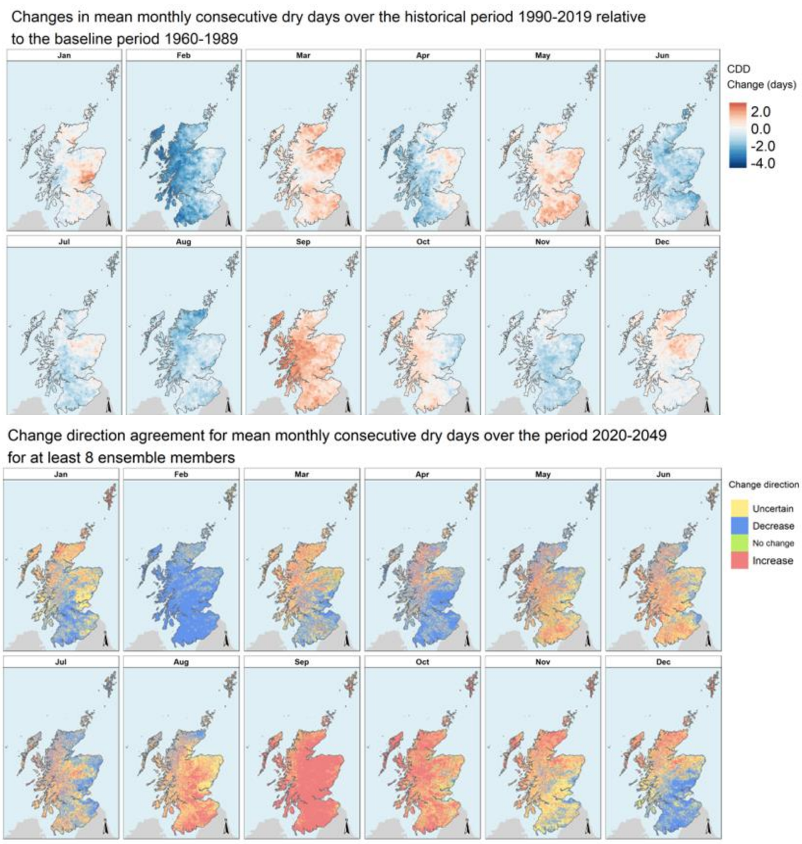
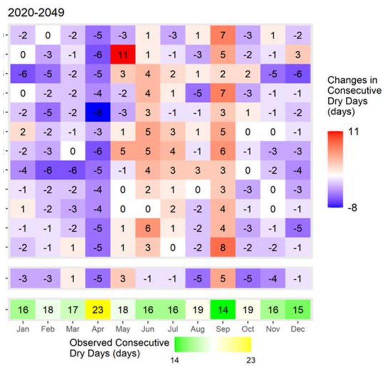
Climate Extremes in Scotland.

Deliverable D2.1b for the

Project D5-2 Climate Change Impacts on Natural Capital

5th March 2023





Summary

This report is a product of the Scottish Government Strategic Research Programme project JHI-D5-2 'Climate Change Impacts on Natural Capital'. **The purpose** of this report is to present spatial and temporal information on climate extremes, presented as a range of indices, in Scotland since 1960 and how they are projected to change in the future. It also demonstrates the increases in analytical and visualisation capabilities developed within the project. **The aim** is to present a set of maps on general summaries of extremes (seven indices) to illustrate the temporal and spatial variability of changes to the climate and what this might mean for impacts on Natural Capital. We present mapped evidence of observed trends in the spatial and temporal distribution of precipitation and temperature across Scotland between 1960 – 1989 and 1990 – 2019. Using data from the UKCP18 climate projections, estimates are made and presented as maps and charts of how extremes may change in the future. **The objective** of the research presented is to support assessments of the impacts of climate change on Natural Capital assets.

Approach: we compare the historical trends in a range of extreme climate Indicators that are derived using observed precipitation, maximum and minimum temperature data from 1990 – 2019 with those from a 1960 – 1989 baseline period. Data from the UKCP18 climate projections (12 individual model simulations) for two time periods, 2020 – 2049 and 2050 – 2079, are compared with the observed 1960 – 1989 baseline to identify potential future changes. The 12 projections are based on the high emissions scenario (RCP8.5) but consist of a range of possible climate change from 1°C increase in temperature and an increase in precipitation total, to 3.7°C and a reduction in precipitation.

Key Findings

There have been observed changes in climate and extremes in Scotland, that are projected to further change in the future. The key findings for the seven indices used are:

Consecutive Dry Days: The count of the number of Consecutive Dry Days (CDD) is an indication of when water may become limited and drought conditions occur. It is the maximum length of a dry spell in any one month (when precipitation is less than 1mm per day).

- Since 1960 there has been a small shift in the number of Consecutive Dry Days per month (median is < +/- 2), with more increases occurring in March, May, September and, for the western half of Scotland, October. With April experiencing an increase in the east as well, the main parts of the growing season for the arable areas of Scotland have experienced longer dry periods. Conversely, February, April (except the east), June to August, October (in the east only) and November have seen a decrease in Consecutive Dry Days per month.
- There is good agreement between the 12 climate projections that from now until 2050 the winter months may experience a decrease in the number of Consecutive Dry Days (change in median of approximately 1 – 3 days), but May through to October are likely to see an increase (approx. 1 – 3 days). For the 2050 – 2079 period these seasonal changes become more pronounced, with the median changes ranging from 1 – 4 days.
- Historically (1960-1989) at the national scale April has had the most Consecutive Dry Days (23) in the most extreme year, but this may decrease by c. 5-6 days between now and 2050, whilst June (16 days) may increase by 1-6 days and September (14) by 2-8 days.

Number of Dry Days: This is a count of the number of Dry Days (DD) per month (when precipitation is < 1mm). As with Consecutive Dry Days, this indicator provides information on the potential for increased dry conditions and risks of drought and heat stress.

- Observed: there has been both a geographical and temporal change in the number of Dry Days since 1960, with a decrease in winter in west and central Scotland, and increase in east. February has seen a decrease and September an increase across most of the country.
- Future: Future: there is a mixed range of uncertainty in the geographical distribution of the number of Dry Days. However, there is good agreement between the 12 projections that there will be decrease in the winter and increase in the summer. Spatially estimates show an increase in Dry Days in the central and southern uplands in August, most of Scotland in September and uplands in October and in the north in November and December.
- Historically (1960-1989) at the national scale April has the most observed Dry Days (28) in the most extreme year, but this has already decreased by four days hence matching the projected decrease by 1-4 days.

Number of Heavy Rain Days: This indicator represents days when precipitation may be considered as 'heavy rainfall' – here we consider the threshold as days when precipitation is ≥ 10mm.

- Since 1960 there has been a small shift in the number of heavy rain days (0 to +3 in the 1990-2019 period compared to the 1960-1989 period) with the highest value reported in winter and little variation in summer and autumn.
- Future projections (both 2020-2049 and 2050-2079 periods) show that the HRD changes in the winter season with an increase up to 4 days, compared to the 1960-1989 period. There is a reduction in summer (from -2 to -4 days). The projections thus seem to affect mainly summer HRD variations with a risk of an increased drought and winter flooding.
- Historically (1960-1989) at the national scale the most Heavy Rain Days in the most extreme year have occurred between October and January (11 days for each month). February has already increased by 3 days (1990-2019) and hence matching the projected decrease by 1-4 days.

Number of Very Wet Days: A very wet day is classified as a precipitation amount that is greater or equal to the 95th Percentile. It is the count of these events and represents the top 5% largest precipitation events per month. It hence represents the changes in the number of extremely large precipitation events.

- There is a clear observed trend and continued future projection that the number of the largest precipitation events, the number of Very Wet Days, is likely to increase in the winter but decrease in the summer. The 1960-1989 baseline shows that the number of Very Wet Days was consistent throughout the year (5-6), but the more recent 1990-2019 period shows there were more in the winter, particularly February (3)
- There is good agreement between the climate projections that the upland areas of Scotland are likely to experience a decrease in the number of Very Wet Days in the summer months. There is medium level of agreement between projections that the lowland eastern parts of Scotland may experience an increase in the number of Very Wet Days.
- At a national level for the most extreme years, the winter is projected to have an increase in Very Wet Days and in August – October a decrease. February has already seen an increase from 5 (1960-1989) to 8 (1990-2019).

Highest Temperature: The Highest Temperature indicator represents the highest daily maximum temperature per month. Increases in HT means that the hottest days per month become even hotter.

- There has been an observed increase in the highest maximum temperature from 1960-1989 to 1990-2019 for all months except June and in some western upland areas in August and October. February, March, May, July (primarily the west) and September have experienced the largest increase, by up to 2.0°C and across the whole of Scotland by 1.3°C.

- The observed trend is projected to continue and increase. For the future period 2020-2049, all months are estimated to experience an increase in Highest Temperature, in the order of 2-3°C. There is near complete agreement between all climate projections used that the highest maximum temperature will increase for all months.
- At the national scale, in the most extreme years, March has seen the largest observed increase in Highest temperature from 16.9°C (1960-1989) to 19.4°C (1990-2019), which is larger than the projected changes. July and August (27.7°C each between 1960-1989) have changed little (-0.3 and 0.1°C, respectively), but are projected to increase by 1.9 to 8.8°C during the period 2020-2049. For the 2050-2079 period for July an August, the Highest Temperature is projected to increase by 3.0 to 11.8°C.

Very Warm Days: The Vary Warm Days indicator is a count of the number of days when the maximum temperature is greater than the 95th percentile of monthly maximum temperature. It represents changes in how long the warmest periods last.

- There has been an observed change in the number of very warm days between the 1960-1989 and 1990-2019 periods, with all months except June (and August in upland areas) seeing an increase. February (9 days) and March (5 days) have had the largest increase, particularly in the south and east of Scotland.
- There is almost complete agreement between climate projections that the number of Very Warm Days will increase in the future for the whole land area of Scotland. February, March and September are projected to have substantial increases, e.g. September, which had 6 days in the 1960-1989 period, but increasing by between 17 to 22 days for the 12 projection, giving a total of 23 to 28 days by 2050.
- Historically (1960-1989) at the national scale the highest number of Very Warm Days in the most extreme year was in August (11 days), which has increased by 1 day (1990-2019), but is projected to increase by 2-11 days up to 2050, and by 9-17 days by 2070. September is projected to see the largest increases of 8-22 and 17-24 days between up to 2050 and 2070, respectively.

Coldest Temperature: The Coldest Temperature indicator provides information about how the lowest temperatures per month have changed and are projected to in the future. CT is the lowest temperature achieved per month.

- There has been an overall increase (warming) of the Coldest Temperature per month since 1960. There is some spatial and temporal variation, with the largest increases (warming) in November, January and February, most noticeably in the Cairngorms area and southern uplands. May, October and December have experienced decreases (colder) in Coldest Temperatures in some parts of the north and west whilst experiencing increases (warmer) elsewhere. January has seen the largest increase (warming) of 2.1°C.
- There is good agreement between the 12 future climate projections that there will likely be a continuation of the historical trend of further increases (warming) in Coldest Temperature in all months across the whole of Scotland.
- Historically (1960-1989) at the national scale in the most extreme year, January and February had the Coldest temperatures (-15.6 and -13.1°C respectively), but these have decreased (warmed) by 4.3 and 3.5°C respectively in the 1990-2019 period. The projections to 2050 indicate decreases (warming) ranging from 1.1 to 8.2°C in January, and 5.3 to 10.6°C by 2070.

Implications for Natural Capital

The purpose for the D5-2 Climate Change Impacts on Natural Capital project is to better understand how changes in the climate impact Natural Capital and their ability to provide ecosystem services and form the basis for Nature Based Solutions. This improved understanding will develop as the project progresses. Here we provide a summary of our interpretations of the implications based on our current knowledge:

Indices	Summary of implications
Consecutive Dry Days	Prolonged periods of drought will have implications for water resources and water quality. Coupled with reduced precipitation, the increased number of dry days in March and April may have negative impacts during a key time of plant growth. Longer dry periods increase the wildfire danger and soil erosion by wind and heavy precipitation.
Number of Dry Days	The impacts of changes in the number of Dry Days in respect of crops, semi- and natural vegetation is likely to vary depending on soil hydrology, with potentially both positive and negative effects, also variable depending on the timing of when dry periods occur. Drier spring and summers on well drained soils are at risk of reduced crop yields and vegetation biomass production (variable depending on species). There is an increased risk of fire danger.
Heavy Rain Days	Increases in Heavy Rain Days in winter are associated with a higher risk of flooding, while fewer HRD in summer may lead to a reduced water availability and higher water stress. In summer, it is expected for many Natural Capital assets: soil, vegetation, waters to face a reduced level of ecological functionality and a potential loss of biodiversity because of the increase in drought and threats from fewer but heavier precipitation events. Floodplains can reduce the assimilative capacity of containing floods and high soil erosion of arable land and uplands can reduce the carbon stock. Summertime water stress can reduce tree and peatland carbon sequestration.
Very Wet Days	The increase in the number of largest precipitation events per month in the winter implies an increased risk of flooding and soil erosion, but the reduced number of Very Wet Days in the summer implies an increased risk of dry soil and habitat conditions and increased fire danger. Large precipitation events occurring when soils are dry will likely result in soil erosion and nutrients lost to surface waters. Potential benefit from wetter conditions in the winter and more Very Wet Days by increasing the potential for recharge of ground water to maintain water table levels.
Highest Temperature	Increases in the extremes of maximum temperature will likely increase heat and water stresses on plants, animals and habitats, potentially damaging ecological function and delivery of ecosystem services. Higher temperatures in spring will drive earlier plant and insect phenological development. Higher maximum temperatures pose threats to people and infrastructure due to heat stress.
Very Warm Days	Increases in the duration of the warmest temperatures per spring, summer and autumn month will likely increase heat stresses on plants and animals, and alongside high maximum temperatures test the thermal range tolerance of species and habitats, whilst altering inter-species competition, driving more rapid phenological development, damaging ecological function and delivery of ecosystem services. Longer warm periods in the winter are likely to increase snow melt and loss of snow cover
Coldest Temperature	The increase (warming) in the Coldest Temperature reflects a higher probability of fewer days of less intense frosts and amount of freezing of open water and in soils. Less intense cold may help improve the over-winter survivorship of some species. There is likely to be less snow consolidation into ice and more snow melt leading to changes in surface albedo resulting in more heat absorption.

Contents

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Introduction

The purpose of this report is to present spatial and temporal information on changes in climate extremes in Scotland since 1960 and how they are projected to change in the future. The context is to build an understanding of what these extremes may mean for Natural Capital in Scotland. This report is a Deliverable for the Strategic Research Programme project 'Climate Change Impacts on Natural Capital' (JHI-D5-2).

The aim is to present a set of maps on trends of extremes, using a set of indices to illustrate the temporal and spatial variability on changes to the climate. This serves as an underpinning ability to provide risk and opportunity assessments of climate change impacts on Natural Capital assets at both a high spatial and temporal resolution. This report on extremes should be used in conjunction with a parallel report 'Climate Trends and Future Projections in Scotland' (Rivington and Jabloun 2022[1]).

The objective is to illustrate how the climate has changed and is projected to change in respect of extremes in the future. We have used the UK Climate Projections 2018 data (UKCP18). A further objective is to demonstrate the analytical and mapping capabilities developed this far within the JHI-D5-2 Project on how climate data is analysed and used. The project will use climate data, the analyses and mapped outputs within models and a new Risk and Opportunities Assessment Framework to spatially and temporally assess impacts of climate change on Natural Capital assets. Hence this report demonstrates the increasing capabilities within the D5-2 project (and others within the Strategic Research Programmes) to analyse and visualise climate trends and projections.

As a broader objective, subsequent research and Deliverables produced by the Climate Change Impacts on Natural Capital project will place trends, extremes and projections into context of the question 'what are the consequences on Natural Capital assets and their ability to both provide ecosystem services and serve as the basis for Nature Based Solutions?'. Planned research will seek to translate the trends, extremes and projections of the climate into risks to and opportunity for Natural Capital assets. This report does not address the issue of extreme event frequency (return period), as this will be covered in a separate project deliverable (D2.1c).

Advances in Technical Capabilities

This report has been developed through technical advances made in the JHI-D5-2 Project. This includes the integration of spatial daily time step climate data sets within a Geographical Information System for map visualisation capabilities, run on a Higher Performance Computer. The purpose of this technical and analytical development is to facilitate the application of climate change data, and information on estimated changes, to a range of Natural Capital assets to assess impacts at a range of spatial scales (<1km to national). Database structures and flows have been established to enable utilisation of the data within a range of spatially applied simulation models, including ecosystem functions, crop growth, land capability, soil water balance.

This advance in technical capability has enabled the generation of hundreds of maps (multiple time periods between 1960 - 2079, monthly and for x12 climate projections) for a large range of analytical and visualisation combinations. This large number means it is not feasible to present all here in this report. Instead, a new web-based visualisation tool has been developed: https://mjabloun.shinyapps.io/agmet-app/ This is a prototype site and will undergo further development during the project.

[1] D2_1a Climate trends summary report FINAL 6-12-22.pdf (hutton.ac.uk)

Defining climate extremes

There are two main approaches to assessing climate extremes, either by considering individual specific events (e.g. very high precipitation or temperature amounts), or by using indicators of more general extreme occurrences. In this report we have used indicators rather than specific events because they facilitate use of maps to convey spatial and temporal distributions of risks. Also, as per the Caveats and Uncertainties section, climate model projections are developed to primarily simulate changes in mean conditions rather than extremes. Evaluation of the HadRM3 Regional Climate Model (used to generate the data for the UKCP18) shows that it has a varied ability to represent more extreme precipitation and temperature events, from good to poor (e.g. Rivington et al 2008).

We have used a set of seven indicators of climate extremes (Table 1) to illustrate past trends and future projections of how extremes have changed and are likely to do so in the future. This is not an exhaustive range of indicators; however they do capture the key factors that will likely have the greatest general impact on Natural Capital. The indices have been estimated and presented as maps of monthly means, with values either being the count of number of days an extreme occurs for (e.g. Consecutive Dry Days), or the largest value (e.g. mean monthly maximum of maximum temperature). The exceptions are the national scale plots detailing the changes in median values for an index or land area proportion experiencing an increase or decrease of the index values.

Table 1. Climate extreme indices and definitions (source: Climdex Project 2023).

Indices (monthly)	Definition
Consecutive Dry Days	**Maximum length of dry spell (CDD)**: maximum number of consecutive days with RR < 1mm Let RRij be the daily precipitation amount on day i in period j. Count the largest number of consecutive days where RRij < 1mm.
Dry Days	**Monthly number of Dry Days (DD):** Considering RRij as daily precipitation amounts on day i in period j, DD represents the number of days where RRij < 1mm.
Heavy Rain Days	**Monthly number of Heavy Precipitation Days (HRD):** Considering RRij as daily precipitation amounts on day i in period j, R10 represents the number of days with RRij ≥ 10mm
Very Wet Days	**Monthly Very Wet Days (R95pTOT):** Precipitation 95th Percentile. Considering RRj as daily precipitation amount on day i in period j and RR95 as the 95th percentile of precipitation in the 1960-1989 period then: RR95pj=∑RRij where RRij>RR95
Highest Temperature	**Monthly maximum value of daily maximum temperature (TXx)**: Maximum Temperature 95th Percentile. Considering Tx as daily maximum temperature in month k, period j, the maximum daily maximum temperature in each month is TXxkj = max (Txkj).
Very Warm Days	**Monthly Very Warm Days (Tx95pTOT):** Considering Txi as daily maximum temperature on day I in period j and Tx95 as the 95th percentile of maximum temperature in the 1960-1989 period then: Tx95pj=∑Txij where Txij>Tx95
Coldest Temperature	**Monthly minimum value of daily minimum temperature (TNn)**: Considering Tn as daily minimum temperature in month k, period j, the minimum daily minimum temperature in each month is TNnkj = min (Tnkj)

Caveats and uncertainties

In interpreting the results presented here it is important to understand the caveats and uncertainties associated with the projections and baseline data used.

The climate projection data used to produce this report represent one set of plausible future climates. The estimates are derived from a sequence of Global (HadGEMN3) and Regional Climate Model (HadRM-3-PPE) dynamic downscaling. Other climate models produce different projection, hence we highlight that caution is required in the interpretation of the results, in that there are other plausible possible futures not represented in this analysis.

Appendix B addresses the caveats and uncertainties associated with the use of the climate projections, and limitation in the use of one, high Representative Concentration Pathway (emissions scenario, RCP8.5). Our perspective is however that the range of the 12 projections used, generated under the RCP8.5 pathways, is that they cover a range of plausible futures that could also be achieved under different (lower) emissions pathways (for example see Figure 63, showing the precipitation and temperature anomaly of each projection from a historical baseline). Appendix C details the methods used and variation between the 12 climate projections, whilst Appendix D details assessment of the skill of the climate model to represent past observed climate variables. This includes a ranking of model skill for representing monthly mean temperature and precipitation based on spatial assessments.

Text Box 1: Notes on observed data utility

It is important to highlight a key issue to understand that the observed base line data at a 1km resolution (HadUK-Grid dataset[2]) used in this study is produced using a spatial interpolation of data between UK Meteorological Office observation stations. As such the interpolation aims to 'fill the gaps' between observation stations to produce a 1km grid surface across the whole of the UK. Cells with an observation station can be considered as highly reliable. The data utility for grid cells without an observation station is best in areas with a sufficiently high density of observation stations and uniform topography but is less so in mountain areas with few stations. The interpolation process does include steps to adjust for distance from the sea and topography, but we recognise that given the diversity of Scotland's topography and density of observation stations in lowland areas, there are concerns on how representative the interpolated data is in 1km cells covering remote and or higher mountain areas. Whilst we are confident in the value of the climate trends analysis, we recommend some caution when interpreting results for higher elevation and remote areas.

Analytical capability

To facilitate further climate change impacts analysis on Natural Capital assets, research and technical developments in the project (and previous Strategic Research Programmes) have:

- Developed an integrated spatial climate database for the whole of the UK. This consists of:
    - UK Met Office Observation stations (MIDAS).
    - 1km resolution interpolated gridded observed daily data starting from 1960.
    - UKCP18 climate projections: daily data from 1980 to 2080 for x12 runs of a Regional Climate Model (for the 'high' emissions scenario, RCP8.5).

[2] HadUK-Grid Overview - Met Office

- Developed a prototype output search and visualisation tool.
- Integrated soils and climate data to enable running of simulation models (e.g. soil water balance, crop growth, land capability).

How to read the maps

We present a range of maps and graphics to communicate spatially and temporally how 7 indices of climate extremes have already changed and may change in the future. Guides on how to read the maps are provided alongside interpretations of the first indicator presented, the number of Consecutive Dry Days (CDD). Please refer to the explanations for reading the CDD maps and graphics to aid reading those for the other indicators. All Indicators are presented using the same maps and graphics and in the same sequence.

Extreme examples

This section provides some examples of observed weather phenomena, with the aim of putting the results for the analysis of the observed and future projections into context.

Attribution studies have shown that the summer 2018 weather conditions could be 30 times more likely due to anthropogenic activities (McCarthy et al. 2019). The UKCP18 climate projections (Lowe et al. 2018) estimate that summers like 2018 could be “more common than not” by the mid-twenty-first century. The most recent heatwave occurred in Scotland in July 2022. On 19th July, a new record high temperature for Scotland of 34.8°C was recorded at Charterhall in the Scottish Borders, with temperatures in southern and eastern Scotland exceeding 30°C on the 18th and 19th July (Scotland environment, 2022).

Winter extreme events like the storm Arwen, a powerful extratropical cyclone, characterised by wind gust of 177 km/h on 26 November 2021 affected the Northeast, Dumfries and Galloway and the Borders. The peak of the disruption saw almost 200,000 energy customers affected, 10,000 properties having experienced water supply issues, telecoms unavailable in parts of the country, school closures, and the cancellation of train and ferry services. Road travel was disrupted by fallen trees, and Forestry and Land Scotland estimate that 4,000 hectares of Scottish forests were affected by storm damage (Gov Scot, 2022).

On 21 February 2022 the southwest of Scotland saw gusts of up to 75mph for a short period caused by Storm Franklin, the seventh named storm in just three months following on from Arwen, Barra, Corrie, Dudley, Eunice and Malik. Seven years earlier (2015), Storm Frank affected rail and road networks, with the A93 in Aberdeenshire closed for 70 miles. Braemar in Aberdeenshire was the wettest place in Scotland after receiving 64mm of rain between midnight and 2pm, while Glasgow was the wettest city with 43mm of rainfall, leading to severe localised flooding. Extreme rainfall also occurred in 2015 caused by storm Desmond that led to widespread flooding. These events cannot be considered just an exceptional circumstance. Analysis of historical observed trends, coupled climate model simulations and a large ensemble of regional model simulations, was adopted to show that the effect of climate change made precipitation events like the one caused by Desmond about 40% more likely (Otto et al., 2018).

The increase of storms can have several impacts on the environment and society: storm Frank flood caused significant local morphological change on the River Dee, Aberdeenshire at a scale <1 km such as bank scour that resulted in channel expansion and lateral migration as well as widespread aggradation on existing gravel beds (Fieman et al., 2020). Storm surges in Scotland have caused severe damage and flooding of coastal regions, with the Firth of Clyde being a region with high risk due to its location and morphology (Sabatino et al., 2016). The possibility to counter negative effects can be partially counter by advanced land use planning models. For instance, water flows in the Tarland catchment in Scotland were modelled using climate projections (UKCP09) combined with afforestation-based land-use change options to show that afforestation could reduce the increased flow from climate change, although positive effects are expected to be reduced for winter-type extreme floods (Iacob et al., 2017).

Negative consequences on the environment and society are expected also by an increase in heatwaves. Climate projections suggest further substantial increases in the likelihood of 2018 temperatures between now and 2050 with major negative impacts especially on rural sectors (Undorf et al., 2020) and the uncertainty about consequences of even higher temperatures and/or repeated heatwaves makes high-temperature extremes very important for climate change adaptation in Scotland, notwithstanding the relatively cool climate.

Other impacts cause several disruptions on the environment. Short term effects on intertidal invertebrates and macroalgae are recorded with a decline in years of more frequent winter cold spells and summer heatwaves (Mieszkowska et al., 2021). Damage in macroalgae was evidenced as dried areas of tissue on many individuals, while mortality-induced reductions in the abundance of only a few invertebrate species was recorded in Scotland and southwest England after the heatwave events in 2018 and 2020. However, storm-damage surveys indicate that there have been no sustained impacts from either extreme thermal or storm events across the rocky intertidal communities (Mieszkowska et al., 2021). Impacts of heatwaves on mussels are also recorded and affected by the thermal buffering provided by endoliths that as conditionally beneficial parasites enhance the host's resistance to intense heat stress (Zardi rt al., 2021).

Effects on economy of heatwaves can be adverse too. A heatwave that occurred in June-July 2015 affected railway services in terms of delays because of reduction of speed and incidents caused by heat and lightning costing an estimated £16 million to the national (UK) economy (Ferranti et al., 2018). In addition, summer heat extremes in the UK have been found to pose a risk to health (amongst other sectors) and this is exacerbated by localised socio-economic factors that contribute to vulnerability (Kennedy-Asser et al., 2022). High temperatures have been found to affect also the health of patients, including increases in fratures. It was recorded that in Scotland, during the 2022 heatwave, there was a significantly higher incidence of orthopaedic polytrauma (Robertson et al., 2022).

Results Part 1: Observed and future trends

Observed change summary:

To help put the changes in extremes in context, we provide here the summary of the observed trends from the D2.1a report 'Climate Trends and Future Projections in Scotland' (Rivington and Jabloun 2022) for two time periods: 1960 – 1989 (the World Meteorological Organisation climate normal baseline period) and 1990- 2019 (the 'current climate'). The observed trends in precipitation, maximum and minimum temperature have been assessed through qualitative interpretation and can be summarised as:

Precipitation:

- There has been an increase in precipitation, with the area experiencing higher precipitation being larger than that of decreases.
- There is a wide variation in spatial and temporal change.
    - In the west precipitation increased in December to May, but either remained similar or decreased in July, August and October.
    - Eastern Scotland became drier in January, March, May, August, September and December, but wetter in February, June, July, October and November.
- The largest increases in precipitation occurred in February.
- There has been mixed response in terms of variability in temporal and spatial patterns of change in precipitation.
    - January, April, July and November (and to a lesser extent August) have seen a decrease in variability in the west.

Temperature:

- For all months there has been an overall increase in temperature, except for the maximum in June and to a lesser extent October and December for the minimum.
- February and March show the largest amount of warming, up to 2°C, whilst other months show an approximate average increase of 1°C.
- The rise in temperature is relatively uniform across the country, and does not reflect the topographical influence, though for some locations there has been little or no change from the 1960 – 1989 baseline period.
- There has been a mixed response on terms of variability of how much change there has been and where this has occurred.
    - January, February and August have seen an almost nationwide shift towards reduced temporal variability (represented as standard deviation), whilst March, April (except the Lochaber and northern Argyll areas), September, October and November have seen a widespread increase
- All months, with the exception of June and to a lesser extent April and August, show a general national trend of a positive increase (warming) in diurnal temperature range.

UK Climate change projections summary

Here we summarise details a set of twelve climate projections generated as part of the UK Climate Projections (UKCP18). From the UKCP18 climate projections (UKMO 2019) the following published key messages can be summarised as:

- Hot summers are expected to become more common. The summer of 2018 was the equal-warmest summer for the UK along with 2006, 2003 and 1976. Climate change has already increased the chance of seeing a summer as hot as 2018 to between 12-25%. With future warming, hot summers (like 2018) by mid-century could become even more common, near to 50%.
- The temperature of hot summer days, by the 2070s, show increases of 3.7 °C to 6.8 °C, under a high emissions scenario, along with an increase in the frequency of hot spells.
- For the RCP8.5 emissions scenario (used in this study) the estimated probabilistic temperature increases for the UK by 2070 ranges between 0.9 °C to 5.4 °C in summer, and 0.7 °C to 4.2 °C in winter.
- UKCP18 Global (60km), Regional (12km) and Local (2.2km) scale climate model simulations all project a decrease in soil moisture during summers in the future, consistent with the reduction in summer rainfall. Locally this could lead to an exacerbation of the severity of hot spells, although large-scale warming and circulation changes are expected to be the primary driver of increases in the occurrence of hot spells.
- The probabilistic projections (12-member ensemble) provide local low, central and high changes across the UK, corresponding to 10%, 50% and 90% probability levels. These local values can be averaged over the UK to give a range of seasonal average precipitation changes between the 10% and 90% probability levels. By 2070, in the high emission scenario, this range amounts to -47% to +2% in summer, and -1% to +35% in winter (where a negative change indicates less precipitation, and a positive change indicates more precipitation).
- Overall increased drying trends in the future, but increased intensity of heavy summer rainfall events, indicating greater variability and increased frequency of extreme events.
- Change in the seasonality of extremes with an extension of the convective season from summer into autumn, with significant increases in heavy hourly rainfall intensity in the autumn.
- By the end of the 21st century, lying snow decreases by almost 100% over much of the UK, although smaller decreases are seen over mountainous regions in the north and west.

Projected Changes in Precipitation

The national monthly precipitation anomaly (Figure 1) shows there has been an overall increase in precipitation between 1990 – 2019 compared to the 1960 - 1989 baseline, except in September, which has become drier. The mean of the projections for next few decades to 2050 indicate Scotland’s climate to be wetter in December (c10%), January (c. 10%), February (45 – 55%) and April (25%) but less so in March (c. 5%). These projected changes align with the observed changes already seen. Whilst May to July show little signs of future change the observed changes indicate a slight increase in precipitation. August, September and October are projected to be drier. These change patterns continue into the 2070’s period, except the June – August period is projected to become drier.

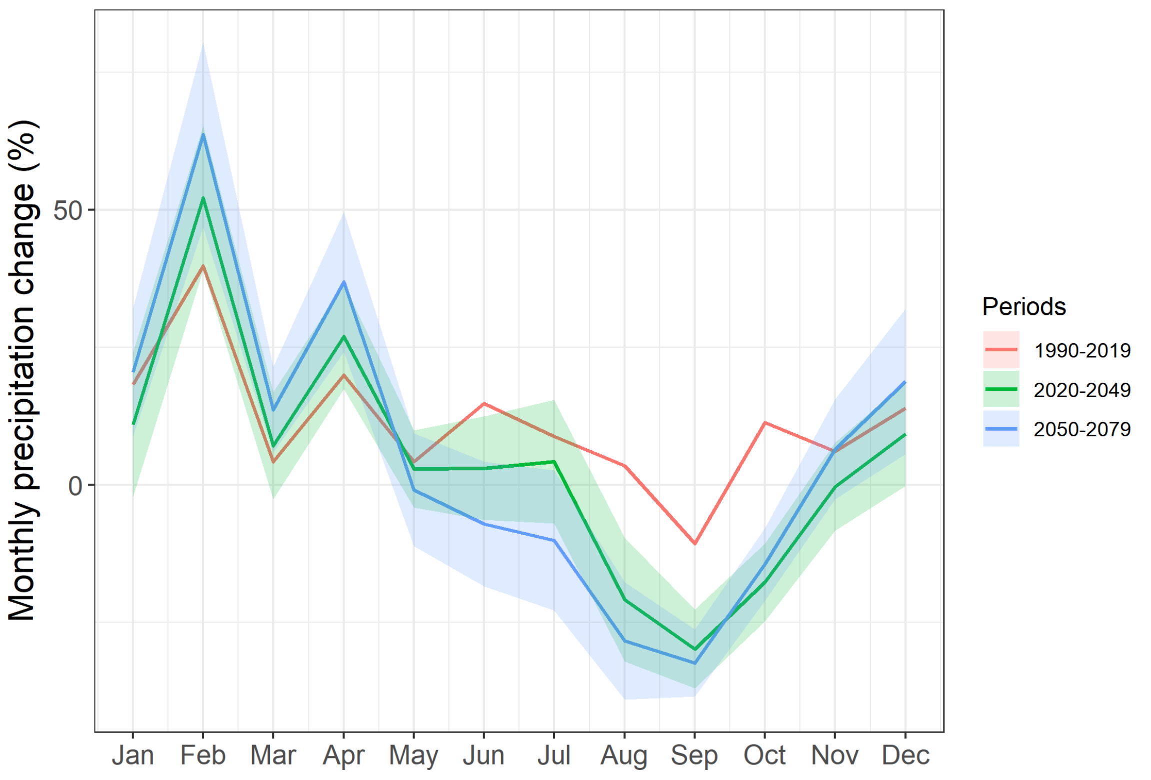


Figure 1. Percent change in the national mean monthly precipitation compared to the 1960-1989 baseline for three time periods. Solid lines: 1990 – 2019 (red, observed data); 2020 – 2049 (green) and 2050 – 2079 (blue) mean of the 12 climate projections. Shaded areas represent the variation between the 12 projections. Note: the 0% line represents the 1960-1989 baseline.

Projected Changes in Temperature

The national mean monthly observed and projected maximum and minimum temperature changes are shown in Figure 2, showing that temperatures have increased from the 1960 – 189 baseline in all months except June and October for the maximum temperature and October for the minimum. February has seen the largest observed increase. Future projections indicate a continued warming, particularly in the summer months.

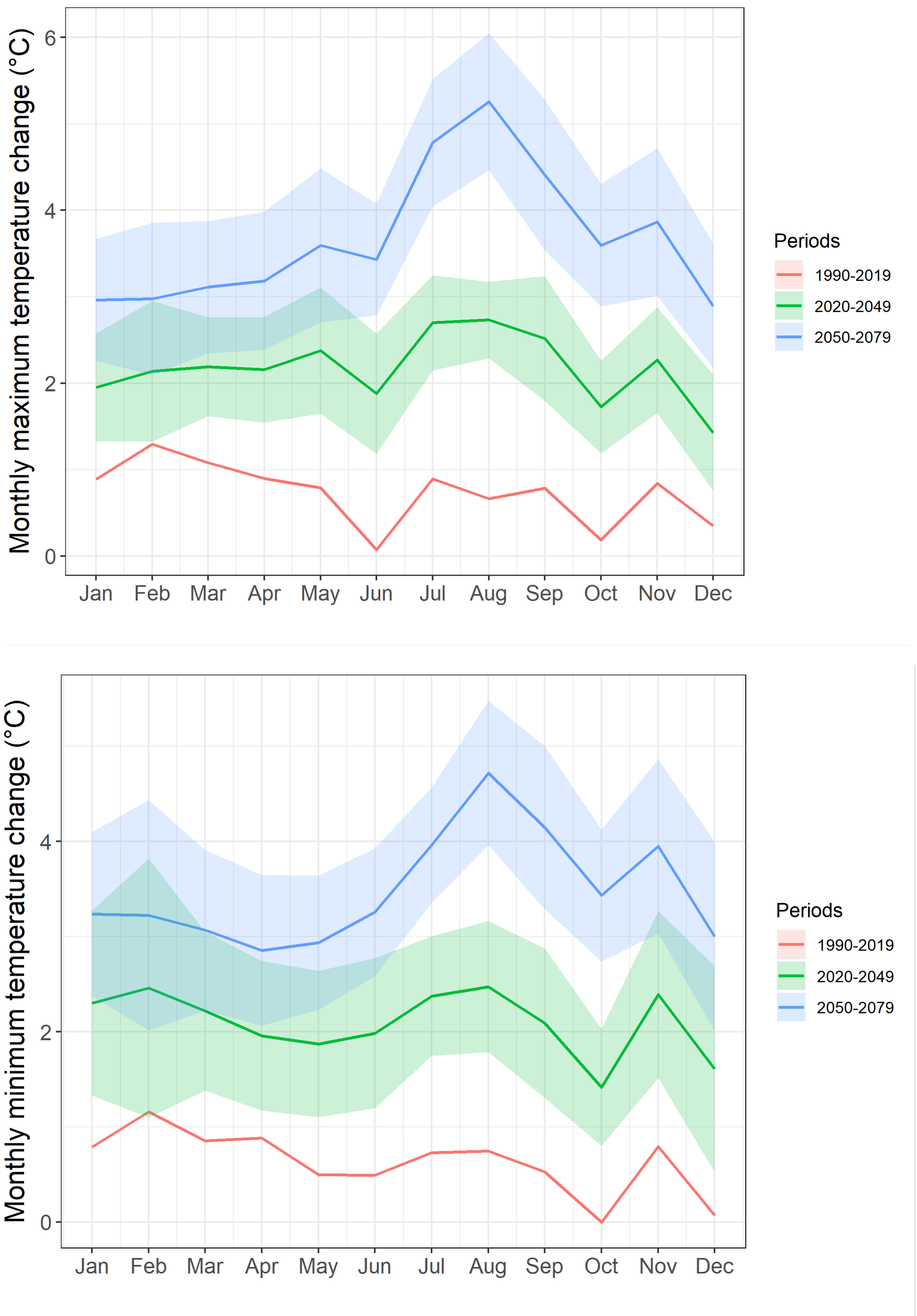


Figure 2. Percent change in the national mean monthly maximum (top) and minimum temperature (bottom) compared to the 1960-1989 baseline for three time periods. Solid lines: 1990 – 2019 (red, observed data); 2020 – 2049 (green) and 2050 – 2079 (blue) mean of the 12 climate projections). Shaded areas represent the variation between the 12 projections. Note: the 0 line represents the baseline.

Future projections summary

Precipitation:

- Projections for the period 2020 to 2049 indicate Scotland's climate to be wetter in December, January (both c.10%), February (45 – 55%) and April (25%) but less so in March (c. 5%).
    - These projected changes align with the observed changes already seen.
- For the same time period August, September and October are projected to become drier.
- These patterns continue in the 2050 – 2079 period with increases in the magnitude of change.
- There is a high level of agreement between projections that February and April precipitation will increase, whilst August, September and October will decrease.
- There is large spatial variation in changes to the monthly mean precipitation between projections: eastern areas may become wetter in some months (February, April, May, November and December); upland areas are likely to decrease in May, August, September and October, and November in the north.

Temperature:

- The observed warming trends in maximum and minimum temperature are projected to continue through the 2020 – 2049 and 2050 – 2079 periods.
    - There is high agreement between all 12 projections on there being continued warming, with all exceeding 2°C by the 2070s.
- There is a greater amount of warming between May and November (up to 4°C per month between 2020 – 2049), but also with substantial warming in the winter (variable by projection, approximately 2-3°C).
- The spatial distribution of change is relatively uniform across Scotland, e.g. does not reflect topographical differences.

Climatic Water Balance Summary

Observed and projected changes in the Climatic Water Balance (precipitation – evapotranspiration) are summarised below.

Observed trends:

- There has been an observed change in Climatic Water Balance, which is variable both spatially and temporally.
    - West coast areas have becoming wetter (increased surplus water) between December to April.
    - March to May have experienced a decrease in CWB (reduced water) in the east as has the whole of Scotland in September.
    - June to August have experience an increase in CWB (precipitation > evapotranspiration).

Projected changes:

- Projections show that there may be a shift in where and when parts of Scotland have a surplus or deficit of water.
- **A key finding** is that some upland areas of central Scotland are projected to shift from water surplus to deficit.

    - Most notably this is seen in May for the central Highlands and in August in the eastern and southern upland areas plus southern Argyll, Islay and Jura and parts of the Outer Hebrides.
    - By 2050 – 2079 for August there is a large increase in this upland area shifting from surplus water to a deficit.
        - Large parts of eastern Scotland in September are projected to see a shift to Climatic Water Balance deficit.
    - Such changes may have substantial impacts on the ecological and hydrological functions of peatlands, as well as other Natural Capital asset types.
- For both the 2020 – 2049 and 2050 – 2079 periods there is good agreement between the 12 projections that October through to March will remain in Climatic Water Balance surplus (precipitation is greater than evapotranspiration.
    - For both periods April shows large uncertainty in the direction of change.

Results Part 2: Future Precipitation Extremes

In this section we present results of analysis for future precipitation extremes. To help place these changes in climatic extremes into context of impacts, at the end of each indicator section (including Part 3: Future Temperature Extremes) we provide our initial interpretation of the changes on a range of land use categories / sectors, taken from the CXC report 'Monitoring soil health in Scotland by land use category - a scoping study' (Neilson et al., 2022) (Monitoring soil health in Scotland by land use category - a scoping study (climatexchange.org.uk)), We use these categories as they have been identified and linked to soil health indicators. It is informative to link the risks and implications of changes in indicator values to these sectors. We emphasise though that a key objective of the whole project is to provide more fully researched impacts on these categories and Natural Capital overall.

Consecutive Dry Days

The count of the number of Consecutive Dry Days (CDD) is an indication of when water may become limited and drought conditions occur. It is the maximum length of a dry spell in any one month (when precipitation is less than 1mm per day). An increase in Consecutive Dry Days implies the probability of increased stress on Natural Capital assets with a dependency on water. For some however, such as cereal crops, an increase may be a benefit if at a beneficial time of year such as at harvest. Conversely, an increase in CDD during early growth stages of many plants may reduce biomass accumulation and impede physiological development.

For the purposes of calculating CDD, it is defined as: **Maximum length of dry spell (CDD)**: maximum number of consecutive days with RR < 1mm. Let RRij be the daily precipitation amount on day i in period j. Count the largest number of consecutive days where RRij < 1mm (Climdex Project 2023). It should be noted that the sequence of consecutive dry days can be interrupted by a single precipitation event larger than 1mm.

How to read the maps: The darkest blue shading indicates the parts of the country with the least number of Consecutive Dry Days per month. Darkest red indicates locations with the most CDD. Figure 4 is the difference between the 1960-1989 baseline and the more recent 1990-2019 period. Darkest blue represents a negative change (fewer CDD) and darkest red shows locations where CDD has increased. In Figure 5 we present an alternative illustration of these changes using a change direction map. Whilst these maps do not quantify the size of change, they provide a clear image of the direction of change and where and when they occur. The direction of change and be either an increase (red, meaning more CDD), green means no change, and blue showing where there has been a decrease.

