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Hadley Centre Technical Note 108:

Evaluating Convection-Permitting Climate Models over the Shetland Islands

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1. Summary Findings

This work aims to investigate whether there is robust climate model information about heavy rainfall events over the Shetland Islands. Most of the UK will be covered by climate information from the FUTURE-DRAINAGE project (Dale et al., 2021); however, this does not cover the Shetland Islands. We assessed convection-permitting model results from the UK Climate Projections (UKCP) over the rest of Scotland, and the European Climate Predictions (EUCP) over Shetland alongside convection-parametrised models from UKCP. We have also assessed whether the changes from the nearby Orkney Islands would be representative of the changes seen over Shetland. However, the requested use of thresholds would lack statistical rigour, because the thresholds are exceeded so rarely even in observational data given for how long the weather has been recorded; instead, we focus on the 99.95th percentile of hourly rainfall.

The climate model data are:

- EUCP CPM, a convection-permitting single model run at 2.2km, covers both Orkney and Shetland.
- UKCP Local, a convection-permitting ensemble at 2.2km, covers Orkney not Shetland.
- UKCP Regional, a convection-parameterised ensemble at 12km, covers both Orkney and Shetland.

We use these data to explore the following research questions

How well do the models compare to observations?

On annual, seasonal and daily timescales, the differences between observations and the EUCP CPM falls within the spread of the differences between observations and the UKCP ensembles, meaning the models agree well with each other in the recent climate. In the hourly data, these biases vary with location on Shetland and with season.

How much value is added by using a high-resolution convection-permitting model, compared to the lower resolution model?

Given that the EUCP CPM is typically within the spread of the UKCP Regional ensemble for precipitation on annual, seasonal and daily timescale, the advantages of using a convection-permitting model (i.e. EUCP CPM) over convection-parameterised models (UKCP Regional) are limited on these timescales. However, the convection-permitting models (CPMs) are much more reliable on sub-daily timescales due to improved representation of convection (Kendon et al. 2019, Fig 2.2). Unlike coarser resolution climate models, CPMs are able to capture the diurnal cycle of rainfall and hourly rainfall extremes. We do not recommend use of UKCP Regional for analysis for rainfall on sub-daily timescales.

How is the climate projected to change in the future? How robust are the future changes?

For seasonal average rainfall, the projections show drier summers and wetter autumns, winters and springs over Shetland. On hourly timescales, the 99.95th percentile of rainfall is projected to increase by the late 21st century in summer, autumn, and winter, with a more mixed picture in spring. However, the UKCP Local ensemble indicates that there is a wide range of possible future projections of heavy rainfall over Orkney.

Comparing models to observations assesses how realistic the model is, and gives some indication of how reliable the model projections are for the future; however, we note that good performance in the past does not necessarily mean good performance in the future. On daily timescales, the differences are similar in magnitude to the future changes, so the future changes are difficult to quantify, for both average and heavy rain. On hourly timescales for heavy rainfall, the future changes are larger in autumn and winter, are similar in summer, and smaller in spring, compared to the differences between the model and the observations.

Another way to understand how robust the future changes are is to compare the magnitude of the future changes to the current climate's year-to-year variability ('signal-to-noise'), to provide context for the detectability of the climate change 'signal'. For heavy daily or hourly rainfall, the future changes are smaller than the year-to-year variability so the future change signal is less robust. Note that other methods of testing for robustness are available, but would require greater data availability.

Recommendations

This work recommends combining use of UKCP Regional and EUCP CPM data over Shetland. This is because the EUCP CPM gives sub-daily information, whereas UKCP Regional ensemble give an idea of uncertainty in the future changes and the range of possible futures for one emissions scenario, as well as covering 100 years compared to the EUCP CPM's 10 years. The spread in projections of heavy hourly rainfall over Orkney means that careful consideration should be given to the treatment of uncertainty in decisions that utilise climate projections.

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2. Introduction

Climate projections provide the best information about how the climate could change in the coming decades. Many assessments of climate change (e.g. IPCC, 2021) compare different climate models and different versions of models, to ascertain where there is strong agreement and confidence in the projected changes and where agreement is weak. The UK Climate Projections (UKCP; Murphy et al., 2018) consist of several strands of information for assessing climate change, although all models contain some biases and should be interpreted carefully. Overall, these show warmer wetter winters, and hotter drier summers but with more heavy downpours of rain (UKCP Team, 2021).

The Shetland Islands are situated 110 miles north of the Scottish mainland, covering an area of 566 square miles with a highest point at 450m (1,480ft). The Islands have a climate that is strongly influenced by the proximity of the sea. They can be affected by strong winds and associated large waves (10-15m), predominately related to midlatitude cyclones in winter, which along with high tides can cause coastal flooding. As well as the associated frontal rainfall, they also experience convective rain, typically in an atmosphere unstable to sea-surface temperatures.

The UKCP Local [2.2km] simulations are run over a domain (Figure 1). The Shetland Islands are close to the edge of the domain and are partly covered by data at 4km resolution and partly by data where the resolution is slowly increasing from 4km to 2.2km. This region should not be used due to the lack of clarity regarding the split between plausible weather and model artefact in the rim of the Local model. UKCP Local rainfall data feed into the FUTURE-DRAINAGE project[1], which quantifies 'uplifts' that represent the effect climate change has on rainfall events. While the FUTURE-DRAINAGE uses the latest climate models to represent heavy rainfall events (Kendon et al., 2021) with hydrological models to provide the information needed for drainage planning (Dale et al., 2021), these data are not available over Shetland. Therefore, an alternative approach is needed over Shetland.

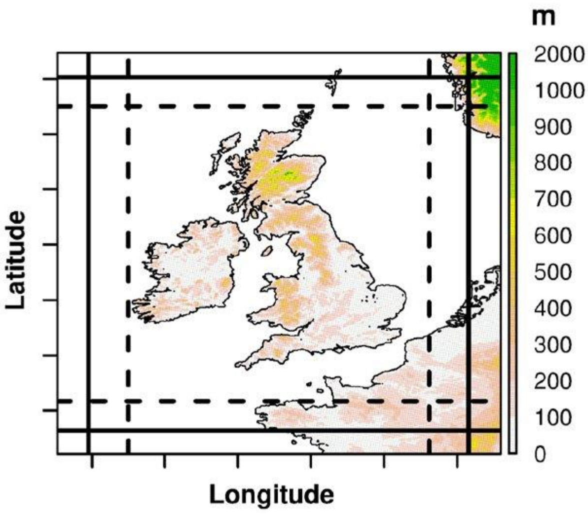


Figure 1: Map of the domain used in the UKCP Local [2.2km] projections. Outside the solid line is run at 4km horizontal resolution; inside the dashed line at 2.2km; and between the two lines the resolution gradually changes from 2.2km to 4km. From Kendon et al. (2019), Figure 2.3.1.

It is part of the Scottish Environment Protection Agency (SEPA)'s remit to provide guidance across Scotland regarding how much leeway should be given for future flooding compared to

[1] https://www.ukclimateresilience.org/projects/future-drainage-ensemble-climate-change-rainfall-estimates-for-sustainable-drainage/

recent climate; the factor is known as catchment uplift. However, compared to much of the Scottish mainland, the Shetland archipelago has smaller river catchments. This would naturally lead to a tendency to use the highest resolution data available, particularly for time as shorter duration (sub-daily) events will give a worse response. Furthermore, SEPA will update their surface water flood maps to include future scenarios that use UKCP18 data.

This work assesses what is the best approach to take over the Shetland Islands, given limited data availability. While higher resolution models are often assumed to be more realistic than their lower resolution counterparts, particularly when the former permits convection (important for heavy rainfall events), it is important to assess the models' strengths and weaknesses and ascertain what data is fit for purpose. This work aims to assess high-resolution convection-permitting climate models against lower resolution models where convection is parametrised but explore uncertainties and against observations. For rainfall over the Shetland Islands, we ask the following research questions:

1. How well do the climate models compare to observations?
2. How much value is added by using a high-resolution convection-permitting model (CPM), compared to the driving model?
3. How is the climate projected to change in future?
4. How robust are the future changes?

