2} for the UKCP 2.2km CPM domain. Initial results suggest that the impact on surface variables is minimal with surface temperature differences less than 0.05°C, nevertheless we plan to additionally fix this grid coordinate error in the new 2.2km CPM runs.

Secondly an error has been found in the code used to generate Easy Aerosol (Stevens et al 2017) ancillaries used in both the UKCP Regional (12km) and Local (2.2km) projections. The error was in the pre-processing code that converts diagnostics output from the 60km GCM to Easy Aerosol input files. It resulted in daylight hours weighting, which is used to calculate shortwave aerosol radiative effects, being set at 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. 10-year test simulations were carried out to assess the impact of this daylight-hours error. In the RCM, the impact was found to be small and less than the spread across the 12-member ensemble (except for precipitation where local differences could be large reflecting just noise due to natural variability). The impact was found to be greatest over central/eastern Europe, where future increases in temperature may be overestimated (by up to 1°C in winter and 0.5°C in summer) in the UKCP Regional projections; over the UK impacts are much smaller (with maximum local impacts of 0.2-0.3°C). On this basis the error was judged to be not significant and there was no evidence to support a rerun of the Regional (12km) projections. Similar results were found on assessing the impact of the daylight-hours error in the CPM. Although the impact of the error is small, we plan to additionally fix this error in the new 2.2km CPM runs. We note that this will introduce a small inconsistency in the aerosol forcing between the 2.2km CPM and the 12km 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 thus is associated with significant uncertainty anyway.

We are also considering additional science changes to include before starting the full set of experiments. Scientific understanding is continually moving forward, and we are considering going beyond the state of understanding at the time of the original UKCP 2.2km release and in particular to include some recent model improvements, where these changes are well tested and known to lead to significant benefits. This includes adding new code which acts to melt graupel at the surface, along with the multi-layer snow scheme. These changes will allow a more physical treatment of graupel and mean that it can be included in the snowpack, rather than just being ignored by the Joint UK Land-Environment Simulator (JULES) land surface model (thereby breaking conservation of water at the surface) as is the case in the original UKCP 2.2km CPM. Using the multi-layer snow scheme, which is a more sophisticated treatment of snow and is now implemented operationally in the UKV, has the added benefit of increasing consistency between the 2.2km CPM and driving 12km RCM (which uses the multi-layer snow scheme).

Testing of these additional science changes is underway and a decision from the UKCP project team will be made which to include, once sufficient data is available to assess the science impact of the new code in the UKCP configuration.

New 2.2km CPM data will be issued, with a planned release for Spring 2021. 20-year runs will take 6 months on the supercomputer, with simulations for time-slice 1 (1980-2000), 2 (2020-40) and 3 (2060-80) all being run in parallel. It is planned that, at least initially, the original UKCP 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.

As a further enhancement for users, not available in the original UKCP 2.2km release, additional simulations for the intervening time periods (2000-2020 and 2040-2060) will be started once time-slices 1-3 are complete. Once these additional simulations are complete, this data will also be provided to users. This represents a key advance, providing for the first time continuous 100-year timeseries of 2.2km data from 1980 to 2080.

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