Observed trends in Consecutive Dry Days

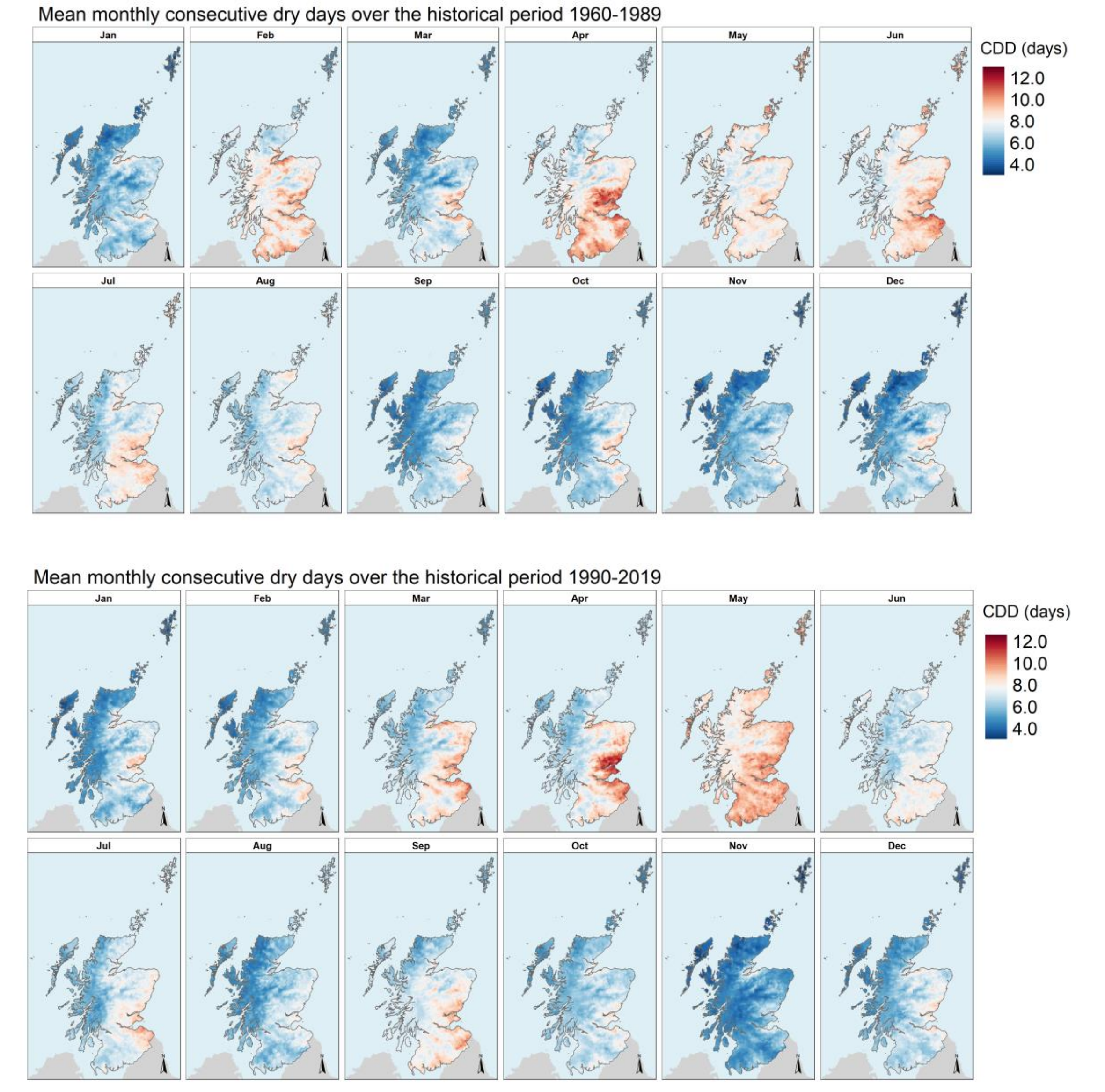


Figure 3 Mean monthly Consecutive Dry Days for two observed periods: 1960 – 1989 and 1990 – 2019

Interpretation: There has been a detectable change in the number of Consecutive Dry Days since the 1960-1989 period. The months with a fewer number of CDD per month are February, April, June to August (Figure 4, see also Figure 10a, b), though with a large spatial variation but concentrated in the eastern areas of Scotland. Figure 4 shows that there has been an increase in CDD, particularly in March, May and September across the whole country, and October in the west and December in the north. Conversely, February, April (except the east), June to August, October (in the east only) and November have seen an increase in CDD. This corresponds to the changes in mean monthly precipitation totals seen in Rivington and Jabloun (2022).

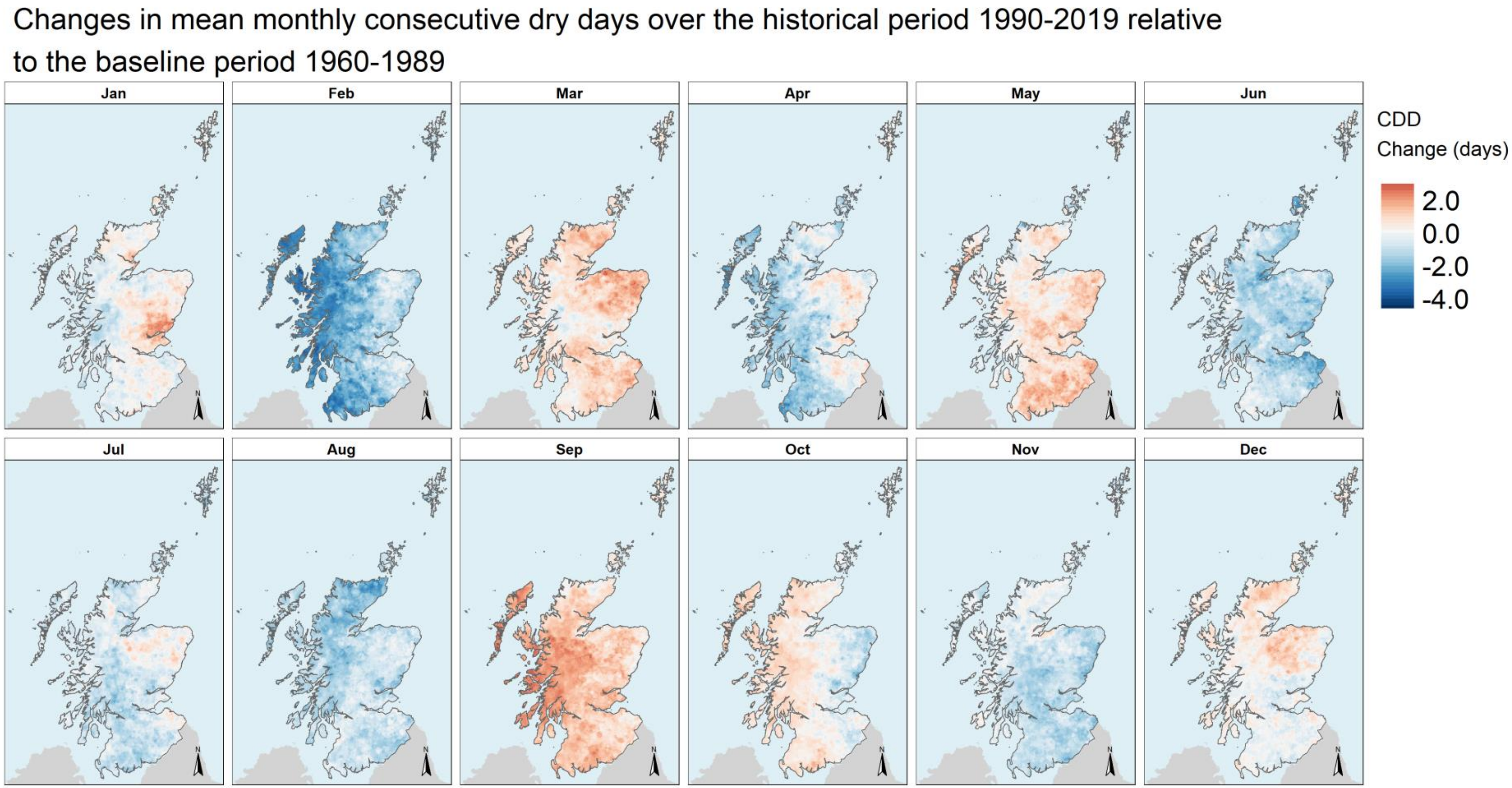


Figure 4. Changes in mean monthly Consecutive Dry Days (defined as precipitation <1mm/day) between 1960 – 1989 and 1990 – 2019.

Figure 5 makes clear that there has already been a change in CDD, and that the direction varies between months, with March, May and September experiencing widespread increases.

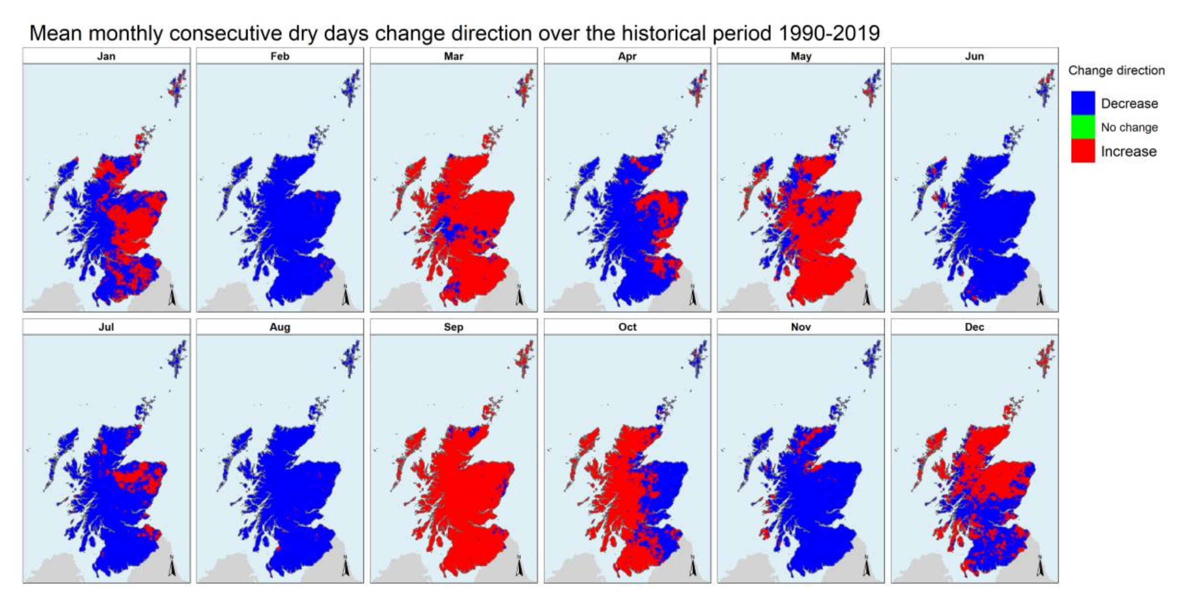


Figure 5. Change direction of mean monthly Consecutive Dry Days from the 1960 – 1989 to 1990 – 2019 period. Blue = increase in CDD, red = decrease, green – no change.

Future projections of Consecutive Dry Days

We have used 12 different climate projections, the first map presented (Figure 6) is one example (ensemble member 01), hence this represents one of 12 possibilities. From this one example it is possible to see that the observed trends are projected to continue in a similar way (except in this case November also sees an increase in CDD), with similar patterns between Figures 5 and 7 for the change direction.

How to read the maps: Figure 6 provides an example of the mean monthly number of Consecutive Dry Days calculated using the daily data generated by the HadRM3 Regional Climate Model, projection (ensemble member) number 01. Hence this is one of the 12 plausible projections we have used. The maps show the change in the number of CDD between the 1960-1990 baseline and the projection for 2020-249 period. Darkest blue shows where and when CDD has decreased, whilst darkest red indicates the largest increases.

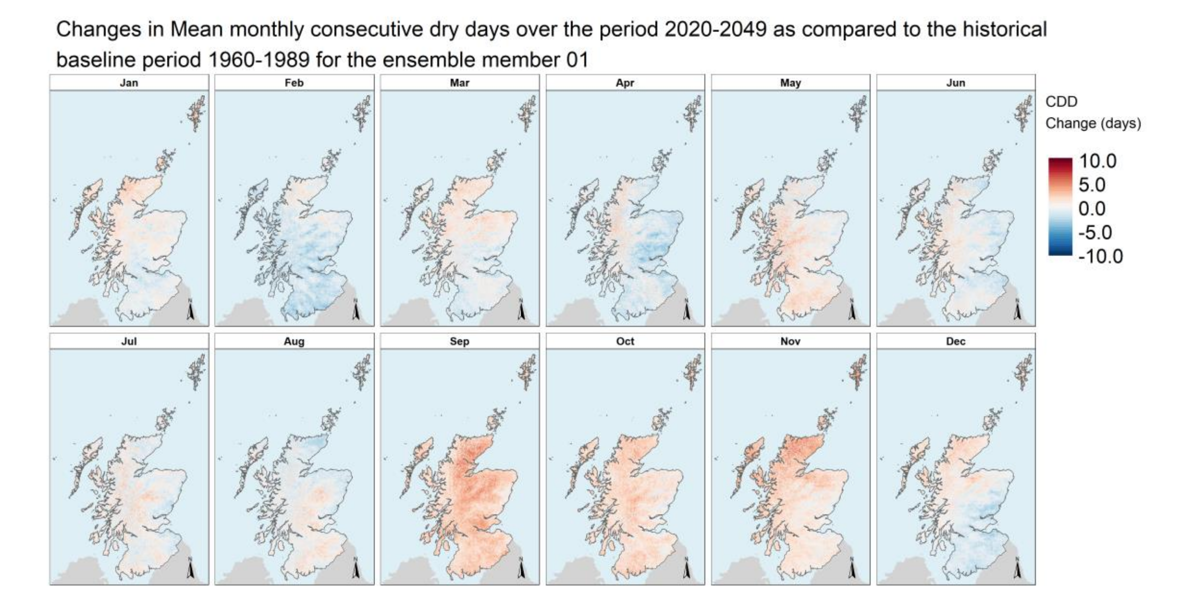


Figure 6. Example future projection (Ensemble Member 01) changes of Consecutive Dry Days between the 2020 – 2049 period and the 1960 – 1989 baseline.

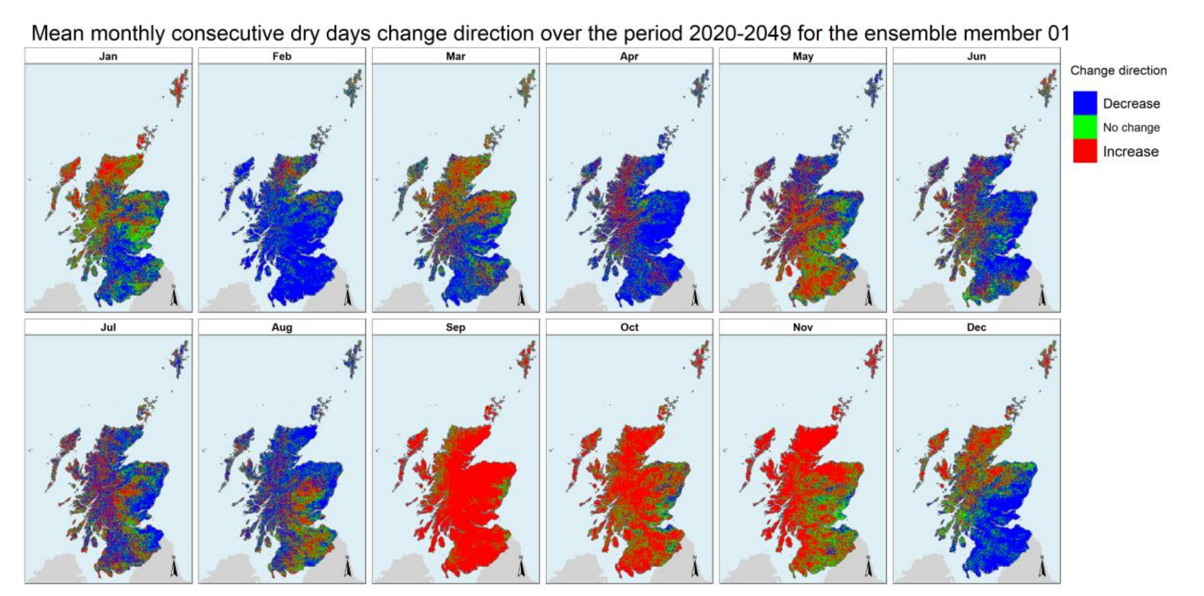


Figure 7. Change direction of mean monthly Consecutive Dry Days from the 1960 – 1989 to 2020 – 2049 period for Ensemble Member 01. Blue = increase in CDD, red = decrease, green – no change.

Care is needed though in interpreting individual projections. To address this, we present agreement maps, illustrating where and when different numbers of projections agree in the direction of change of CDD. Figures 8 and 9 show the change direction of CDD for 8, 10 and 12 projections for the two future time periods of 2020-2049 and 2050-2079.

Figure 8. Change direction agreement for 8 (top), 10 (middle) and 12 (bottom) climate projections (ensemble members) for the period 2020 - 2049.

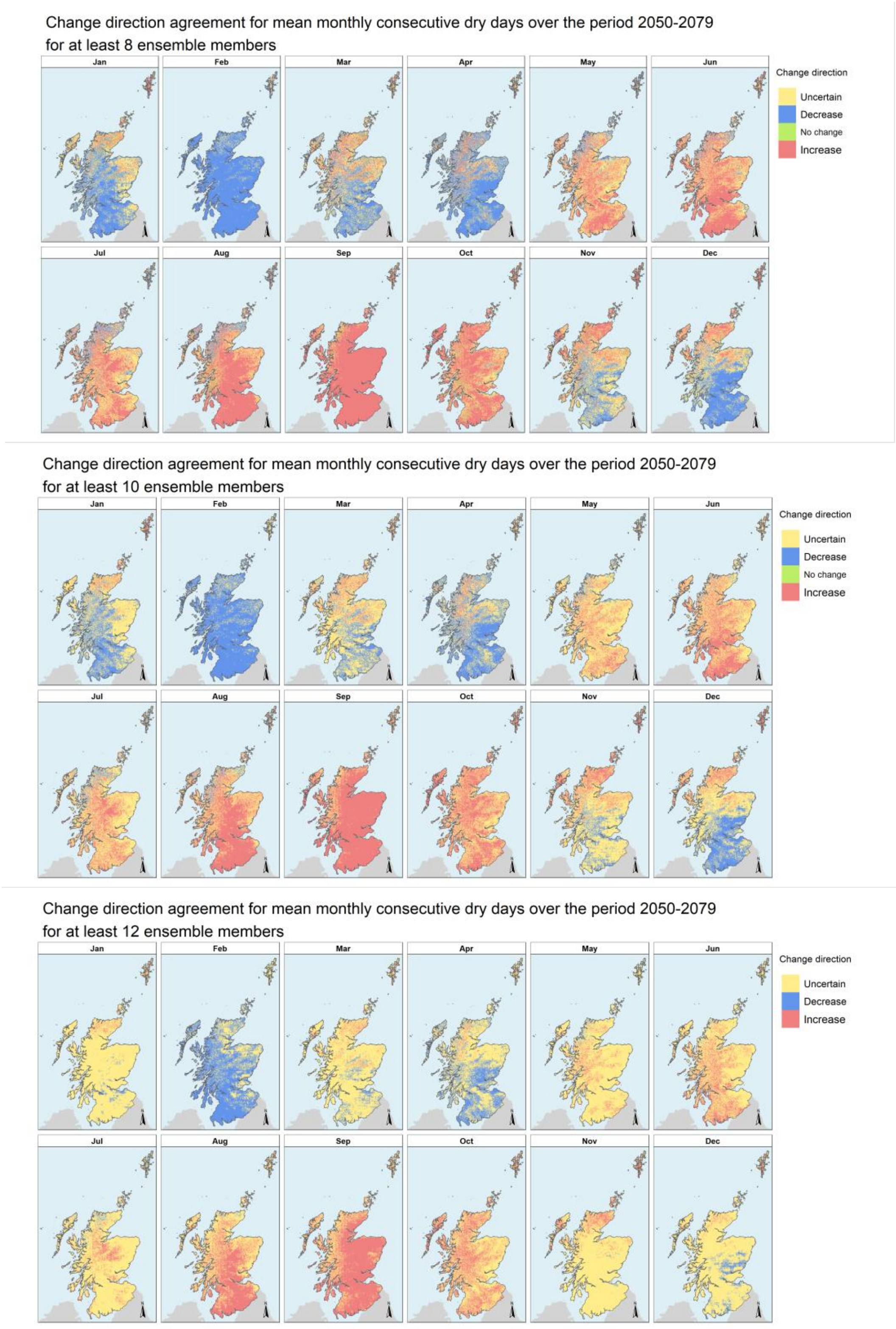


Figure 9. Change direction agreement for 8 (top), 10 (middle) and 12 (bottom) climate projections (ensemble members) for the number of Consecutive Dry Days in the period 2050 - 2079.

From Figures 8 and 9 there is good agreement that February is expected to experience fewer CDD, whilst August and September (and to a lesser extent June) will see more. The basis for confidence in this result is that the more projections that indicate a change (increase or decrease), then the more confident we can be about that change. Overall, the winter months may experience a decrease in the number of Consecutive Dry Days, but summers will see an increase.

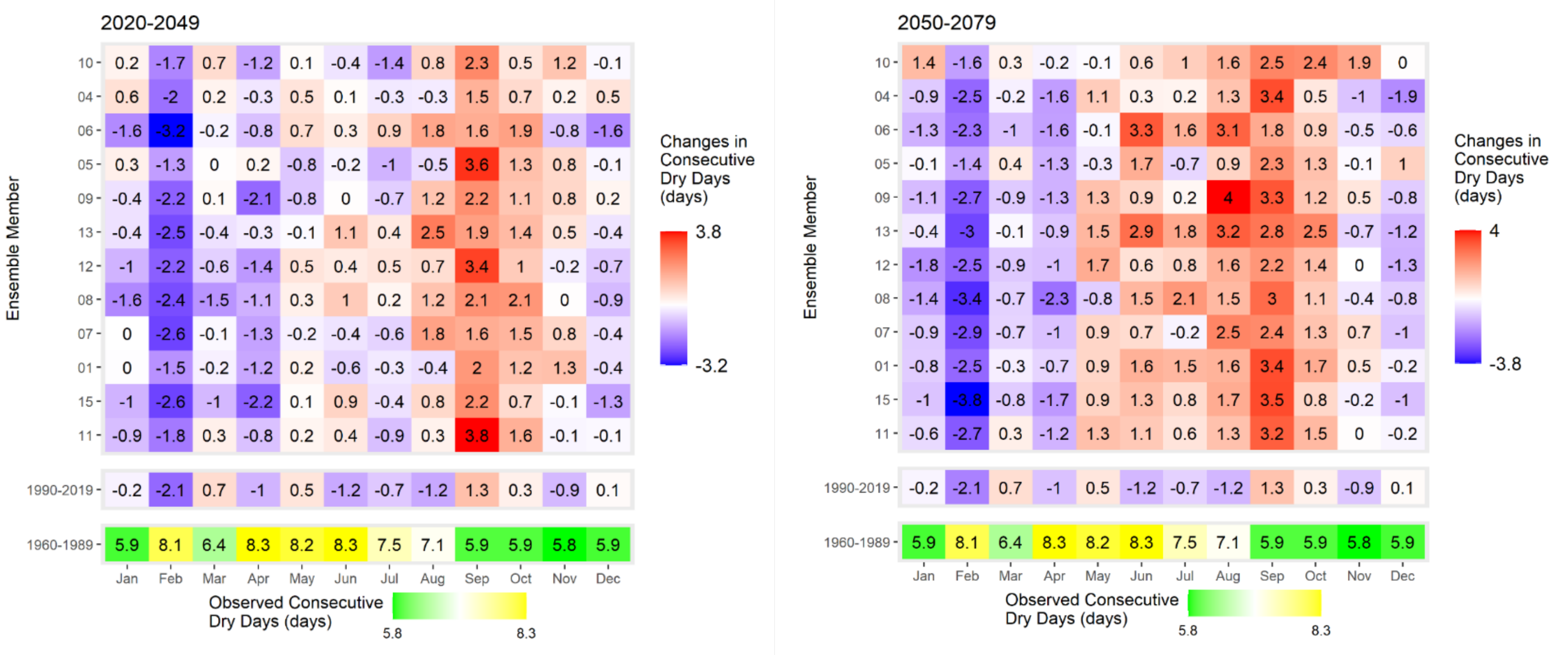
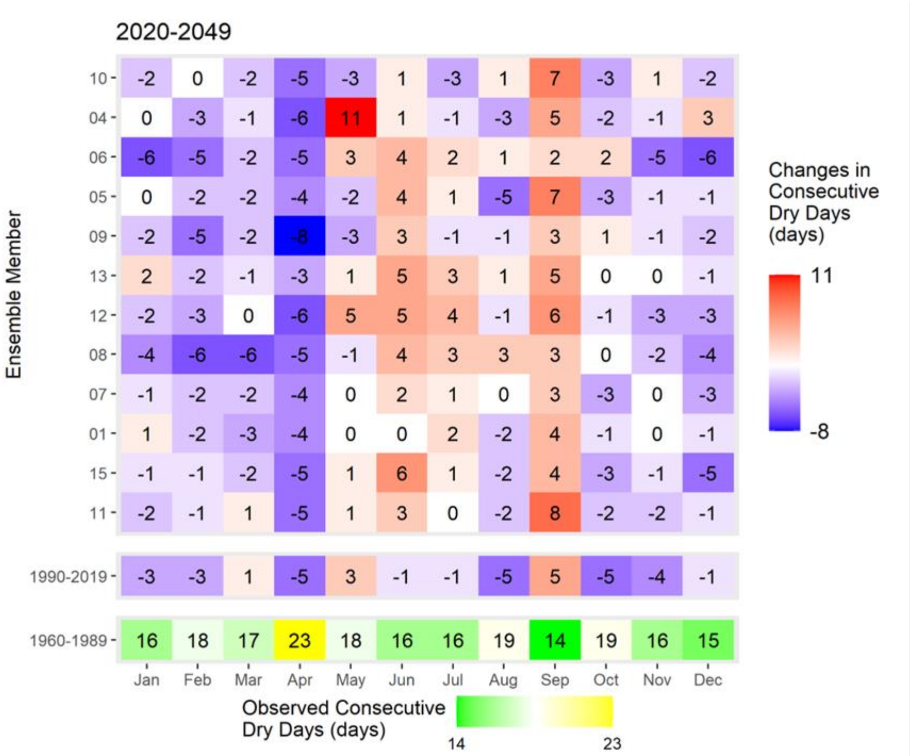


*Figure 10a. National scale changes in the number of **median** monthly Consecutive Dry Days for the two observed periods (1960 – 1989, 1990 – 2019) and per climate projection for 2020 – 2049 (top) and 2050 – 2079 (bottom). Note: scales are slightly different between plots.*

A further way to illustrate change is using 'heat plots' (Figure 10). Here the **median** number of Consecutive Dry Days for the 1960-1989 baseline oberved period is provided in the bottom row, and the change from the baseline to the 1990-2019 period in the second from bottom row. The future estimates for each ensemble member are shown in the top 12 rows and are ordered best performing at the bottom, worst at the top (in respect of model skill – see Appendix D). Red indicates an increase in CDD, blue a decrease. **Note:** To get the total number of CDD in the future, add the change values to the total for each month in the 1960-1989 baseline row. Figure 10a shows that the most CDD occurred in the April – August periods (yellow in the botton row), and that there has already been some change since the 1960-1989 baseline, the largest increase being 1.3 days in September, and largest decrease in February of -2.1 days. For the future projections, there may be a shift towards more CDD from May onwards. September is estimated to continue to have the largest increase, with May to October estimated to experince increases.



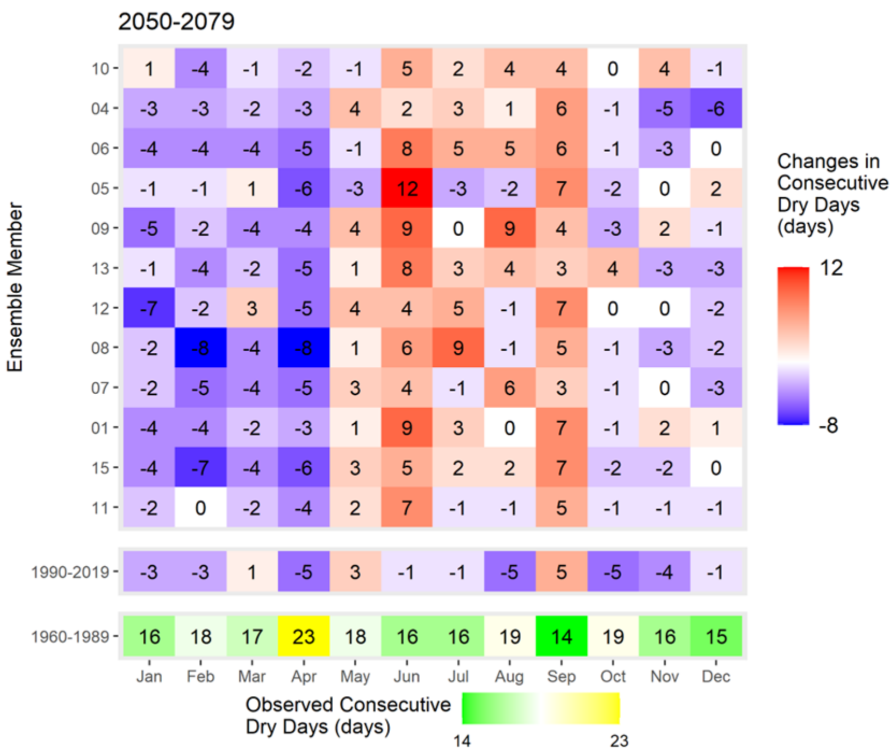


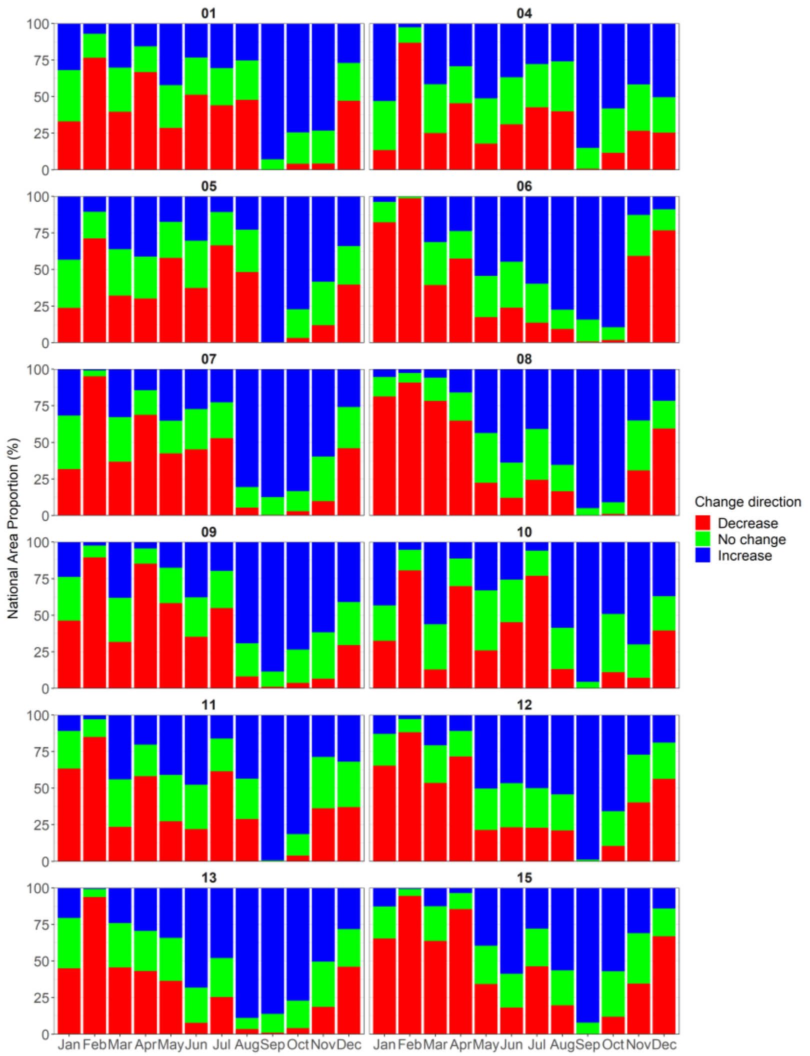
Figure 10b. National scale changes in the number of monthly Consecutive Dry Days in the most extreme year for the two observed periods (1960 – 1989, 1990 – 2019) and per climate projection for 2020 – 2049 (top) and 2050 – 2079 (bottom). Note: scales are slightly different between plots.

Figure 10b provides the national scale number of observed Consecutive Dry Days for the most extreme year between 1960-1989 (bottom row, green = 14 to yellow = 23), and then the changes in the 1990-2019 period (second from bottom row, blue = decrease, red = increase. To estimate the number of

Consecutive Dry Days in the 1990-2019 period per month, add the change to the 1960-1989 value (e.g. for May 18 + 3 = 21). The same process applies to the future projected changes (e.g. for September using EM11 the change between 1960-1989 and 2020-2049 is 14 + 8 = 22). The projections are ordered with the best performing ensemble member (with the best skill for simulating observed precipitation, see Appendix D) on the bottom row (EM11).

Figure 10b shows that there has been temporal variation in changes to the number of Consecutive Dry Days, with increases in March (1), May (3) and September (5), but decreases in all other months, with April, August and October see 5 fewer CDD. This pattern is generally projected to continue in the future, with more CDD in the summer and fewer in the winter. In the summer, for example 2020-2049 using EM11, September may experience c. 22 CDD in the most extreme year (1960-1989 was 14 + 8 from EM11 = 22).

In Figure 11 we present the land are proportions estimated to experience changes in the number of Consecutive Dry Days for each projection and month. This reinforces that there is likely to be an increase in land area experiencing an increase in CDD in the summer and a decrease in the winter.



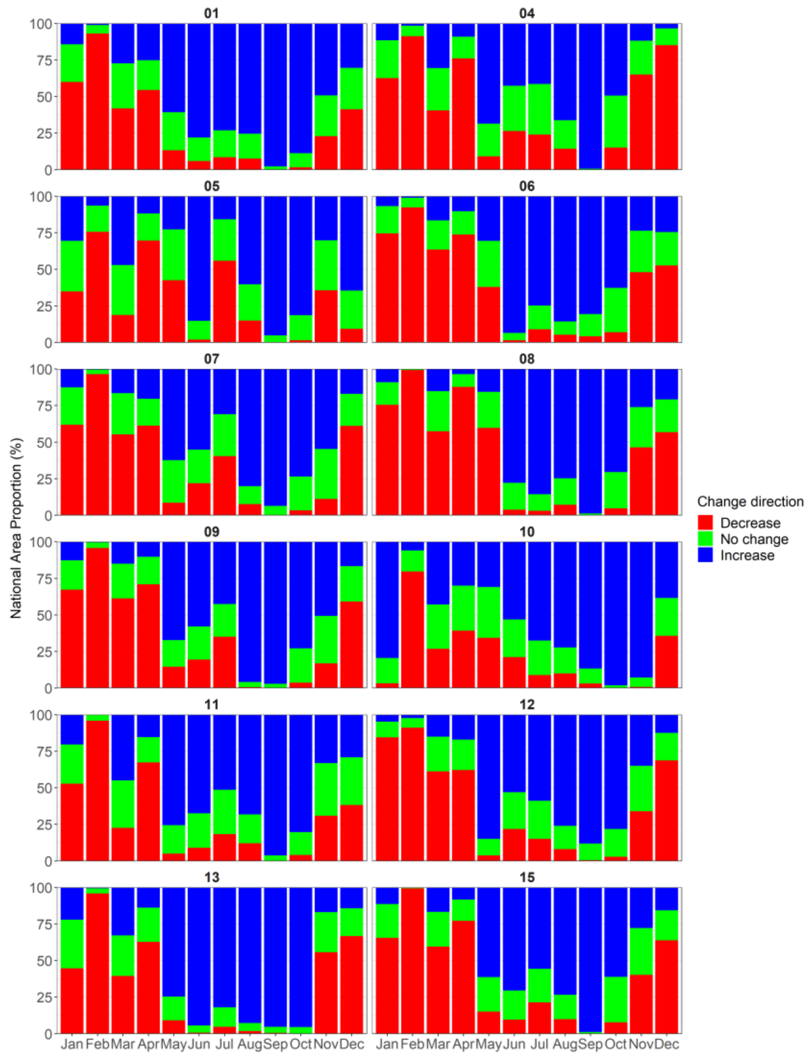


Figure 11. National land area proportions estimated to experience a decrease (red), increase (blue) or no change (green) in mean monthly Consecutive Dry Days for each projection (ensemble member) for the 2020 – 2049 (left) and 2050 – 2079 (right) future periods.

Implications of changes in Consecutive Dry Days

In respect of impacts on Natural Capital, of concern is the trend for March and May (and April in the east) having more Consecutive Dry Days, as this is a key biotic growth period. To assess the full impact of these changes it is also necessary to understand the changes in temperature, precipitation amount and evapotranspiration rates.

Observed precipitation amount changes in the west have increased in December to May, but either remained similar or decreased in July, August and October. Eastern Scotland became drier in January, March, May, August, September and December, but wetter in February, June, July, October and November. Projections for the period 2020 to 2049 indicate Scotland's climate to be wetter in December, January (both c.10%), February (45 – 55%) and April (25%) but less so in March (c. 5%). For the 2020 to 2049 period, August, September and October are projected to become drier (Rivington and Jabloun 2022).

Based on these changes in precipitation amount, an increase in CDD implies a higher likelihood of water stress occurring. The consequences of this will be variable depending on soil hydrological characteristics and tolerance ranges of species, with some plants potentially benefitting (e.g. due to changed competitive advantage) or being more at risk (e.g. due to low desiccation tolerance).

Longer dry periods increase the risk of fire occurrence[3] and soil erosion by wind and heavy precipitation, and place additional pressures on irrigation demand. The overall picture of wetter winters and drier summers implies an increased pressure on ecosystems to cope with changes in the amount of water available.

Land use category / sector impacts:

- Water supply: increased risk of drought risk, resulting in low flow and restrictions on licensed water abstractions.
- Water quality: increased risk of impaired water quality due to low dilution of pollutants.
- Agriculture (uncultivated): increased risk of reduced biomass production, less livestock feed and fire occurrence in summer (especially September).
- Open upland habitats: increased risk of drought, fire occurrence and altered inter-species competition.
- Environmentally sensitive areas: increased risk of drought, reduced water availability and changes to nutrient cycles.
- Grassland: increased risk of reduced biomass production, less livestock feed and fire occurrence in summer (especially September).
- Arable: Potential for yield reduction if longer dry periods in the spring, but may be favourable if at cereal harvest time.
- Peatlands: increased risk of drought, fire occurrence and altered inter-species competition. May result in more exposure of peat, desiccation and carbon loss.
- Forestry: increased risk of drought, fire occurrence and altered inter-species competition.
- Urban: higher demand for water in summer, possible association with increased heat stress.
- Amenity/leisure: potentially more favourable weather for outdoor activities, but higher fire occurrence risk.

[3] See D5-2 Deliverable D2.3b Fire Danger Assessment of Scottish Habitat Types (Gagkas et al 2023), available on the project website: [Climate Change Impacts on Natural Capital | The James Hutton Institute]

- Transport infrastructure: possible association with increased heat stress.
- Biodiversity: increased risk of drought, fire occurrence and altered inter-species competition.
- Climate change: reduced mitigation potential due to limitations on plant growth.

Consecutive Dry Days summary

Observed trends:

- Since 1960 there has been a small shift in the number of Consecutive Dry Days per month (median is < +/- 2), with more increases occurring in March, May, September and, for the western half of Scotland, October.
    - With April experiencing an increase in the east as well, the main parts of the growing season for the arable areas of Scotland have experienced longer dry periods.
- Conversely, February, April (except the east), June to August, October (in the east only) and November have seen a decrease in Consecutive Dry Days per month.

Future Projections:

- There is good agreement between the 12 climate projections that from now until 2050 the winter months may experience a decrease in the number of Consecutive Dry Days (change in median of approximately 1 – 3 days), but May through to October are likely to see an increase (approx. 1 – 3 days).
- Historically (1960-1989) April has had the most Consecutive Dry Days (23) in the most extreme year, but this may decrease by c. 5-6 days between now and 2050, whilst June (16 days) may increase by 1-6 days and September (14) by 2-8 days.
- For the 2050 – 2079 period these seasonal changes become more pronounced, with the median changes ranging from 1 – 4 days.

Dry Days

This is a count of the number of Dry Days (DD) per month (when precipitation is < 1mm). As with Consecutive Dry Days, this indicator provides information on the potential for increased dry conditions and risks of drought and heat stress.

Monthly number of Dry Days (DD): Considering RRij as daily precipitation amounts on day i in period j, DD represents the number of days where RRij < 1mm (Climdex Project 2023).

Observed trends in Dry Days

There is a clear west to east gradient in fewer (blue shading) to more (red) Dry Days that is also related to topography and elevation, with upland areas have less Dry Days (Figure 12).

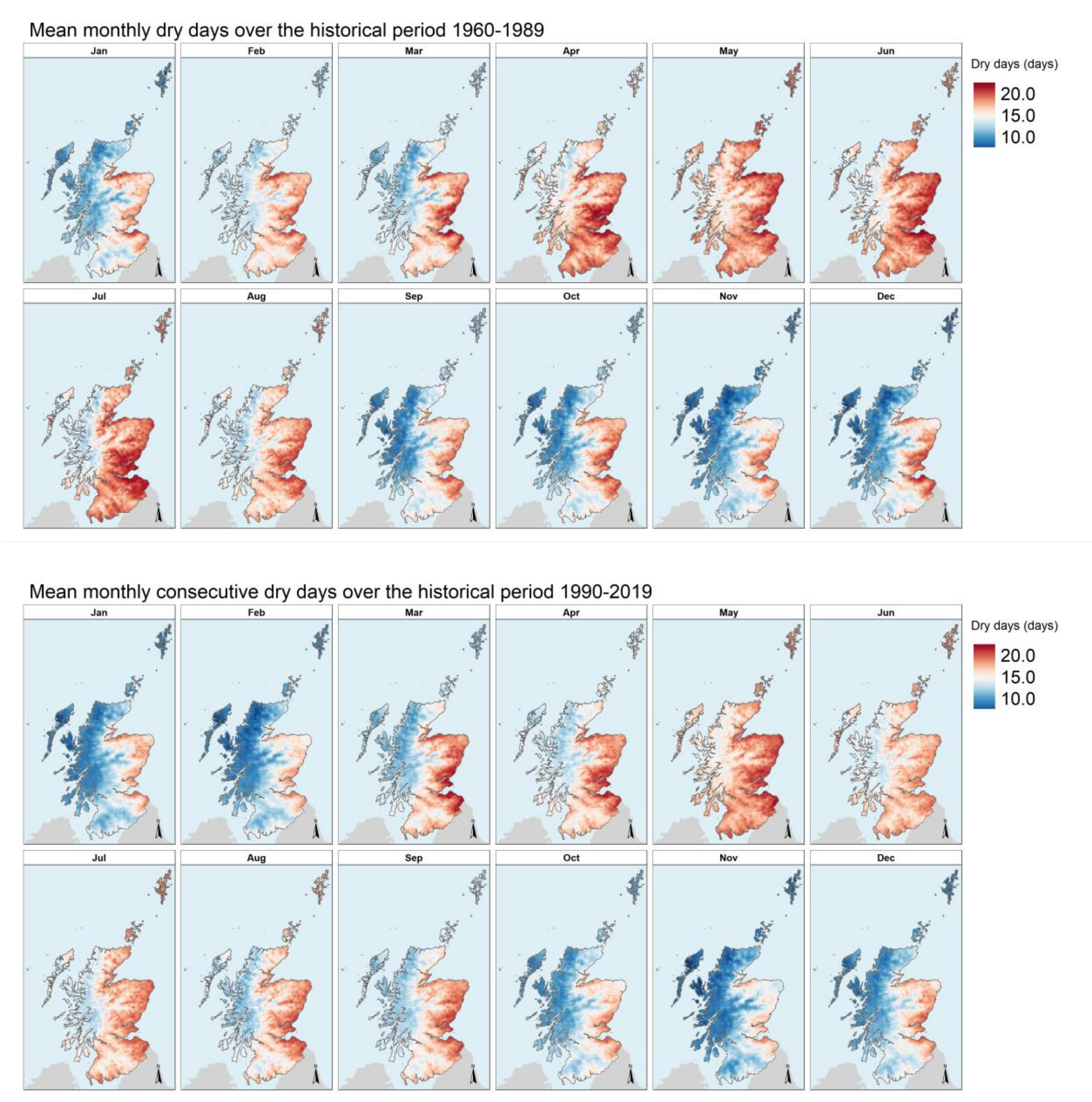


Figure 12. Mean monthly number of Dry Days for two observed periods: 1960 – 1989 (top) and 1990 – 2019 (bottom).

Figure 13 shows that there has been a geographically variable pattern in DDs in different seasons. Winter has seen a decrease in DD in west and central Scotland and an increase in late winter on the East, while in spring the pattern was more variable, with more DD initially only in the NE in April, followed by more DD in most of Scotland in May and fewer DD in most of Scotland in June, but little change in NW coastal areas. Late summer (September) has been characterised by a widespread increase in DD in most of the country, while autumn has seen a split pattern with more DD in the North and fewer in the rest of the country.