We discuss the data available and methods used, before presenting results. The limitation of UKCP Local data availability over Shetland could be resolved by: (1) using uplifts from Orkney as indicative of those over Shetland; (2) using another CPM projection alongside the UKCP Regional projections. These potential solutions inform the choice of data and plots used, but ultimately are the focus of the discussion section.

3. Data

This work focusses entirely on precipitation data. For observations, we use two datasets:

- HadUK-Grid data gives daily gridded data for a range of weather variables at 1km resolution, derived from observations from weather stations (Hollis et al., 2019).
- CEH-GEAR 1hr estimates hourly rainfall, derived from gauge data (Lewis et al., 2018)

For climate modelling, we use data from two projects: the UK Climate Projections (UKCP) and the European Climate Predictions (EUCP). There are some notable differences between them (see table below). While the EUCP CPM has high-resolution data over the Shetland Islands, it comprises only one model run; the UKCP models are ensembles giving an illustration of spread and uncertainty in the projected changes. Note that EUCP is being updated to include additional high-resolution CPM model runs; however, these are not included here due to the timing of data availability and using underlying climate models from different modelling centres can confuse identifying the reasons why projections differ. However, use of simulations from other modelling centres could form some work in future.

	UKCP	**EUCP**
Chosen data strand(s) [resolution space, time, emissions scenario]	Regional [12km, daily, RCP8.5] Local [2.2km, hourly, RCP8.5]	CPM [2.2km, hourly, RCP8.5]
Details	Ensemble of 12 equally-plausible potential future climates	Single model run

Domain	Regional – Europe (incl. Shetland) Local – UK (not Shetland)	CPM – Europe (including Shetland)
Dates	Regional: 1981-2080 Local: 1981-2000, 2021-2040, 2061-2080	CPM: 1998-2007, 2040-2049, 2095-2105

SEPA requested the analysis be performed for the 2050s, 2070s and late 21st century. The limited availability of years for the models mean that the time periods analysed could not be those specified by SEPA; the table below shows what time periods include which data.

SEPA specified	Years Used	Available Data
2050s	2040-2049 ie the 2040s	EUCP CPM UKCP Regional
2070s	2070-2079	UKCP Local UKCP Regional
Late C21st	2095-2105	EUCP CPM

4. Method

The aim of this work is to answer the research questions assessing the different model experiments against observations and each other, with focus on Shetland and on SEPA's use case. The method followed is similar to those in UKCP Science Reports, starting with assessing rainfall on longer timescales (e.g. annual cycle), through shorter periods until considering hourly rainfall (e.g. Kendon et al., 2021). This allows thorough assessment of the models' strengths and weaknesses, and how the differences from observations in recent climate ('biases') compare to the projections in the future. Assessing the climate model data on daily and longer timescales also allows comparison with HadUK-Grid data, whereas on hourly timescales the CEH-GEAR data are used.

4.1 Percentiles or thresholds

For this work, SEPA stated that their focus is on precipitation, including sub-daily data. SEPA operationally apply thresholds to rainfall on a range of timescales (1, 3, 6, 9, 12 and 24 hourly) from their forecasting handbook, based on observational data and expert elicitation of the impacts of different rainfall amounts. Note that these are expected to be rarely exceeded; the significant and severe impacts associated with medium and high rainfall amounts would be sufficiently disruptive that adaptation measures would be considered, especially if experienced more frequently.

Pluvial	Low	Medium	High
1-hourly [mm/hour]	15	20	30
3-hourly [mm/3hr]	20	30	40
6-hourly [mm/6hr]	25	40	50

Fluvial	Low	Medium	High
3-hourly [mm/3hr]	20 [25]	30 [40]	50 [50]
6-hourly [mm/6hr]	30 [40]	40 [60]	100 [100]
9-hourly [mm/9hr]	35 [45]	60 [80]	130 [130]
12-hourly [mm/12hr]	40 [50]	80 [100]	150 [150]
24-hourly [mm/24hr]	60 [80]	120 [140]	200 [200]

Table 1: Summary of rainfall thresholds from SEPA, that trigger flood warnings. Top are the pluvial thresholds; bottom are fluvial, with the values for wet soils first and for dry soil in square brackets.

In the below table, comparing these to the highest point value over Shetland for 99.95th percentile (by time) in CEH-GEAR 1km for different accumulation periods shows that these thresholds are rarely exceeded, even in the observational data; indeed, the medium and high thresholds never are exceeded, only the low (highlighted in yellow). However, beyond the 99.95th percentile, any analysis would lack statistical rigour due to the relatively short observational record without taking a specialist approach, such as extreme value analysis. Therefore, for high hourly rainfall rates we focus on the 99.95th percentile (as in Kendon et al., 2019 and 2021), which maintains statistical rigour while indicating how high rainfall rates are projected to change in the future.

	Winter (DJF)	Spring (MAM)	Summer (JJA)	Autumn (SON)
1-hourly [mm/hour]	7.8	6.2	9.6	8.9
3-hourly [mm/3hr]	17.5	14.0	19.5	17.9
6-hourly [mm/6hr]	29.2	21.5	33.6	27.5
9-hourly [mm/9hr]	36.3	26.4	43.3	36.9
12-hourly [mm/12hr]	42.5	31.2	48.6	43.3
24-hourly [mm/24hr]	52.3	41.6	95.0	66.8

4.2 Orkney Islands

During discussion with SEPA, one possible solution for rainfall uplifts over Shetland could be to use those uplifts provided by FUTURE-DRAINAGE for the Orkney Islands. They are geographically close, with a similar typical climate and similar exposure to wind and rain. In showery situations, the meteorological setup is likely similar. However, Orkney is closer to mainland Scotland and is more strongly influenced by it, particularly in a south-westerly wind which typically occur in meteorological situations with large-scale low pressure systems and fronts. That the highest rainfall events occur in summer and autumn implies that Shetland sees heavy rainfall caused by showers or by fronts. Therefore, careful consideration should be given as to whether uplifts in Orkney are a reasonable proxy for those in Shetland.

5. Results

5.1. How well do the models compare to observations?

Annual cycle: Over both Shetland and Orkney, Figure 2 shows the annual cycle of rainfall in the UKCP model ensembles and EUCP CPM is similar to the observations. The observations are broadly within the spread of the UKCP models, as is the case with the EUCP CPM. The one exception is in August, when the EUCP CPM is has a stronger wet bias than the UKCP ensembles over both Shetland and Orkney (where bias refers to the difference between climate model and observations in the recent climate).

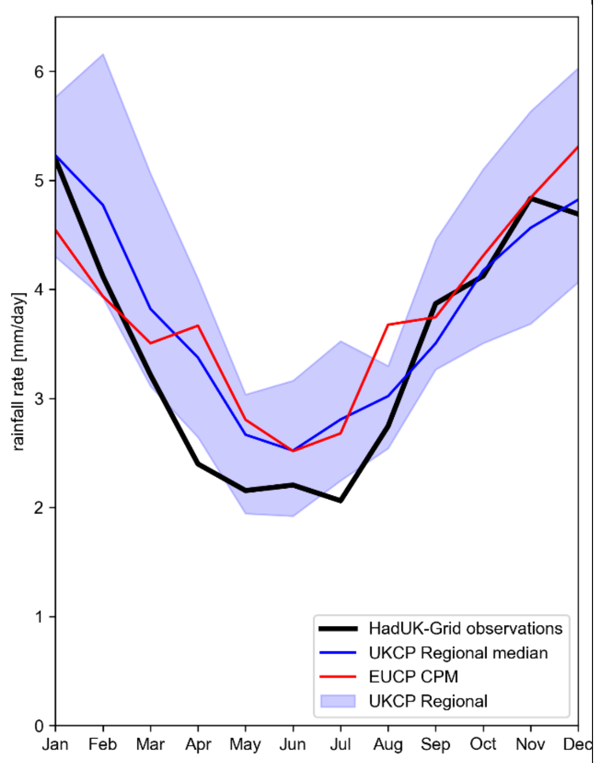
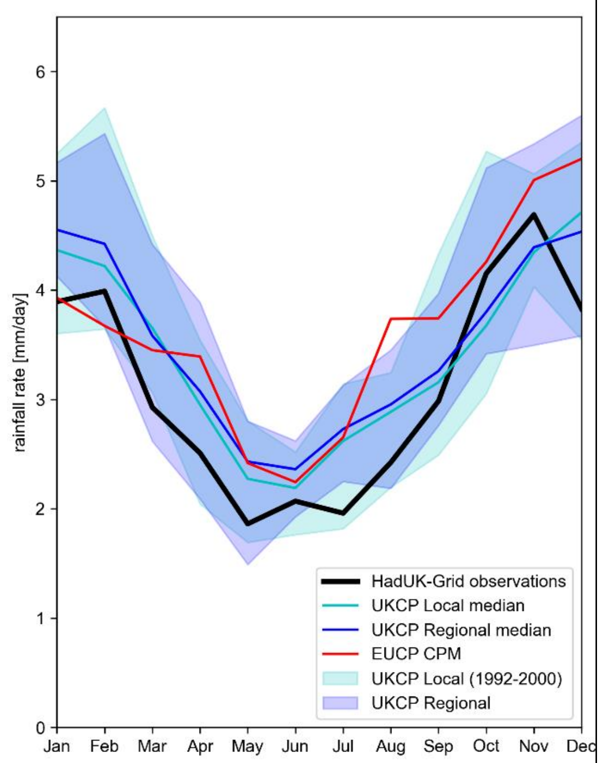
Shetland Islands	Orkney Islands
	

Figure 2: Annual cycle of monthly mean rainfall rate [mm/day] averaged over [left] the Shetland Islands and [right] the Orkney Islands in recent climate (1999-2007). The black line is the HadUK-Grid observations; shaded in blue are the UK Climate Projections (UKCP) Regional ensemble, with the ensemble median as a blue line; the red line represents the European Climate Predictions (EUCP) convection-permitting model (CPM). For Orkney, the UKCP Local ensemble is shaded in cyan with the ensemble median as a cyan line but uses a different averaging period (1992-2000).

Seasonal variation: Figure 2 shows that in winter, UKCP Regional ensemble median overestimates rainfall in the area, but there is variation between ensemble members that encompasses both over- and underestimation in all parts of both Orkney and Shetland (not shown). For winter, the EUCP CPM is within the variability between UKCP Regional ensemble members. In spring and summer, UKCP Regional models overestimate rainfall consistently across the ensemble. In these three seasons, the EUCP CPM is within the spread of the UKCP Regional ensemble.

Hourly rainfall: In terms of hourly mean rainfall, the differences between model and observations are small and at most 0.1mm/hour maximum (not shown). In the 99.95th percentile of hourly rainfall (Figure 3), the biases are larger (up to 5mm/hour), reflecting the higher rainfall rates. The differences between the EUCP CPM and CEH-Gear observations are not consistent spatially (ie wetter in some areas, drier in others) in all seasons except spring when the model is mostly consistently wetter than the observations. Therefore, when comparing to the future changes, the biases in recent climate should be considered specifically for the different seasons and areas of Shetland.

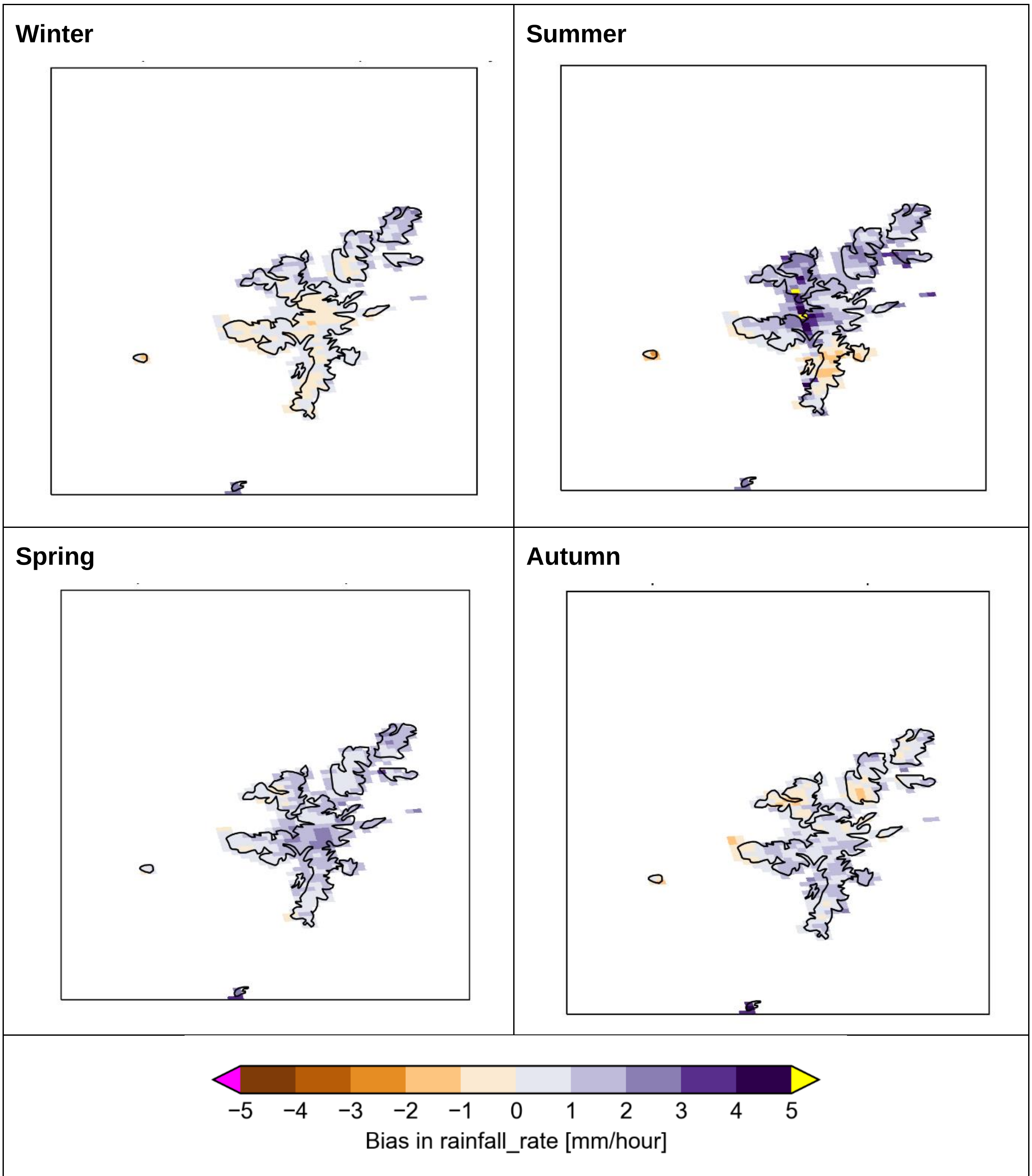


Figure 3: Maps showing difference between modelled and observed value of 99.95th percentile of rainfall in the baseline period (1998-2007). The model is the EUCP CPM, and the observations are from CEH-GEAR. Positive values indicate the model is higher; negative that the observations give higher values.

Figure 4 [left] illustrates that over Shetland and for the 99.95th percentile of hourly rainfall, the differences between the observations and model are smaller than the differences between different years (the interannual variability). This puts the above biases in the context of being relatively small. The interannual variability is larger in summer than winter, which is particularly clear over Orkney.