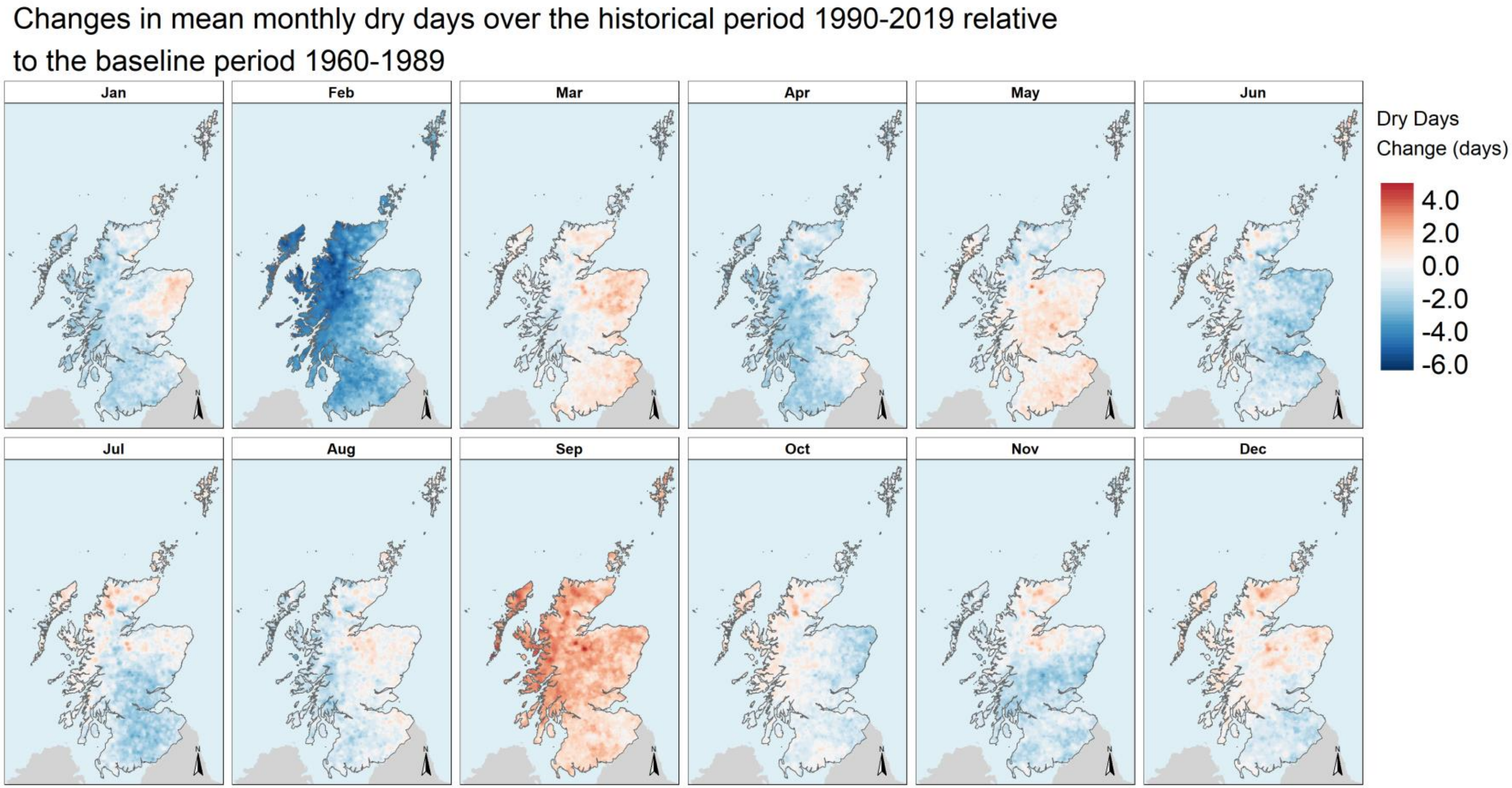


Figure 13. Changes in the number of Dry Days between the 1960 – 1989 baseline and 1990 – 2019 period.

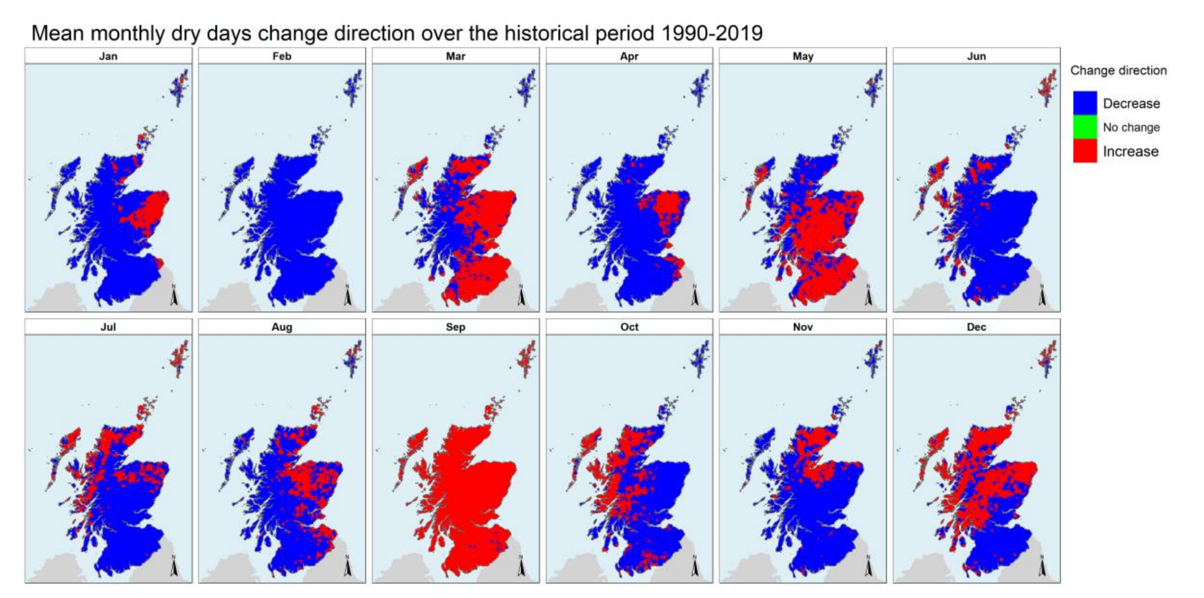


Figure 14. Change direction maps of mean monthly number of Dry Days.

There has been a nationwide increase in the number of Dry Days in September, and most of the east and south in March and May (Figure 14). Conversely February has experienced a nationwide decrease in the number of Dry Days, with more land area having a decrease overall across the year.

Future projections of Dry Days

In the example future projection (EM01) shown in Figure 15, there is estimated to be an overall increase in the number of Dry Days in the future. In this example the increase is more in the west than the east. September to November are estimated to have the largest increases.

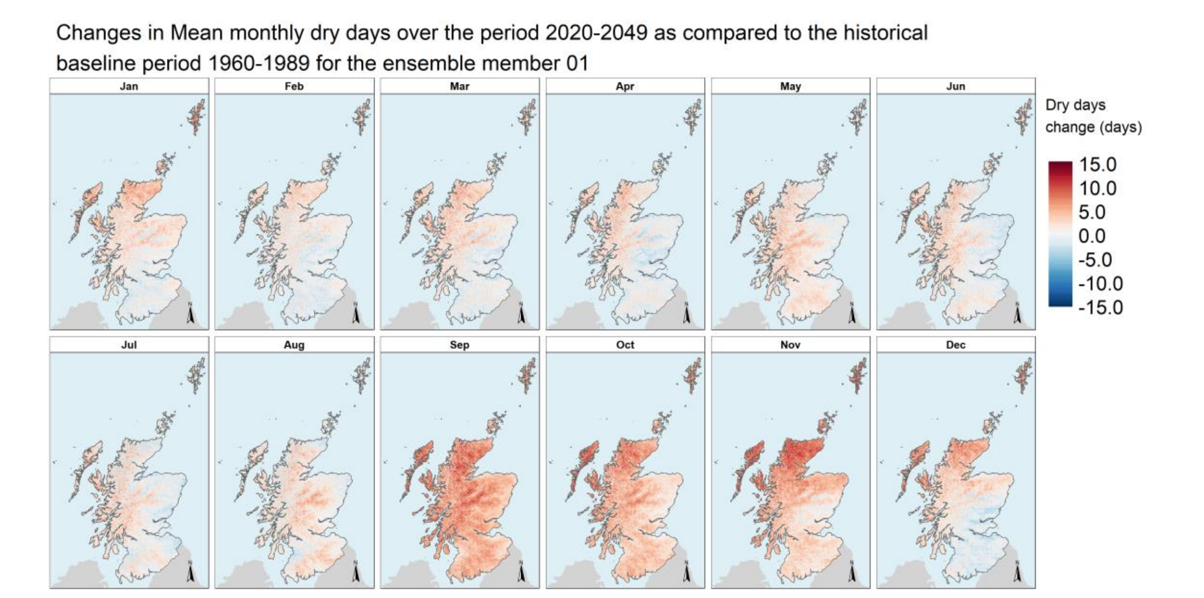


Figure 15 Example future projection (Ensemble Member 01) changes of the number of Dry Days between the 2020 – 2049 period and the 1960 – 1989 baseline.

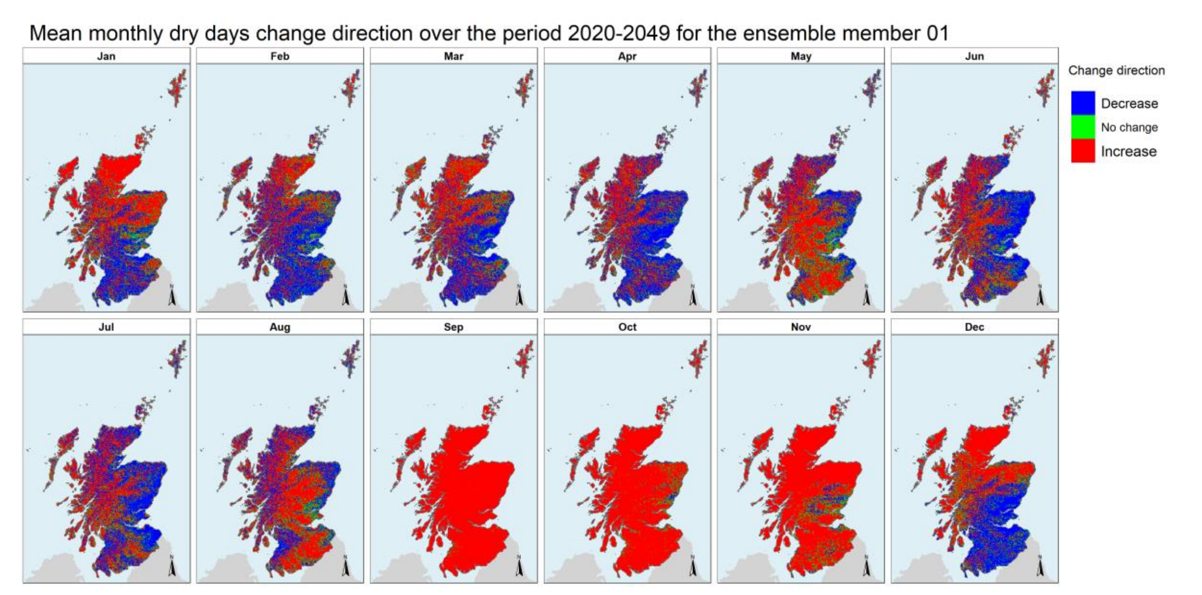


Figure 16. Change direction of mean monthly number of Dry Days from the 1960 – 1989 to 2020 – 2049 period for Ensemble Member 01. Blue = increase in DD, red = decrease, green – no change.

The example change direction map (EM01, Figure 16), highlights the increase in the number of Dry Days in September to November, but decreases in the east or southeast for all other months. This is only one realisation of a plausible future.

For the period 2020-2049 there is some uncertainty, with different model runs projecting different patterns of DD in most areas of the country, which lowers the confidence in the projection for a given area (Figure 17). When all 12 ensemble members are considered there is moderate evidence for a split pattern, with more DD in winter in all areas except the N and NE of the country. Projections are more consistent in the second part of the year, with DD projected to increase virtually in all areas except in December. September is consistently expected to experience a decrease in the number of Dry Days across the whole of Scotland (all 12 ensemble members).

The trend in DD is also uncertain in most areas for the period 2050-2079 for winter, spring and early summer, while August September and October are more consistently projected to have fewer DD (Figure 18).

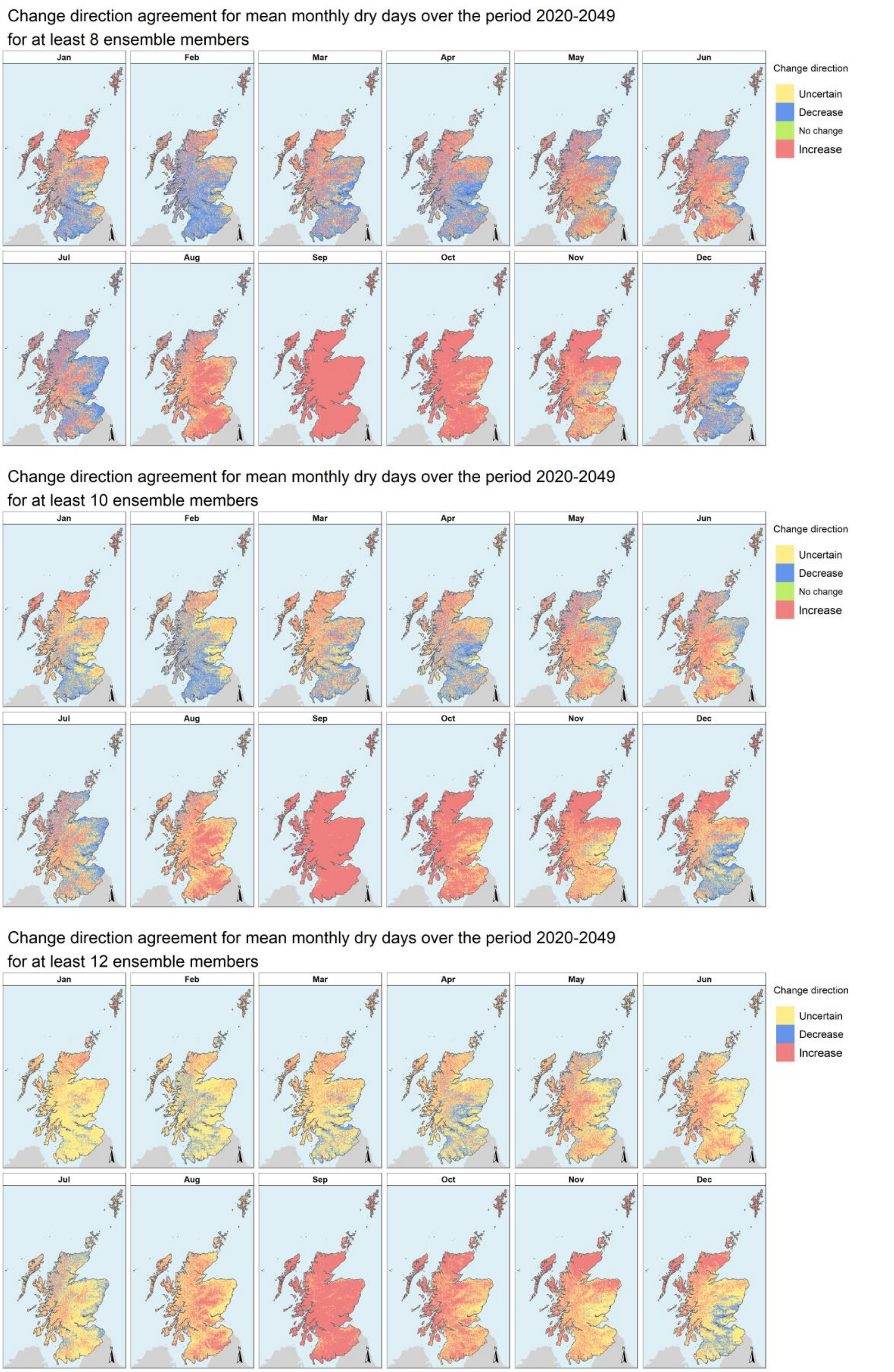


Figure 17. Change direction agreement for 8 (top), 10 (middle) and 12 (bottom) climate projections (ensemble members) for the number of Dry Days in the period 2020 - 2049.

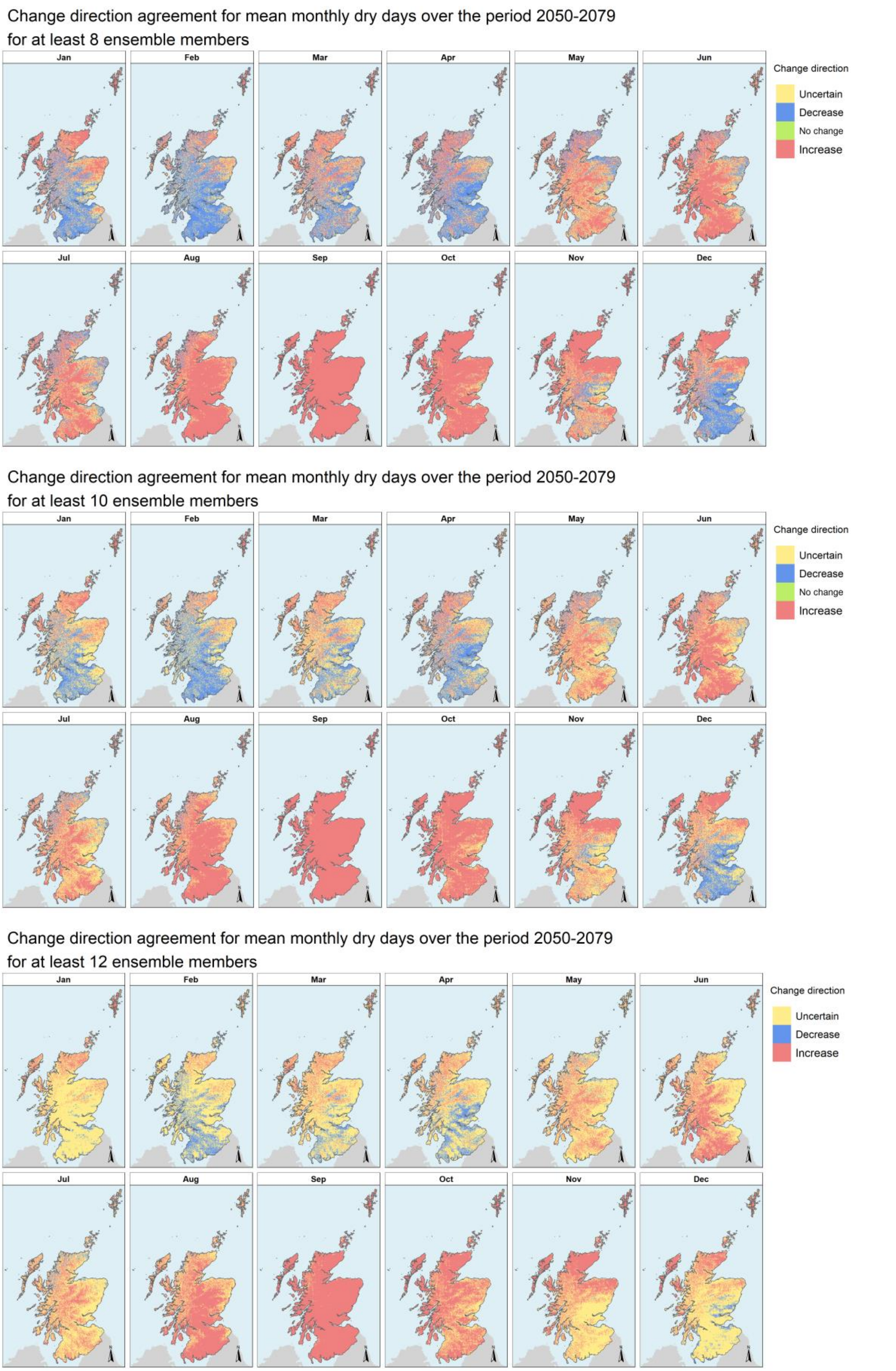


Figure 18. Change direction agreement for 8 (top), 10 (middle) and 12 (bottom) climate projections (ensemble members) for the number of Dry Days in the period 2050 - 2079.

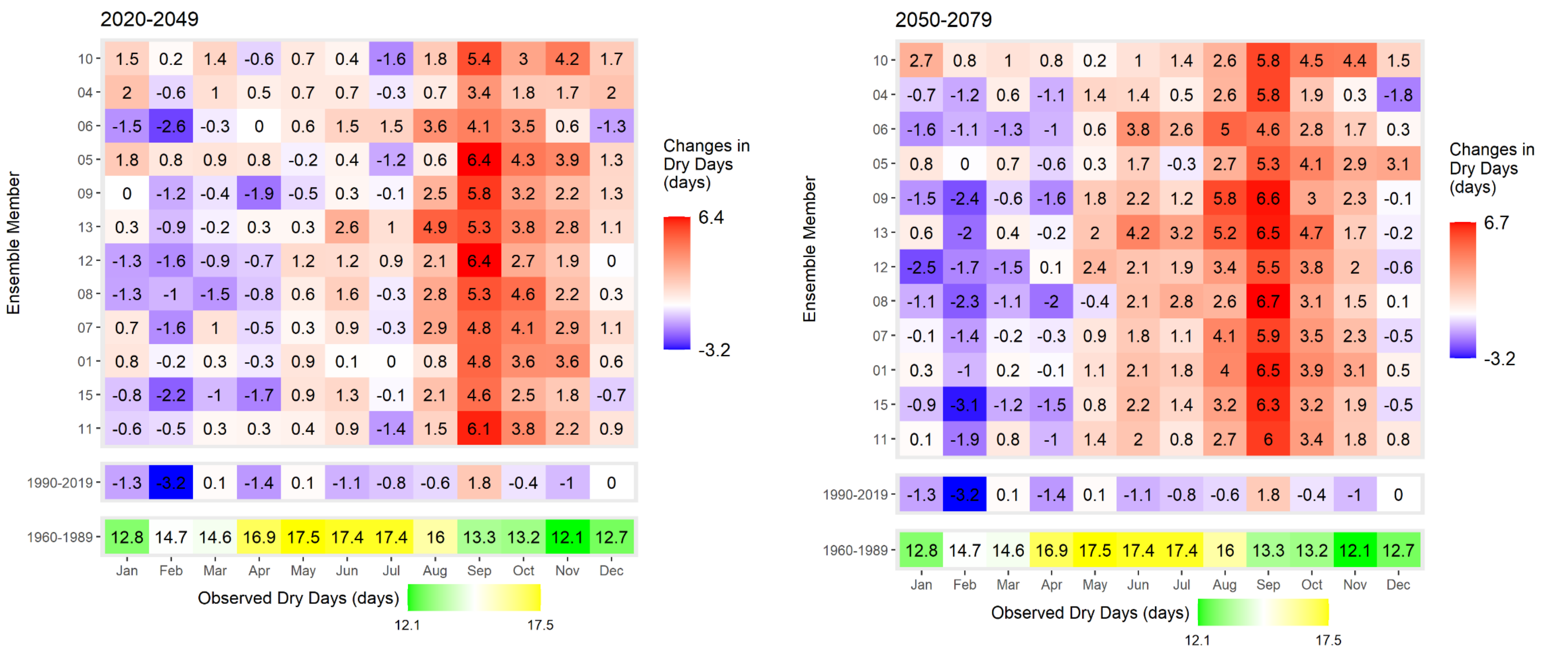


*Figure 19a. National scale changes in the **median** monthly number of Dry Days for the two observed periods (1960 – 1989, 1990 – 2019) and per climate projection for 2020 – 2049 (top) and 2050 – 2079 (bottom).*

There has been an observed change in the number of dry days since the 1960-1989 baseline period, with the median number of Dry Days decreasing by -3.2 in February. The change in other months is small, being c. 1 day or less, except September when Dry Days increased by 1.8 days. The colour shading in Figure 19a emphasises that the summer, particularly September and the autumn and likely to become drier in the future, but the winter is likely to become wetter.

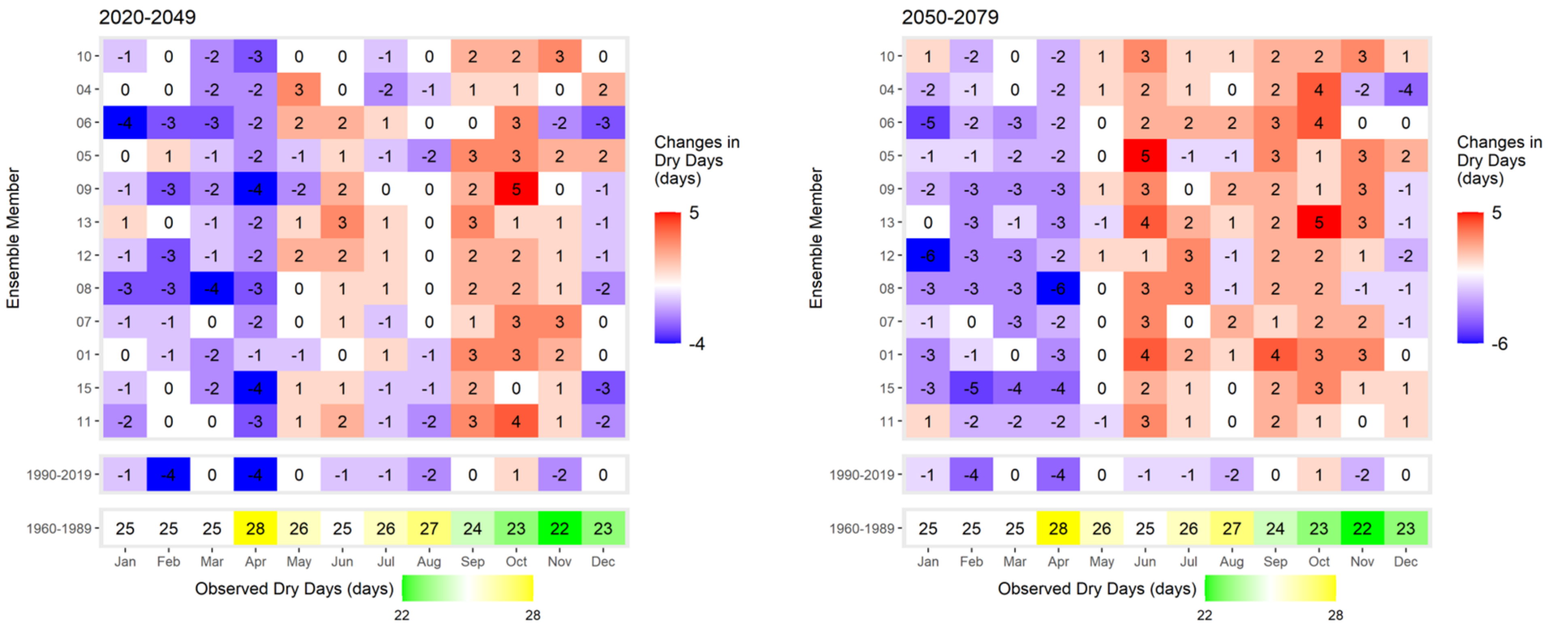
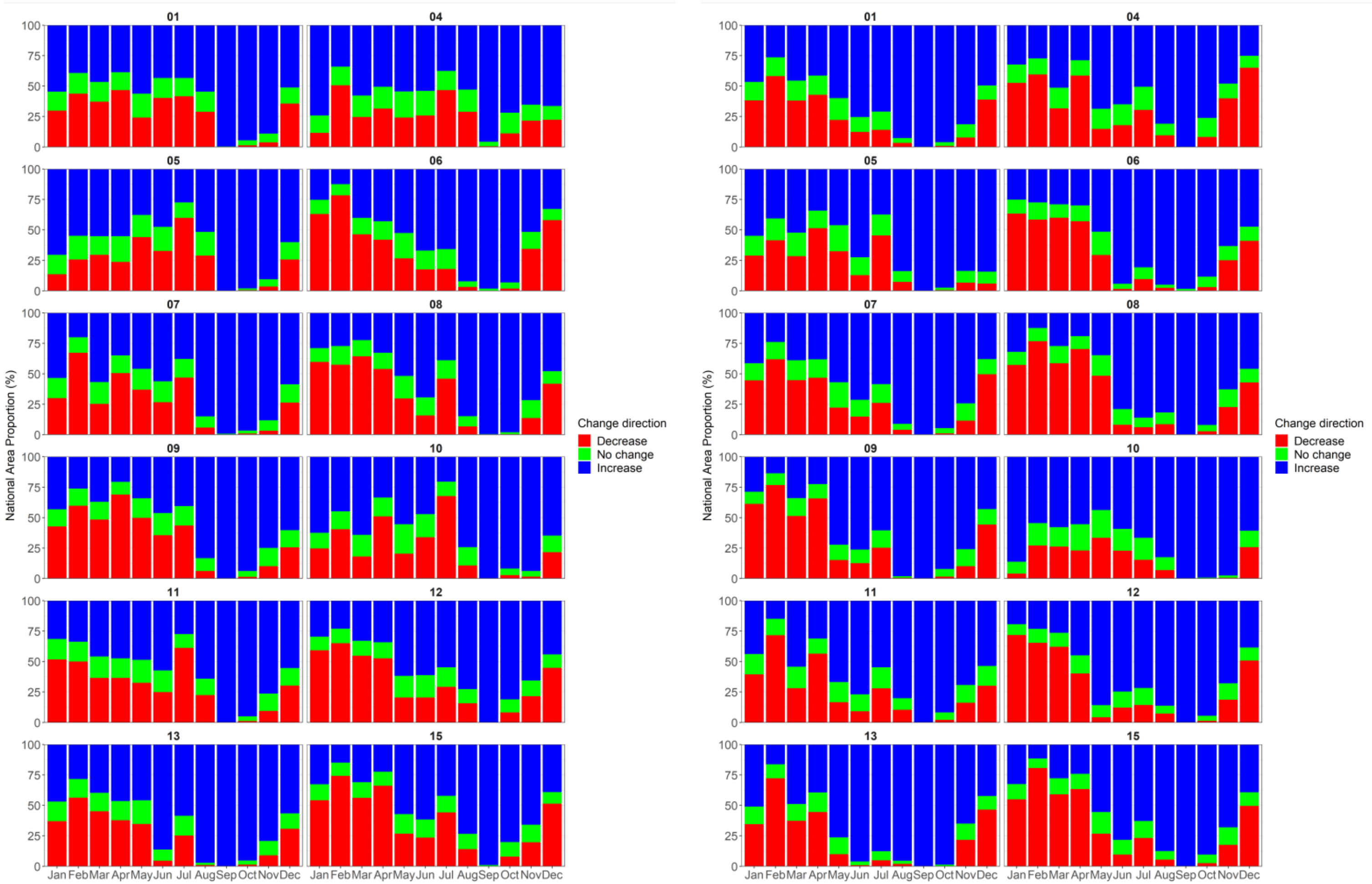


Figure 19b. National scale changes in the monthly number of Dry Days for the most extreme year for two observed periods (1960 – 1989, 1990 – 2019) and per climate projection for 2020 – 2049 (top) and 2050 – 2079 (bottom). Note: scales are different between the two future periods.

There has been an observed change in the number of Dry Days for the most extreme year, with February have 4 fewer days. The overall pattern of wetter winter and drier summers, and in this case autumn as well, is clearly highlighted by the blue and red shading.



The seasonal variation pattern between wetter winters and drier summers is also visible in the land area estimated to have either an increase (blue) or decrease (red) in the number of Dry Days (Figure 20). In the summer and autumn (August to November) there is clearly more land area with an Increase, though the pattern is less distinction in the winter and spring months.

Figure 20. National land area proportions estimated to experience a decrease (red), increase (blue) or no change (green) in mean monthly Consecutive Dry Days for each projection (ensemble member) for the 2020 – 2049 (left) and 2050 – 2079 (right) future periods.

Implications of changes in Dry Days

The climate indicator Dry Days is calculated to assess the possible effect on water resources, drought risk, and impact on crops and wild vegetation, with the number of dry days proportional to the likelihood that an area will experience water shortages. However, DD should be seen in the context of other variables, such as temperature and the related evapotranspiration, and soil hydrology.

Depending on soil hydrology, areas of Scotland where Dry Days are projected to increase in winter can experience both negative and positive consequences for agriculture, with winters likely to have a smaller effect than drier springs, as many crops are dormant in winter. Nonetheless, in winters with several dry days, soil moisture deficit can build up and partially limit the water available for crops when they begin to grow again in the spring. Also, dry (and windy) winters can increase the risk of soil erosion, which can worsen conditions for crop growth. However, in areas with poorly drained soils, drier winters can also be beneficial, and lead to an earlier end of field capacity with better trafficability conditions in spring, thus facilitating field operations. And conversely, in areas with fewer winter DD early spring trafficability problems could emerge.

In well-drained areas that are projected to experience more dry days in spring and summer, there is a risk of a decrease in average crop yields, while poorly drained soils could see improved crop growth conditions.

Pests and diseases could increase due to dry and warm conditions, which can further reduce yields, while wild vegetation is more exposed to the risk of fire occurrence. Finally, drought conditions could affect the ability to irrigate which can also lead to yield decreases in some areas.

For other vegetation it is more difficult to assess the impact of changes in DD on growth and productivity as this will depend on the ecological tolerance of the individual species involved, with some winners and some losers.

Land use category / sector impacts:

Given the large spatial variation in changes in the number of Dry Days, the impacts below are based on those areas where there is a higher level of agreement in the direction of change.

- Agriculture (uncultivated): drought stress reduces biomass production and yield of crops.
- Open upland habitats: increased fire occurrence risk and more severe fires, desiccation of vulnerable plant species.
- Environmentally sensitive areas: changes to inter-species competition (more drought tolerant plants become more dominant), increased fire occurrence.
- Grassland: reduction in biomass production, loss of individual plants creates bare ground suitable for invasion by other species (Pakeman et al. 2002).
- Arable: in spring this may reduce establishment and through the growing period it will reduce yields. More dry days at harvest will reduce drain drying costs.
- Peatlands: increases the risk to key plant species and fall in water table may mean the system switching to a source of carbon dioxide rather than being a sink. There is also an increased risk of severe fire occurrence.
- Forestry: increased fire occurrence and potential losses of young trees.
- Urban: increased water demand, increased fire occurrence risk.
- Amenity/leisure: increased water demand for gardens, parks and golf courses.
- Transport infrastructure: likely no affect.

- Biodiversity: species dependent on high humidity will decline, especially in more open situations.
- Climate change: reduced resilience and loss of mitigation potential, especially on peatlands.

Number of Dry Days summary

- Observed: there has been both a geographical and temporal change in the number of Dry Days since 1960, with a decrease in winter in west and central Scotland, and increase in east. February has seen a decrease and September an increase across most of the country.
- Future: Future: there is a mixed range of uncertainty in the geographical distribution of the number of Dry Days. However, there is good agreement between the 12 projections that there will be decrease in the winter and increase in the summer. Spatially estimates show an increase in Dry Days in the central and southern uplands in August, most of Scotland in September and uplands in October and in the north in November and December.
- Historically (1960-1989) April has the most observed Dry Days (28) in the most extreme year, but this has already decreased by four days hence matching the projected decrease by 1-4 days.

Heavy Rain Days

This indicator represents days when precipitation may be considered as 'heavy rainfall' – here we consider the threshold as days when precipitation is ≥ 10mm. Heavy Rain Days (HRD) may be used as an indicator of increased risk of flooding, potentially not directly from very large precipitation amounts (see indicator Very Wet Days), but in contributing to preceding conditions that make flash flooding more likely.

For the purposes of calculation, Monthly number of Heavy Precipitation Days (HRD): Count of days when PRCP ≥ 10mm. Considering RRij as daily precipitation amounts on day i in period j, R10 represents the number of days with RRij ≥ 10mm (Climdex Project 2023).

Interpretation: Figure 21 shows that mean monthly heavy precipitation is consistent between the two historical periods, being higher on the west coast than the eastern coast. From Figure 22 and 23 it is evident an increase in heavy rain in the second historical period (1990-2019), in particular in January, February April and December, while September shows a significant reduction. On the east coast the months of January, March, May and August report the largest reduction in heavy rain.

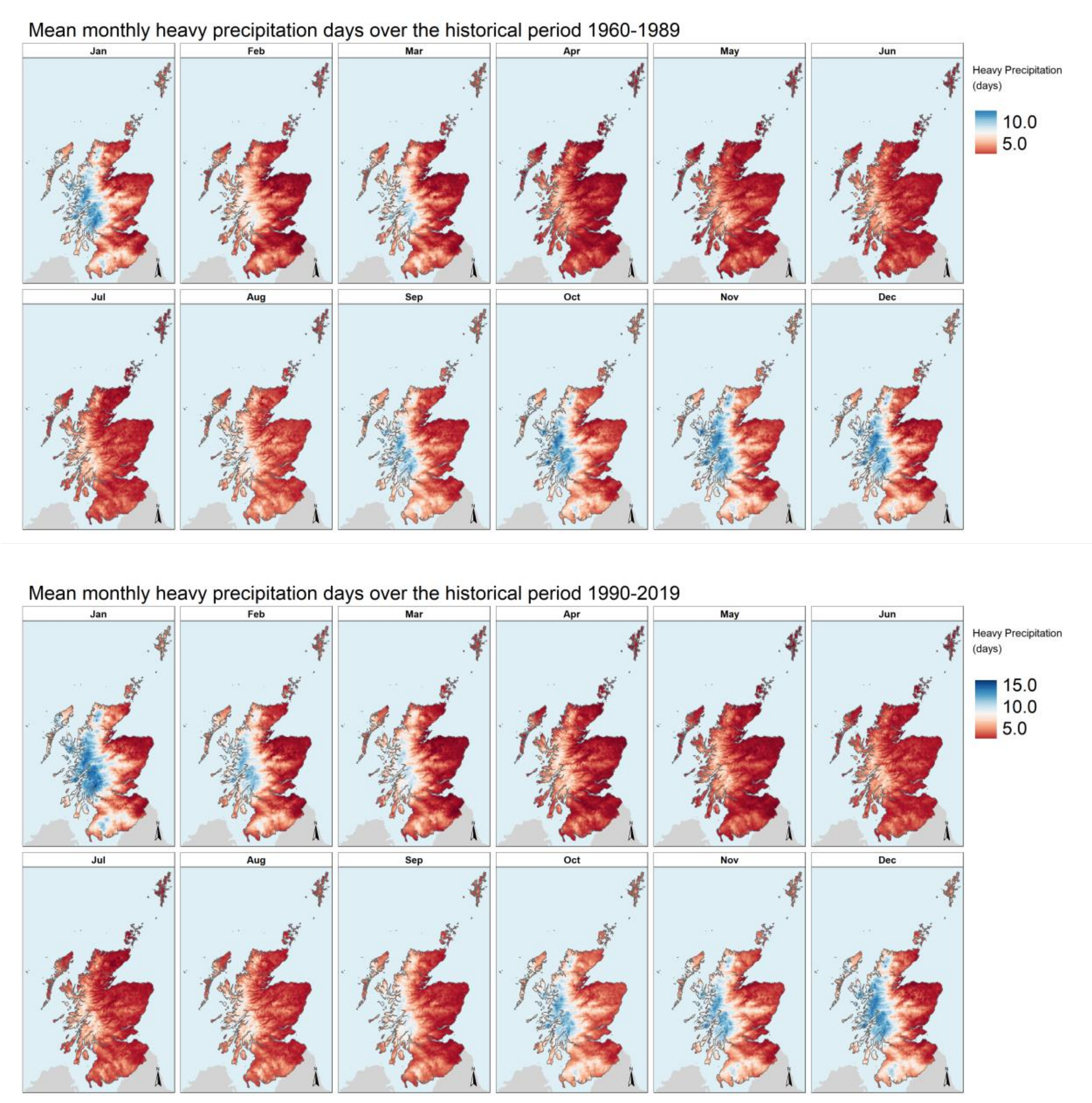


Figure 21. Mean monthly number of Heavy Rain Dry Days (≥ 10mm) for two observed periods: 1960 – 1989 (top) and 1990 – 2019 (bottom).

There has been an increase in the number of Heavy Rain Days in the west particularly in the winter months (Figure 22). February has seen the largest increase of approximately 4 days. The west has experienced and overall increase in most months, except March (southwest), June and July (northwest), August, September (whole of Scotland, except the far northeast), October (western coast and Islands) and November (north). August and September has experienced a widespread decrease in HRD. There is a general pattern of decreased HRD in the northeast, except in April (upland areas), June and October.

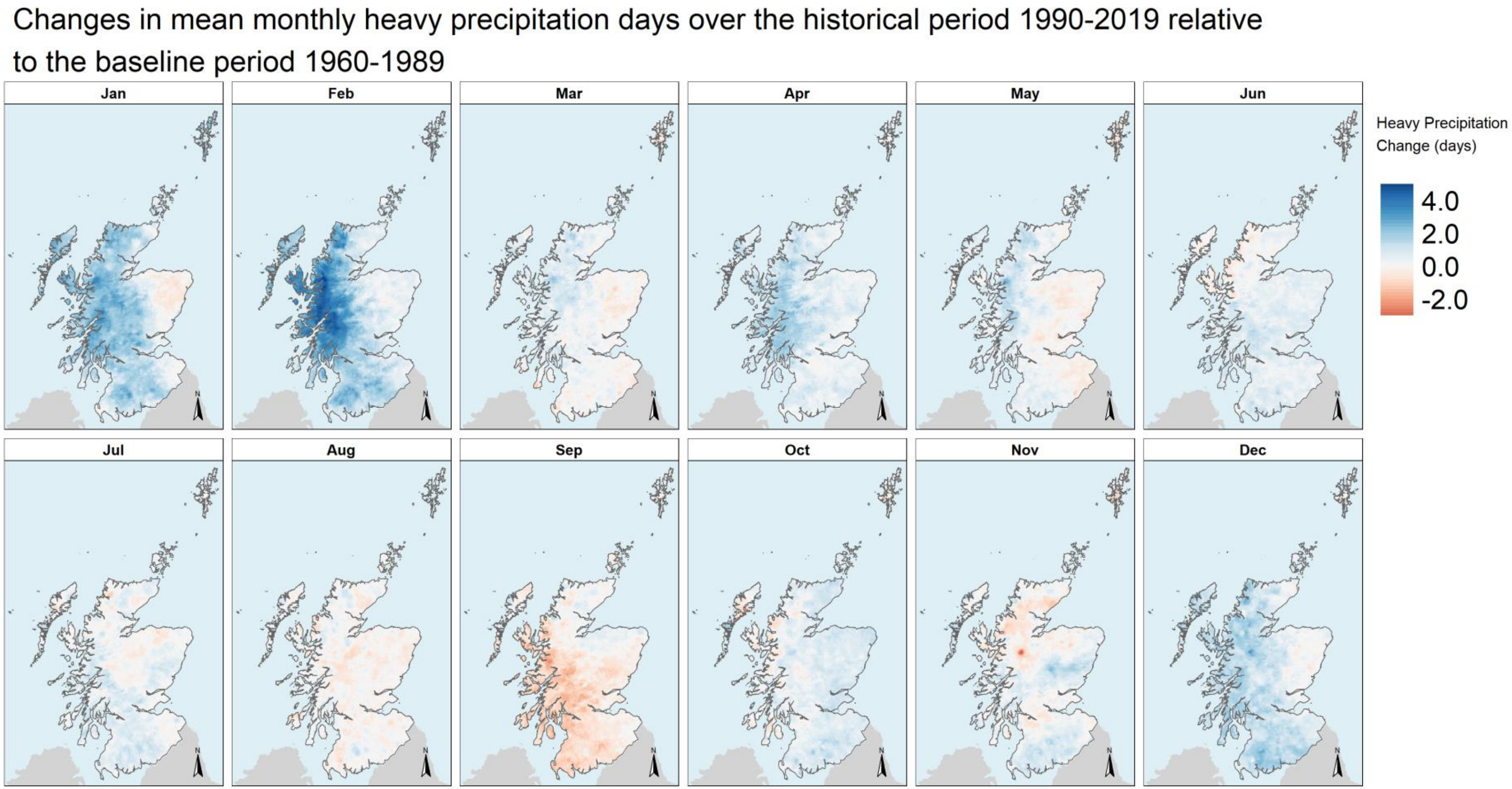


Figure 22. Changes in the number of Heavy Rain Days (≥ 10mm) between the 1960 – 1989 baseline and 1990 – 2019 period.

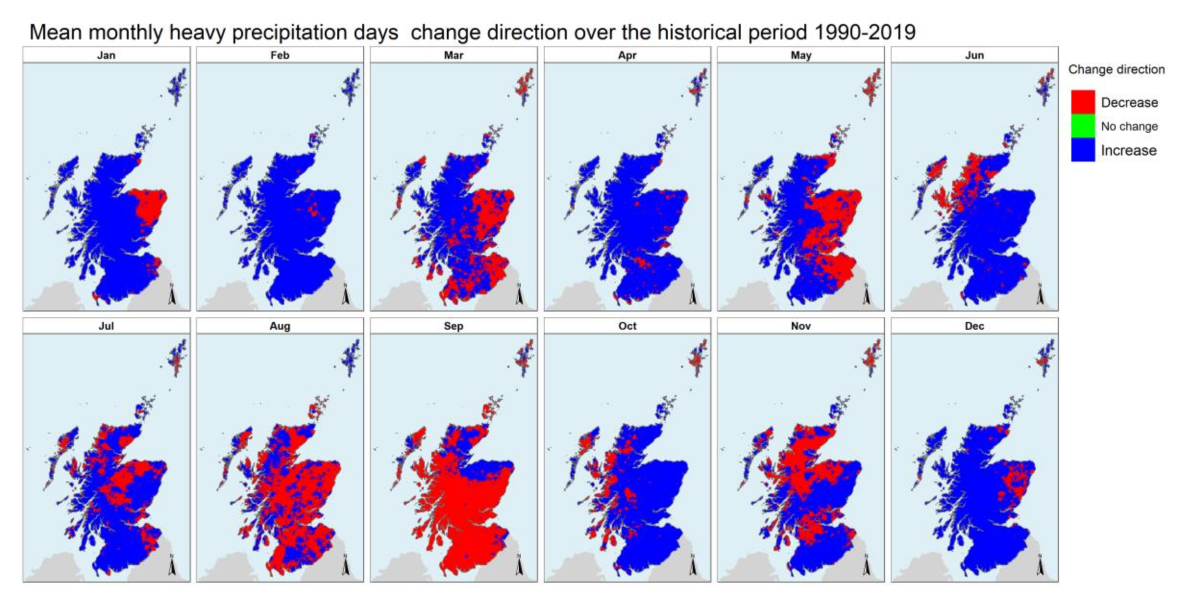


Figure 23. Change direction of mean monthly number of Heavy Rain Days (≥ 10mm) from the 1960 – 1989 to 1990 – 2019. Blue = increase in HRD, red = decrease, green – no change.

Figure 23 highlights the direction of change in increases (blue) or decrease (red) in the number of Heavy Rain Days. The reduced number in March and May potentially could have had benefits for crop cultivation by enabling soil workability, but may also a have reduced the quantity of water available for crop growth.