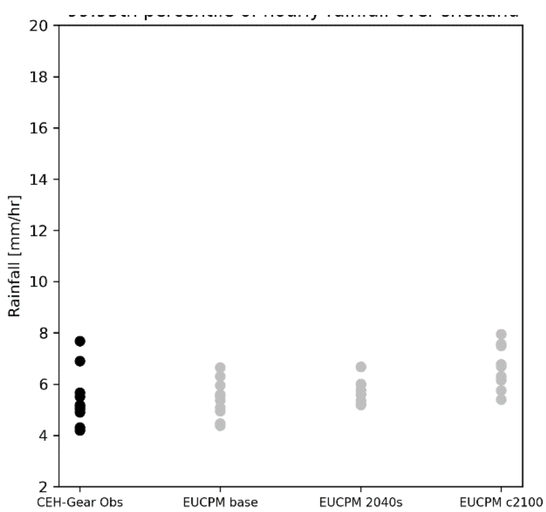
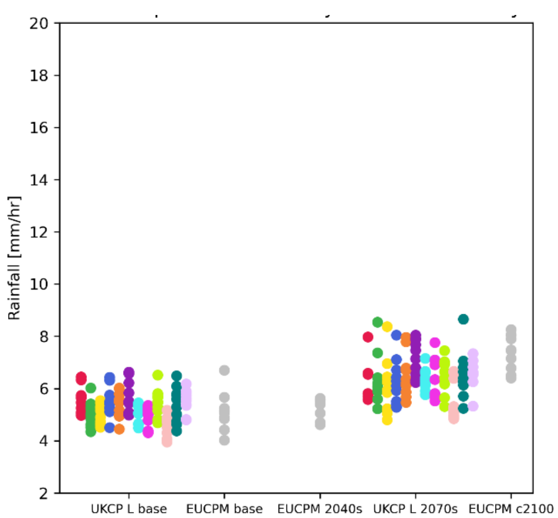
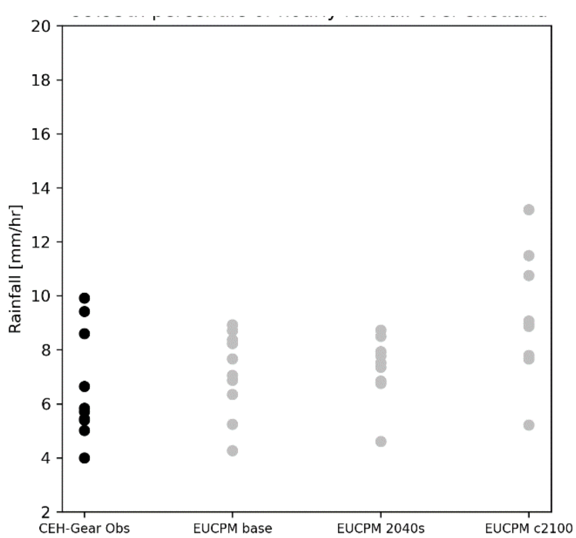
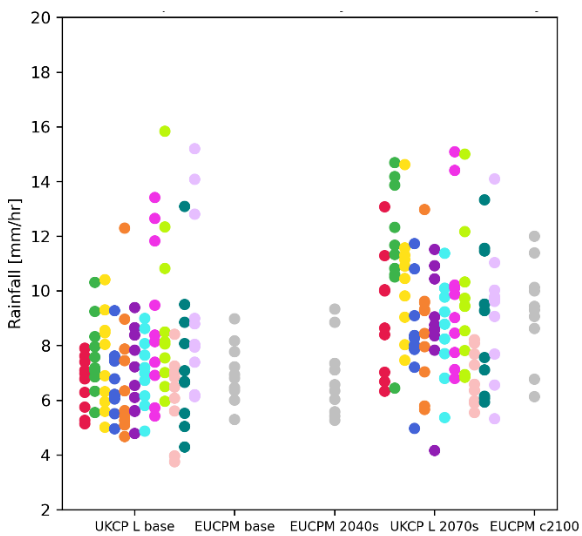
Shetland Islands	Orkney Islands
Winter 	**Winter** 
Summer 	**Summer** 

Figure 4: The 99.95th percentile of hourly rainfall for each year in the observations or model and time period specified on the x-axis, calculated over all hours in [top] winter or [bottom] summer and over every point on [left] the Shetland Islands and [right] the Orkney Islands.

5.2. How much value is added by using a high-resolution convection-permitting model, compared to the lower resolution model?

From Figure 2, EUCP CPM model (red) is mostly within the UKCP model ensemble spread, which means that the UKCP Regional is able to capture the outcome provided by the EUCP CPM. However, in August the EUCP CPM is wetter than UKCP Regional over both Orkney and Shetland, but the EUCP CPM is further from observations than the UKCP models. Therefore, it is difficult to comment specifically on the merits of using a single convection-permitting model from EUCP over an ensemble of coarser convection-parameterising models from UKCP for heavy rainfall daily over Shetland.

On sub-daily timescales, the convection-permitting models are generally more reliable, with improved diurnal cycle and ability to capture hourly rainfall extremes unlike coarser resolution models (Kendon et al. 2019, Fig 2.2; Kendon et al., 2021). Higher resolution models would typically be more appropriate over regions with small river catchments. However, over Shetland much of the rainfall is caused by processes other than convection (e.g. fronts that are likely to be captured well by coarser resolution models) which should be seen in UKCP Regional. Much of the convection over Shetland is initiated over the sea and advected inland, when a convection-permitting model would better resolve the coastline and island topography as these showers interact with the land surface and would better advect the convection.

Climate model data can be 'bias corrected', that is quantifying the differences between model and observations in recent climate and adjusting the model in future climate by the same quantities. However, Bias correction is not performed on any data used in this report, because this introduces another layer of uncertainty, and it is not clear that bias corrections in the present-day climate are valid for a future warmer climate. Also, bias correction means differences between models are not necessarily related to their representation of the key processes, and it is these processes that we want to explore. It is important to use a model that is able to capture the key local processes involved in driving future changes, and for changes in hourly rainfall extremes this means using a convection-permitting model.

5.3 How is the climate projected to change in the future? How robust are the future changes?

Comparing models to observations assesses how realistic the model is and indicates how robust the model projections are for the future. However, good performance in the past does not necessarily mean good performance in the future. We also compare the projected changes to interannual spread ie the variations in rainfall year-to-year.

Before assessing the projections on hourly timescales, we ascertain the average signal shown by climate change. This allows us to put the projections for Shetland in the context of those for the UK, and to put changes on sub-daily timescales into the context of changes over longer periods. Note that it is not possible to consider whether the EUCP results are within the spread of the UKCP Local ensemble, because they cover different time periods (2095-2105 and 2060-2080, respectively).

Projected Changes to Annual Cycle

As for the rest of the UK (UKCP Team, 2021), the Northern Isles are projected to have wetter winters and drier summers, on average. By the 2040s (not shown), little signal emerges which makes comparing the UKCP ensemble to the EUCP model difficult though the latter is generally within the former's ensemble spread. The pattern is clear from the 2070s (Figure 5), and is more marked over Orkney Islands than the Shetlands. In the 2070s over Orkney, there is good agreement between the UKCP Local and Regional ensembles.

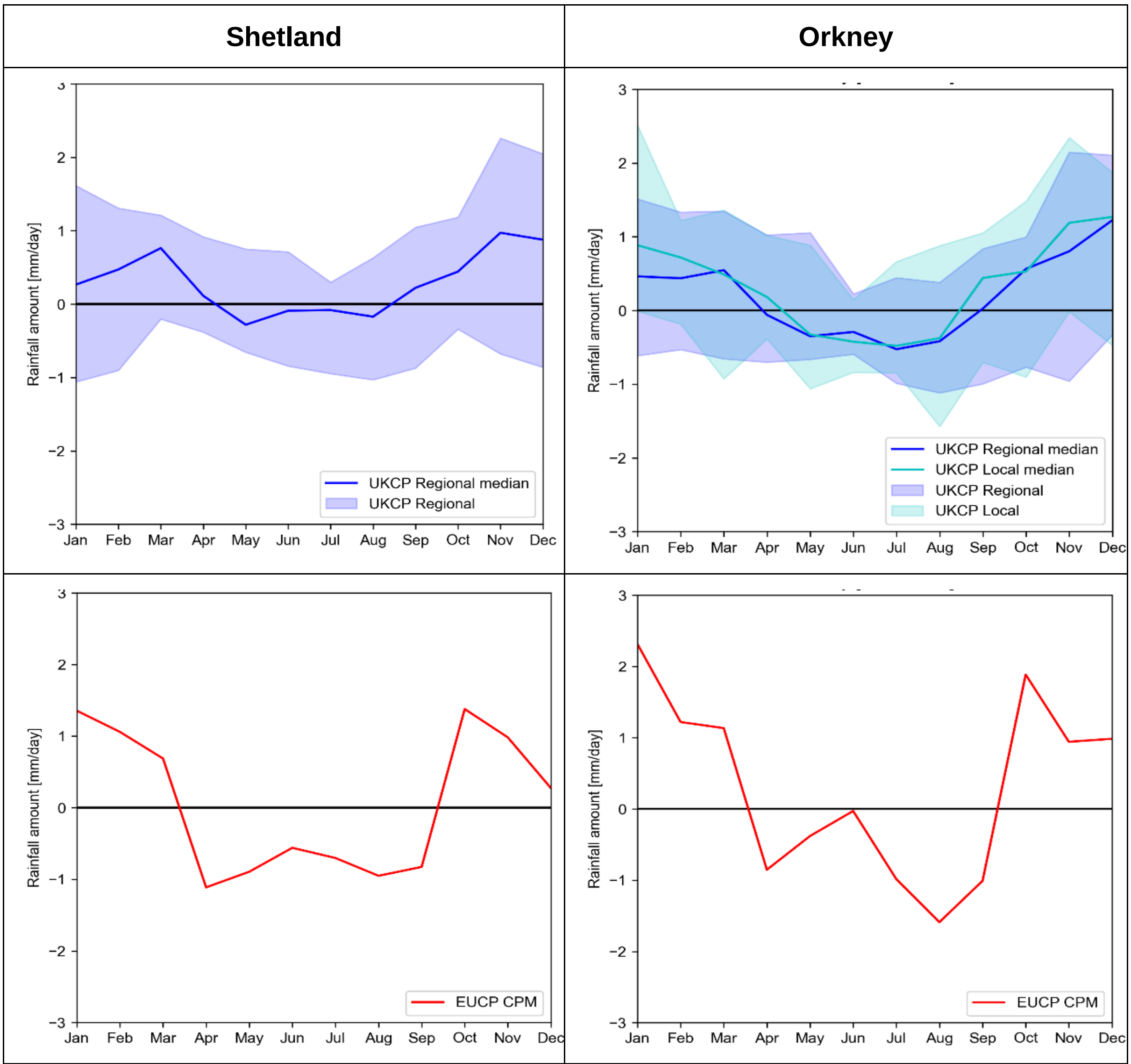


Figure 5: Projections of the annual cycle of rainfall [mm/day], as the difference between the future period and baseline, over the [left] Shetland and [right] Orkney Islands.The future periods are [top] 2070-2079 and [bottom] 2096-2105. Shaded in blue are the UKCP Regional ensemble, with the ensemble median as a blue line; the red line represents the EUCP CPM. For Orkney, the UKCP Local ensemble is shaded in cyan with the ensemble median as a cyan line.

One way to consider the robustness of the projected changes is to compare their size to the year-to-year variability of rainfall in the climate model. This allows us to put the projected change in the context of how much the rainfall would vary from year-to-year, and whether that change would be noticeable within the interannual variability. For mean rainfall, the projected changes are smaller than the year-to-year variability, meaning that the change would be difficult to detect given how much rainfall varies between years.

Comparison of Figure 5 to Figure 2 allows consideration of how the projected changes (i.e. model in future climate minus recent climate) compare to the biases (i.e. in recent climate, model minus observations). For the 2040s, the projected changes are similar or smaller than the spread across the UKCP ensemble including both projected increases and decreases in all months, meaning the signal due to climate change cannot be identified. The projected changes become larger in the 2070s and even larger by the late 21st century, to being larger than the biases. The relative size of the biases and projected changes mean the latter are difficult to quantify, but confidence is good in the direction of projected changes.

Projected Changes to Daily Rainfall

The 2040s (not shown) again have a small signal for climate change in mean rainfall, when compared to the UKCP Regional ensemble spread, the interannual variability or the differences between the models and observations in recent climate. There is also low agreement about the direction of change in between the EUCP CPM and UKCP Regional and within the UKCP Regional ensemble.

By the 2070s, the UKCP Regional ensemble mean shows a stronger signal for drier summers, and wetter autumns, winters and springs on average (Figure 6). However, the average change is small compared to the range of results shown by the ensemble members, some of which project changes of the opposite sign in winter, spring and summer (not shown).

For the late 21st century (not shown), the EUCP CPM shows small projected changes to average rainfall compared to the interannual variability or differences between model and observations in recent climate.

When examining the 99th percentile of daily rainfall (Figure 7), the projected changes are small compared to the spread in UKCP Regional projections, with some members showing an increase and others a decrease for any given season. The projected change is also small compared to the interannual variability. When the projections are examined for each ensemble member (not shown), there is also considerable spatial variation, with some members showing different direction of future change over Orkney and Shetland, and others showing differences between different parts of Shetland.

In summary, though there is a trend towards on average drier summers and wetter autumns, winters and springs, confidence in these projections is low due to the size of the interannual variability, the biases in recent climate and the spread across the UKCP Regional ensemble. This is the case over both the Orkney and Shetland Islands and using both UKCP and EUCP models.