Future projections of Heavy Rain Days

Future projections of Heavy Rain Days (HRD) in the period 2020-2049 as compared to the baseline 1960-1989 (see Figures 24 and 25) for the example projection (EM01) depict a negative change in the autumn and winter months especially along the west coast and an increase from February to April for the entire country. The east coast seems overall to be affected by an increase in heavy rain with the exclusion of the summer and autumn season. This pattern is confirmed in the Figure 26 for both 8 and 10 ensemble members, while a high level of uncertainty is expected for a projection made considering at least 12 ensemble members.

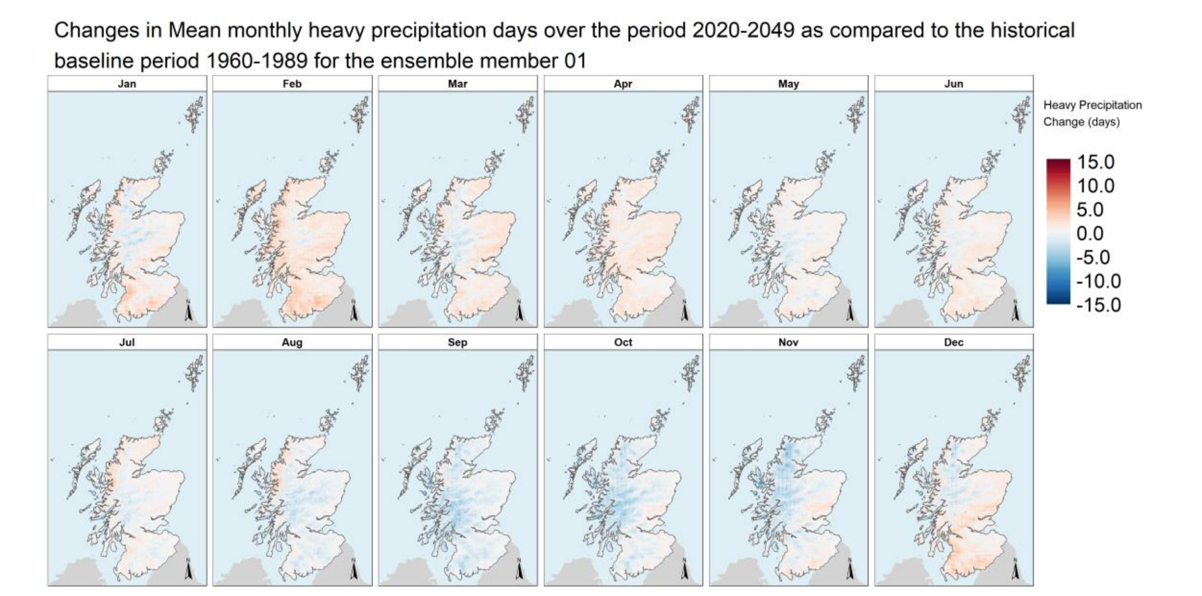


Figure 24. Example future projection (Ensemble Member 01) changes of the number of Heavy Rain Days between the 2020 – 2049 period and the 1960 – 1989 baseline.

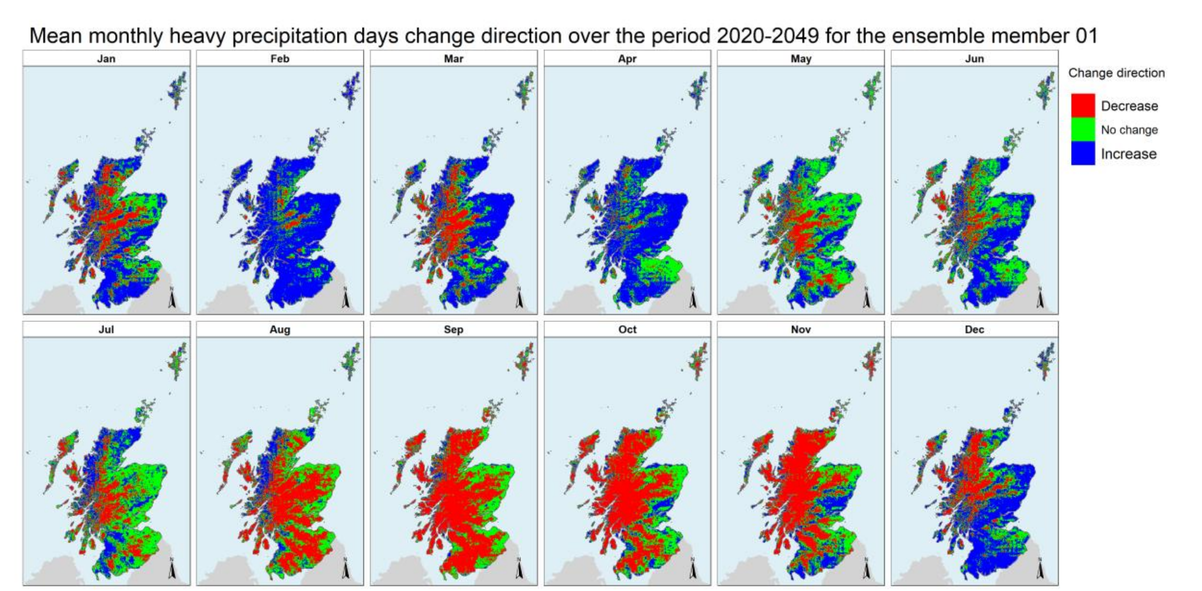


Figure 25. Change direction of mean monthly number of Heavy Rain Days from the 1960 – 1989 to 2020 – 2049 period for Ensemble Member 01. Blue = increase in HRD, red = decrease, green – no change.

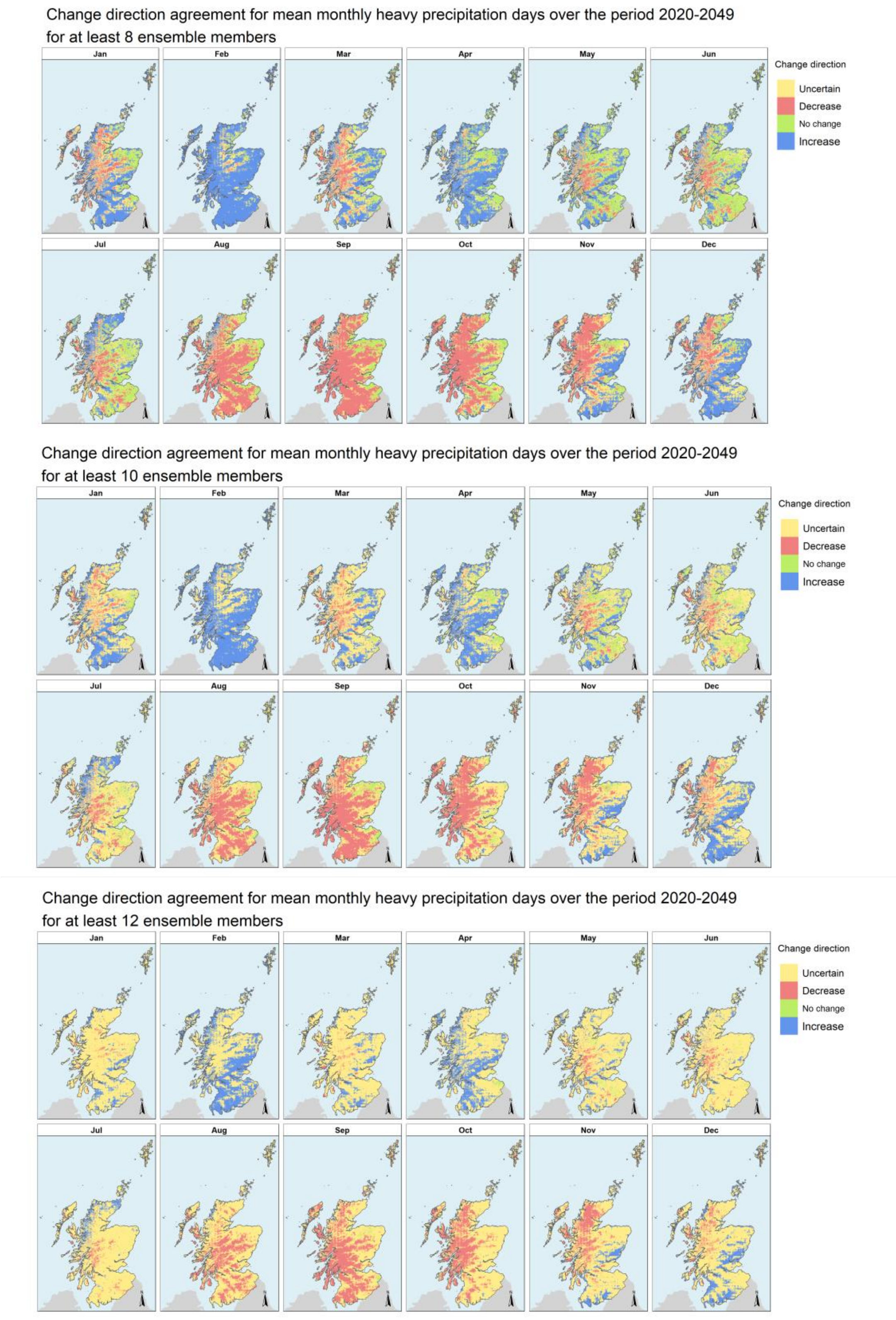


Figure 26. Change direction agreement for 8 (top), 10 (middle) and 12 (bottom) climate projections (ensemble members) for the number of Heavy Rain Days in the period 2020 - 2049.

Figure 27 shows the direction agreement for 8, 10 and 12 climatic projections for the period 2050-2079. The projections made with 8 and 10 ensemble members provides an overall picture of increase in heavy rain days in the winter and months until April, limited changes, especially in the east part of Scotland, during the spring season, and a decrease from July to October, mainly along the west coast.

Areas of uncertainty increases by using 12 climatic projections, during spring and summer, but there is consistency across all projections of areas in the uplands where there is a decrease in the number of Heavy Precipitation Days from August to October. This pattern fits with the general trend of drier summers seen in the linked report on climate trends and projections (Rivington and Jabloun 2022).

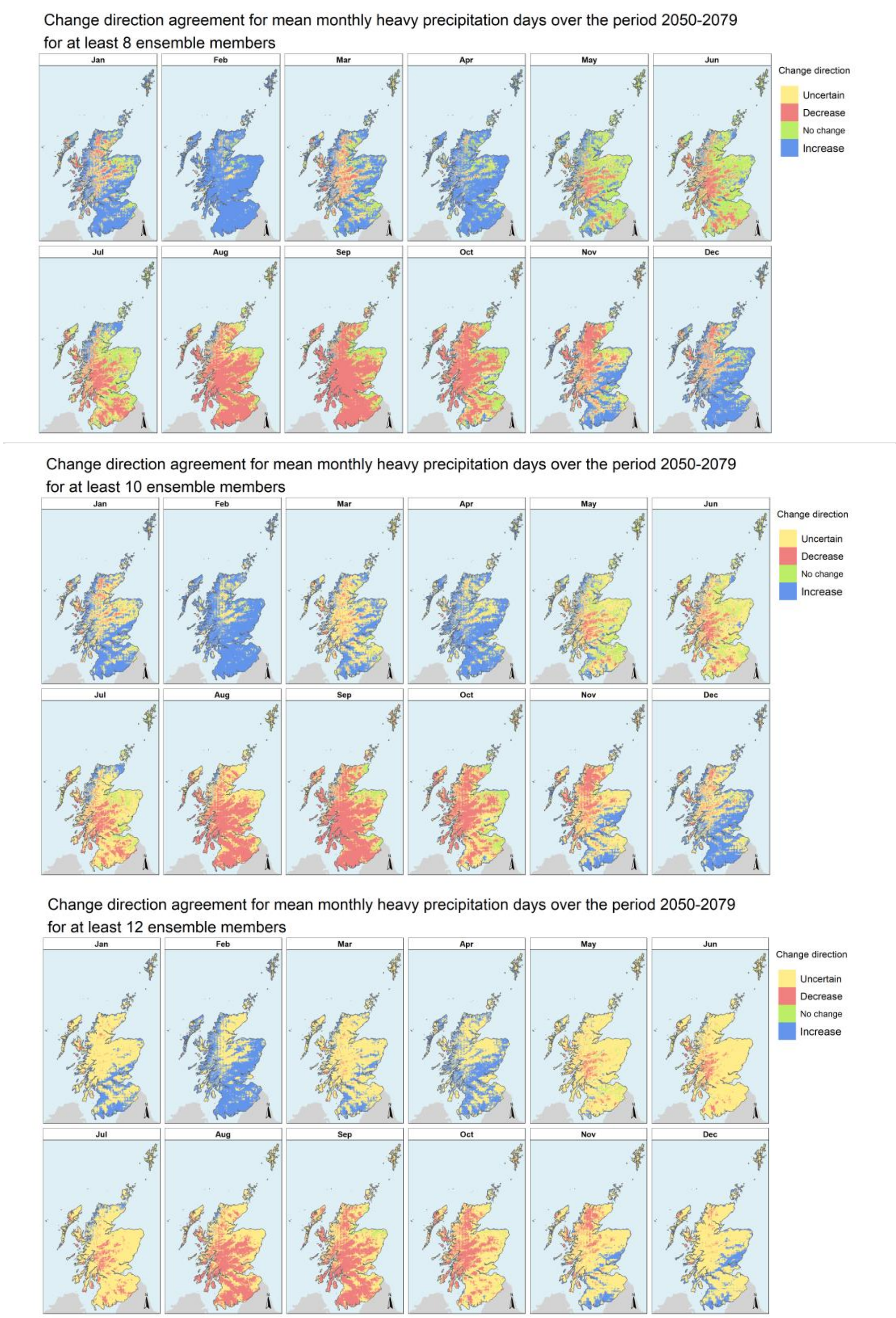


Figure 27. Change direction agreement for 8 (top), 10 (middle) and 12 (bottom) climate projections (ensemble members) for the number of Heavy Rain Days in the period 2050 - 2079.

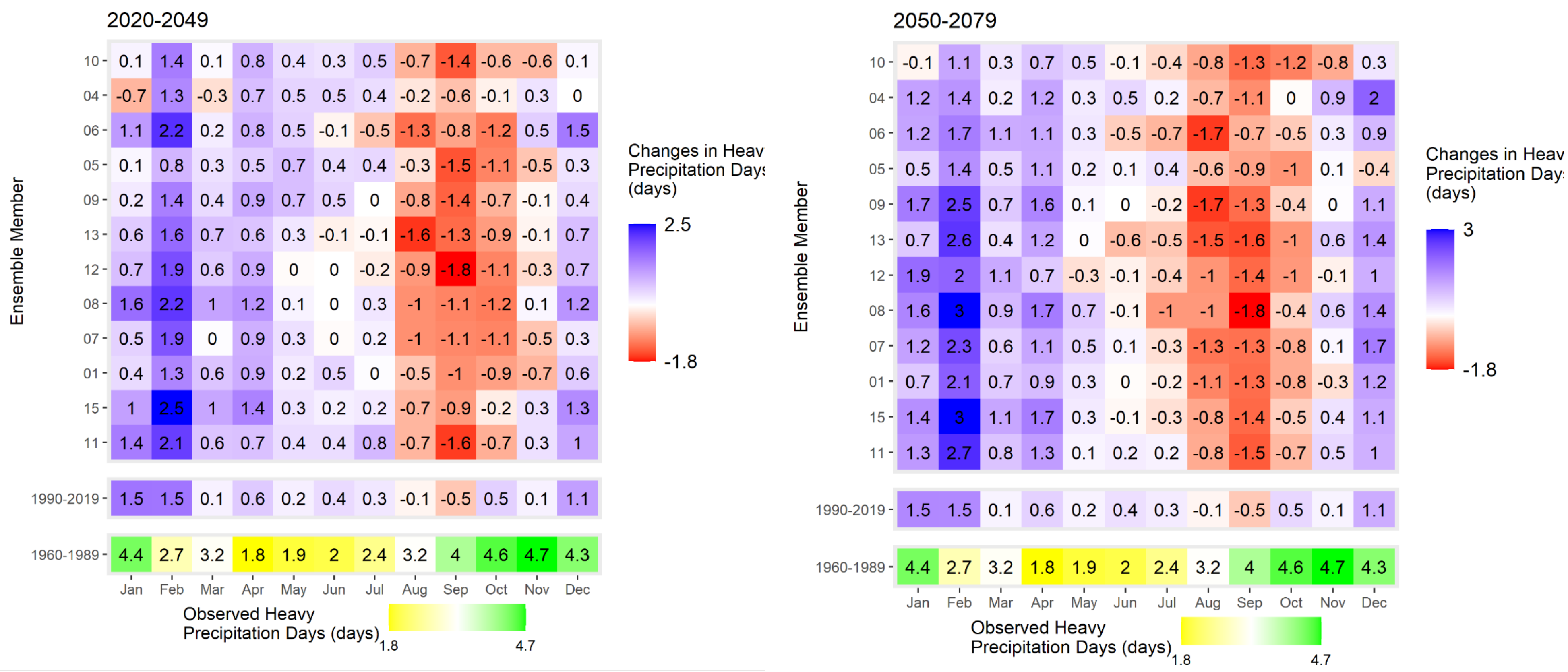


Figure 28a. National scale changes in the ***median*** *monthly number of Heavy Rain Days for the two observed periods (1960 – 1989, 1990 – 2019) and per climate projection for 2020 – 2049 (top) and 2050 – 2079 (bottom).*

Figure 28a presents in a clear way the change in direction in the median monthly number of Heavy Rain Days for the two historical periods, and in each of the 12 projections for the 2020-2049 (top) and 2049-2070 (bottom) future periods. Both projections show a reduction in HRD mainly in August and September (from 1 to 1.8 days) and the maximum increase in January and February (from 0.8 to 3), reinforcing the current pattern of heavy rain changes observed in 1990-2019 compared to the period 1960-1989. Analogue observation can be made observing Figure 28b, showing the national scale changes in the number of HRD.

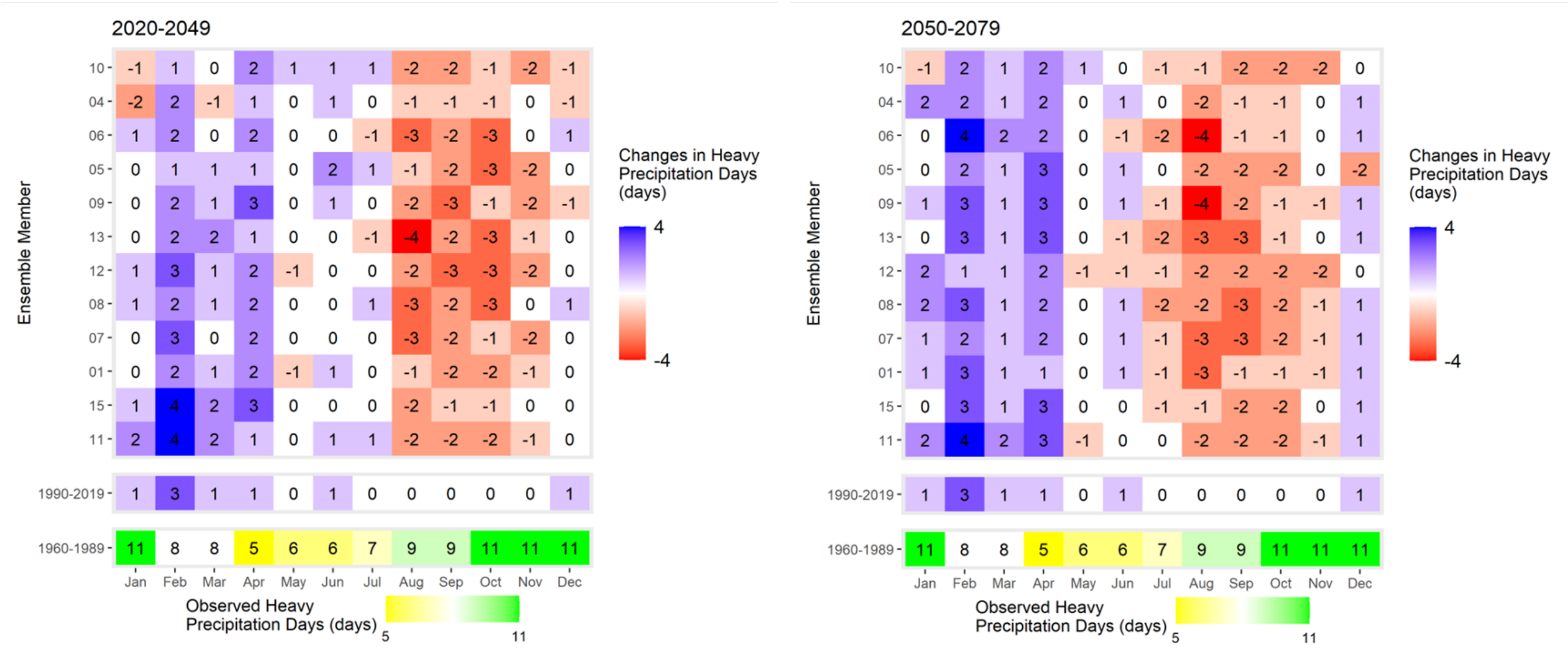
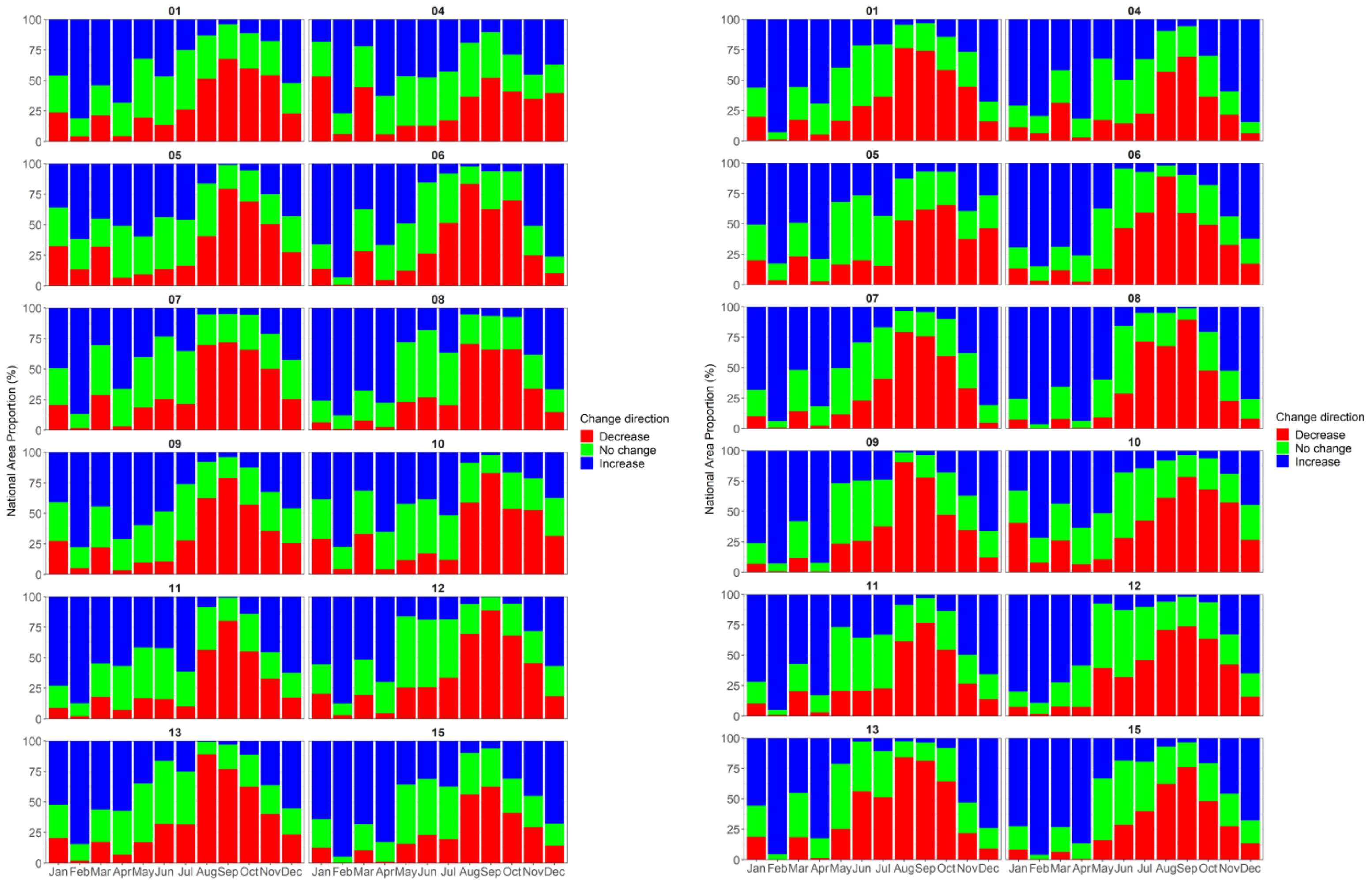


Figure 28b. National scale changes in the monthly number of Heavy Rain Days for the most extreme year from two observed periods (1960 – 1989, 1990 – 2019) and per climate projection for 2020 – 2049 (top) and 2050 – 2079 (bottom).

Figure 28b proposes a similar graph to depict the change of monthly number of Heavy Rain Days with extreme values of 4 days of heavy rain in February and a reduction of 3 to 4 days in August. Compared to the historical period 1990-2019 there is not an important change in the increase of HRD in winter, but a relevant decrease in summer. The shading pattern of red in summer and blue in winter months further illustrates the overall trend to wetter winters and drier summers.



Finally, Figure 29 shows for the two forecasted periods the change in the land area affected by Heavy Rain Days with the project period 2020-2049 showing a consistent pattern with 50% to 75% of land affected by heavy ran days in winter and spring, and only 25% of land influenced by this pattern in summer. The climatic projections for the 2049-2070 forecast show a similar pattern to that proposed in the period 2020-2049, especially for the winter season, but with a higher high level of uncertainty in summer.

Figure 29. National land area proportions estimated to experience a decrease (red), increase (blue) or no change (green) in mean monthly Heavy Rain Days for each projection (ensemble member) for the 2020 – 2049 (left) and 2050 – 2079 (right) future periods.

Implications of changes in Heavy Rain Days

The expected increase in Heavy Rain Days in winter can be associated with a higher risk of flooding and conversely with fewer HRD in summer leading to a higher risk of reduced water availability and higher stress. A slight increase in the impact for manufactured infrastructures and human lives and health can be expected in winter. There may be major negative effects on Natural Capital assets represented by soil, vegetation, river and ground waters in the summertime when it is expected that there may be a reduced level of ecological functionality and a potential loss of biodiversity because of the important increase in drought. Also, in summer, higher levels of stress is expected to impact crop production, highly water-intense industries and human consumption.

Land use category / sector impacts:

- Agriculture (uncultivated): flooding increase in winter, vegetation dieback or fire occurrence risk increase in summer.
- Open upland habitats: flooding and erosion increase in winter and fire occurrence risk increase in summer.
- Environmentally sensitive areas: increased risk of flooding, erosion and nutrient transport in the winter, reduced water input in the summer altering ecological functions.
- Grassland: risk of lodging (flattening) may increase in spring, reducing grazing quality; higher risk of desiccation in the summer.
- Arable: fewer Heavy Rain Days may reduce the risk of lodging in the summer; more HRD in the autumn / winter may reduce days when cultivation can occur and increase risks of flooding and erosion of exposed soils.
- Peatlands: more heavy rain days may help water recharge in the winter but also increase risk of erosion of exposed peat. Fewer HRD in summer may reduce potential for alleviation of desiccation after a dry period.
- Forestry: increased risk of water stress and fire occurrence risk in the summer with reduced carbon sequestration (Martínez-sancho et al., 2022). Reduced assimilative capacity of absorbing water in the wettest forest soil with higher run off rate.
- Urban: increased risk of flooding in the winter, fewer options for sewage discharge into rivers.
- Amenity/leisure: damage from flooding in winter, higher probability of water stress in summer.
- Transport infrastructure: higher probability of infrastructure damage in the winter.
- Biodiversity: increased risk due to physical impacts (e.g., flooding, waterlogging) in the winter and desiccation in the summer leading to changes in inter-species competition and species loss.
- Climate change: reduced resilience and altered potential for mitigation from Nature Based Solutions.

Number of Heavy Rain Days summary

- Since 1960 there has been a small shift in the number of heavy rain days (0 to +3 in the 1990-2019 period compared to the 1960-1989 period) with the highest value reported in winter and little variation in summer and autumn.
- Future projections (both 2020-2049 and 2050-2079 periods) show that the HRD changes in the winter season with an increase up to 4 days, compared to the 1960-1989 period. There is a reduction in summer (from minus 2 to minus 4). The projections thus seem to affect mainly summer HRD variations with a risk of an increased drought and winter flooding.

- Historically (1960-1989) the most Heavy Rain Days in the most extreme year have occurred between October and January (11 days for each month). February has already increased by 3 days (1990-2019) and hence matching the projected decrease by 1-4 days.

Very Wet Days

This indicator provides information on the mean monthly number of Very Wet Days (VWD). A very wet day is classified as a precipitation amount that is greater or equal to the 95th Percentile. The VWD indicator is the count of these events and represents the top 5% largest precipitation events per month. It hence represents the changes in the number of extremely large precipitation events.

For the purposes of calculation, **Monthly Very Wet Days (R95pTOT):** Considering RRj as daily precipitation amount on day i in period j and RR95 as the 95th percentile of precipitation in the 1960-1989 period then: RR95pj=∑RRij where RRij>RR95 (Climdex Project 2023). It is important to note that Very Wet Days are therefore identified in relation to a fixed period of time, not in relation to the 'moving average' as climate trends shift. Changes in Very Wet Days therefore represent an absolute change and not a change in the proportion in any one year (or longer period over which changing climate averages might be taken).

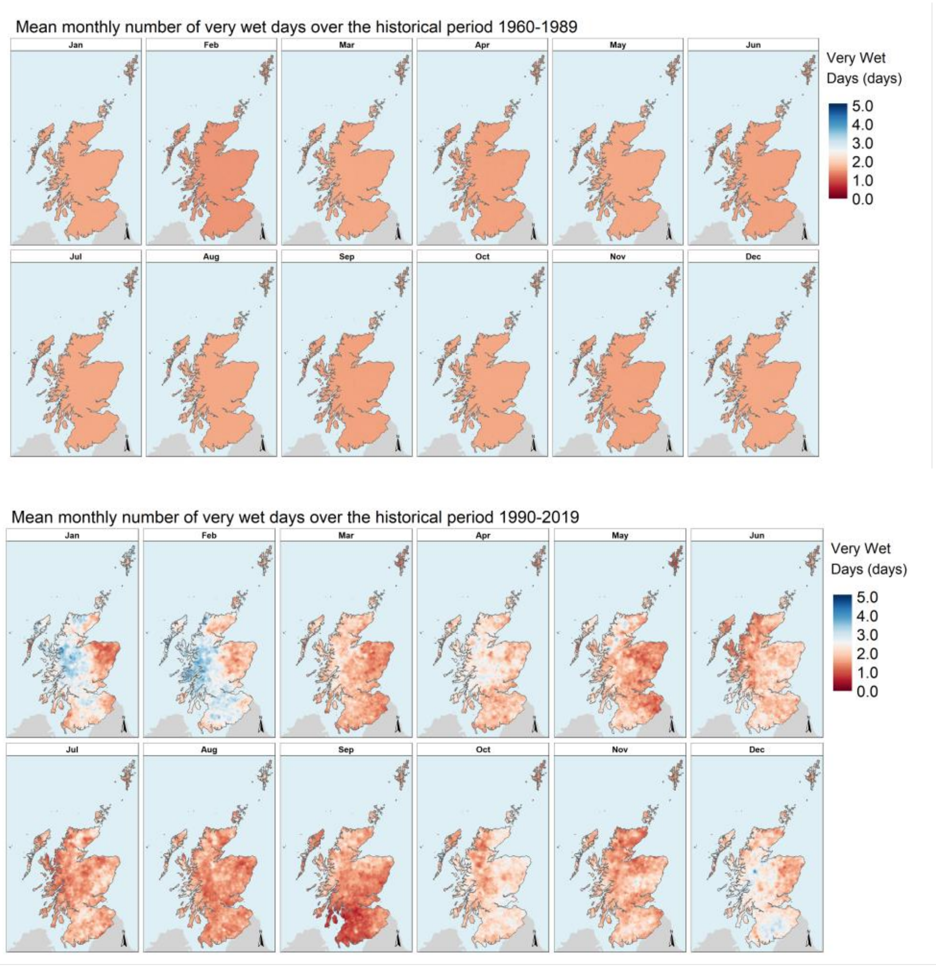


Figure 30a. Mean monthly number of Very Wet Days for two observed periods: 1960 – 1989 (top) and 1990 – 2019 (bottom)[4]*.*

[4] The 95th percentile (extreme rainfall) is calculated for the baseline period and also used to calculated the VWD for the same period which resulted in a very narrow range of VWD (ranging from 1.2 to 1.5 days as average over the 30 years) and thus the 'uniform' maps.

How to read the maps: The darkest red shading in Figure 30a (bottom) indicates the parts of the country with the least number of Very Wet Days per month. Dark blue shading indicates locations with the most Very Wet Days per month. In Figure 30b we show the difference between the periods 1960-1989 and 1990-2019 from one randomly selected location. Figure 31 shows the difference in mean Very Wet Days per month between these two periods.

The results for the 1960-1989 period (Figure 30a, top) indicate that there are few days when the number of Very Wet Days is greater or equal to the 95th percentile, with slightly more in February. Figure 30b, provided as an example, shows that the 95th percentile amount is generally (for nine months out of twelve) higher in the 1990-2019 period, and that from one randomly chosen grid cell in 1960, there are few days of precipitation per month above the 95th percentile (dots above the box). In this example it is worth noting the low precipitation totals for March and May.

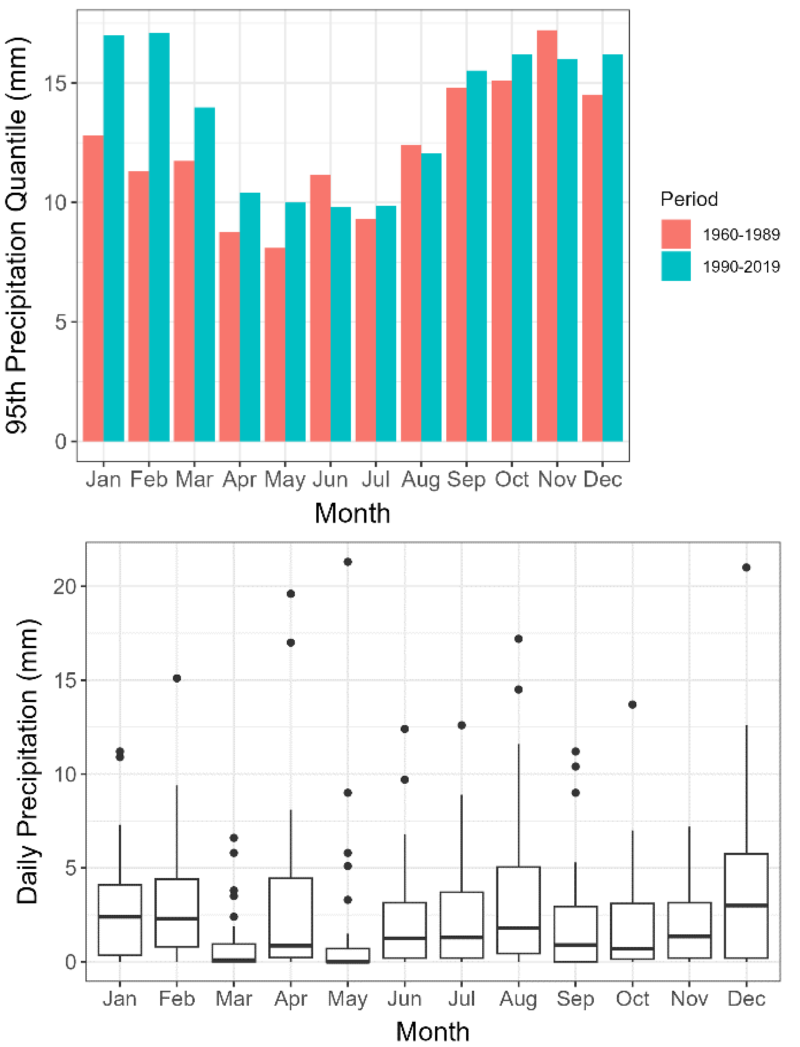


Figure 30b. Comparison of the 1960-1989 baseline with the 1990-2019 period precipitation 95th percentile (mm) per month (left) and specific data from a randomly chosen grid cell for 1960 (right)

We highlight here the details in Text Box 1 on the utility of the spatially interpolated observed baseline, and the potential for data utility to decrease closer to 1960 due to fewer meteorological stations to use for the interpolation.

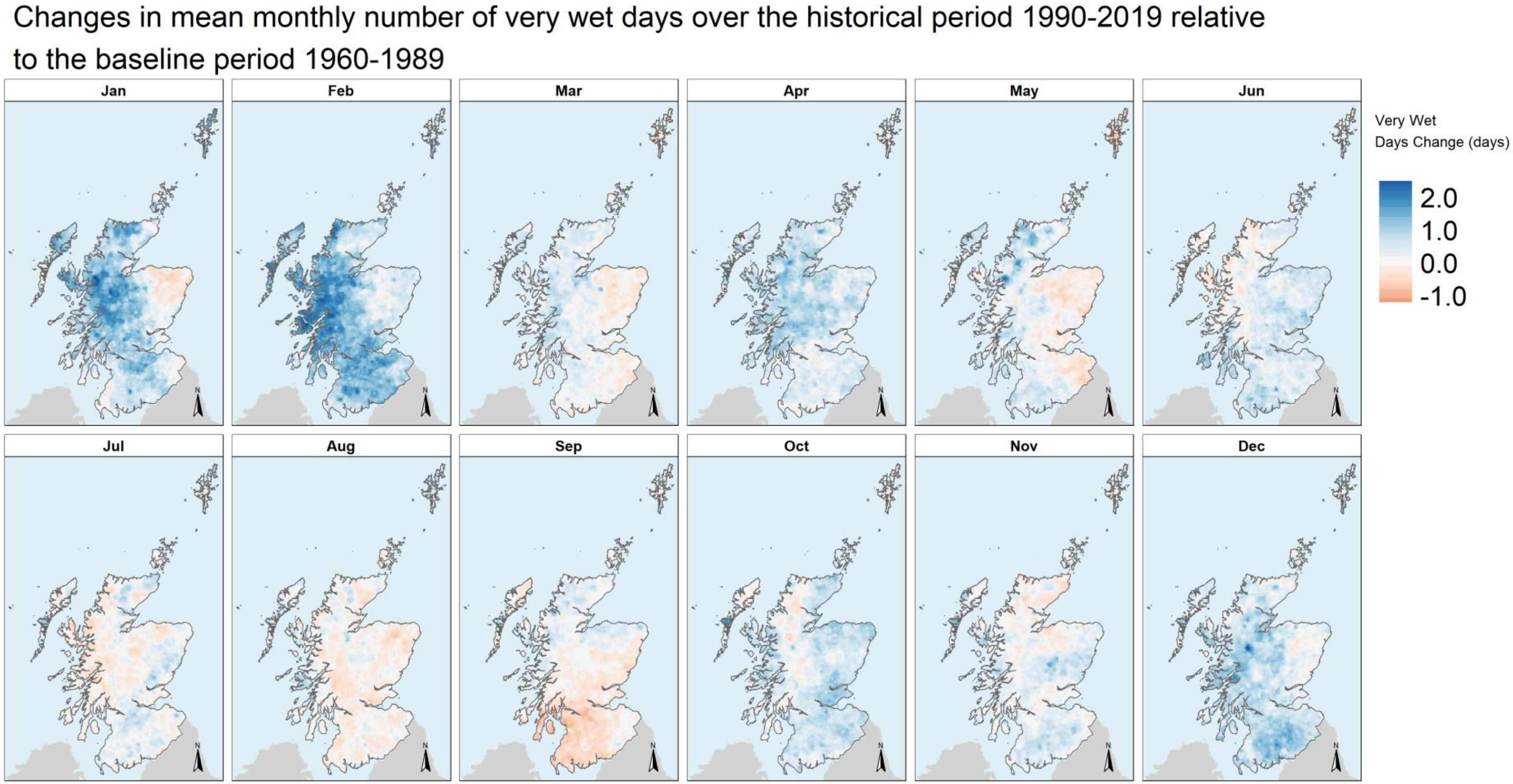


Figure 31. Changes in the number of Very Wet Days between the 1960 – 1989 baseline and 1990 – 2019 period.

The change on monthly mean Very Wet Days (VWD) between 1960-1989 and 1990-2019 shows that during winter months, there is a higher number of VWD in the west and south, and a slight reduction in VWD in the north-east. During summer months the trends are less clear, with a shifting pattern of generally fewer VWD per month across the country. These trends are more clearly represented in Figure 32 below. In the south of Scotland (below the Central Belt) the mean monthly VWD increases for every month except August and September. The far north and west of the country also shows predominantly increases in mean monthly VWD.

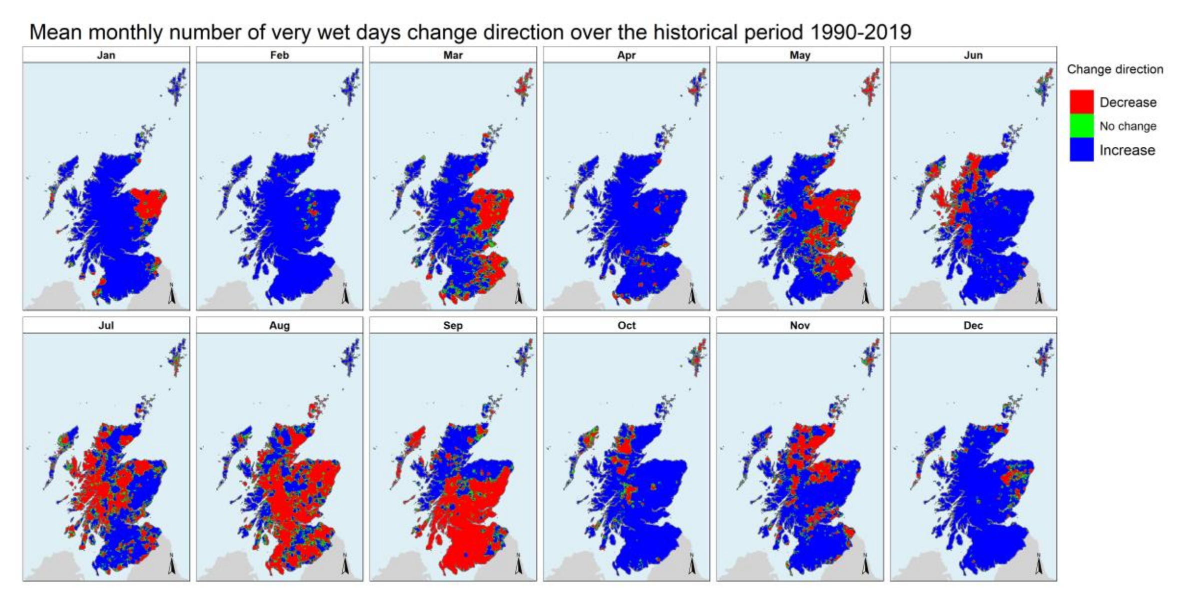


Figure 32. Change direction of mean monthly number of Very Wet Days from the 1960 – 1989 to 1990 – 2019. Blue = increase in VWD, red = decrease, green – no change.

Future projections of Very Wet Days

Of the 12 different climate projections explored, one example is shown in Figures 33 and 34 below (ensemble member 01). Overall, the mean monthly VWD decreases more in the west than in the east, and more in the north than in the south. However, monthly variation does not show a strong pattern throughout the year. In Figure 34, the spatial variation of decrease vs increase appears to match elevation more than latitude or longitude, with higher ground consistently seeing a mean monthly decrease in VWD and lower ground seeing a consistent increase.

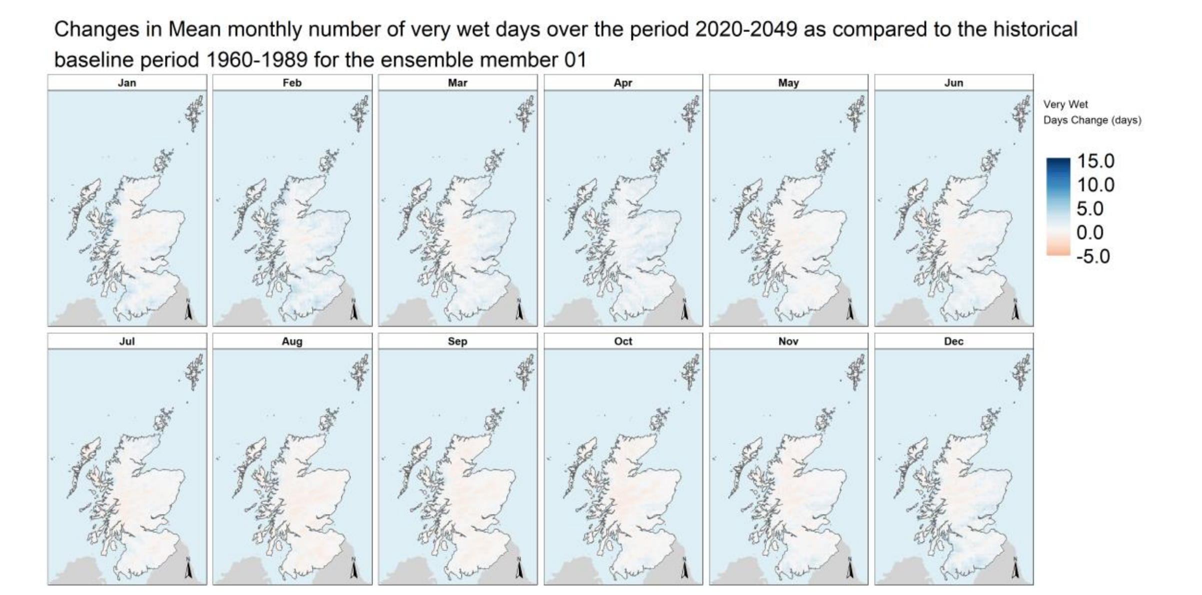


Figure 33. Example future projection (Ensemble Member 01) changes of the number of Very Wet Days between the 2020 – 2049 period and the 1960 – 1989 baseline.