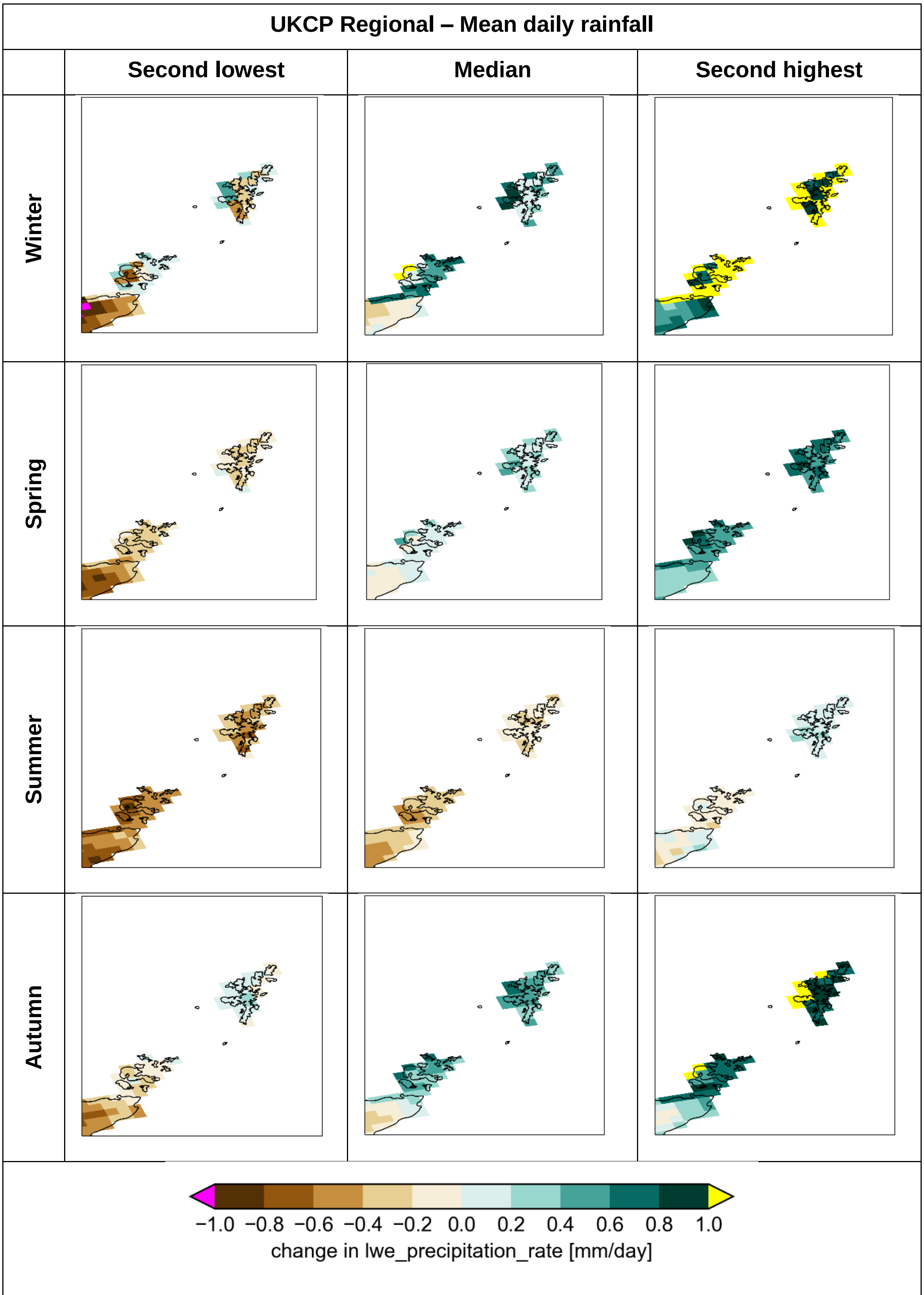


Figure 6: Maps of the UKCP Regional ensemble's projected second highest, median and second lowest change mean daily rainfall by the 2070s at each grid point for each season from top: winter (Dec Jan Feb), spring (Mar Apr May), summer (Jun Jul Aug), autumn (Sep Oct Nov).

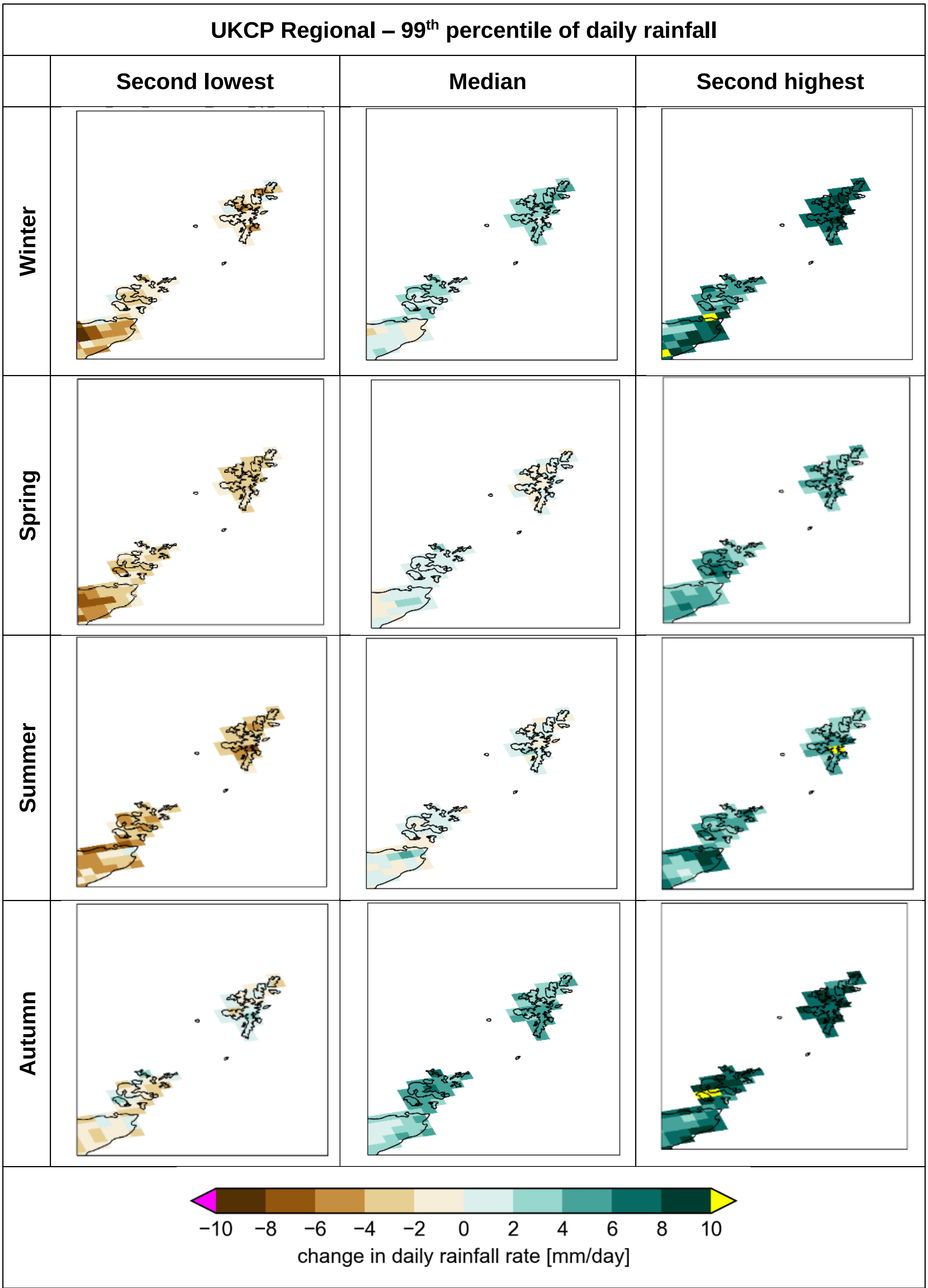


Figure 7: Maps of the UKCP Regional ensemble's projected second highest, median and second lowest change in 99th percentile of daily rainfall by the 2070s at each grid point for each season from top: winter, spring, summer, autumn.

Projected Changes to Hourly Rainfall

For the 2040s (Figure 4), the projected changes to hourly rainfall are small compared to both the interannual variability and the differences between models and observations in recent climate. By the late 21st century, the EUCP CPM's mean hourly rainfall rate (not shown) is projected to increase in autumn and winter, and decrease in spring and summer, as per the changes to daily rainfall. The 99.95th percentile of hourly rainfall is projected to increase by the late 21st century in summer, autumn, and winter (Figure 8). However, in spring, the projected changes are much smaller than in the other three seasons, and show an increase in some areas and a decrease in others, making unclear the overall signal due to climate change. These projected changes are smaller than the interannual variability (Figure 4), which makes the changes due to a changing climate difficult to pick out of the 'noise' of the year-to-year differences. However, the median of the values for each year changes significantly when the EUCP baseline period is compared with values for the late 21st century, using a Mann-Whitney test, in both summer and winter, indicating that the projected increases in the EUCP CPM are statistically significant.

Figure 8 shows that the pattern of projected change in heavy hourly rainfall is similar over Orkney and Shetland in the EUCP CPM projections, which would support the use of Orkney's uplifts over Shetland. However, the EUCP CPM shows only one possible future, and the projected changes to daily rainfall in UKCP Regional show different patterns over Orkney and Shetland.

A major caveat of the hourly data over Shetland is that only one ensemble member is available for the EUCP CPM data. This means this is only one realisation of the future projections, and their uncertainty is not sampled. When the UKCP Local ensemble for Orkney is examined for future changes in the 99.95th percentile of rainfall, a range of outcomes occur, including increases and decreases in different ensemble members in spring and summer (Figure 9), indicating the effect on convection may differ between ensemble members. However, there is a consistent increase projected in autumn and winter.