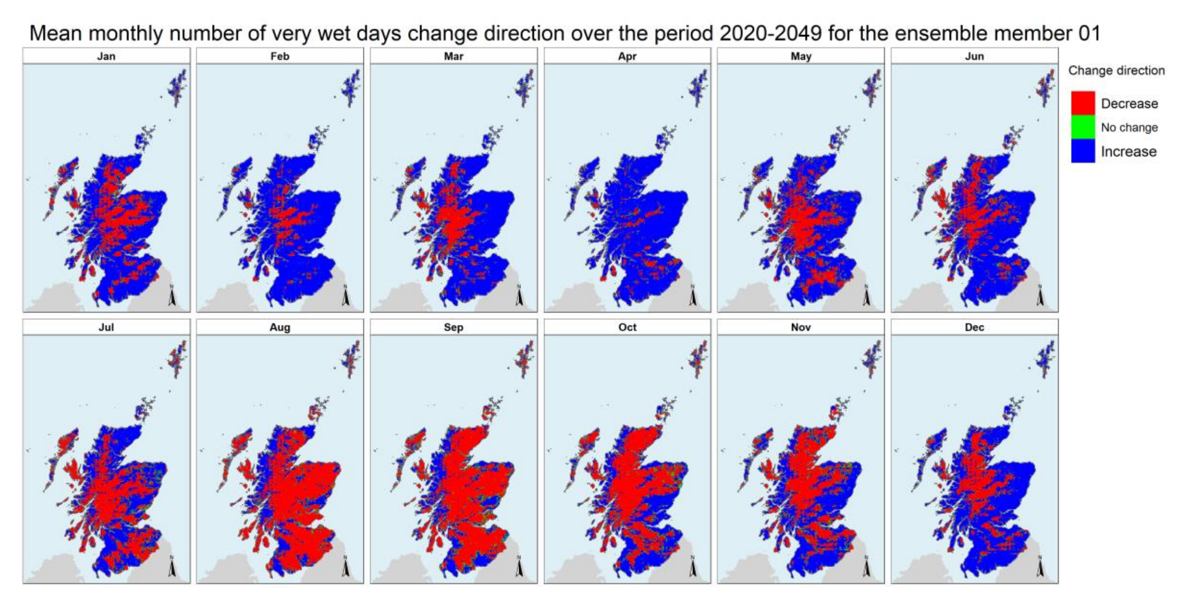


Figure 34. Change direction of mean monthly number of Very Wet Days from 1960 – 1989 to 2020 – 2049 for Ensemble Member 01. Blue = increase in VWD, red = decrease, green – no change.

Figure 35 shows projections in mean monthly VWD across multiple climate ensemble members (top – at least 8; middle – at least 10; bottom – at least 12) for the period 2020 to 2049. What this shows is how clearly the ensemble members agree or disagree in the spatial distribution of change in VWD. In the top panel there is very little uncertainty/disagreement with a relatively clear pattern in increasing mean monthly VWD at lower altitudes and decreasing VWD at higher altitudes (as shown for ensemble member 1 in Figure 34). Conversely there is a clear trend that August and September especially (and to some extent July and October) are estimated to have a decrease in VWD, for all areas except the north-west coast. In the middle panel there is more uncertainty (yellow) but the spatial (and therefore elevation) distribution of this trend is still clear. In the bottom panel the uncertainty dominates during most months, with the only areas of clear increase or decrease being either closest (increase) or furthest (decrease) to/from the coast.

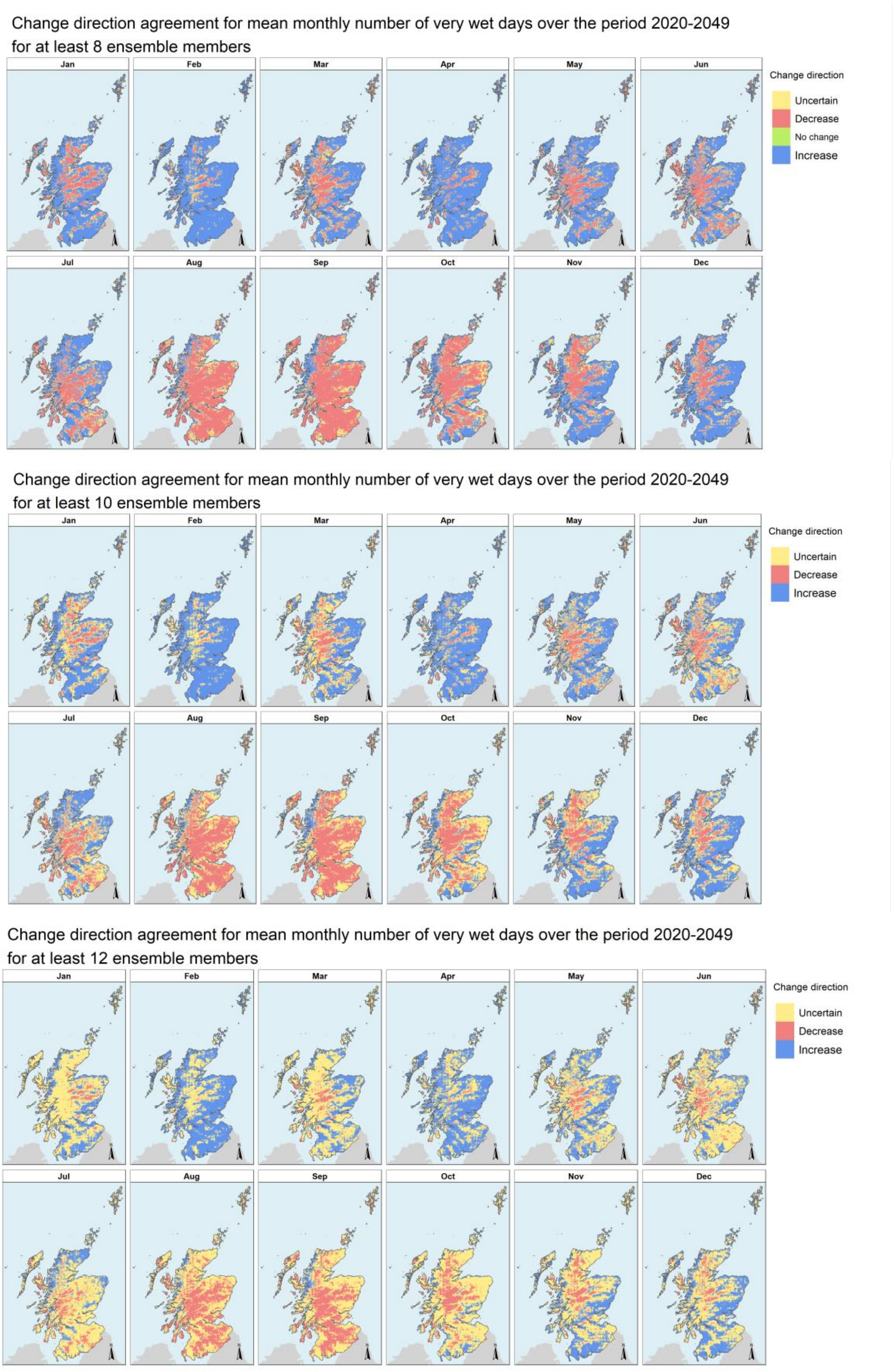


Figure 35. Change direction agreement for 8 (top), 10 (middle) and 12 (bottom) climate projections (ensemble members) for the number of Very Wet Days in the period 2020 - 2049.

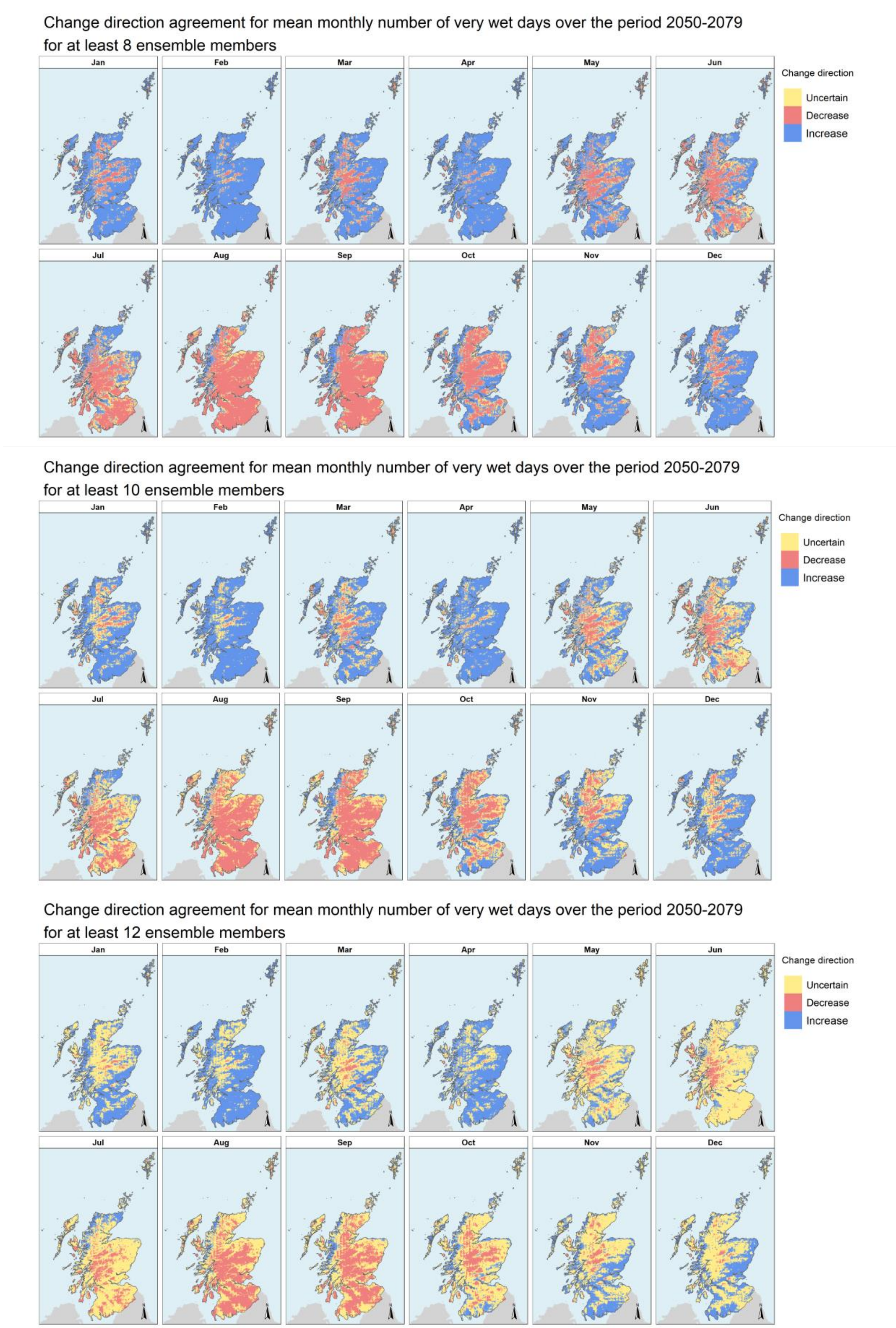


Figure 36. Change direction agreement for 8 (top), 10 (middle) and 12 (bottom) climate projections (ensemble members) for the number of Very Wet Days in the period 2050 - 2079.

Figure 36 shows projections in mean monthly VWD across multiple climate ensemble members (top – at least 8; middle – at least 10; bottom – at least 12) for the period 2050 to 2079. In comparison to the three sets of maps shown in Figure 35, these panels show similar trends in agreement and uncertainty from less (with fewer ensemble members) to more (with more ensemble members). The panels also show similar spatial/elevation distributions between increases and decreases in VWD for individual months, with one main difference; the winter months are more strongly associated with increases in VWD and the summer months have larger areas of decrease in VWD than for the 2020-2049 projections. What is being shown therefore is that while there is uncertainty across a wide range of climate ensemble members, there is a trend towards more significant seasonality in relation to mean monthly VWD (more in winter, fewer in summer).

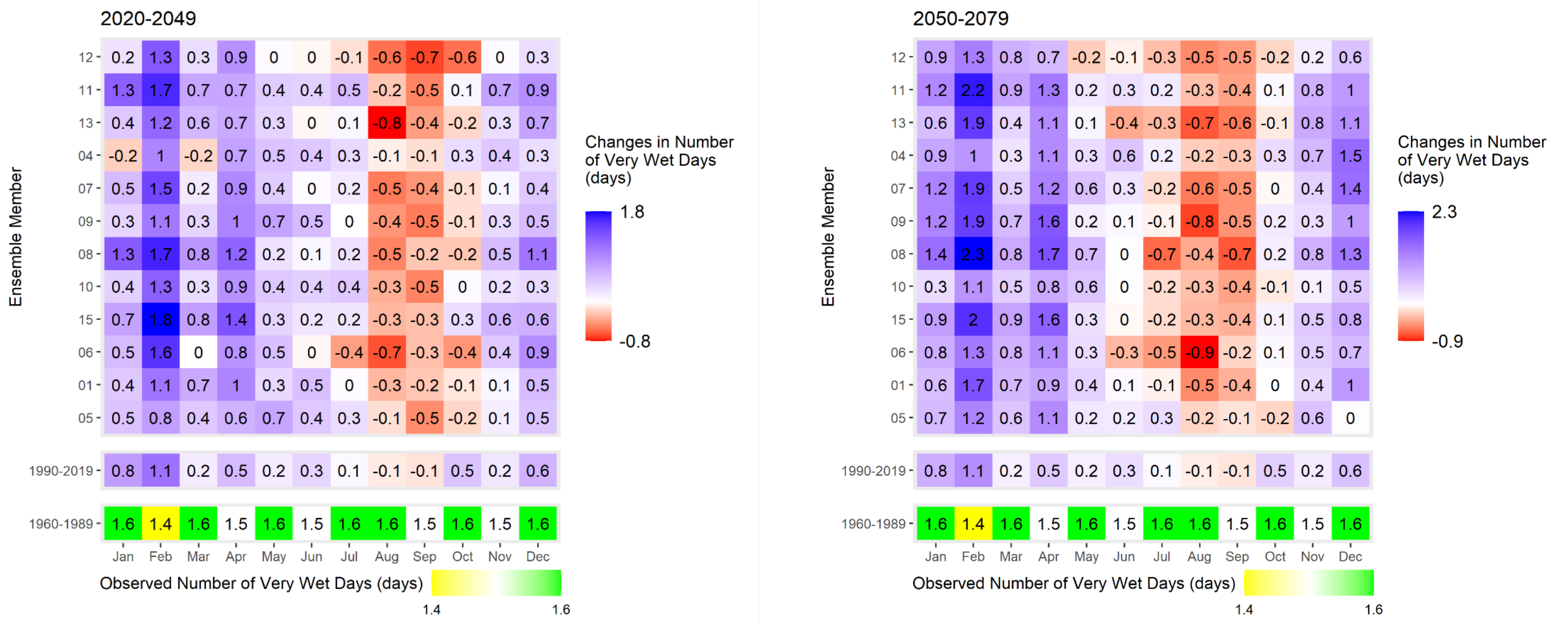


*Figure 37a. National scale changes in the **median** monthly number of Very Wet Days for the two observed periods (1960 – 1989, 1990 – 2019) and per climate projection for 2020 – 2049 (top) and 2050 – 2079 (bottom).*

Figure 37a shows a more detailed look at the uncertainty across ensemble members by month rather than across the country. This figure gives the median (the value separating the higher half of the population from the lower half of the population) monthly number of VWD. For both the top (2020-2049) and bottom (2050-2079) panels there is a clear pattern of increases in winter months and decreases in summer months. The values shown in the individual cells (add these to the 1960-189 baseline values to get the estimated future total) also show a continuation of the observed trend in polarisation over time, with more VWD per month in winter and fewer in summer. While there is variation between ensemble members during each month, this variation is less than the trend in change from month to month. The pattern of change is consistent across all projections and months, except June, July and October. Note: Figure 37a is the national median of the average VWD and 37b is the national median of the maximum VWD (extreme year) over the 30 years period.

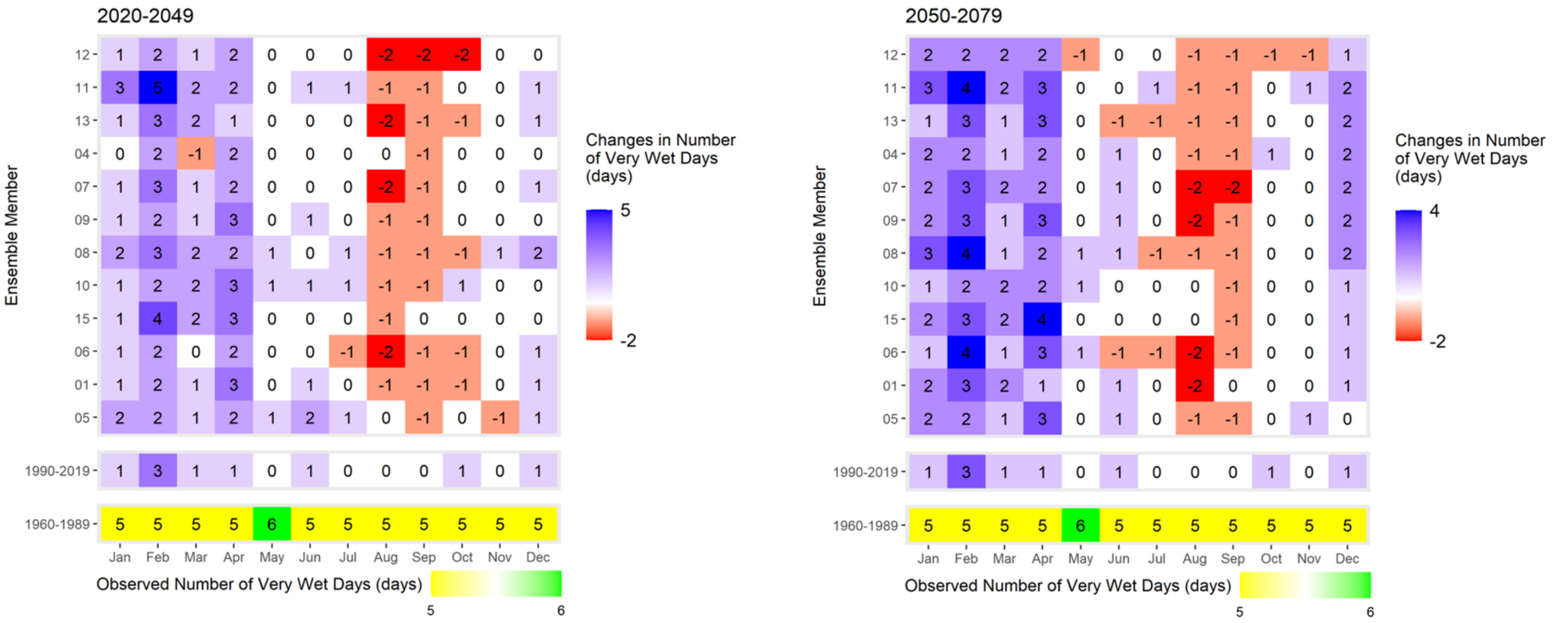


Figure 37b. National scale changes in the monthly number of Very Wet Days for the most extreme year from two observed periods (1960 – 1989, 1990 – 2019) and per climate projection for 2020 – 2049 (top) and 2050 – 2079 (bottom).

Figure 37b again shows a more detailed look at the uncertainty across ensemble members by month rather than across the country. As in Figure 37a, for both the top (2020-2049) and bottom (2050-2079) panels there is a clear pattern of increases in winter months and decreases in summer months. The values shown in the individual cells also, again, show a trend in polarisation over time, with more VWD per month in winter and fewer in summer. There is more variation between ensemble members during each month, but as in Figure 37a this variation is less than the trend in change from month to month.

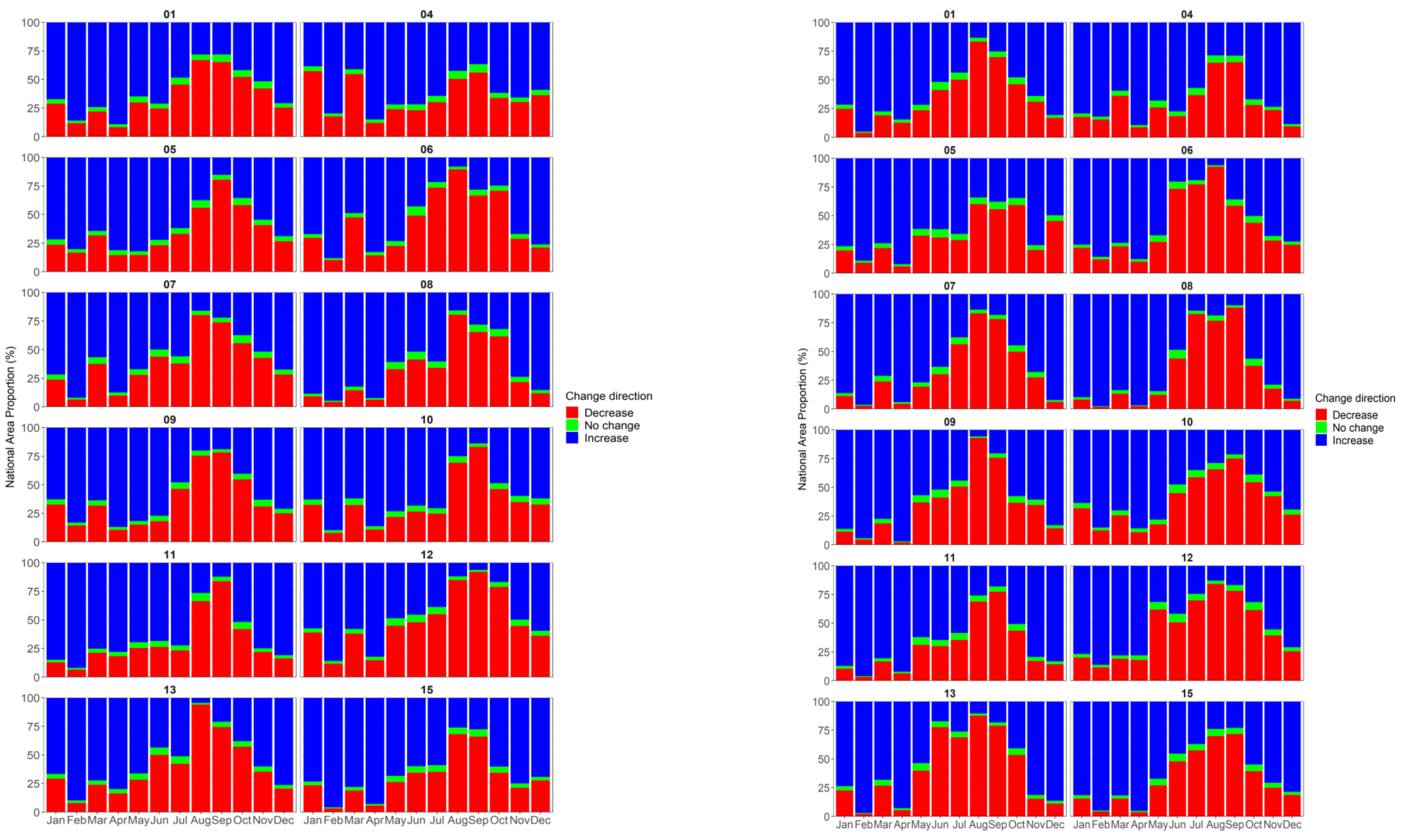


Figure 38. National land area proportions estimated to experience a decrease (red), increase (blue) or no change (green) in mean monthly Very Wet Days for each projection (ensemble member) for the 2020 – 2049 (left) and 2050 – 2079 (right) future periods.

In Figure 38, the proportional area in Scotland that is estimated to see an increase, decrease or no change in monthly mean VWD is shown. On the left, this shows the estimates for the period 2020-2049 while on the right the estimates for 2050-2079 are shown. Within both left and right, each panel shows the estimates for a different ensemble member. In all panels, a seasonal trend is seen where a high proportion of land area is estimated to see an increase in mean monthly VWD in winter, while a high proportion of land area sees a decrease in mean monthly VWD in summer. The proportion of land area that sees 'no change' throughout remains small but varies between 0-10%. The size of the seasonal variation in proportional areas seeing increases or decreases in VWD varies somewhat between climate ensemble members, as does the shape of the seasonality curve. However, there is no disagreement that this seasonal variation in mean monthly VWD is there or that winter will see more areas with increased VWD and summer will see more areas with decreased VWD.

Implications of changes in Very Wet Days

An increase in the number of the largest precipitation events per month in the winter implies an increased risk of flooding and soil erosion. Conversely the reduced number of Very Wet Days in the summer implies an increased risk of dry soil and habitat conditions, but this may be associated with reduced risks of flooding. However, large precipitation events occurring when soils are dry will likely result in soil erosion. Fewer Very Wet Days in summer might reduce the amount of cereal crop yield losses due to lodging[5].

There may however be a benefit from the overall wetter conditions in the winter and more Very Wet Days, in that it increases the potential for recharge of ground water to maintain water table levels. This may be important as a buffer against reduced water availability in the summer and help to maintain ecological functions, i.e., peatlands through remaining wet.

Land use category / sector impacts:

- Surface waters – higher precipitation rates will most likely lead to increased delivery of nutrients to surface waters and hence higher pollutant loads, with implications for river and lake water quality (e.g. Ockenden et al .2017).
- Agriculture (uncultivated): flooding increase in winter, vegetation dieback or fire occurrence risk increase in summer.
- Open upland habitats: fire occurrence risk increase in summer.
- Environmentally sensitive areas: flooding in winter, species change or fire occurrence risk increase in summer.
- Grassland: decreased grazing potential in summer.
- Arable: crop damage in winter, decreased or loss of yield in summer.
- Peatlands: flooding or bog slide in winter, bog erosion and carbon loss in summer.
- Forestry: fire occurrence risk in summer.
- Urban: flooding in winter, increase in pollution from poor sewage flushing in summer.
- Amenity/leisure: damage from flooding in winter.
- Transport infrastructure: damage from landslides in winter
- Biodiversity: species loss or change in winter and summer.
- Climate change: reduced resilience throughout the year.

[5] Lodging is the physical damage such as flattening caused to cereal crops, for example when combined with wet soils and strong winds. It can account for 20% losses to winter wheat every 3-4 years. An introduction to lodging in cereals | AHDB

Text Box 2: Climate Change Impacts on surface waters.

A recent Centre of Expertise on Water (CREW) report 'Assessing climate change impacts on the water quality of Scottish standing waters' highlighted the following key impacts:

- Climate change is affecting the water quality of Scottish standing waters, specifically in relation to algal blooms, at multiple scales; mostly through increases in air temperatures and changes in rainfall patterns.
- Increases in Scottish loch and reservoir temperatures are closely related to changes in air temperatures; rapid and extensive climate change-driven warming of these standing waters has already occurred in recent years and is expected to continue increasing.
- Water temperature increases in many lochs and reservoirs have already been recorded; standing waters are projected to get warmer in the south and east of Scotland but this climate-related risk will spread further and reach all parts of Scotland by 2040.
- Climate change will increase the risk of algal blooms developing in Scottish lochs and reservoirs – especially potentially harmful cyanobacteria.
- Increases in algal blooms are often associated with a higher risk of potentially harmful toxins from cyanobacteria being released into the water; the likelihood of this occurring will increase with warmer temperatures and lower flushing rates.
- Currently, all types of Scottish standing waters in all areas and locations are at high risk of climate change impacts.
- Different types of lochs and reservoirs will respond differently to climate change impacts, with some more likely to develop water quality issues than others.
- Water temperatures across different types of lochs and reservoirs are already warming in most places; this climate-driven trend is projected to further increase from south to north, with an exacerbated water temperature situation expanding to all parts of Scotland by 2040.
- Climate change driven increases in water temperature and nutrient availability, and reductions in flushing rates, will increase the risk of water quality issues developing in Scottish lochs and reservoirs.

The full report is available here: [Assessing climate change impacts on the water quality of Scottish standing waters] | CREW | Scotland's Centre of Expertise for Waters

Number of Very Wet Days summary

- There is a clear observed trend and continued future projection that the number of the largest precipitation events, the number of Very Wet Days, is likely to increase in the winter but decrease in the summer.
    - The 1960-1989 baseline shows that the number of Very Wet Days was consistent throughout the year (5-6), but the more recent 1990-2019 period shows there were more in the winter, particularly February (3)
- There is good agreement between the climate projections that the upland areas of Scotland are likely to experience a decrease in the number of Very Wet Days in the summer months.
- There is medium level of agreement between projections that the lowland eastern parts of Scotland may experience an increase in the number of Very Wet Days.

- At a national level for the most extreme years, the winter is projected to have an increase in Very Wet Days and in August – October a decrease. February has already seen an increase from 5 (1960-1989) to 8 (1990-2019).

Results Part 3: Temperature Extremes

It is worth noting here that temperature as a weather variable is more spatially contiguous compared to precipitation, which is both highly variable spatially and in magnitude. This means that it is somewhat easier to model the spatial distribution of temperature, both with the interpolation of observed and climate models, compared with precipitation.

Highest Temperature

The Highest Temperature indicator (HT) represents the highest daily maximum temperature per month. Increases in HT means that the hottest days per month become even hotter. Highest Temperature is calculated as: **Monthly maximum value of daily maximum temperature (TXx)**: Considering Tx as daily maximum temperature in month k, period j, the maximum daily maximum temperature in each month is TXxkj = max (Txkj) (Climdex Project 2023).

Observed mean Highest Temperature trends.

Figure 39 shows the observed spatial distribution of HT for the two observed periods.

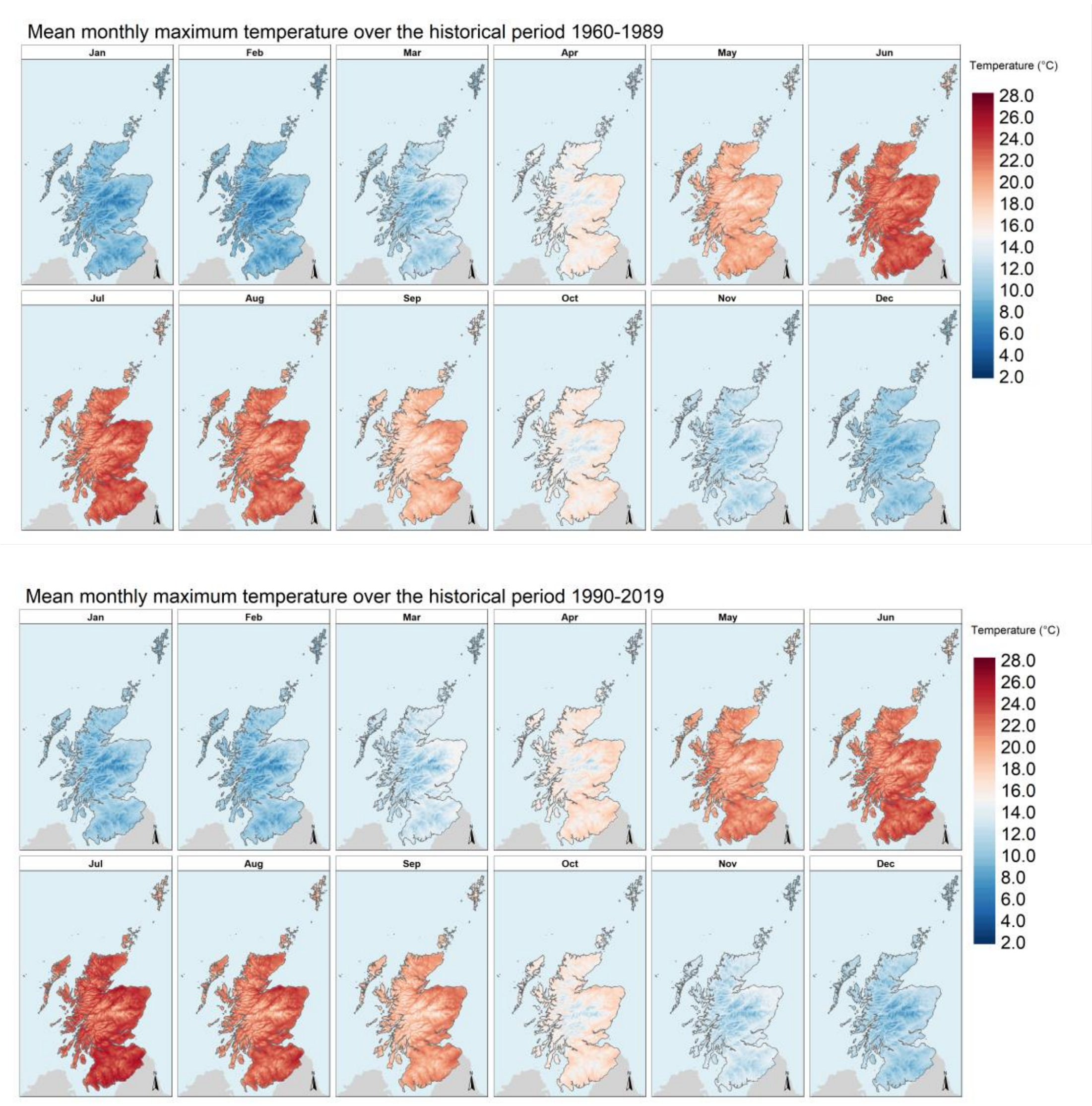


Figure 39. Mean monthly number of Highest Temperature for two observed periods : 1960 – 1989 (top) and 1990 – 2019 (bottom).

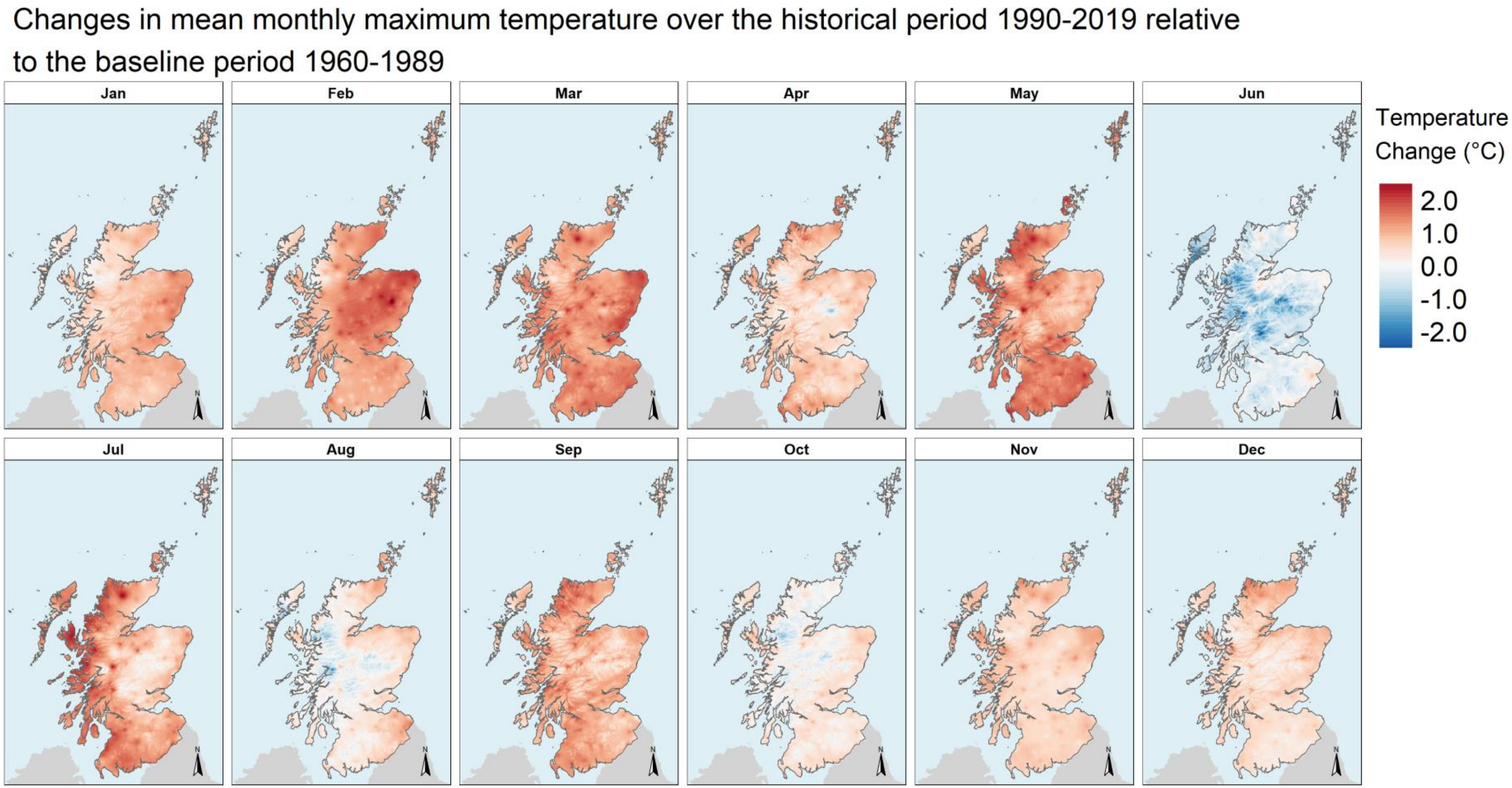


Figure 40. Changes the Highest Temperatures between the 1960 – 1989 baseline and 1990 – 2019 period.

There has been an observed increase in HT from 1960-1989 to 1990-2019 (Figure 40) for all months except June and in some western upland areas in August and October. February, March, May, July (primarily the west) and September have experienced the largest increase, by up to 2.0°C and across the whole of Scotland by 1.3°C. June has experienced a slight decrease in Highest Temperature in upland areas by up to 2.0°C, and on average by up to 0.4°C nationally.

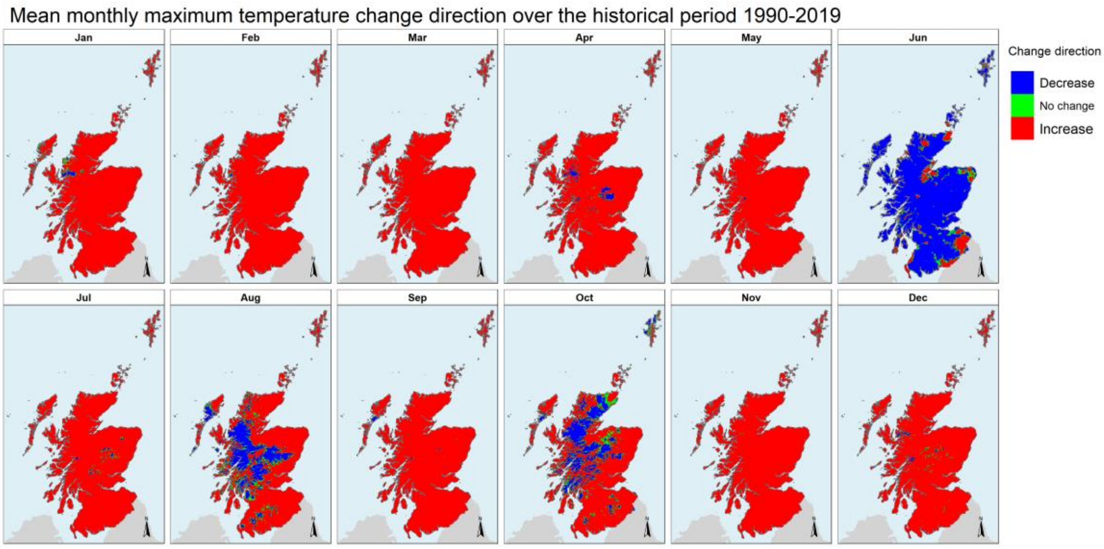


Figure 41. Change direction of mean monthly Highest Temperature from the 1960 – 1989 to 1990 – 2019. Blue = increase in HRD, red = decrease, green – no change.

Figure 41 highlights the change direction per month described above for Figures 39-40. There are few locations where there has been no change (green), and from November to May the direction is almost entirely an increase in HT.

Future projections of Highest Temperature

The example future projection (ensemble member 01, Figures 42-43) shows that, for the period 2020-2049, all months are estimated to experience an increase in HT, in the order of 2-3°C.

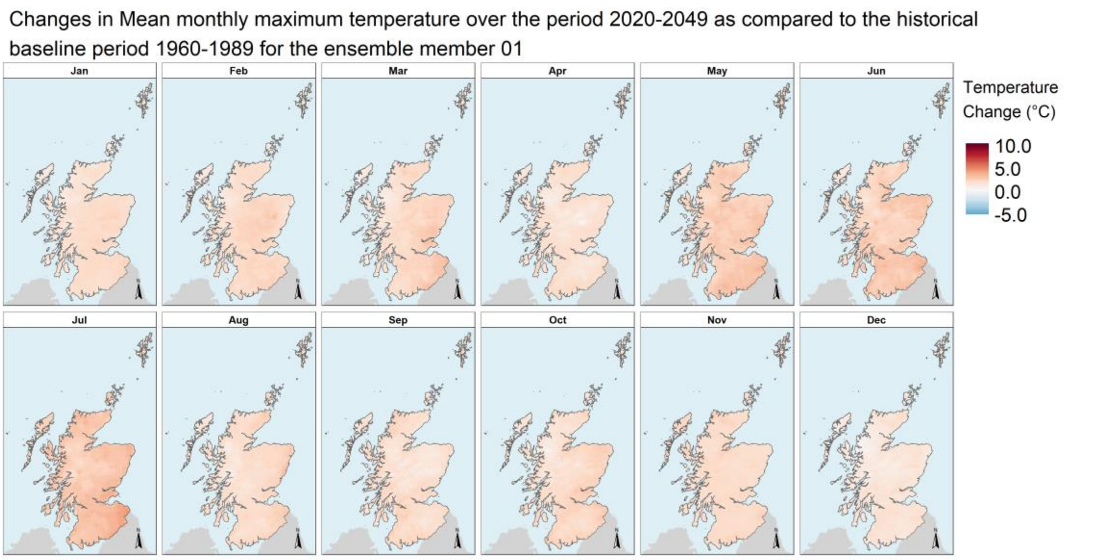


Figure 42. Example future projection (Ensemble Member 01) changes of the mean monthly Highest Temperature between the 2020 – 2049 period and the 1960 – 1989 baseline.

There is estimated to be a uniform increase (red) change in direction in Highest Temperature across the whole of Scotland in the future (Figure 43).

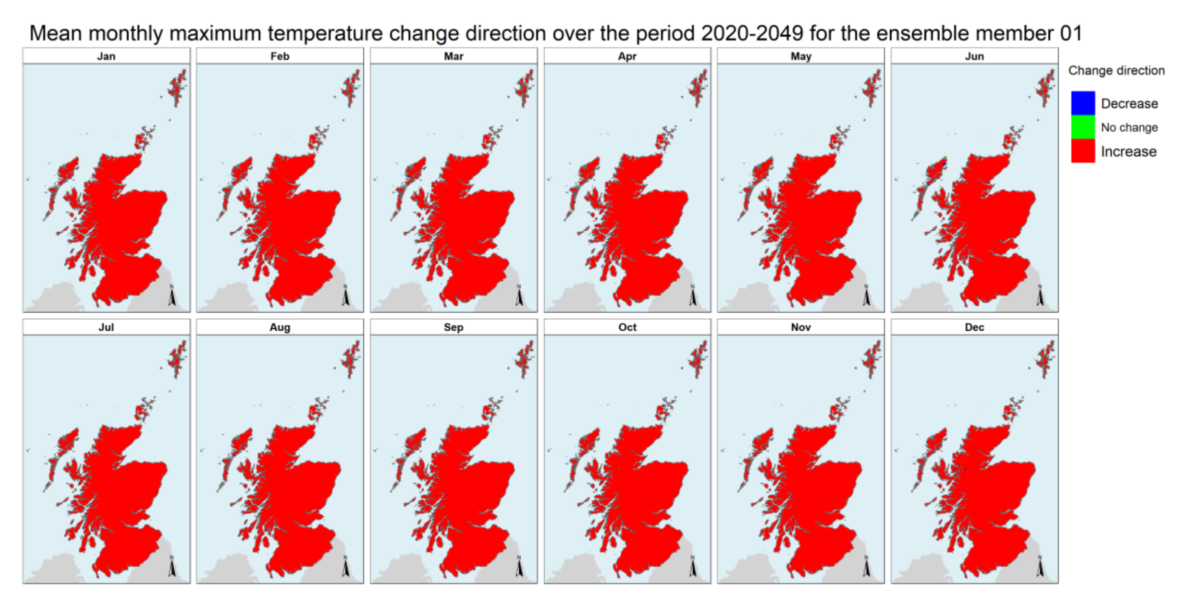


Figure 43. Change direction of mean monthly Highest Temperature from the 1960 – 1989 to 2020 – 2049 period for Ensemble Member 01. Blue = increase in HT, red = decrease, green – no change.

In respect of the agreement between the climate projections, there is near complete agreement that all months in the years between the modelled 2020-2049 period with experience an increase in Highest Temperature (Figure 44). None of the projections produce results where there is a decrease. There is a small amount of uncertainty as to whether June will see higher HT values in a few parts of the country (yellow areas in Figure 44).

Note: We have not presented the agreement maps for Highest Temperature for the 2050 – 2079 period as all projections show an increase, where all maps per month are red and there is no lack of agreement between projections (uncertainty).

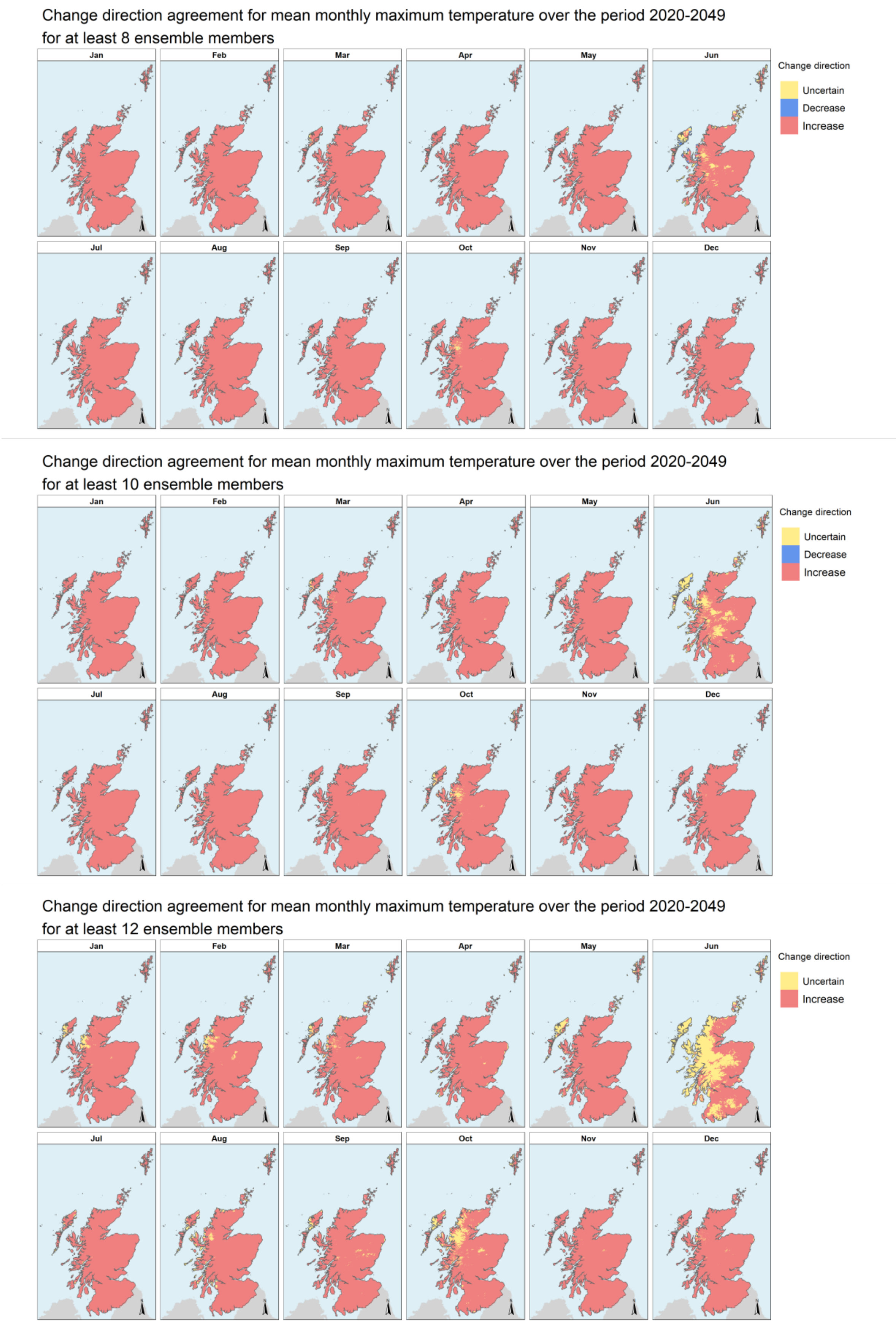


Figure 44. Change direction agreement for 8 (top), 10 (middle) and 12 (bottom) climate projections (ensemble members) for the Highest Temperatures in the period 2020 - 2049.

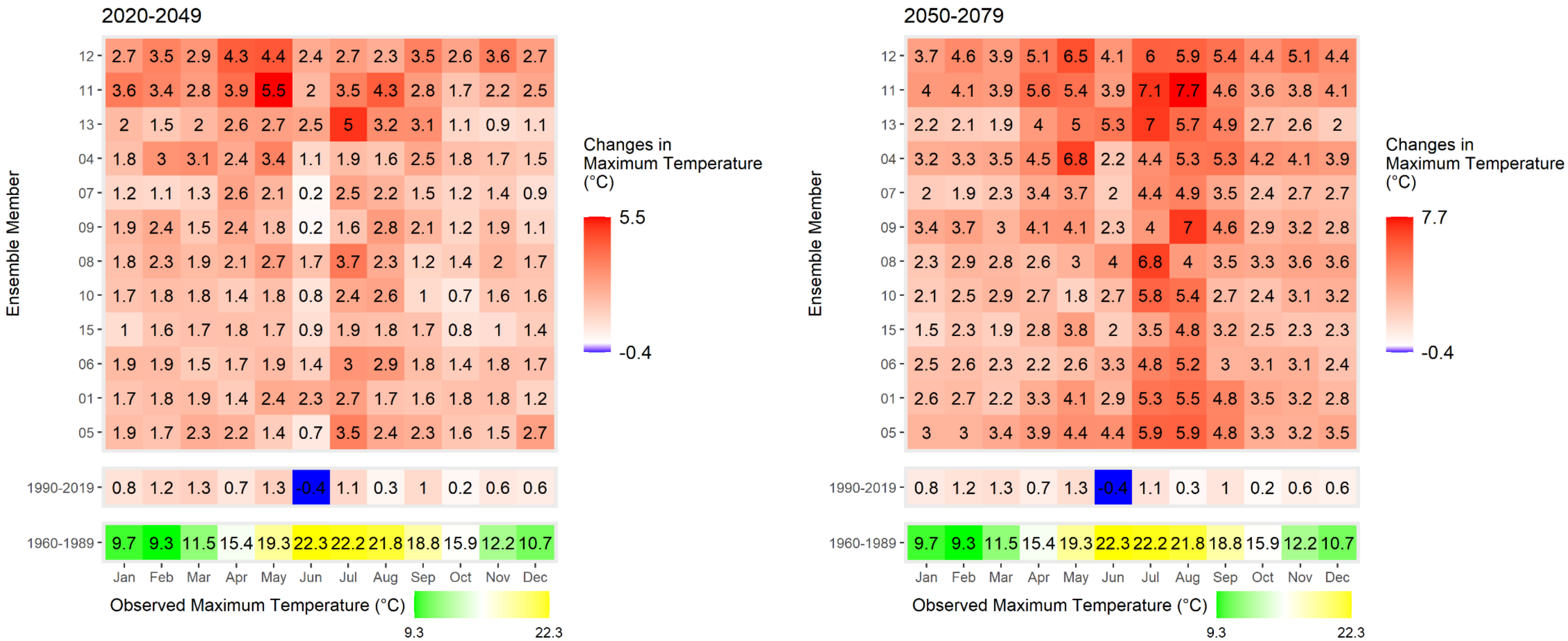


Figure 45a. National scale changes in the Median monthly Highest Temperature for the two observed periods (1960 – 1989, 1990 – 2019) and per climate projection for 2020 – 2049 (top) and 2050 – 2079 (bottom). Note: scales are different between plots.

As stated above, there has been an increase in the median monthly Highest Temperature from 1960-1989 to 1990-2019 for all months except June (Figure 45a), and this trend is projected to continue in the future throughout the year (including June becoming warmer). In the period 2020-2049 the different projections indicate a relatively even spread in the increase across the year, but by 2050-2079, there is a larger increase in the late spring and summer months.

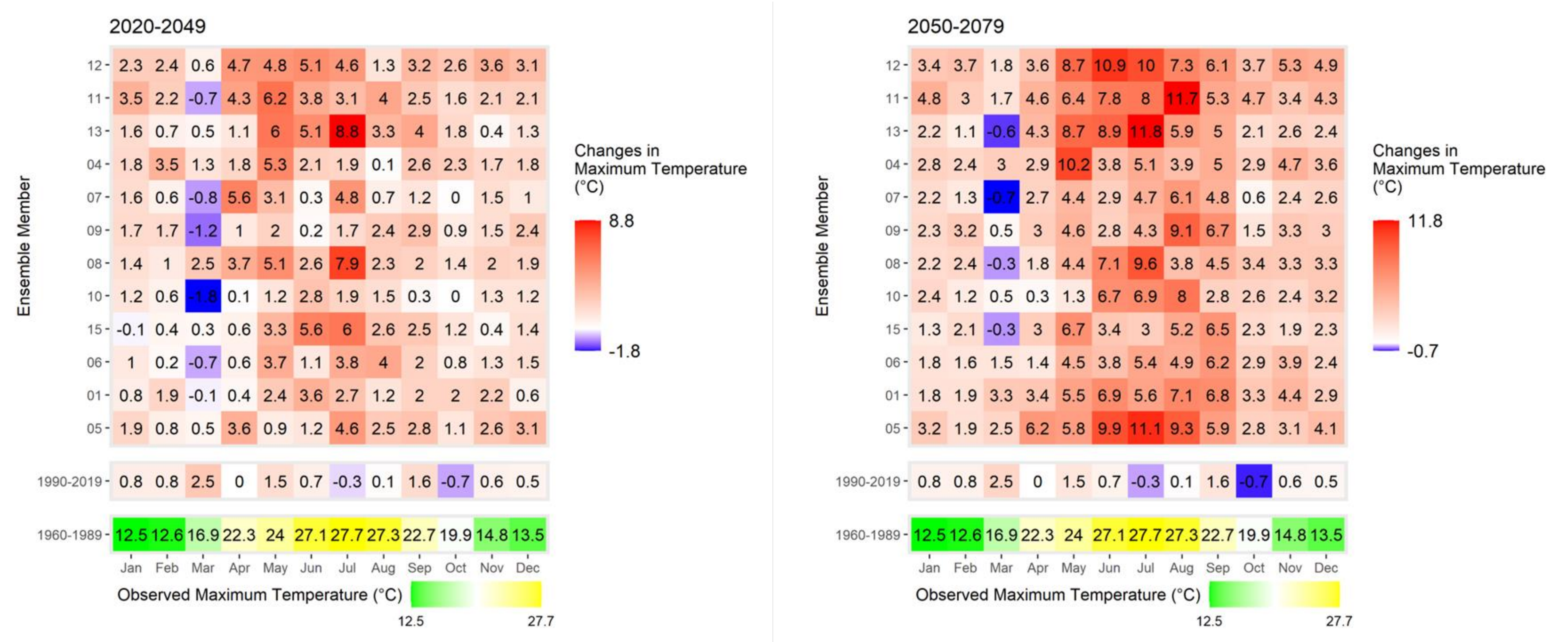


Figure 45b. National scale changes in the monthly Highest Temperature for the most extreme year from two observed periods (1960 – 1989, 1990 – 2019) and per climate projection for 2020 – 2049 (top) and 2050 – 2079 (bottom). Note: scales are different between plots.

We know from assessments of skill of the ensemble members to estimate temperature (Appendix D, see Figure 69) that projection 05 performs the best. From Figure 45b, EM05 indicates the largest increase in actual Highest Temperature is 4.6°C, in July, raising the 1960-1989 baseline observed from 27.7°C to 32.3°C. Other projections may have lower skill in representing the observed temperature (e.g. EM08), but have projected increases of HT by as much as 7.9°C.

By the 2050-2079 period EM05 produces estimated increases of 11.1°C in July, giving a potential total of 38.8°C. To put this into perspective, the highest temperature in Scotland during the 2022 heatwave was 34.8°C (at Charterhall in the Berwickshire).

The land area proportion projected to experience an increase in Highest Temperature if 100% in almost all months and projections. Figure 46 illustrates this, where only June (and to a lesser extent October) may potentially have a decrease in the 2020-2049 period according to some of the projections.

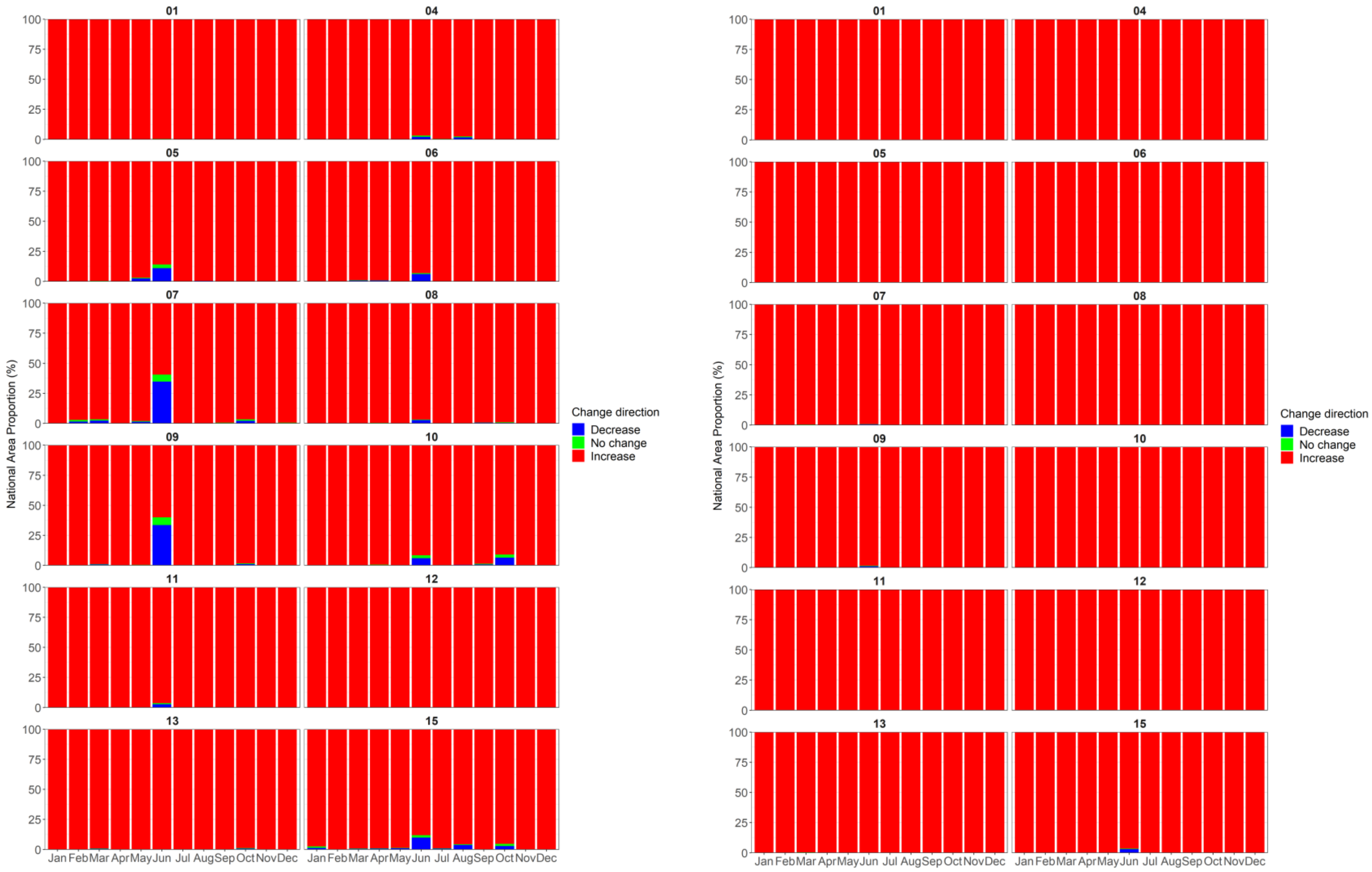


Figure 46. National land area proportions estimated to experience an increase (red), decrease (blue) or no change (green) in mean monthly Highest Temperature for each projection (ensemble member) for the 2020 – 2049 (left) and 2050 – 2079 (right) future periods.

Implications of changes in Highest Temperature

The increase in Highest Temperature already observed and projected to occur even more in the future have implications on many aspects of Nature and society. Increases in the extremes of maximum temperature will likely increase heat and water stresses on plants, animals and habitats, potentially damaging ecological function and delivery of ecosystem services. As the observed and projected increases occur throughout the year, the implications vary.

In the winter, there is likely to be an increase in rapid snow melt and loss of snow cover (Rivington et al 2019). Higher temperatures in spring will affect plant and insect phenology and timing on behaviour, with risks of earlier emergence from hibernation, leaf and bud formation, but when threats of damage by frost remain. High temperatures during anthesis (flowering) in summer reduces crop yield. High temperatures are also associated with increased rates of evapotranspiration and hence more rapid and severe drying of soils and vegetation, which may also increase the amount of combustible material increase the risks of fire occurrence.

Higher maximum temperatures also pose threats to people and infrastructure due to heat stress.

Land use category / sector impacts:

- Surface waters: affecting the quality of Scottish standing waters, esp. in relation to algal blooms
- Agriculture (uncultivated): heat stress induced reduced biomass, or if water and nutrients are not limited, increased biomass production.
- Open upland habitats: increased fire occurrence risk, desiccation of vulnerable plants if water is limited
- Environmentally sensitive areas: changes to inter-species competition (more heat tolerant plants become more dominant), increased fire occurrence risk.
- Grassland: heat stress induced reduced biomass, or if water and nutrients are not limited, increased biomass production.
- Arable: varies depending of timing – if in spring or at anthesis, may reduce yields, or if in the summer may aid harvest conditions and reduce grain drying costs. May increase risk of fire occurrence.
- Peatlands: increases the probability of desiccation of key plant species (e.g. *Sphagnum*) and drying of expose peat leading to loss of carbon and increased exposure to erosion from heavy precipitation events.
- Forestry: increased fire occurrence risk, potentially reduced water availability impacting seedlings.
- Urban: increased demand for water by people, increased fire occurrence risk.
- Amenity/leisure: increased demand for water for gardens and parks, increased fire occurrence risk
- Transport infrastructure: infrastructure damage (e.g. melting road surfaces).
- Biodiversity: additional heat stress, changed phenology, altered inter-species competition (potentially favouring invasive non-native species).
- Climate change: reduced resilience and loss of mitigation potential.

Highest Temperature summary

- There has been an observed increase in the highest maximum temperature from 1960-1989 to 1990-2019 for all months except June and in some western upland areas in August and

October. February, March, May, July (primarily the west) and September have experienced the largest increase, by up to 2.0°C and across the whole of Scotland by 1.3°C.

- The observed trend is projected to continue and increase. For the future period 2020-2049, all months are estimated to experience an increase in Highest Temperature, in the order of 2-3°C.
- There is near complete agreement between all climate projections used that the highest maximum temperature will increase for all months.
- At the national scale, in the most extreme years, March has seen the largest observed increase in Highest temperature from 16.9°C (1960-1989) to 19.4°C (1990-2019), which is larger than the projected changes. July and August (27.7°C each between 1960-1989) have changed little (-0.3 and 0.1°C, respectively), but are projected to increase by 1.9 to 8.8°C during the period 2020-2049. For the 2050-2079 period for July an August, the Highest Temperature is projected to increase by 3.0 to 11.8°C.

Very Warm Days

The Vary Warm Days (VWD) indicator is a count of the number of days when the maximum temperature is greater than the 95th percentile of monthly maximum temperature. It represents changes in how long the warmest periods last. **The number of Very Warm Days per month (Tx95pTOT):** Considering Tx_i as daily maximum temperature on day I in period j and Tx95 as the 95th percentile of maximum temperature in the 1960-1989 period then: $Tx95p_j = \sum Tx_{ij}$ where $Tx_{ij} > Tx95$ (Climdex Project 2023).

There has been an observed change in the number of very warm days between the 1960-1989 and 1990-2019 periods. Figure 47 shows that for the baseline there were generally very few (1-2 days) when the daily maximum temperature was above the 95th percentile. By the 1990-2019 period this had changed per month, with all months except June seeing an increase. March seeing the largest increase, particularly in the south and east of Scotland. Conversely, and as seen for the Highest Temperature indicator, June has experienced a decrease in Very Warm Days, whilst April, July, August and September have seen a slight decrease in some upland areas (Figure 48).

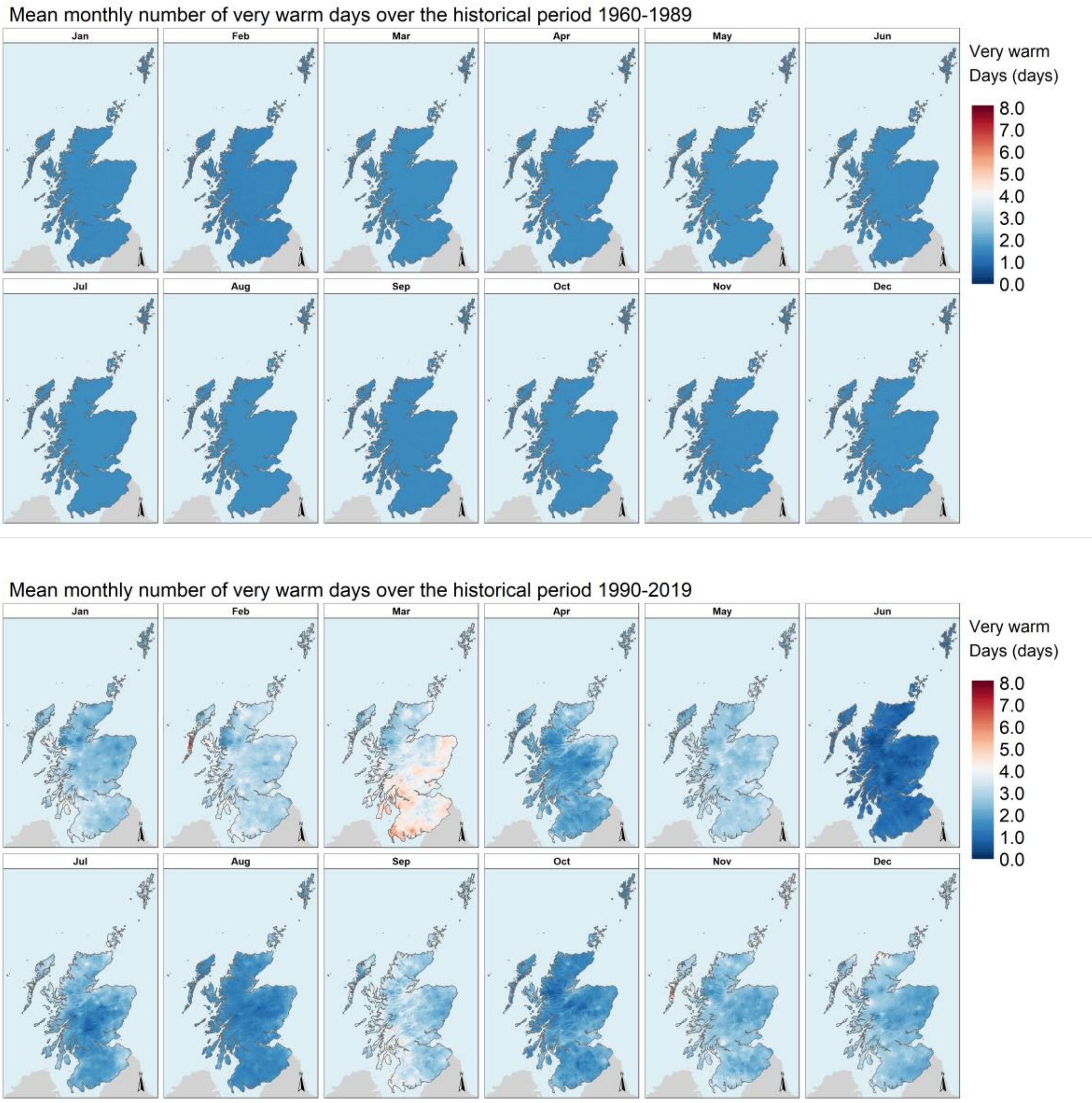


Figure 47. Mean monthly number of Very Warm Days for two observed periods: 1960 – 1989 (top) and 1990 – 2019 (bottom).

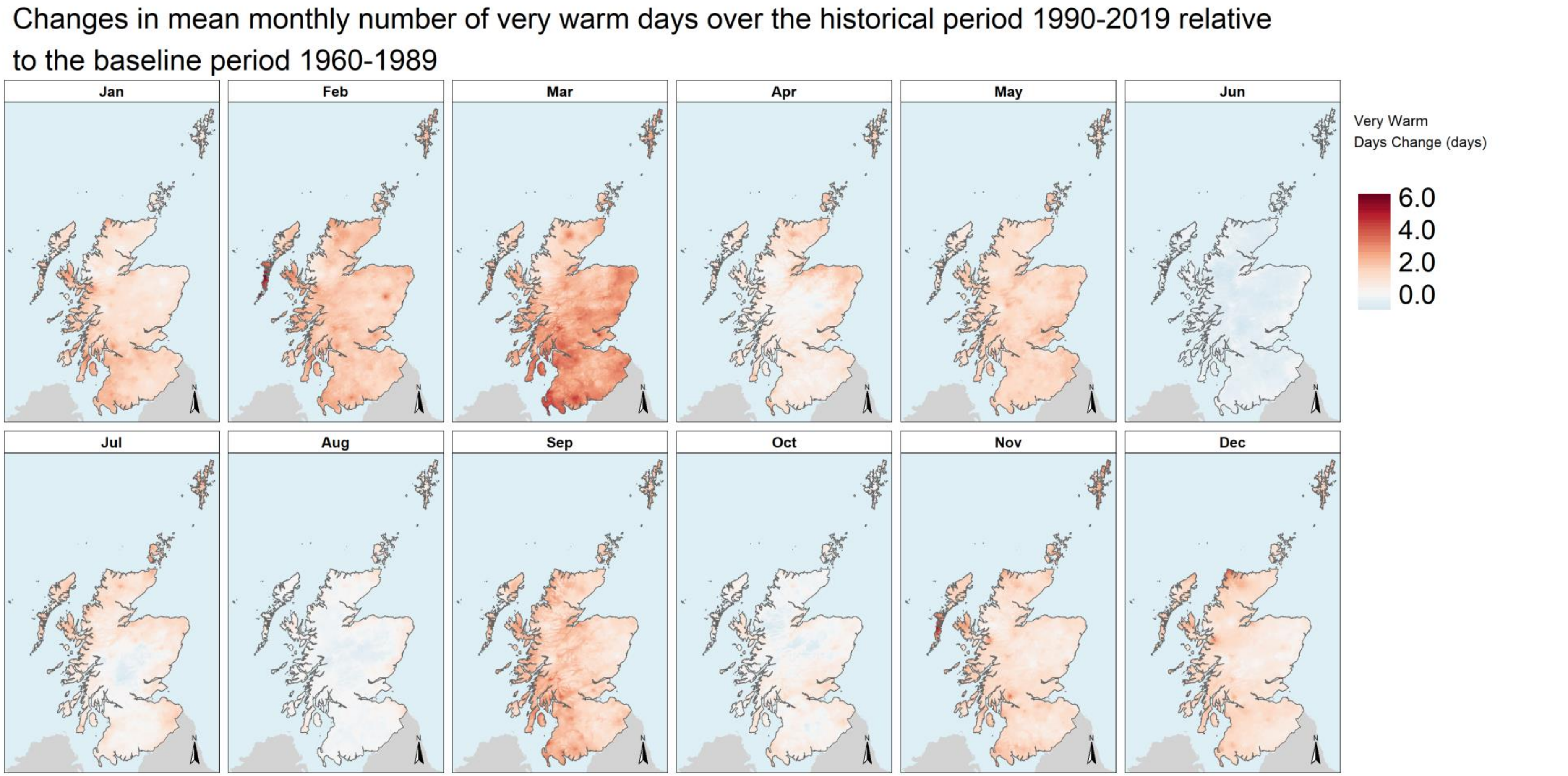


Figure 48. Changes in the number of mean monthly Very Warm Days between the 1960 – 1989 baseline and 1990 – 2019 period.

The change direction in the number of Very Warm Days is made clear in Figure 49, showing that for most months the has been an increase in the number of Very Warm Days. In June, virtually the whole country has experienced a decrease, with upland areas in August, and to a lesser extent July and October also seeing a decrease.

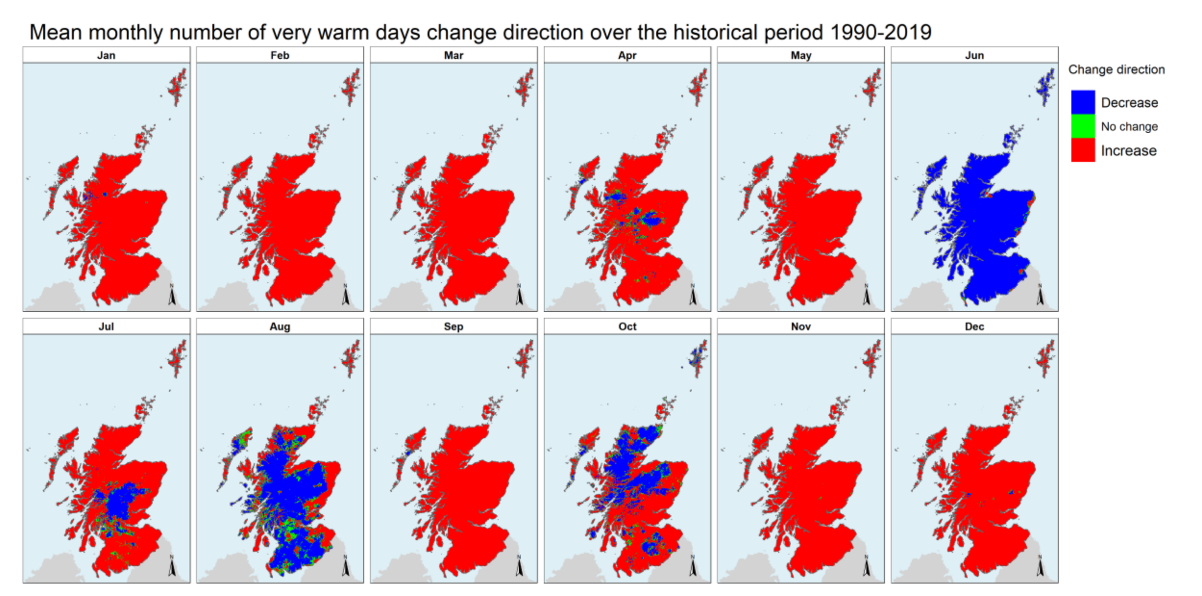


Figure 49. Change direction of mean monthly number of Very Warm Days from the 1960 – 1989 to 1990 – 2019. Blue = increase in VWD, red = decrease, green – no change.

Future projections of the Very Warm Days

The example future projection (ensemble member 01) indicates an overall increase in the number of Very Warm Days for all months across the whole of Scotland, but with little change in some upland areas.

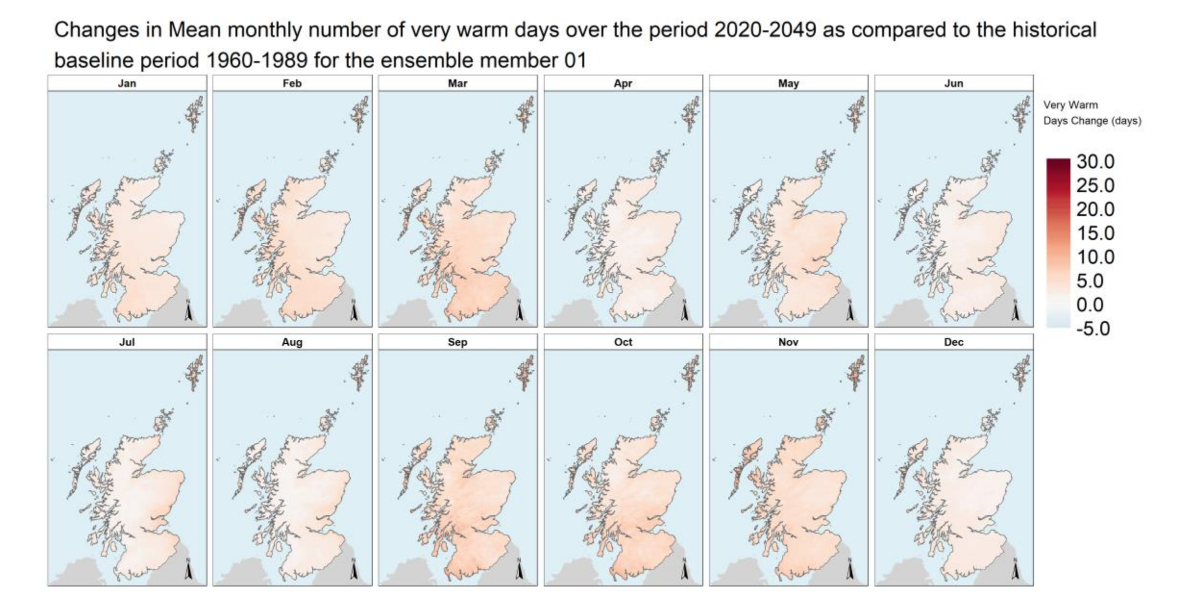


Figure 50. Example future projection (Ensemble Member 01) changes of the mean monthly of Very Warm Days between the 2020 – 2049 period and the 1960 – 1989 baseline.

In the projection 01, the change direction is a uniform increase (red) across the whole country. There are no locations estimated to experience a decrease (blue) or no change (green) in Figure 51.

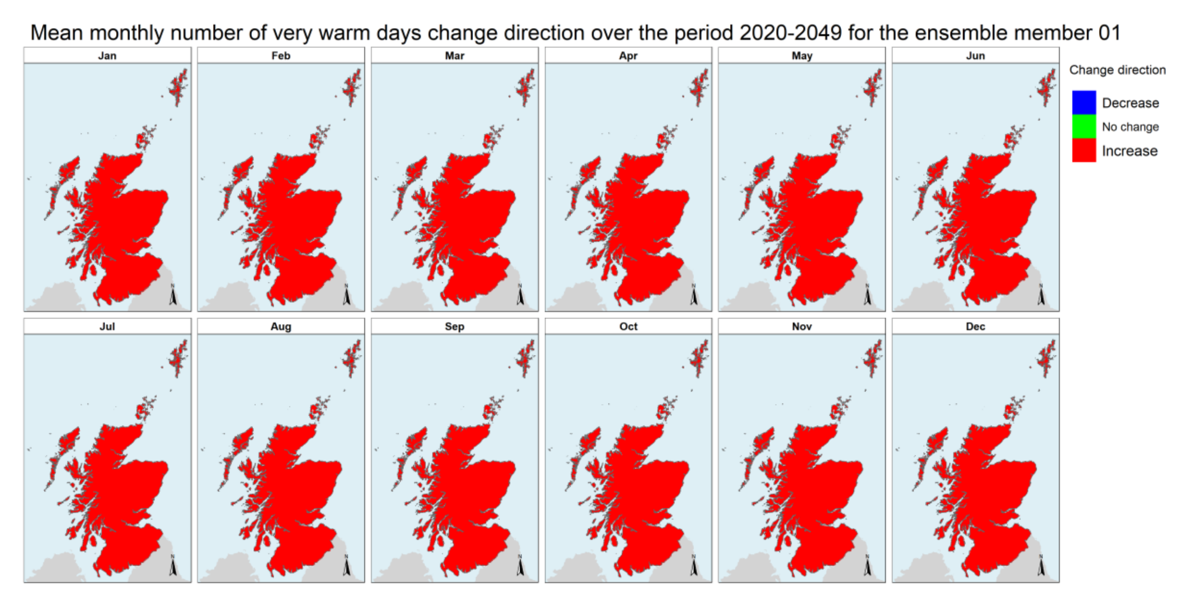


Figure 51. Change direction of mean monthly number of Very Warm Days from the 1960 – 1989 to 2020 – 2049 period for Ensemble Member 01. Blue = increase in HT, red = decrease, green – no change.

There is almost complete agreement between climate projections that the number of Very Warm Days will increase (Figure 52). There is a small amount of uncertainty concerning the direction of change for June in the west, central and southern uplands, plus just a few locations in February, May and October when considering all 12 projections.

We have not presented the agreement maps for mean monthly number of Very Warm Days for the 2050 – 2079 period as all projections show an increase, i.e., all maps per month are red meaning all 12 projections agree that the number of Very Warm Days will increase across the whole of Scotland for all months.

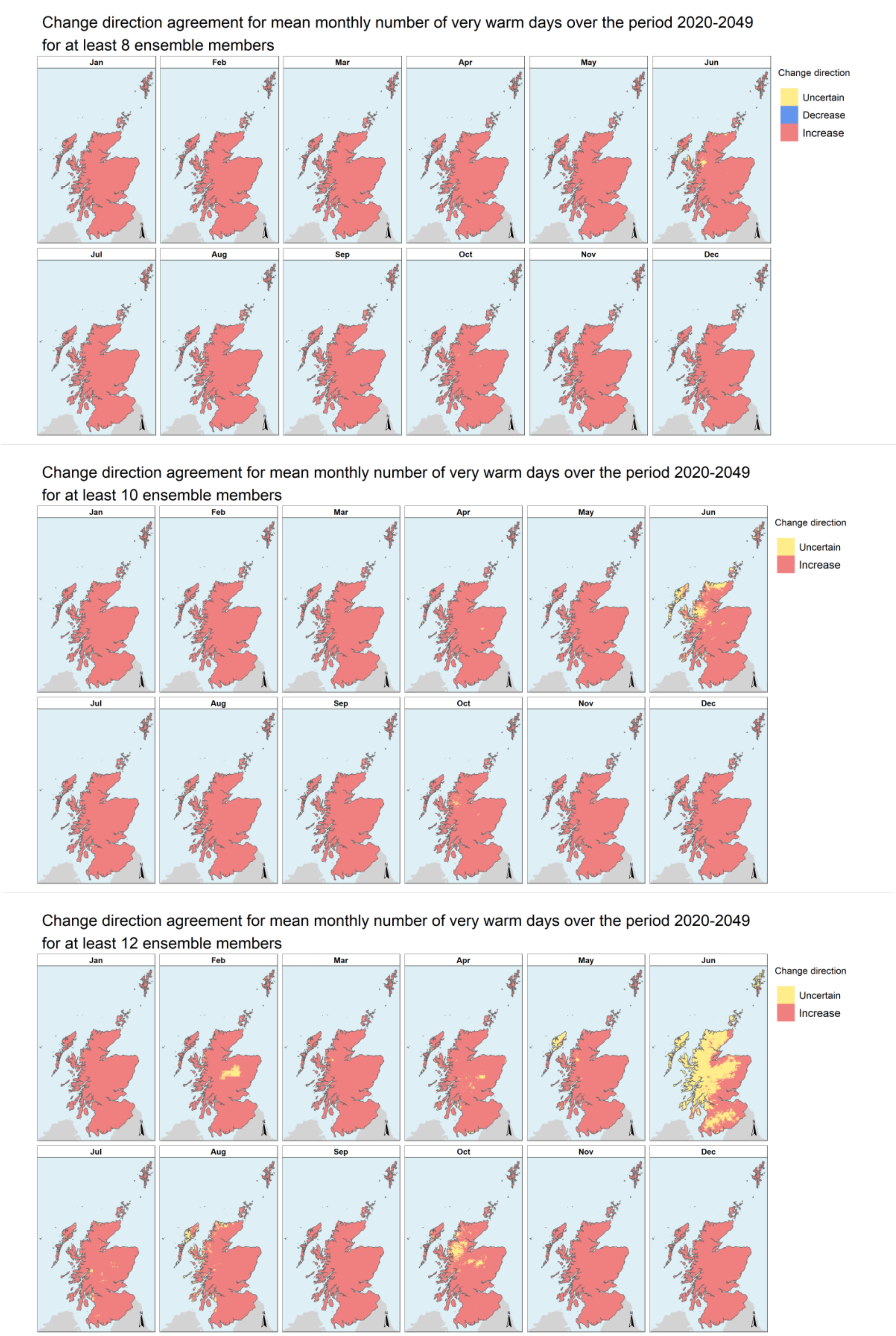


Figure 52. Change direction agreement for 8 (top), 10 (middle) and 12 (bottom) climate projections (ensemble members) for the mean monthly number of Very Warm Days in the period 2020 - 2049.

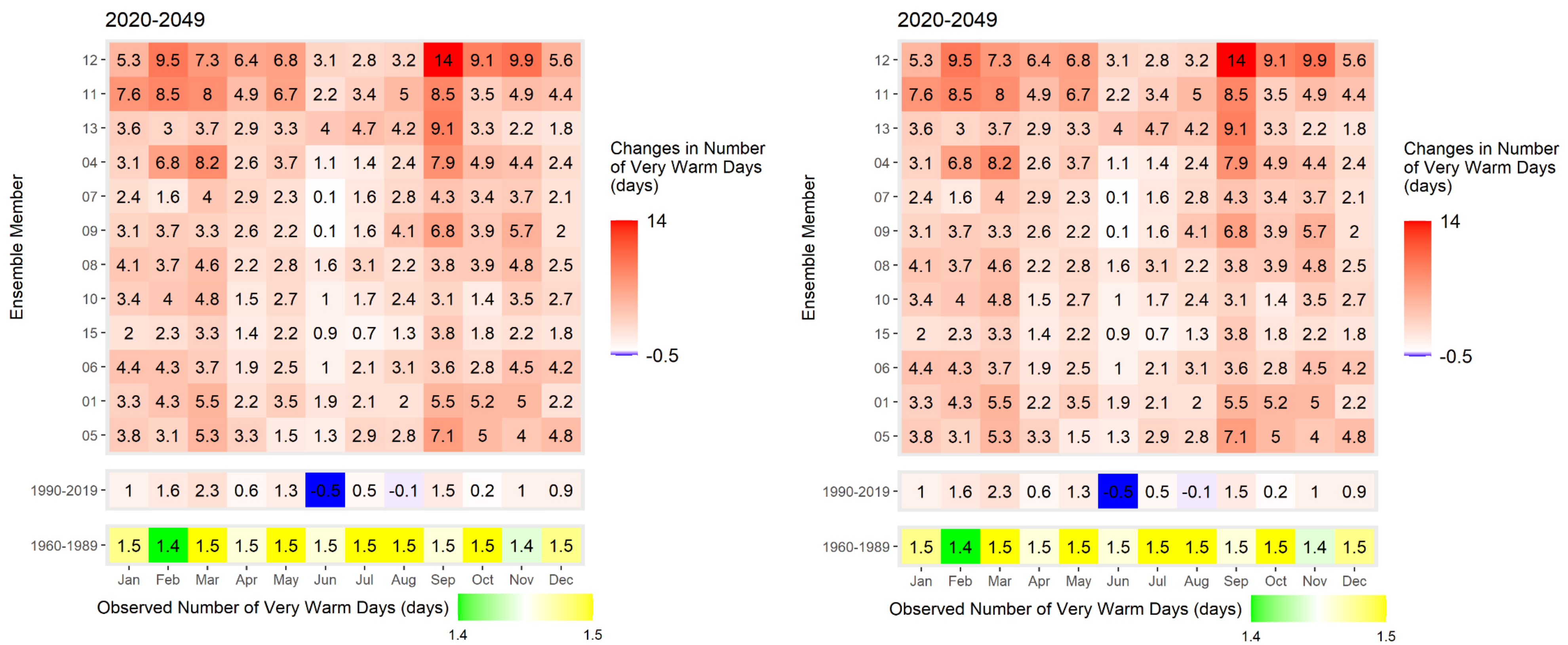


Figure 53a. National scale changes in the median monthly number of Very Warm Days for the two observed periods (1960 – 1989, 1990 – 2019) and per climate projection for 2020 – 2049 (top) and 2050 – 2079 (bottom). Note: scales are different between plots.

There has been a detectable change in the number of Very Warm Days since per month 1960 (Figure 48), with the median increasing by as much as 2.3 days in March (Figure 53a), but also decreasing slightly (0.5 days) in June. The ensemble members with the better skill at simulating temperature (EM 05, 01, 06) estimate increase in VWD by up to 7.1 days (EM05 in September) for the future period 2020-2049. This increases to 16.6 days (EM01) in the 2050-2079 period, but may be more at +20 days.