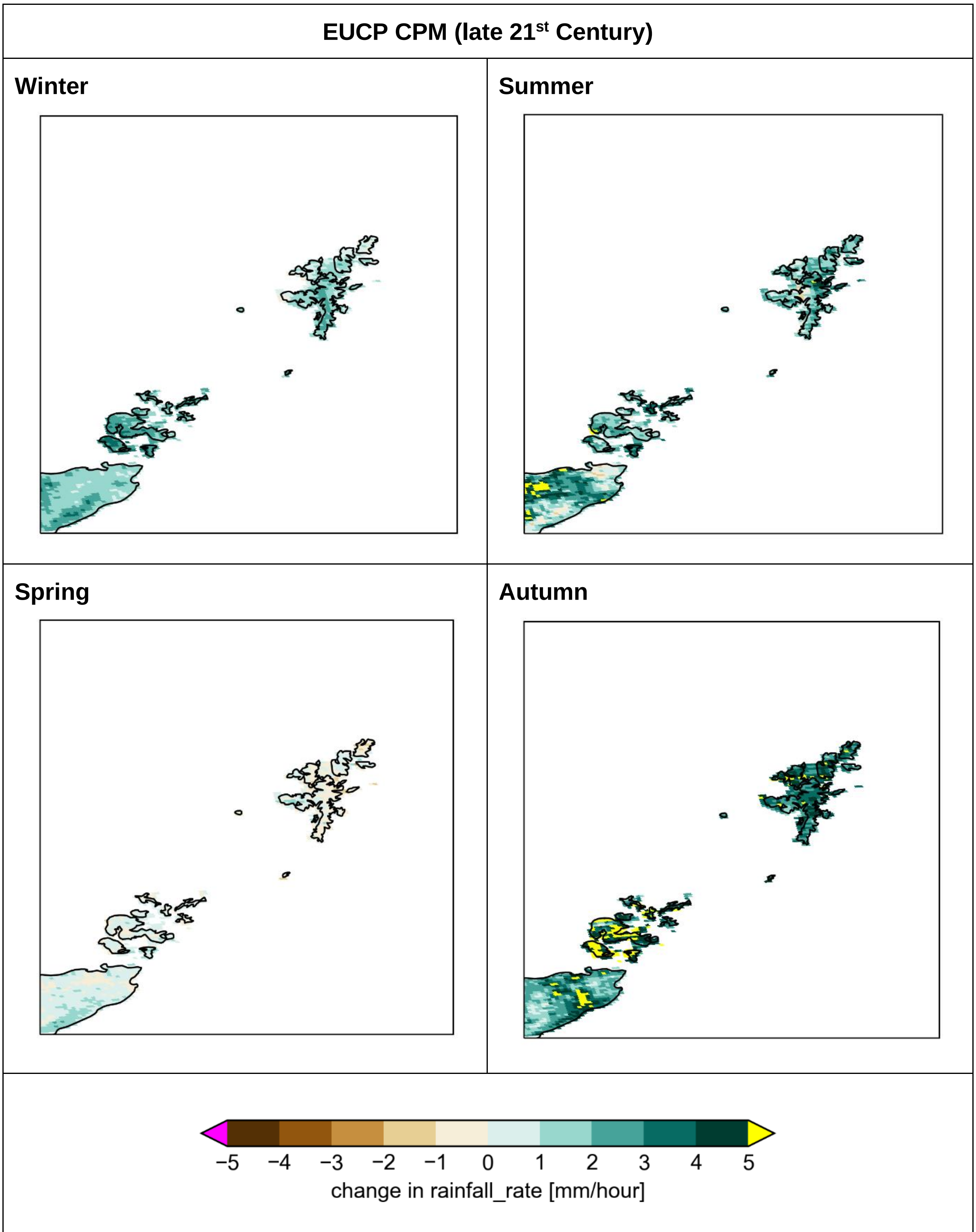


Figure 8: Maps of projected changes by the late 21st century in 99.95th percentile of hourly rainfall in the EUCP CPM, for each season. Winter refers to December, January and February; spring to March April and May; summer to June, July and August, autumn to September, October and November.

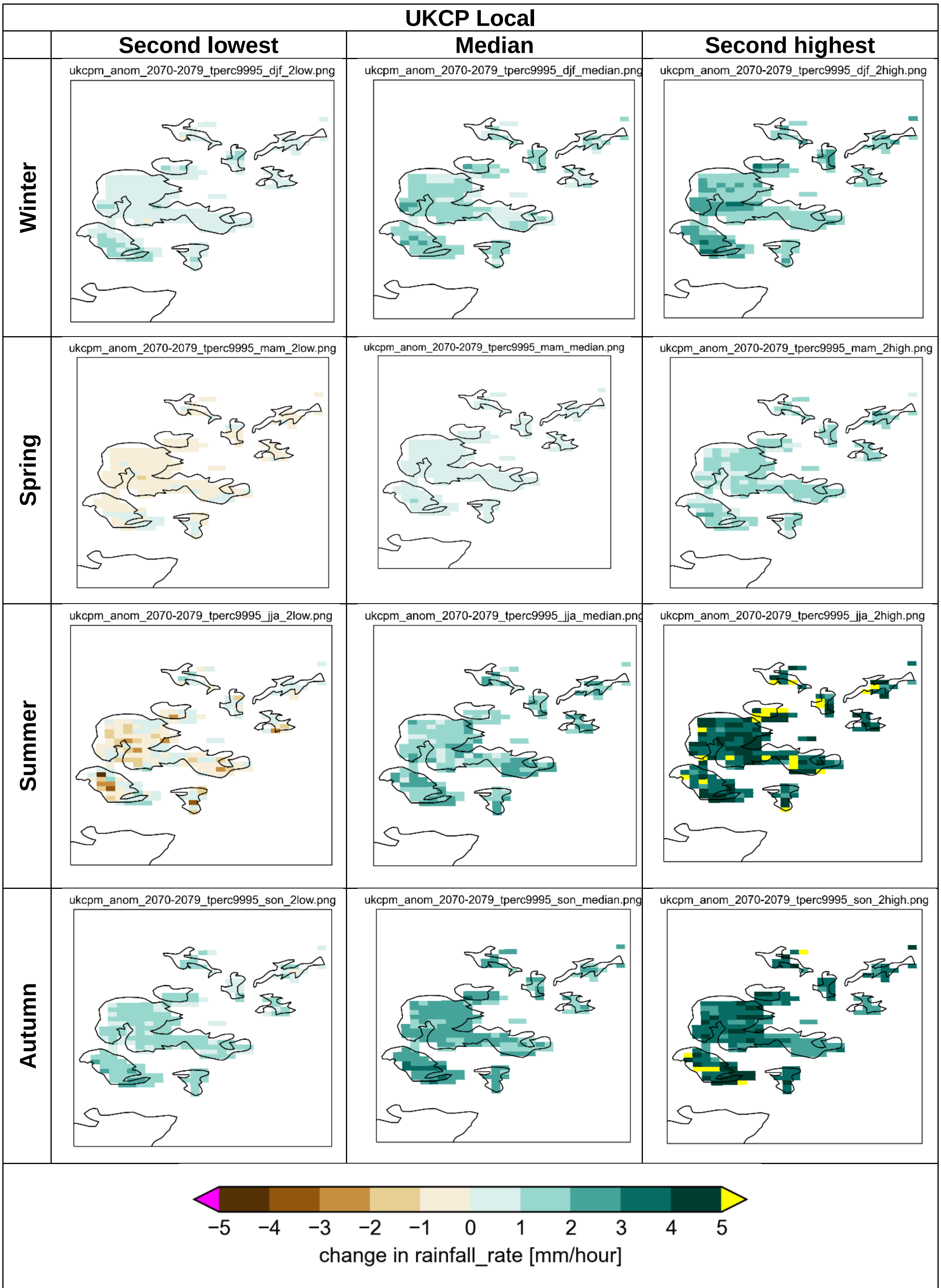


Figure 9: Maps of the UKCP Local ensemble's projected second highest, median and second lowest change in 99.95th percentile of hourly rainfall at each grid point for each season from top: winter (December January February), spring (March April May), summer (June July August), autumn (September, October November).