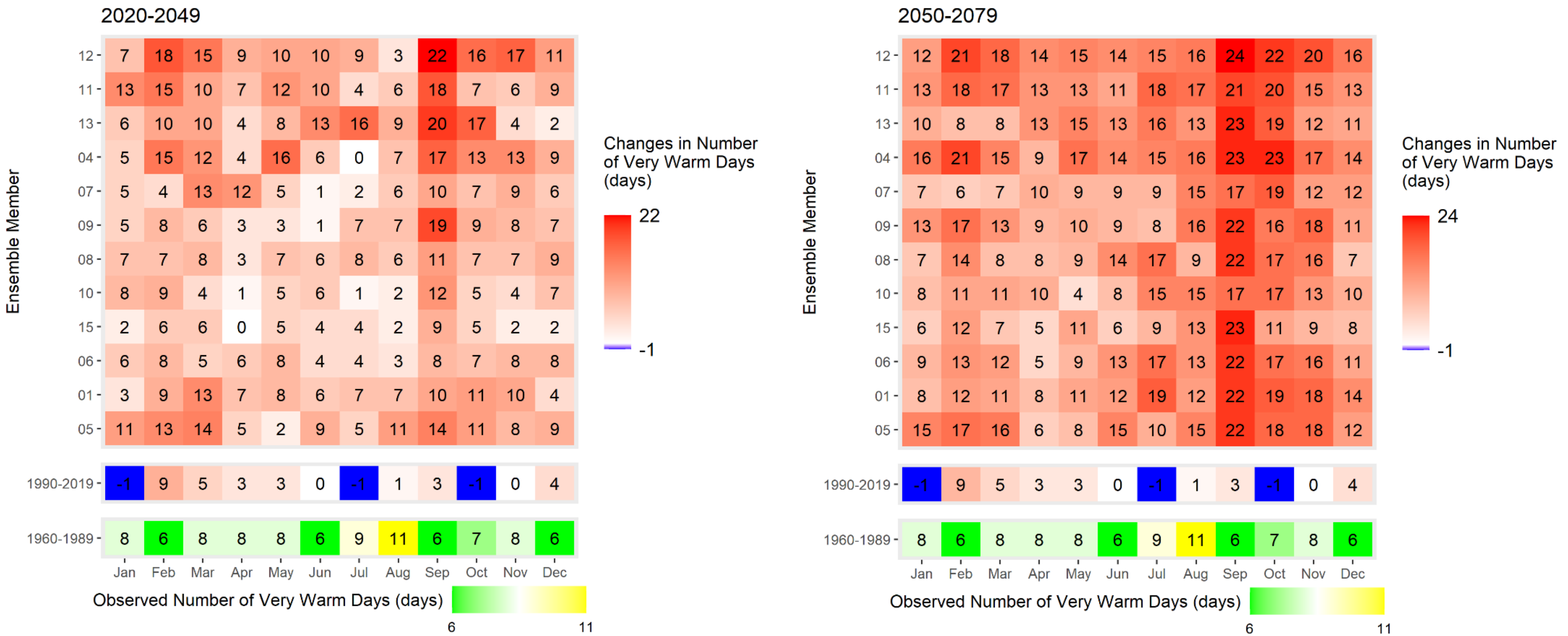
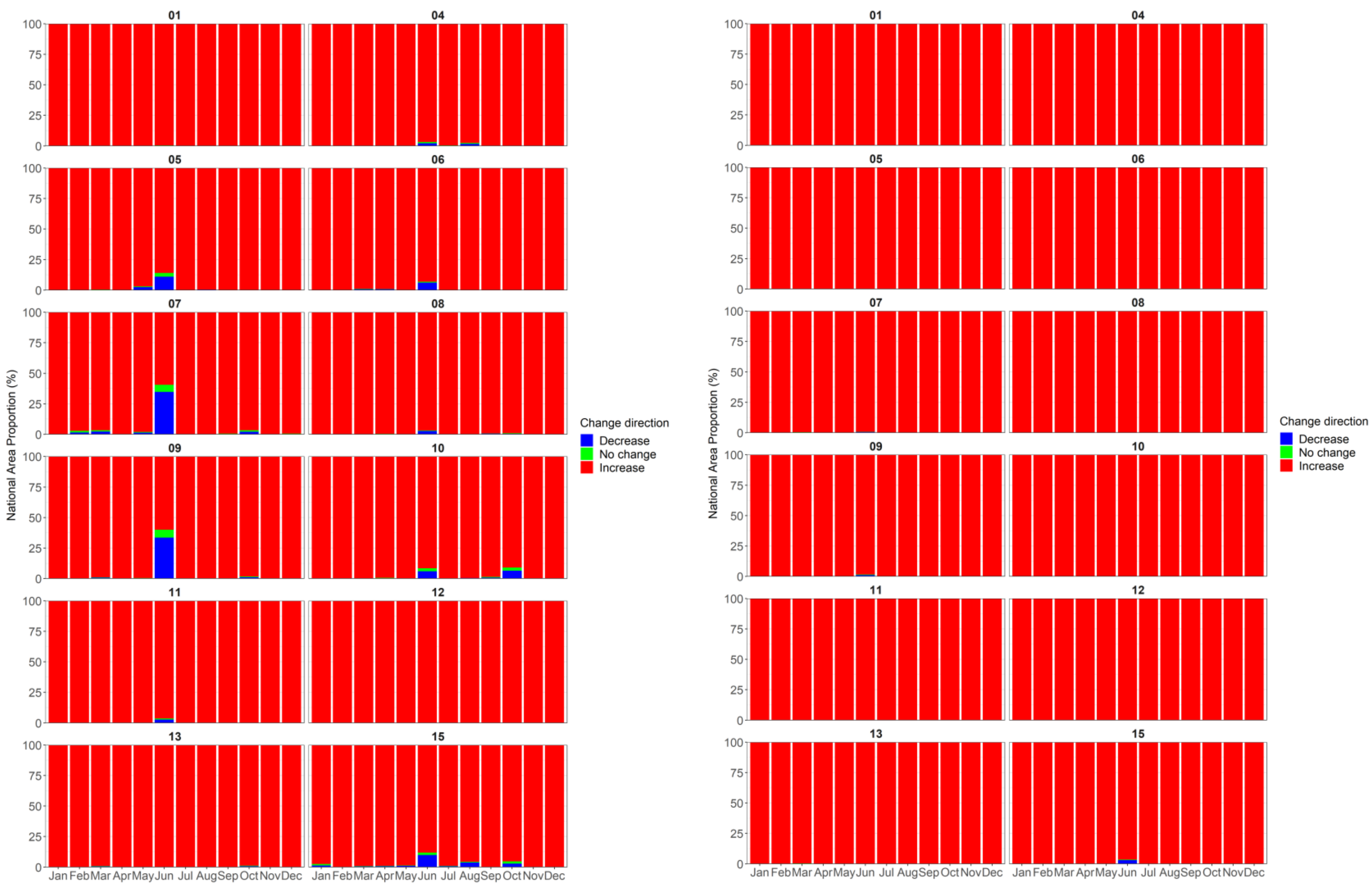


Figure 53b. National scale changes in the total monthly number of Very Warm Days for the two observed periods (1960 – 1989, 1990 – 2019) and per climate projection for 2020 – 2049 (top) and 2050 – 2079 (bottom). Note: scales are different between plots.

The total number of VWD has already increased by 9 days in February, but decreased by 1 day in January, July and October (Figure 53b). Both future projection periods estimate the potential for all months likely to see a substantial increase in the total number of VWD per month, with September consistently estimated to have the largest increases (6 days in the 1960-1989 period, increasing by 17 to 22 days = 23 to 28 days).



The whole of the land area of Scotland is estimated to experience an increase in the number of Very Warm Days (Figure 54), except for some areas in June for some projections. This means that up to 28 days in September in the 2050-2079 period will greater than the warmest days (95th percentile) in the 1960-1989 period.

Figure 54. National land area proportions estimated to experience an increase (red), decrease (blue) or no change (green) in mean monthly number of Very Warm Days for each projection (ensemble member) for the 2020 – 2049 (left) and 2050 – 2079 (right) future periods.

Implications of changes in Very Warm Days

The increase in the number of Very Warm Days already observed and projected to occur even more in the future have implications on many aspects of Nature and society. Increases in the duration of the warmest temperatures per spring, summer and autumn month will likely increase heat stresses on plants and animals, testing the thermal range tolerance of species and habitats. This may potentially alter inter-species competition, damage ecological function and delivery of ecosystem services.

Longer warm periods in the winter are likely to increase snow melt and loss of snow cover (Rivington et al 2019) and increase stream temperature affecting aquatic biodiversity. High temperatures lasting for longer will result in more rapid thermal time accumulation driver more rapid phenological development which will affect the timing of plant and insect development, with risks of earlier emergence from hibernation, leaf and bud formation, but when threats of damage by frost remain. The longer duration of high temperatures increases the risk that heat stress will occur during anthesis (flowering) in summer which can reduce crop yield. High temperatures are also associated with increased rates of evapotranspiration (see Rivington and Jabloun 2022 – Climatic Water Balance estimates) and hence more rapid and severe drying of soils and vegetation. This, combined with longer duration warm periods are likely to increase the amount of combustible material increasing the probability of wildfires.

Higher maximum temperatures also pose threats to people and infrastructure due to heat stress.

Land use category / sector impacts:

- Agriculture (uncultivated): heat stress induced reduced biomass, or if water and nutrients are not limited, increased biomass production.
- Open upland habitats: increased fire occurrence risk, desiccation of vulnerable plants if water is limited.
- Environmentally sensitive areas: changes to inter-species competition (more heat tolerant plants become more dominant), increased probability of desiccation and fire occurrence risk.
- Grassland: increased probability of desiccation and heat stress induced reduced biomass, or if water and nutrients are not limited, increased biomass production.
- Arable: varies depending of timing – if in spring may reduce yields due to more rapid phenological develop (less time to accumulate biomass), or if in the summer may aid harvest conditions and reduce grain drying costs. May increase risk of fire occurrence.
- Peatlands: increases the probability of desiccation of key plant species (e.g. *Sphagnum*) and drying of expose peat leading to loss of carbon and increased exposure to erosion from heavy precipitation events.
- Forestry: increased fire occurrence risk, potentially reduced water availability impacting seedlings. Altered species distribution range.
- Urban: increased demand for water by people, increased fire occurrence risk.
- Amenity/leisure: increased demand for water for gardens and parks, increased fire occurrence risk.
- Transport infrastructure: infrastructure damage (e.g. melting road surfaces).
- Biodiversity: additional heat stress and risk of desiccation, changed phenology altering food chains, altered inter-species competition (potentially favouring invasive non-native species).
- Climate change: reduced resilience and loss of mitigation potential.

Very Warm Days summary

- There has been an observed change in the number of very warm days between the 1960-1989 and 1990-2019 periods, with all months except June (and August in upland areas) seeing an increase. February (9 days) and March (5 days) have had the largest increase, particularly in the south and east of Scotland.
- There is almost complete agreement between climate projections that the number of Very Warm Days will increase in the future for the whole land area of Scotland. February, March and September are projected to have substantial increases, e.g. September, which had 6 days in the 1960-1989 period, but increasing by between 17 to 22 days for the 12 projection, giving a total of 23 to 28 days by 2050.
- Historically (1960-1989) at the national scale the highest number of Very Warm Days in the most extreme year was in August (11 days), which has increased by 1 day (1990-2019), but is projected to increase by 2-11 days up to 2050, and by 9-17 days by 2070. September is projected to see the largest increases of 8-22 and 17-24 days between up to 2050 and 2070, respectively.

Coldest Temperature

The Coldest Temperature (CT) indicator provides information about how the lowest temperatures per month have changed and are projected to in the future. CT is the lowest temperature achieved per month. Changes in minimum temperature are important in terms of its influence on crop and insect phenology, requirement for chilling (vernalisation), snow formation, cover and melt, stream temperature etc.

The Coldest Temperature is calculated as: **Monthly minimum value of daily minimum temperature (TNn)**: Considering Tn as daily minimum temperature in month k, period j, the minimum daily minimum temperature in each month is TNnkj = min (Tnkj) (Climdex Project 2023).

For the future projections, we re-emphasise that the HadRM3 Regional Climate Model used to generate the daily climate projections data does not generally perform well in simulating specific extreme low temperatures (Rivington et al 2008). Assessments indicate that there is a systematic error within the model that results in low minimum temperatures being over-estimated by about 1°C. However, allowing for this error, the climate change signal (the continuation of observed increase trends into the future) does appear to be well represented by the model (e.g. see Braemar site specific example in Rivington and Jabloun 2022).

Observed trends in Coldest Temperature

The Coldest Temperatures may normally be expected to occur at higher elevations and distances further from the sea, which is illustrated in the data shown in Figure 55 for the two observed periods.

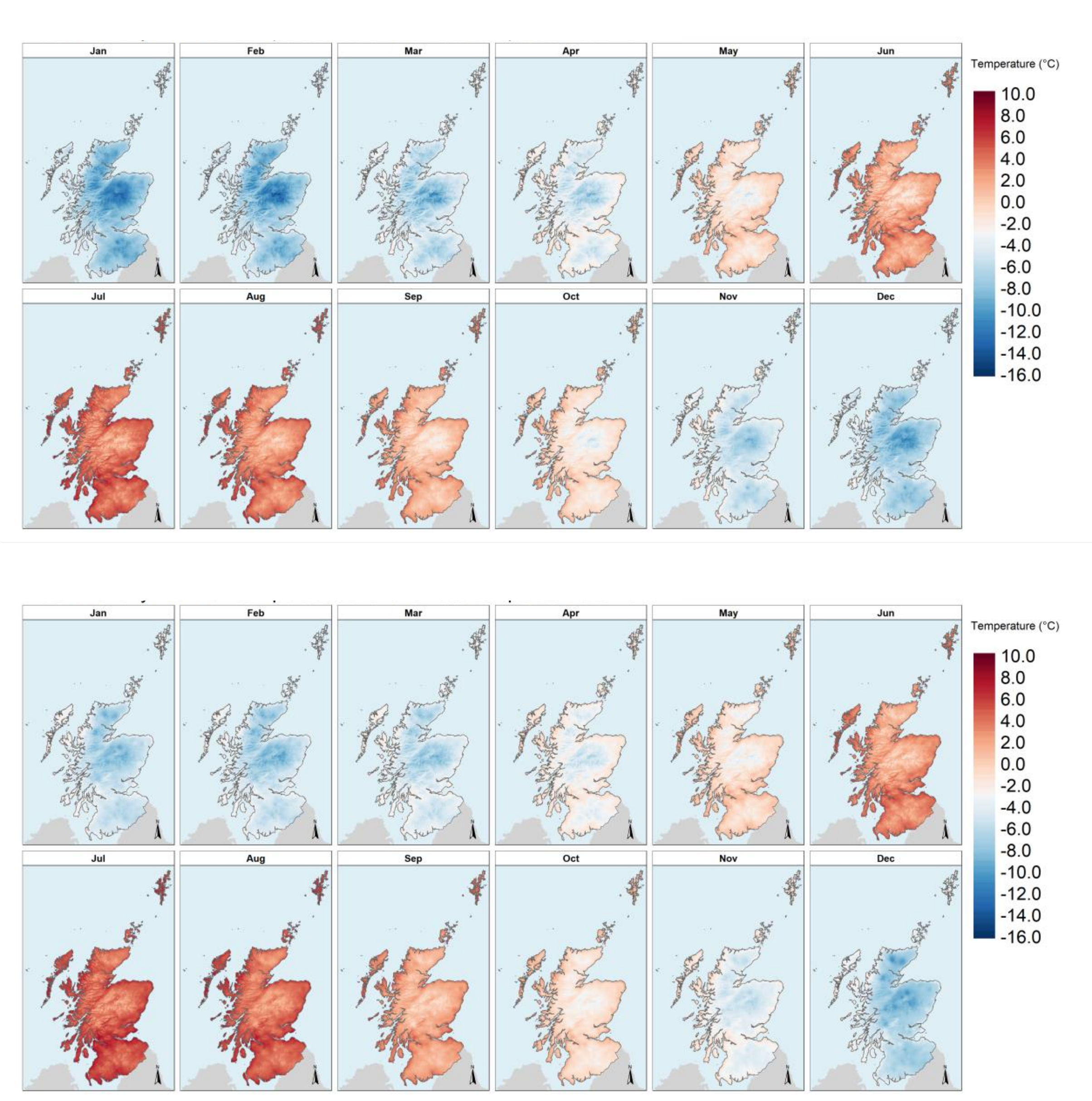


Figure 55. Lowest minimum temperature for two observed periods: 1960 – 1989 (top) and 1990 – 2019 (bottom).

There has generally been an increase (warmer) in the Coldest Temperature in all months since the 1960-1989 period (red shading in Figure 56), with the largest increases occurring November, January and February, most noticeably in the Cairngorms area and southern uplands. May, October and December have experienced decreases (colder) in Coldest Temperatures in some parts of the north and west (blue shading in Figure 56), whilst experiencing increases (warmer) elsewhere. These trends align with the overall decreases in minimum temperature (warming) detailed in Rivington and Jabloun 2022).

This pattern of changes however, may also be a result in difficulties in spatially interpolating the lowest minimum temperatures (See Text Box 1: Notes on observed data utility).

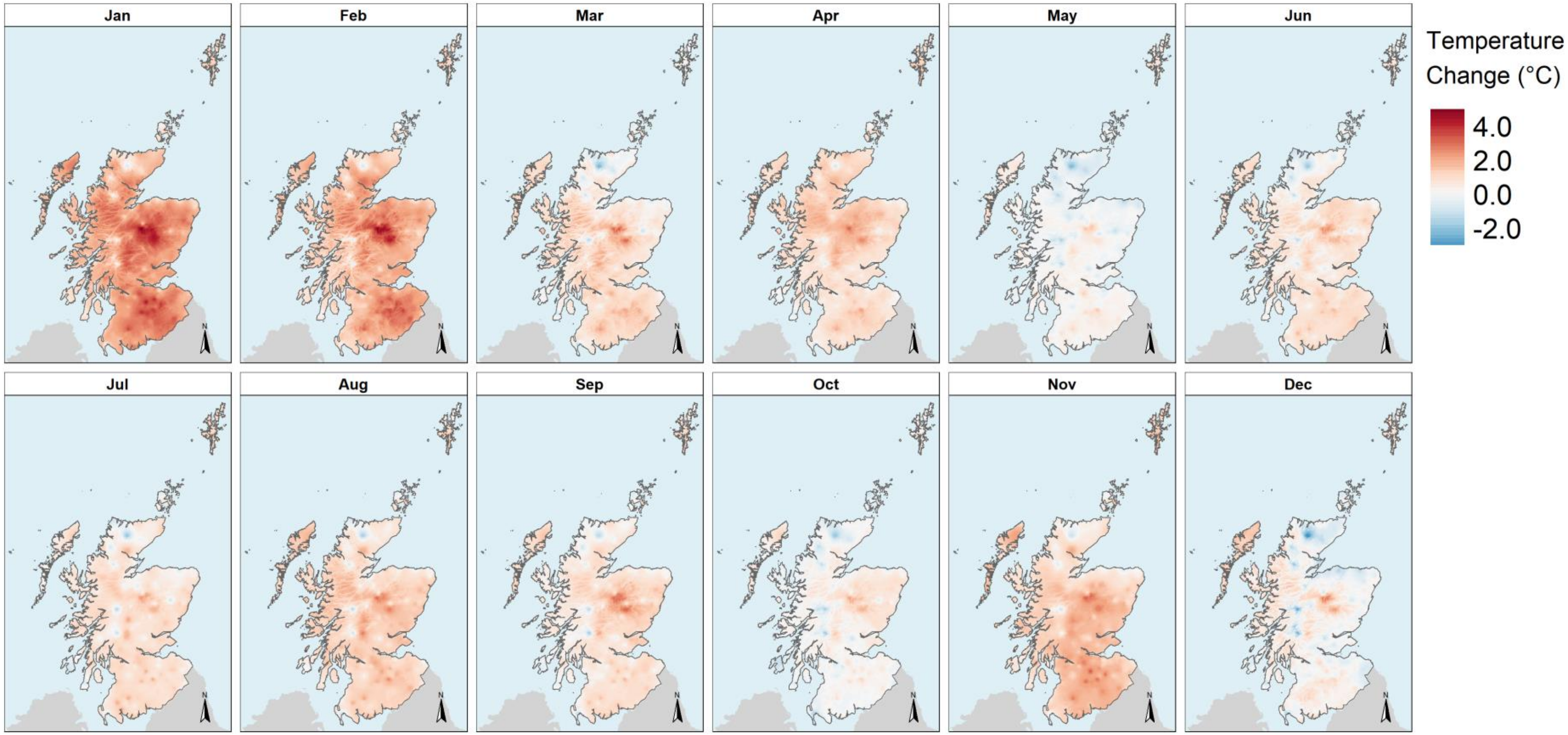


Figure 56. Changes in the lowest monthly Coldest Temperatures between the 1960 – 1989 baseline and 1990 – 2019 period.

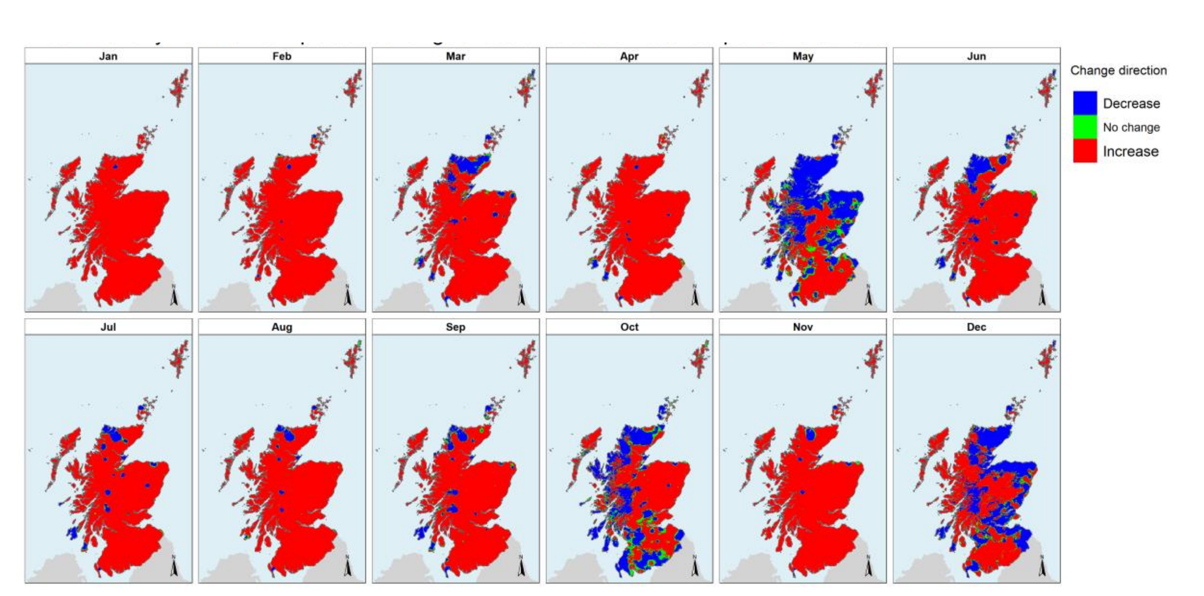


Figure 57. Change direction of mean monthly Coldest Temperatures from the 1960 – 1989 to 1990 – 2019. Blue = increase in CT, red = decrease, green – no change.

The observed change direction is overall towards an increase (warmer) lowest minimum temperature, the Coldest Temperature (red shading in Figure 57), but also with some parts of Scotland experiencing a decrease (colder, blue shading). The lower Coldest Temperatures in May might be significant in terms of risks to biota of late spring frosts.

Future projections of Coldest Temperature

Starting with the example projection (Ensemble Member 01), there is likely to be a continuation of the observed trend in a decrease (warmer) in Coldest Temperature in all months in the future (Figure 58). In this example, November and March are estimated to have the largest changes.

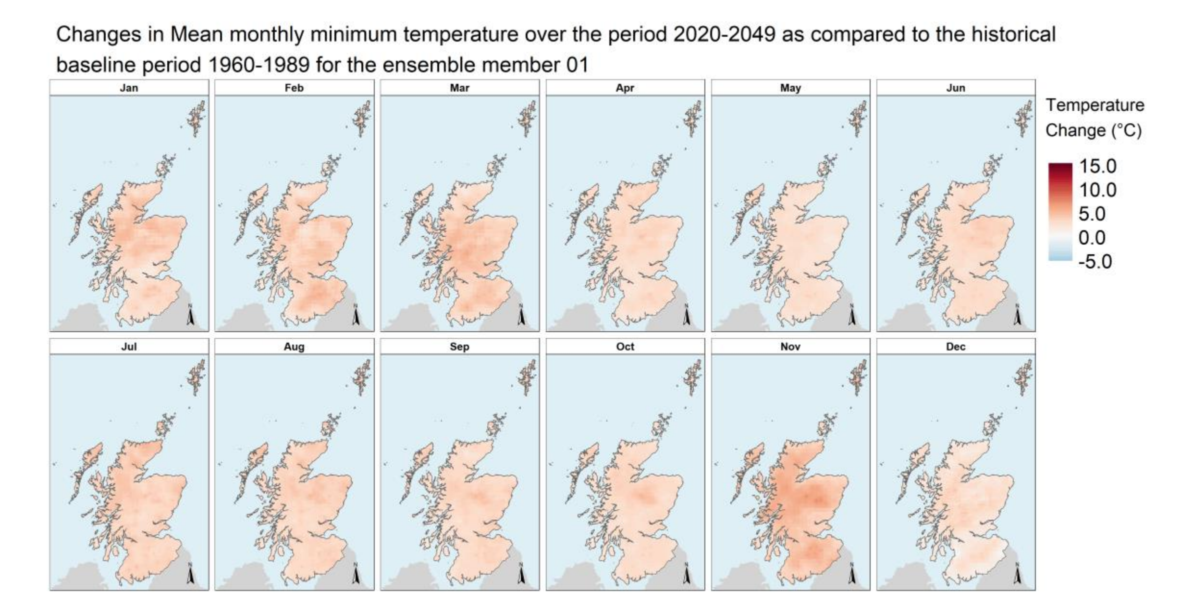


Figure 58 Example future projection (Ensemble Member 01) changes of the mean monthly Coldest temperature between the 2020 – 2049 period and the 1960 – 1989 baseline.

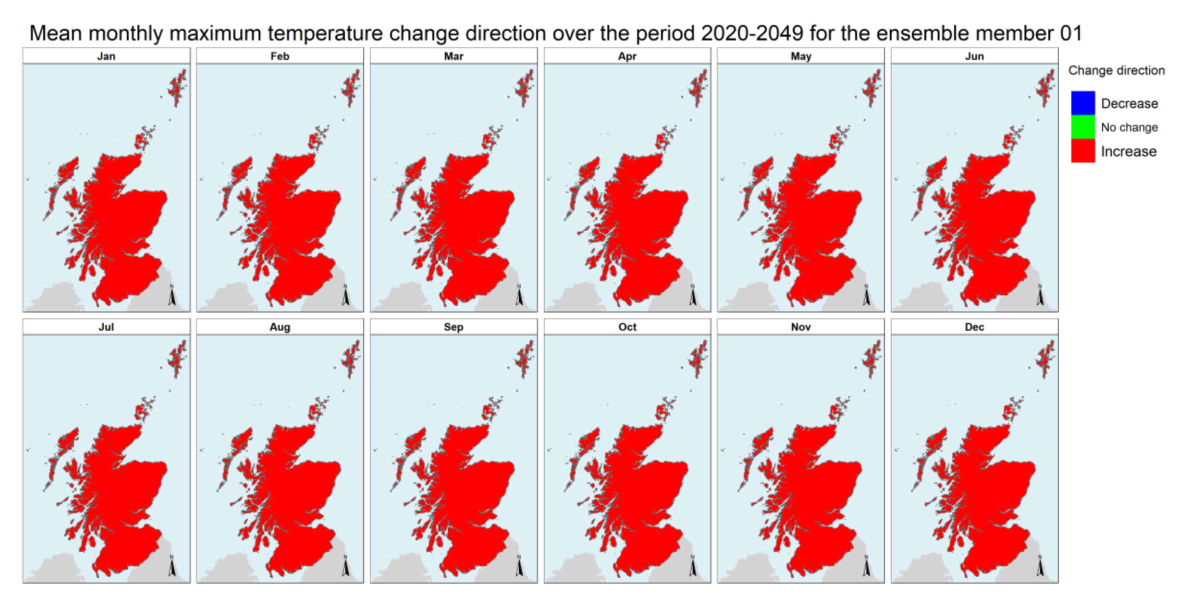


Figure 59. Change direction of mean monthly Coldest Temperature from the 1960 – 1989 to 2020 – 2049 period for Ensemble Member 01. Blue = decrease in HT, red = increase, green – no change.

Figure 59 illustrates that for the example (EM01), the direction of change is uniformly an increase (warmer) in the Coldest Day across the whole of Scotland for every month.

This uniformity of projected increase (warming) in the Coldest Day is seen across the majority of ensemble members (Figure 60), with uncertainty (lack of agreement between projections, yellow shading) only appear in February and October for some parts of the country, and most of Scotland in December, when all 12 projections are used in the agreement maps.

We have not presented the agreement maps for mean monthly Coldest Temperature for the 2050 – 2079 period as all projections show an increase (warming), i.e. all maps per month are red.

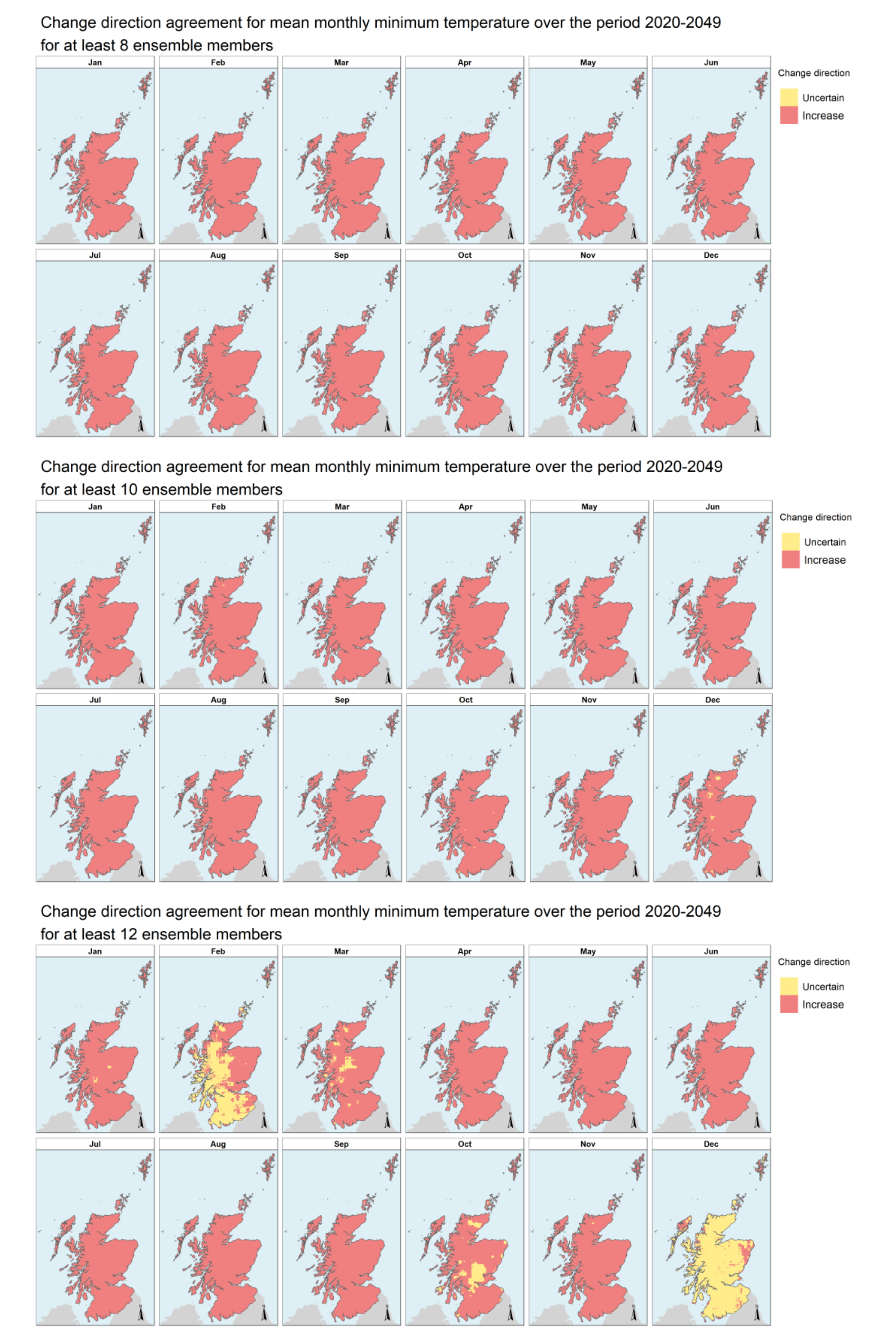


Figure 60. Change direction agreement for 8 (top), 10 (middle) and 12 (bottom) climate projections (ensemble members) for the monthly Coldest Temperatures in the period 2020 - 2049.

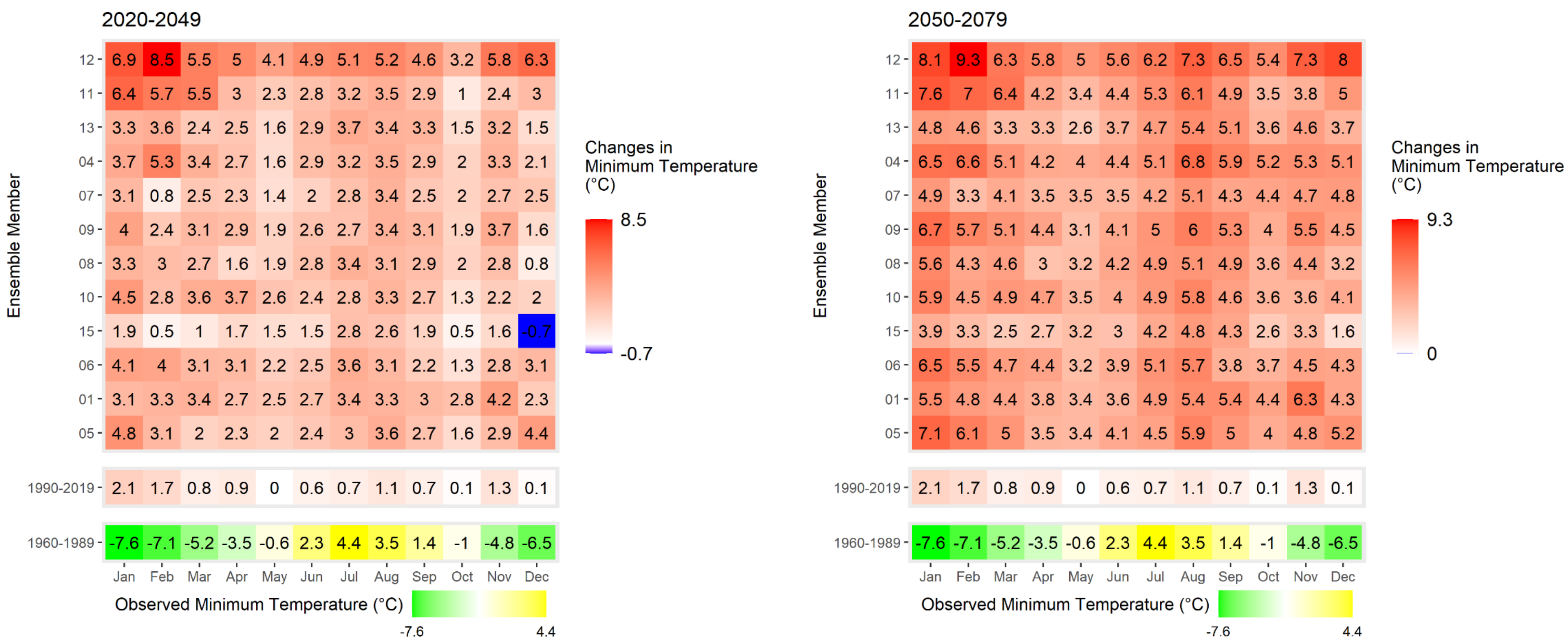


Figure 61a. National scale changes in the median monthly Coldest Temperature for the two observed periods (1960 – 1989, 1990 – 2019) and per climate projection for 2020 – 2049 (top) and 2050 – 2079 (bottom). Note: scales are different between plots.

At the national level, there has been a warming shift in the median Coldest Temperature since 1960 in all months except June (Figure 61a). January has seen the largest increase (warming) of 2.1°C. For all future projections there is an estimation of continued warming (except EM15 in December) for the 2020-2049 period. There is greater warming estimated for the winter months than for the summer Coldest Temperatures. This warming trend increases in the 2050-2079 period.

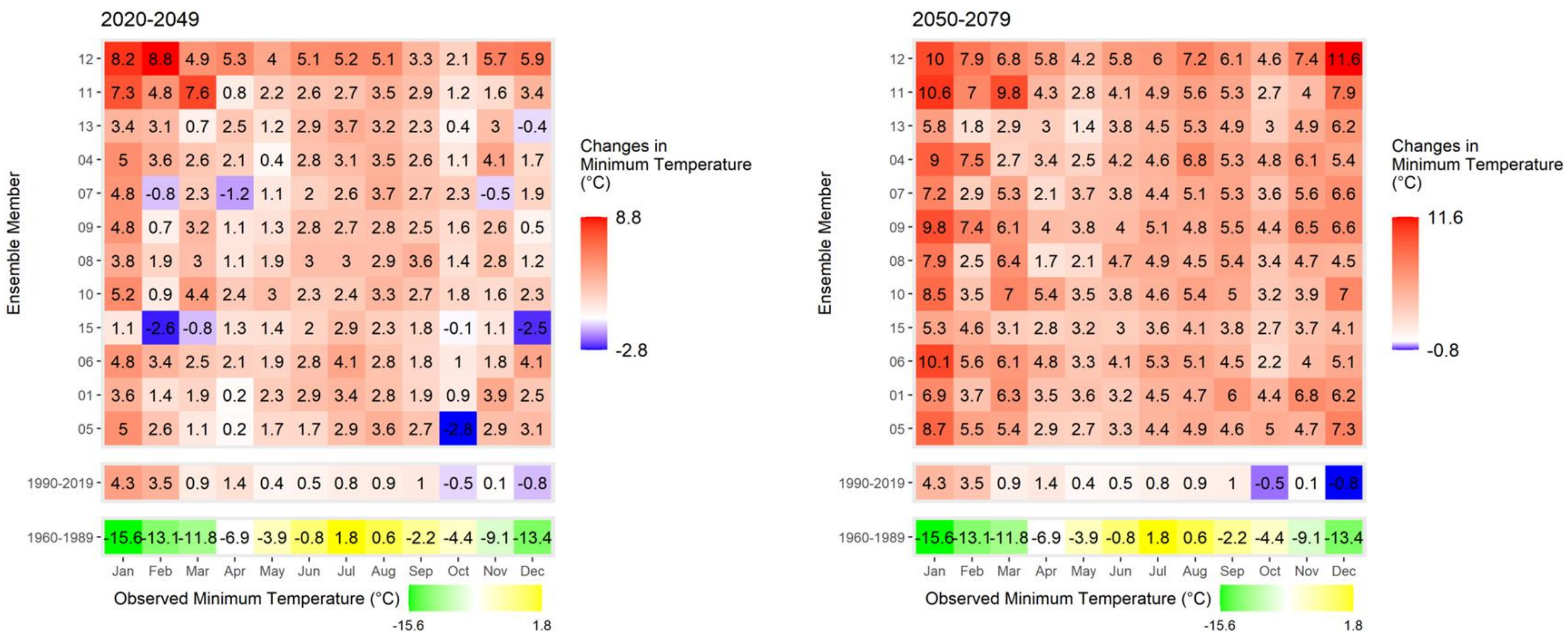


Figure 61b. National scale changes in the monthly Coldest Temperature for the two observed periods (1960 – 1989, 1990 – 2019) and per climate projection for 2020 – 2049 (top) and 2050 – 2079 (bottom). Note: scales are different between plots.

In terms of the changes in Coldest Temperatures values at the national scale, Figure 61b shows that whilst there has been a slight decrease (cooling) in October (-0.5°C) and December (-0.8°C) since 1960, overall there has been an increase (warming) by as much as 4.3°C in January. Several of the future projections for 2020-2049 indicate the potential for continuation of this trend, but most projections estimate warming for all months. By the 2050-2079 period all projections indicate an increase (warming) to the extent that the Coldest Temperature with be less than half (warmer) of it's current value per month, with CT is negative.

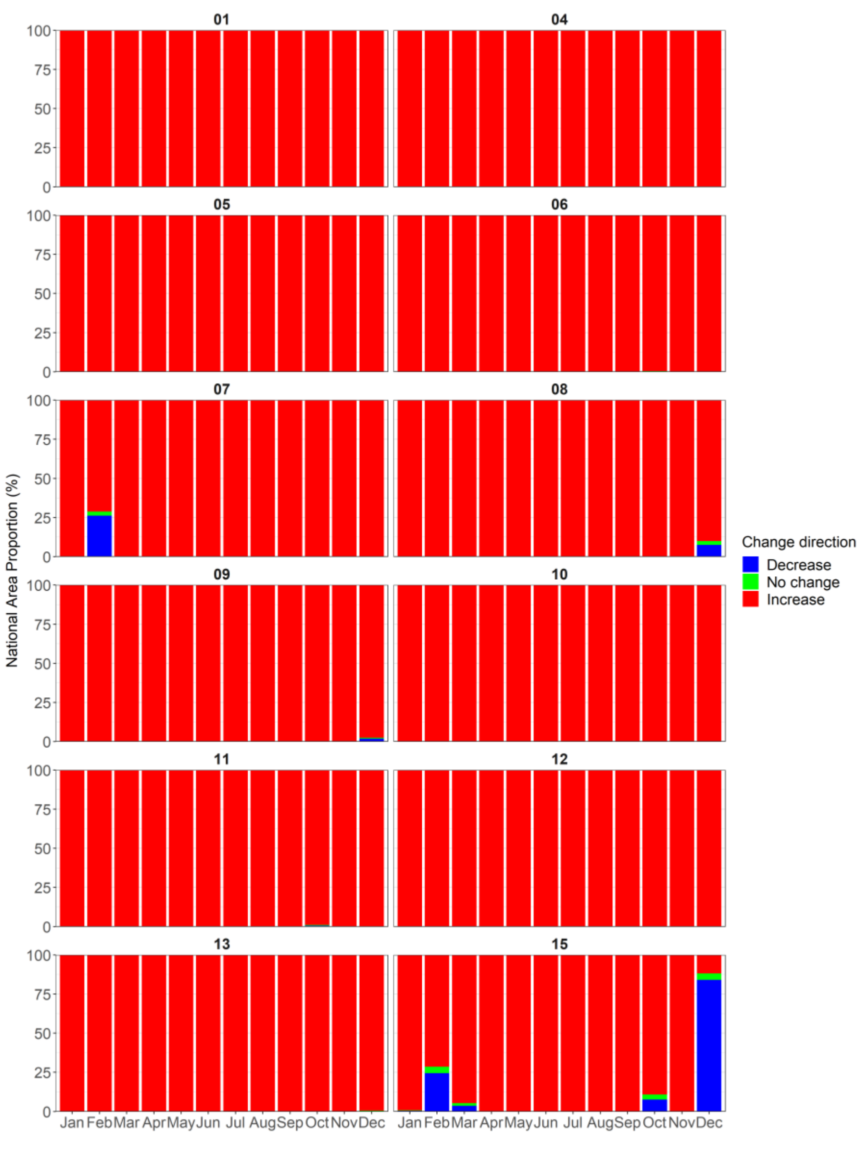


Figure 62. National land area proportions estimated to experience an increase/ warmer (red), decrease/ colder (blue) or no change (green) in mean monthly Coldest temperature for each projection (ensemble member) for the 2020 – 2049 period.

The national land area proportion experiencing increases (warming) in Coldest Temperature is almost uniformly 100% for all climate projections used (Figure 62). We have not presented the national land area proportion plot for Coldest Temperature for the 2050-2079 as all projections show an increase / warming for all months.

Implications of changes in Coldest Temperature

The increase (warming) in the Coldest Temperature reflects a higher probability of fewer days of less intense frosts. This may have benefits in some respects of crop cultivation, especially for horticulture. However, there is a trade-off in that many crops require vernalisation (also called chilling, the cooling of seed during germination in order to accelerate flowering when it is planted). In the summer, potato tuber formation may be impacted if minimum temperature is above 20°C.

Warmer Coldest Temperature may result in less open and ground surface water freezing, which may produce a positive feedback loop of additional warming associated with changes in albedo, where ice may previously have reflected solar radiation, whereas darker unfrozen water will absorb more heat energy. Similarly, less intense cold may reduce the consolidation of snow into ice, meaning snow cover may be more likely to melt, again changing the surface albedo white to dark and so increasing the probability of additional heat energy absorption. A benefit may be reduced frost heave and loosening of soil surfaces which in some circumstances may reduce risks of erosion.

Changes in the Coldest Temperature, coupled with overall warming in the winter and fewer frosts may have implications in respect of cold temperature control of crop and livestock pests and diseases and their vectors. There may also be disruption to hibernation patterns, potentially resulting in emergence of species too early, leaving them exposed to later frosts. Conversely, a potential benefit is that less intense cold may help improve the over-winter survivorship of some species.

Land use category / sector impacts:

- Agriculture (uncultivated): reduced intense cold stress in winter; potentially increased biomass production in summer.
- Open upland habitats: changed albedo impact on heat energy balance.
- Environmentally sensitive areas: changed albedo impact on heat energy balance; reduced intensity of cold stresses.
- Grassland: easing of cold-based limitations to grass growth, i.e. more days when minimum temperature is > 5.7°C (above which grass is likely to grow); reduced frozen ground and possibly increased poaching by livestock.
- Arable: may increase pest and disease risk and impacts, improve over-winter cache crops but may negatively impact vernalisation.
- Peatlands: reduced frozen surface water freezing, albedo change to darker surfaces and more heat energy absorption, increasing risk of carbon loss.
- Forestry: reduced risk of frost damage to seedlings, higher summertime minimum temperatures may increase risk of fire occurrence.
- Urban: reduced cold stress in winter, but higher risk of heat stress on people in the summer (warmer over-night temperatures)
- Amenity/leisure: less cooling affect, may reduce winter sports activities.
- Transport infrastructure: reduced cold stress in winter on infrastructure.
- Biodiversity: possible increased over-winter survivorship
- Climate change: altered albedo which may increase heat energy absorption, which may have positive and negative effects on mitigation potential.