Projected Changes in Uplifts from FUTURE-DRAINAGE

The FUTURE-DRAINAGE project (Dale et al., 2021) has used UKCP Local data to estimate peak rainfall intensity uplifts for the British Isles, except Shetland due to the lack of data coverage. Some example plots of these uplifts are shown in Figure 10, for events lasting three hours and a 1-in-100-year return period as stipulated by SEPA. Uplifts are calculated for both the 2050s and 2070s, but here only the latter are shown. These data are included here to inform discussion of the potential uses of proxy locations for uplifts over Shetland.

The uplifts show a broad northwest-southeast gradient over the UK and over Scotland, with the highest values for the Outer Hebrides and Northwest Highlands and lower values in the southeast. While from this it could be inferred that the Outer Hebrides are a more appropriate proxy for Shetland than Orkney, the Outer Hebrides has different exposure and topography to Shetland, and discerning their relative appropriateness is left for future work.

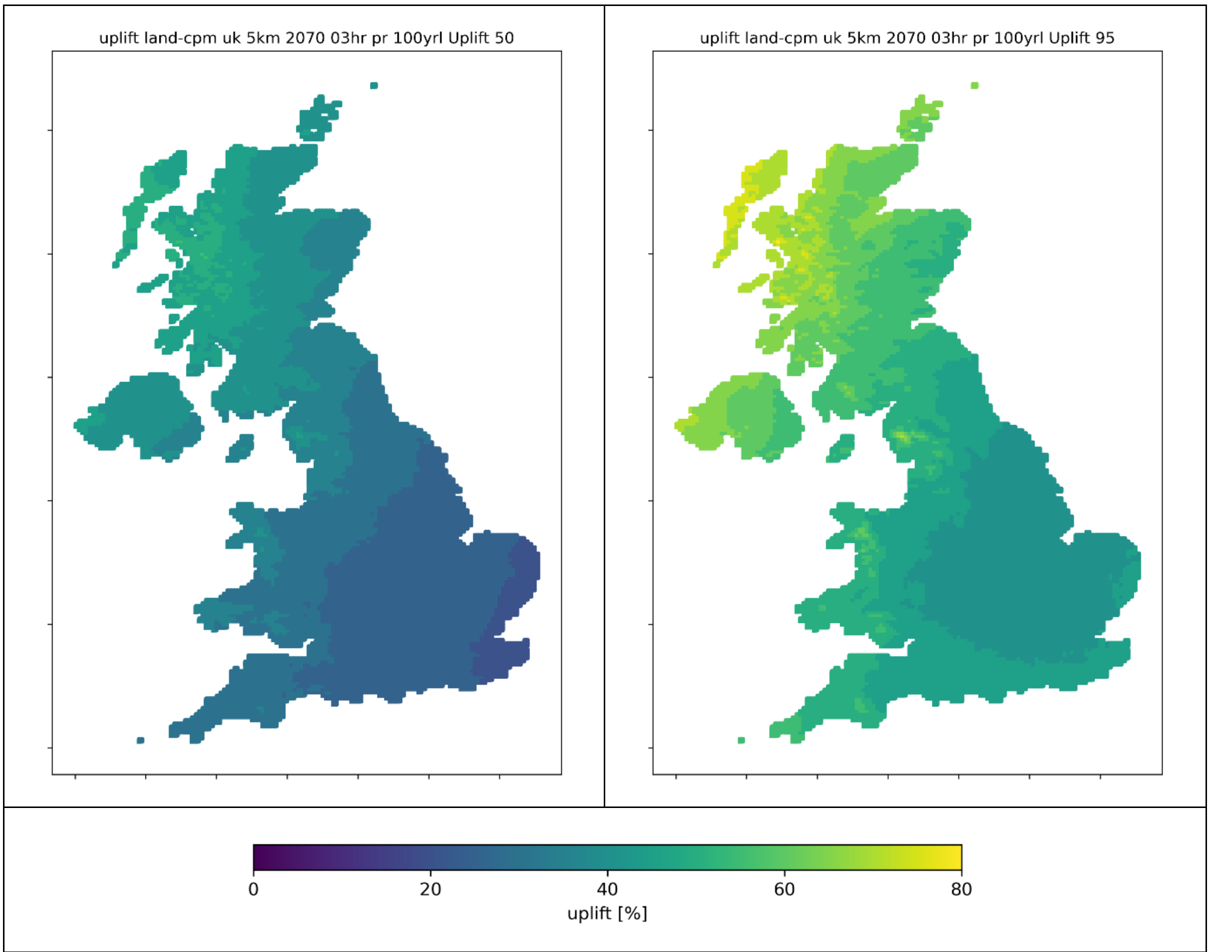


Figure 10: Maps showing the uplift (%) for 2070 over the British Isles except the Shetland Islands, for rainfall events lasting 3 hours with a return period of 100 years, [left] the central estimate (50th percentile), and [right] the high estimate (95th percentile).

6. Discussion

The projections generally show that the Northern Isles will have wetter winters and drier summers, on average. For the changes to daily rainfall, the projected changes are small compared to the natural differences that occurs in rainfall from year-to-year (interannual variability). Furthermore, there is spread in the UKCP Regional ensemble, including some ensemble members that show the opposite sign (increase or decrease) for future projections. Therefore, how best to use projections on these timescales depends on what decisions will be made based upon the analysis; for example, whether the project would be better planning for an ensemble average or a worst-case scenario.

For heavy hourly rainfall, the EUCP CPM projections show an increase in summer, autumn and winter and a less clear signal in spring over Shetland and Orkney. Over Orkney, the UKCP Local illustrates that there is a spread in the projections, including in summer when some members that show an increase and others show a decrease. While the EUCP CPM is within this spread, it gives only one solution and no indication of the modelling uncertainty in these projections. The interannual variability is larger than the projected changes in rainfall, so the climate change 'signal' is obscured by the natural year-to-year differences (the 'noise'). Furthermore, the year-to-year differences are likely underestimated, because due to the limited periods over which the EUCP model is run, the time periods considered cover only ten years, whereas climate studies typically use 20 or 30 years to fully represent the year-to-year differences, as well as using multiple ensemble members.

The two potential approaches for analysis were earlier identified as:

- Using uplifts from Orkney as indicative of those over Shetland;
- Using EUCP CPM projection alongside the UKCP Regional projections.

That the climate change signal is consistent over Orkney and Shetland in the EUCP CPM supports the translation of Orkney's uplifts to Shetland. However, based on the spread in the UKCP Local ensemble, the translation of uplifts from Orkney to Shetland would be heavily caveated, particularly for applications sensitive to heavy summer downpours when there is large spread in the projections over Orkney. Also, the precipitation processes can be quite different; Orkney feels the rain shadow from mainland Scotland in a prevailing southwesterly wind, whereas Shetland receives less shelter. Furthermore, examination of the uplifts indicates that higher uplifts are given for the Outer Hebrides than Orkney, which could be related to the former's greater exposure in southwesterly winds. Therefore, for subdaily rainfall the combined use of the EUCP CPM and the UKCP Local projections is recommended, with analysis of the latter being use-focussed. Note that UKCP Regional should not be used for rainfall on sub-daily timescales but can be used for daily or longer.

The current approach to flood forecasting uses thresholds of rainfall to infer impacts. These thresholds have been derived from observations and expert elicitation. However, in the context of assessing climate change, the use of thresholds will prove difficult, given the infrequency of these events even in the observational record. This infrequency means that the performance of the climate model in recent climate is difficult to assess (the number of events over an absolute threshold could be slightly higher or lower in the model, but this would be a large fraction of the observed events), which would cascade into the reliability of the future projections. However, the infrequency of the events is to be expected, given the impacts that the rainfall and associated flooding would have on society. Taking an approach that would be rigorous statistically could involve extreme value analysis, but this would also need to consider the ensemble spread and the sensitivity of the final decision(s) to that spread.

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