Coldest Temperature summary

- There has been an overall increase (warming) of the Coldest Temperature per month since 1960. There is some spatial and temporal variation, with the largest increases (warming) in November, January and February, most noticeably in the Cairngorms area and southern uplands. May, October and December have experienced decreases (colder) in Coldest Temperatures in some parts of the north and west whilst experiencing increases (warmer) elsewhere.
    - January has seen the largest increase (warming) of 2.1°C.
- There is good agreement between the 12 future climate projections that there will likely be a continuation of the historical trend of further increases (warming) in Coldest Temperature in all months across the whole of Scotland.
- Historically (1960-1989) at the national scale in the most extreme year, January and February had the Coldest temperatures (-15.6 and -13.1°C respectively), but these have decreased (warmed) by 4.3 and 3.5°C respectively in the 1990-2019 period. The projections to 2050 indicate decreases (warming) ranging from 1.1 to 8.2°C in January, and 5.3 to 10.6°C by 2070.

Conclusions

There have been detectable changes in Scotland's' climate in terms of both mean and extreme conditions as illustrated by the seven extreme indicators used in this study. The results show that climate extremes in Scotland are likely to become more extreme in the future. These changes are spatially and temporally variable with the type of indicator. Precipitation based indicators show larger spatial and temporal variation, and associated levels of certainty in the projections, compared to indicators derived from temperature.

The use of twelve climate change projections cover a range of plausible futures, from relatively little changes in precipitation but temperature increases of about 1.5°C, to more severe changes of c.15% reduction in precipitation and more than 3°C temperature rises. This has helped capture some of the uncertainty in visualising and analysing what Scotland's future climate might look like. This range of plausible future climate conditions also highlights the issue of needing to plan for and adapting to a 'worse case' scenario.

The results as presented help illustrate the need to go beyond simple descriptions of change such as "warmer wetter winters and hotter drier summers". The results show that the ways climate change will manifest itself, in terms of Scotland's weather and associated amounts of precipitation and temperature and their extremes, is likely to be complex. To understand better how climate change will impact Natural Capital, it is essential to be able to explore the range of changes in conditions in any one location, including shifts in temporal patterns. This research has demonstrated the benefit of assessing these changes at both a high spatial and temporal scales.

We have provided an initial interpretation of what the observed and future estimated climatic changes may mean for broad categories of Natural Capital. The challenge for the project will now be to translate the climatic changes into more nuanced assessments of impacts, through the use of simulation models and detailed literature reviews on research conducted on specific Natural Capital assets.

The utility of this research approach can be improved by increasing the quality of the interpolated observed baseline data, against which analysis is conducted to detect changes that have already occurred and what future projections indicate. Flaws in the interpolated observed data will manifest themselves as errors in change detection. Similarly, use of a broader range of climate projections derived from more global and regional models, and for a wider number of emissions scenarios, will help better capture the range in future climate uncertainty.

Next Steps

Having identified the observed trends and potential future climate changes for every 1km grid cell covering Scotland (c. 78,789) as well as the caveats associated with the different data sets, the next steps are to:

- Improve the utility of the interpolated observed gridded baseline data, particularly for precipitation. This is important as all future projected changes are compared against the baseline.
- Improve the utility of the future projections through incorporation of knowledge on climate model skill (see Appendix C), to account for known model biases.
- Explore options for diversifying the range of climate projections used from other climate models and for different emissions scenarios (e.g. Euro-CORDEX-UK, CHESS-SCAPE).

- Develop the data pipelines to enable ecosystem services and impacts models to be run using the climate change projections.
- Link the visualisation of climate trends and extremes with other tools and websites (e.g. Agrometeorological Indicators – see Appendix E.

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Appendix A: Global and UK Perspective

Global observed climate changes

How climate change impacts Scotland, it's people and Natural Capital, will be a function of global scale atmospheric, terrestrial and oceanic processes. We present here first a summary of the IPCC 6th Assessment Report Working Group 1 (2021) on the global trends and projections to help put changes in Scotland in context. It is essential to recognise that trends and future changes in Scotland are determined by global scale processes. This section summaries the key observed drivers and trends (summarised from IPCC 2021, confidence levels in *italics*):

- The scale of recent changes across the climate system as a whole – and the present state of many aspects of the climate system – are unprecedented over many centuries to many thousands of years.
- Global surface temperature has increased faster since 1970 than in any other 50-year period over at least the last 2000 years (*high confidence*). Temperatures during the most recent decade (2011–2020) exceed those of the most recent multi-century warm period, around 6500 years ago [0.2°C to 1°C relative to 1850–1900] (*medium confidence*).
    - Each of the last four decades has been successively warmer than any decade that preceded it since 1850. Global surface temperature in the first two decades of the 21st century (2001–2020) was 0.99 [0.84 to 1.10] °C higher than 1850–1900. Global surface temperature was 1.09 [0.95 to 1.20] °C higher in 2011–2020 than 1850–1900, with larger increases over land (1.59 [1.34 to 1.83] °C) than over the ocean (0.88 [0.68 to 1.01] °C).
    - It is *virtually* certain that hot extremes (including heatwaves) have become more frequent and more intense across most land regions since the 1950s, while cold extremes (including cold waves) have become less frequent and less severe.
- Globally averaged precipitation over land has *likely* increased since 1950, with a faster rate of increase since the 1980s (*medium confidence*). It is *likely* that human influence contributed to the pattern of observed precipitation changes since the mid-20th century and *extremely likely* that human influence contributed to the pattern of observed changes in near-surface ocean salinity.
    - The frequency and intensity of heavy precipitation events have increased since the 1950s over most land area for which observational data are sufficient for trend analysis (*high confidence*), and human-induced climate change is likely the main driver.
    - Human-induced climate change has contributed to increases in agricultural and ecological droughts in some regions due to increased land evapotranspiration (*medium confidence*).
- Mid-latitude storm tracks have *likely* shifted poleward in both hemispheres since the 1980s, with marked seasonality in trends (*medium confidence*). For the Southern Hemisphere, human influence *very likely* contributed to the poleward shift of the closely related extratropical jet in austral summer.
- Changes in the land biosphere since 1970 are consistent with global warming: climate zones have shifted poleward in both hemispheres, and the growing season has on average lengthened by up to two days per decade since the 1950s in the Northern Hemisphere extratropics (*high confidence*).

- It is *virtually certain* that the global upper ocean (0–700 m) has warmed since the 1970s and extremely likely that human influence is the main driver.
    - Marine heatwaves have approximately doubled in frequency since the 1980s (*high confidence*).
- Human influence is *very likely* the main driver of the global retreat of glaciers since the 1990s and the decrease in Arctic sea ice area between 1979–1988 and 2010–2019 (decreases of about 40% in September and about 10% in March)
- In 2011–2020, annual average Arctic sea ice area reached its lowest level since at least 1850 (*high confidence*). Late summer Arctic sea ice area was smaller than at any time in at least the past 1000 years (*medium confidence*). The global nature of glacier retreat since the 1950s, with almost all of the world's glaciers retreating synchronously, is unprecedented in at least the last 2000 years (*medium confidence*).
    - Human influence *very likely* contributed to the decrease in Northern Hemisphere spring snow cover since 1950.
- Human influence has likely increased the chance of compound extreme events since the 1950s. This includes increases in the frequency of concurrent heatwaves and droughts on the global scale (*high confidence*), fire weather in some regions of all inhabited continents (*medium confidence*), and compound flooding in some locations (*medium confidence*).

Further to this, the World Meteorological Organisation State of the Global Climate 2021 report (WMO 2022) states:

- Greenhouse gas concentrations continue to rise, reaching a new global high in 2020 when the concentration of carbon dioxide (CO_2) reached 413.2 parts per million (ppm) globally or 149% of the pre-industrial level. Data from specific locations indicate that they continued to increase in 2021 and early 2022, with monthly average CO_2 at Mona Loa in Hawaii reaching 416.45 ppm in April 2020, 419.05 ppm in April 2021, and 420.23 ppm in April 2022.
- The global annual mean temperature in 2021 was around 1.11 ±0.13 °C above the 1850-1900 pre-industrial average, less warm than some recent years owing to cooling La Niña conditions at the start and end of the year. **The most recent seven years, 2015 to 2021, are the seven warmest years on record**.

Future global projections

Future global projections:

- Global surface temperature will continue to increase until at least mid-century under both low and high emissions scenarios. Global warming of 1.5°C and 2°C will be exceeded during the 21st century unless deep reductions in CO2 and other greenhouse gas emissions occur in the coming decades.
    - Compared to 1850–1900, global surface temperature averaged over 2081–2100 is *very likely* to be higher by 1.0°C to 1.8°C under the very low (SSP1-1.9), by 2.1°C to 3.5°C in the intermediate (SSP2-4.5) and by 3.3°C to 5.7°C under the very high GHG emissions scenario (SSP5-8.5).
- Global warming of 2°C, relative to 1850–1900, would be exceeded during the 21st century under the high and very high GHG emissions scenarios (SSP3-7.0 and SSP5-8.5, respectively). Global warming of 2°C would extremely likely be exceeded in the intermediate GHG emissions

scenario (SSP2-4.5). Under the very low and low GHG emissions scenarios, global warming of 2°C is extremely unlikely to be exceeded (SSP1-1.9) or unlikely to be exceeded (SSP1-2.6).

- Crossing the 2°C global warming level in the mid-term period (2041–2060) is *very likely* to occur under the very high GHG emissions scenario (SSP5-8.5), *likely* to occur under the high GHG emissions scenario (SSP3-7.0), and *more likely than not* to occur in the intermediate GHG emissions scenario (SSP2-4.5).

- Global warming of 1.5°C relative to 1850–1900 would be exceeded during the 21st century under the intermediate, high and very high GHG emissions scenarios.
- Many changes in the climate system become larger in direct relation to increasing global warming, including increases in the frequency and intensity of hot extremes, marine heatwaves, heavy precipitation, and, in some regions, agricultural and ecological droughts; an increase in the proportion of intense tropical cyclones; and reductions in Arctic sea ice, snow cover and permafrost.
- Continued global warming is projected to further intensify the global water cycle, including its variability, global monsoon precipitation and the severity of wet and dry events
    - It is *very likely* that heavy precipitation events will intensify and become more frequent in most regions.
- The Arctic is likely to be practically sea ice-free in September at least once before 2050.

Consequences on Natural Capital:

- Ocean and land carbon sinks are projected to be less effective at slowing the accumulation of CO_2 in the atmosphere.
    - While natural land and ocean carbon sinks are projected to take up, in absolute terms, a progressively larger amount of CO_2 under higher compared to lower CO2 emissions scenarios, they become less effective, that is, the proportion of emissions taken up by land and ocean decrease with increasing cumulative CO2 emissions. This is projected to result in a higher proportion of emitted CO2 remaining in the atmosphere (*high confidence*).
- Many changes due to past and future greenhouse gas emissions are irreversible for centuries to millennia, especially changes in the ocean, ice sheets and global sea level.
    - Past GHG emissions since 1750 have committed the global ocean to future warming (*high confidence*). Over the rest of the 21st century, likely ocean warming ranges from 2–4 (SSP1-2.6) to 4–8 times (SSP5-8.5) the 1971–2018 change.
    - Mountain and polar glaciers are committed to continue melting for decades or centuries (*very high confidence*).

Appendix B: Climate Change Projections for Scotland

The results presented here use data from the UKCP18 climate projections. We used 12 projections, referred to as Ensemble Members (EM), from a Regional Climate Model (HardRM3-PPE) used to produce the UKCP18 projections.

A new downscaling and partial bias-correction method was applied to the UKCP18 climate projections to improve the granularity from 12km to 1km and to reduce known systematic errors (Rivington et al 2008a). Here climate model data were means and variance bias corrected against observed data (the same as used to produce the trends analysis in Part 2) for each 1km grid cell.

The emissions scenario under which the climate models were run is referred to as the Representative Concentration Pathway 8.5 (RCP 8.5) (Moss et al 2010, Raihi 2017). This RCP8.5 is considered as a high and continued rate of emissions and reflects the current increasing rates of emissions (IEA 2021, NOAA 2022). This scenario may not be likely if progress to achieve mitigation targets are reached, but its overall atmospheric greenhouse gas concentrations may still remain feasible given risks of positive feedback responses by natural systems (e.g. carbon and methane emissions from melting Arctic tundra) and loss of ecosystem services such a climate regulation due to deforestation.

As such the RCP8.5 represents the high-end emissions scenarios, but as can be seen in Figures 63 (and Figures 64-65), some of the projections have temperature increases that are less than 2°C and precipitation either increases or decreases by small percentages. These are comparable to those for lower emissions scenarios (RCP 2.6, 4.5, 6.0), hence the 12 projections used represent a broad range of possible plausible future climates resulting from different emissions scenarios.

Caveats for the use of climate model data

The data used to produce this report is one set of plausible future climates. The estimates are derived from a sequence of Global (HadGEMN3) and Regional Climate Model (HadRM-3-PPE). Other climate models produce different projection data, hence we highlight that caution is required in the interpretation of the data's use, in that there are other plausible possible futures not represented in these results.

Variability in climate projections used

To help understand the range of estimates for future projections in Scotland, it is useful to understand the range of plausible future conditions for different simulations of the climate. Figure 63 details the precipitation and temperature anomaly for each projection, that is, the change between each future projection and the observed 1960-1989 baseline. Figure 63 (and similarly 64-65) shows how all projections have a temperature increase, but some (e.g. 04, 10) may have an increase in precipitation, whereas others are similar to the present or may have as much as a 20% reduction (e.g. EM13 for the 2070s).

Some of the projections may be consider less feasible than others, for example EM12 has a projected temperature increase of c. 3.5°C within the 2040s and more than 5°C within the 2070's. It is worth including these high-end possibilities as it helps enable assessments of extreme impacts.

Knowing the differences between projections helps us to understand the variation in time and space of estimated future trends. **Appendix D** (Assessing climate model utility and uncertainty) provides details of the skill of the climate models' by assessing their ability to simulate observations.

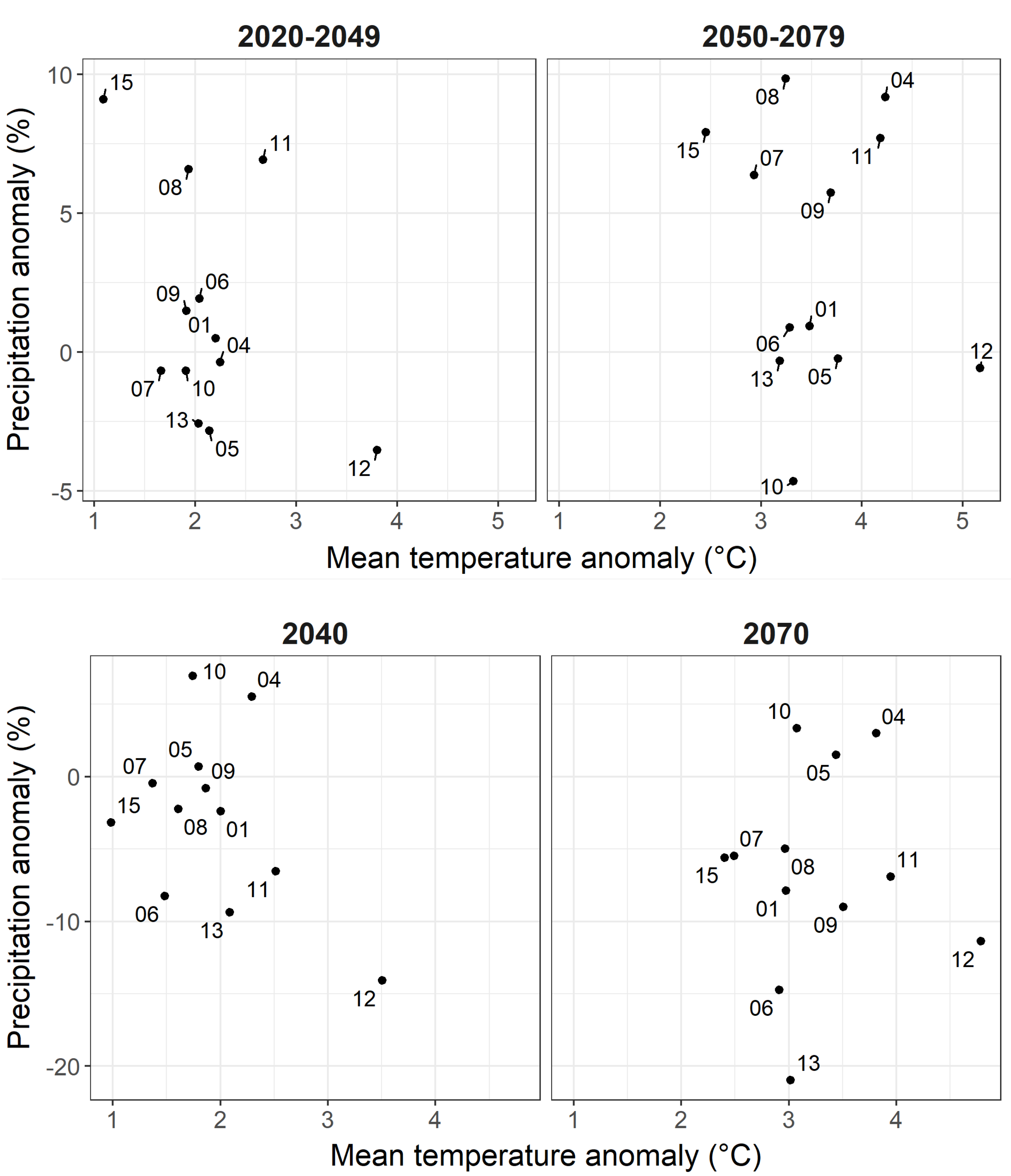


Figure 63. Climate change signal for the 12 projections used. Top: Annual precipitation and temperature anomaly under RCP8.5 for 2020-2049 ('2040') and 2050-2079 ('2070') with respect to 1994-2015 baseline. Bottom: Comparison of the Scotland arable area-wide mean climate change signal in the growing season only (March to September).

Figure 63 shows that there is a wide range in precipitation and temperature responses in the 12 future projections, with 6 indicating either little or up to 9% increase in precipitation and temperature rises in the 2040's between 1 and 2.5°C, but up to 3.8°C (however, we consider EM12 to be and extreme example). The annual anomaly plot indicates that

Appendix C: Methods

Climate Projection Data

The results presented are based on the use of the UKCP18 Climate Projections. This data is estimated using a UK Meteorological Office Regional Climate Model (HadRM3) (CEDA 2021)[6]. There are 12 different projections of the future climate made using this model, providing 12 unique data sets (also referred to as Ensemble Members).

Each projection is based on the same emissions scenario (below) but with slightly different model settings. This was done to capture the range of possible climate responses to the level of atmospheric greenhouse gas concentrations resulting from the emissions scenario. Each of the twelve HaDRM3 simulations is referred to as an 'Ensemble Member'.

To aid interpretation of results, it is important to understand the differences between the ensemble members' data in respect of their temperature and precipitation differences from the past climate (1960-1990). This is illustrated in Figures 63-67, showing the differences (anomaly) between ensemble members for two future time periods: 2030-2049 (2040s) and 2060-2079 (2070s), with respect to baseline periods. For example, ensemble member 07 has a 1.4°C temperature increase by the 2040s period, but the same precipitation amount compared to the baseline period (i.e. no change). By the 2070s, ensemble member 07 becomes 2.5°C warmer and has 5% less precipitation. In contrast, ensemble member 13 is 2.1°C warmer and 9% drier by the 2040s, and 3°C warmer and 21% drier by the 2070s.

The emissions scenario under which the HadRM3 model was run is referred to as the Representative Concentration Pathway 8.5 (RCP 8.5) (Moss et al 2010, Raihi 2017). RCP8.5 is considered as a high and continued rate of emissions and reflects the current increasing rates of emissions (IEA 2021, NOAA 2022). This scenario may not be likely if mitigation efforts are intensified and targets are reached, but its overall atmospheric CO_2 concentrations may yet still remain feasible given risks of positive feedback responses by natural systems (e.g. carbon and methane emissions from melting Arctic tundra) and loss of natural carbon capture (e.g. reduced functioning of rainforests and phytoplankton activity in the oceans). The RCP8.5 UKCP18 data has been used as it is it the only high-resolution daily data currently available. This scenario represents a plausible 'worst case' but also sets a range of future conditions that are useful in respect of adaptation. It is important to also note that there are few differences in the climate projections up to c. 2040 between the high (RCP8.5) and low (RCP2.6) emissions scenarios.

Temporal variation in the climate change signal

There is a wide range in variation between each month and ensemble member in terms of the climate change signal (anomaly from a baseline). Figures 64 and 65 illustrates this for the precipitation and temperature anomalies per month for the 12 projections for the 2020 – 2049 and 2050 – 2019 periods respectively compared toa 1994 – 2015 baseline.

[6] Dataset Collection Record: Met Office Hadley Centre Regional Climate Model (HadRM3-PPE) Data (ceda.ac.uk)

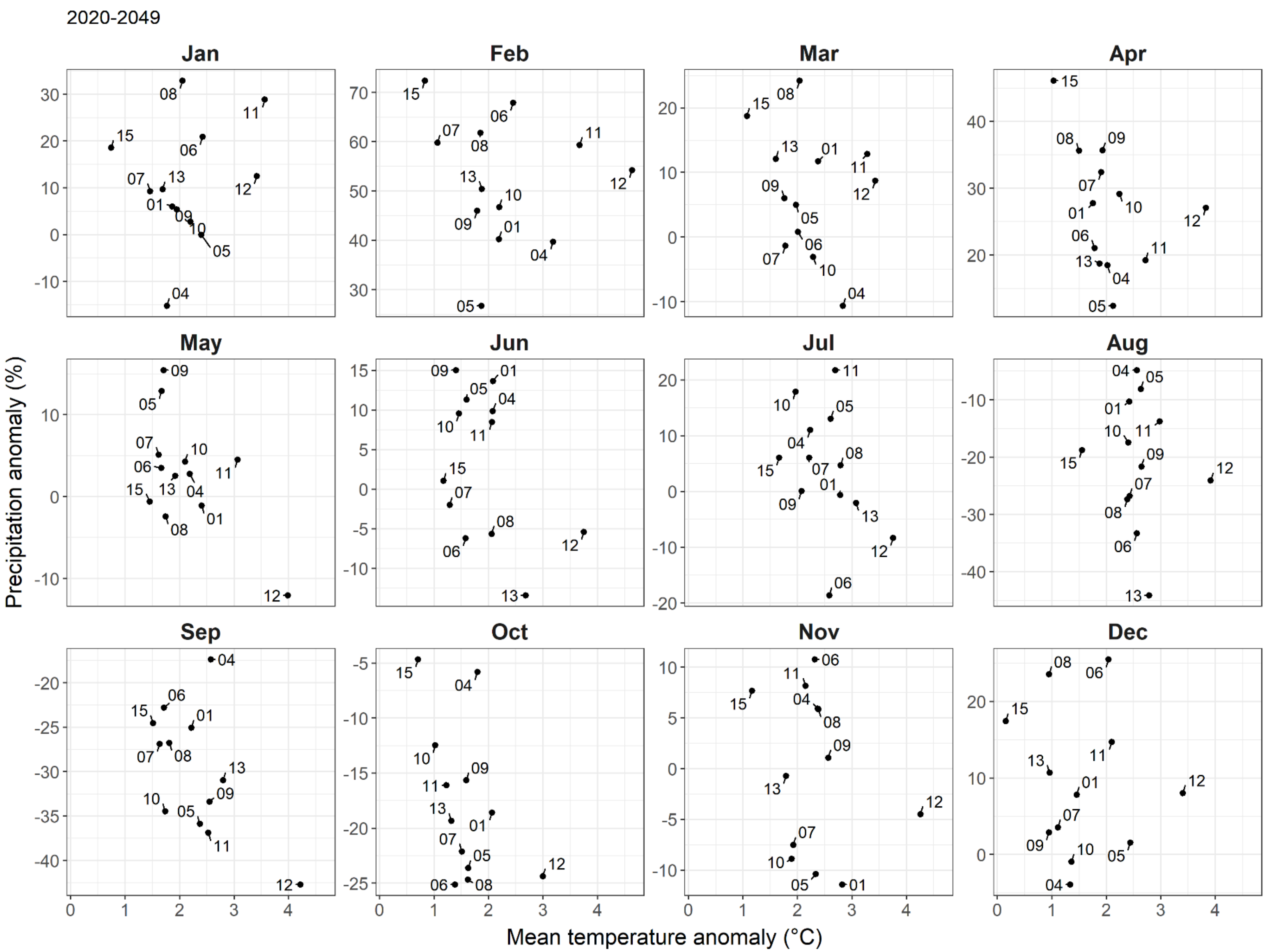


*Figure 64. Climate change signal per ensemble member and monthly anomaly under RCP8.5 for 2020-2049 ('2040') with respect to 1994-2015 baseline. **Please note** different axis scales per month.*

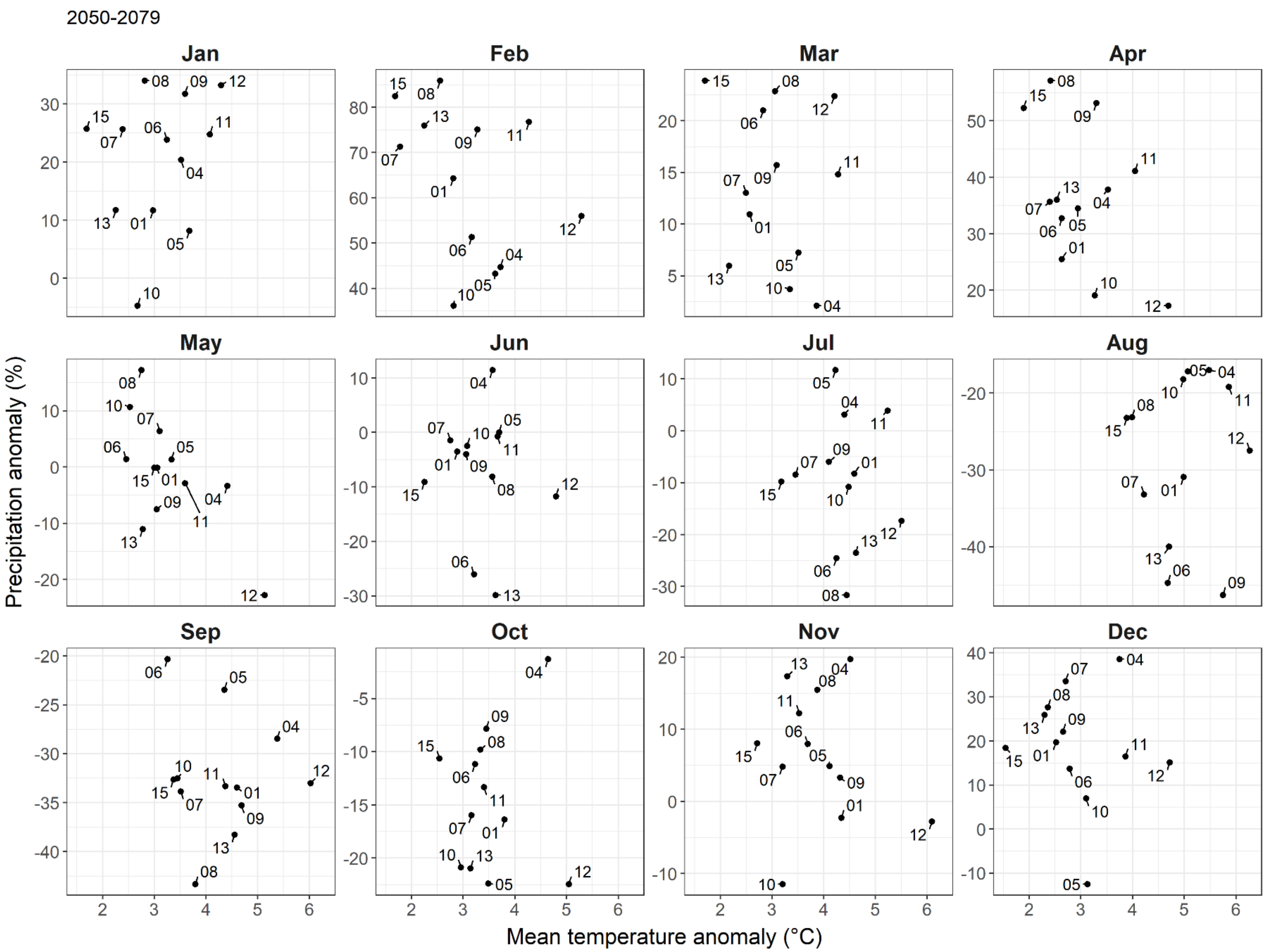


Figure 65. Climate change signal per ensemble member and monthly anomaly under RCP8.5 for 2050-2079 ('2070') with respect to 1994-2015 baseline. ***Please note*** *different axis scales per month.*

References:

CEDA (2021) Met Office Hadley Centre Regional Climate Model (HadRM3-PPE). Dataset Collection Record: Met Office Hadley Centre Regional Climate Model (HadRM3-PPE) Data (ceda.ac.uk)

IEA (2021) Global Energy Review 2021. International Energy Authority. https://www.iea.org/reports/global-energy-review-2021/co2-emissions

Moss RH et al (2010) The next generation of scenarios for climate change research and assessment. Nature 463, 747-756. doi:10.1038/nature08823

NOAA (2022) Trends in atmospheric carbon dioxide. National Oceanic & Atmospheric Administration. https://gml.noaa.gov/ccgg/trends/mlo.html

Riahi K et al (2017) The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: An overview. Global Environmental Change 42, 153-168. http://dx.doi.org/10.1016/j.gloenvcha.2016.05.009

Appendix D: Assessing climate model utility and uncertainty.

It is essential to understand the utility of the climate model data to enable meaningful interpretations of projections allowing for model error and biases. A key step is in comparing the ability of the climate model to simulate observations.

Previous assessments (e.g. Rivington et al 2008a) have assessed the HadRM3 Regional Climate Model's ability to represent observations, finding that it was able to make good and poor estimates. In lowland areas with uniform topography the model was able to perform well, but in upland areas the type and magnitude of errors increased. Bias correction (e.g. Rivington et al 2008b) helps reduce systematic errors (e.g. too many days with 'drizzle' precipitation < 0.3mm, over-estimation of temperature). The data used in this report originates from the HadRM3 model at a spatial scale of 12km and has been partially-downscaled to 1km and bias corrected for means and variance. However, as illustrated below, biases and errors still remain.

Firstly we present analysis of the ability of the climate model, per ensemble member, simulate observed climatic values, to illustrate model skill. Secondly we present evidence of the spatial variability in model skill.

The purpose of the evidence is to serve as a caution against use of the downscaled and bias corrected data climate projections for use in impacts assessments without prior evaluation, understanding of utility and consequences on impacts interpretation.

Climate Model Skill

The ability of the climate model to estimate observed climatic values, referred to as model skill, is a useful indication of future projection utility, as future impacts can be interpreted in the knowledge of known biases and systematic errors.

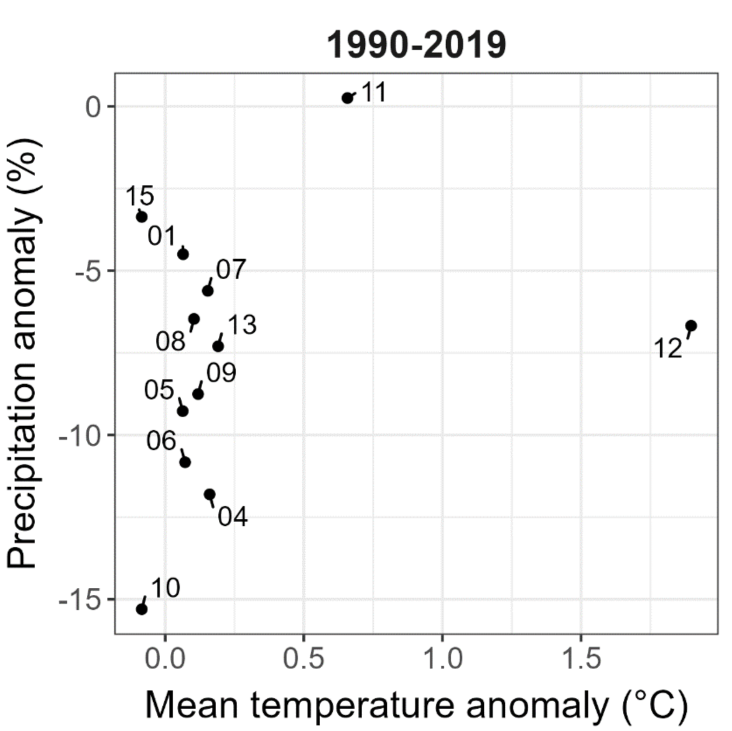


Figure 66. National scale comparison of the ability of the climate model per ensemble member to simulate annual observed climate indicated by the mean temperature and precipitation anomaly between each Ensemble Member and the 1990 – 2019 baseline. The 0 lines represent the baseline.

Figure 66 shows that each projection (ensemble member) varies in skill for both precipitation and temperature. For example, EM11 matches well to precipitation but over-estimates temperature by approximately 0.6°C, EM15 slightly under-estimates temperature by 0.2°C but also under-estimates precipitation by. In the case of EM12 it both over-estimates temperature (c. 1.9°) and under-estimates precipitation (c 7%). EM10 has good skill in respect of temperature but poor (-15%) in representing precipitation.

Temporal variability in model skill

The skill level also varies temporally, with some ensemble members having high skill for either or both temperature and precipitation for some months, but worse in others (Figure 67).

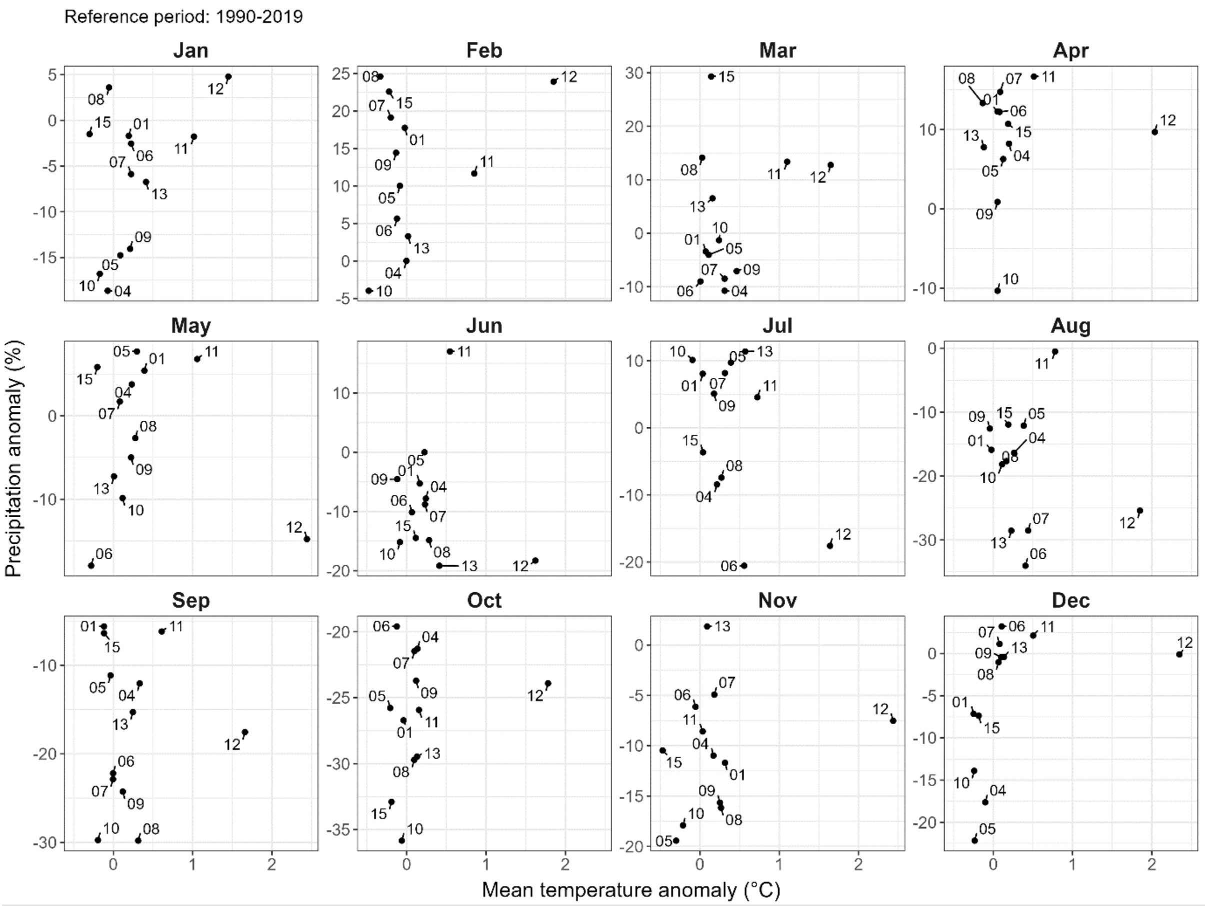


Figure 67. National scale comparison of the ability of the climate model per ensemble member to simulate monthly observed climate indicated by the mean temperature and precipitation anomaly between each Ensemble Member and the 1990 – 2019 baseline. The 0 lines represent the baseline.

Some ensemble members show good skill at simulating observed mean temperature per month (Figure 67), where plotted values are on or close to the 0 value. However, few ensemble members have performance for simulating precipitation is poor (up to a 35% anomaly from the observed data). This means that the model tends to under-estimate precipitation, but this issue is further complicated due to the uncertainties in the utility of the observed interpolated baseline data (see Text Box 1).

Few ensemble members show consistently good skill for both precipitation and mean temperature per month. Some perform well for individual months, e.g. EM04 in February, EM09 in April (very high skill). No ensemble member preforms consistently well for both precipitation and temperature for al months.

Ranking model skill

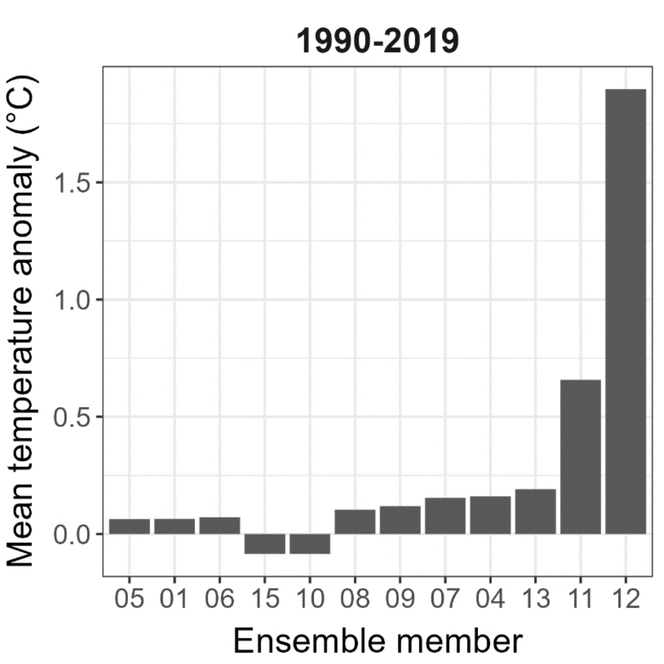


Figure 68. Ranking of climate model skill to represent the 1990 – 2019 baseline mean temperature per ensemble member

For the annual mean temperature anomaly (Figure 68), the EMs are ranked as follows (best -> worst): 05, 01, 06, 15, 10, 08, 09, 07, 04, 13, 11, 12. This result shows that for EM12, it has a large mean temperature anomaly (error) in simulating the observed value, whereas others produce estimates close to the observed value. Knowledge of this range in skill is essential in helping to interpret the utility of the future projections, assuming that errors occurring in estimates for the past climate are repeated for the future.

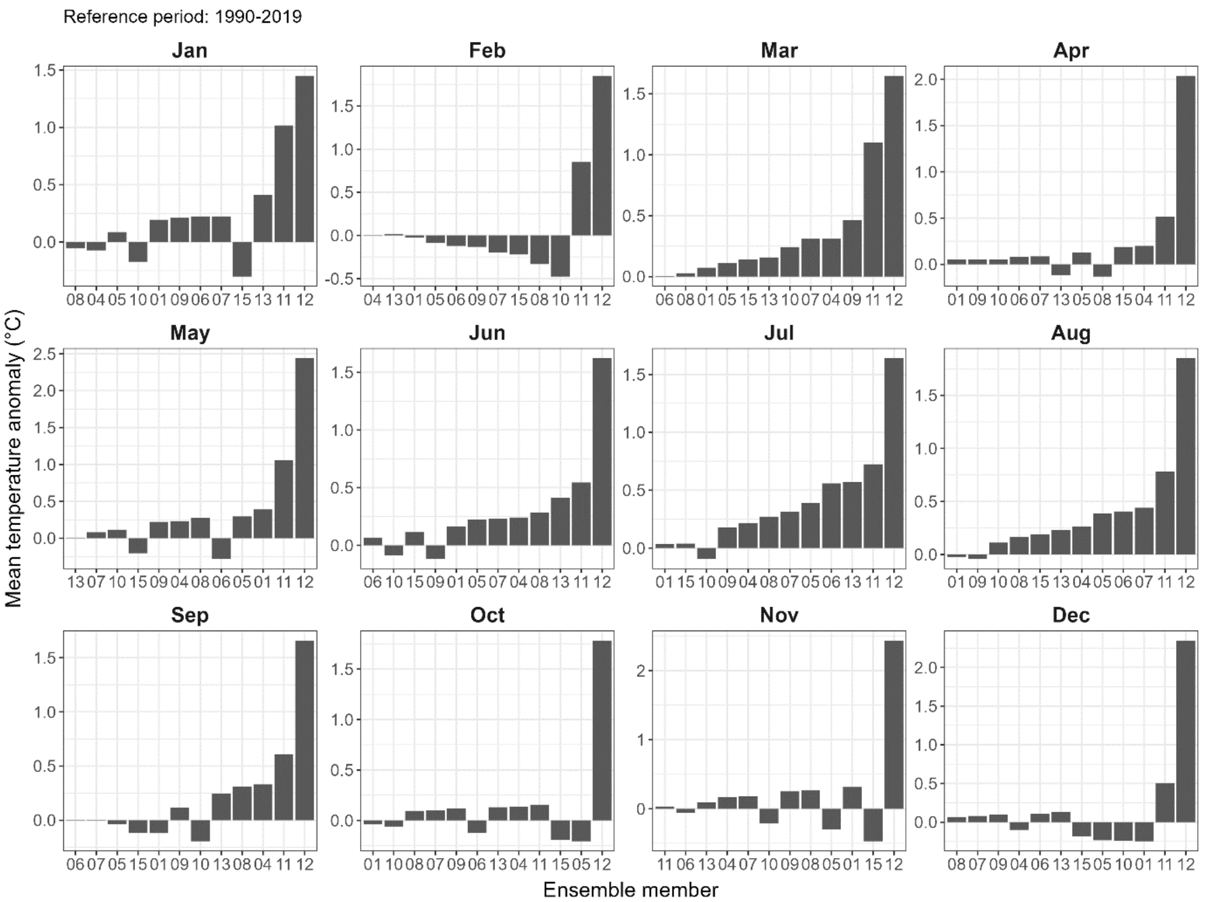


Figure 69. Ranking of climate model skill to represent the 1990 – 2019 baseline mean monthly temperature per ensemble member

Some ensemble members, particularly EM12, show consistent low skill in representing the past climate (Figure 69).

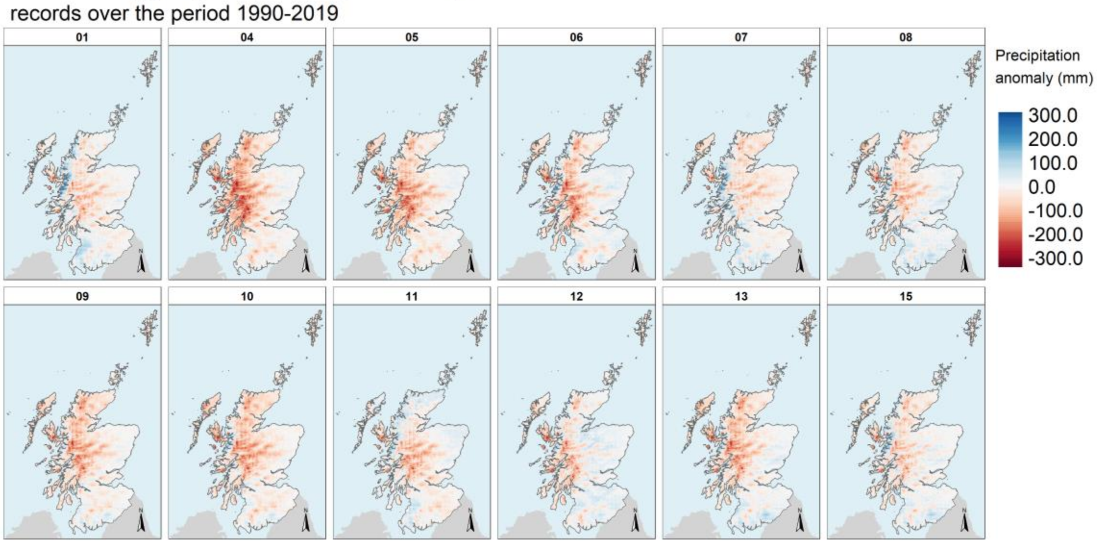
Spatial variability in model skill

Here we present evidence of each ensemble member's ability to spatially represent precipitation, maximum and minimum temperature per month, illustrated with four example months: January, March, August and November.

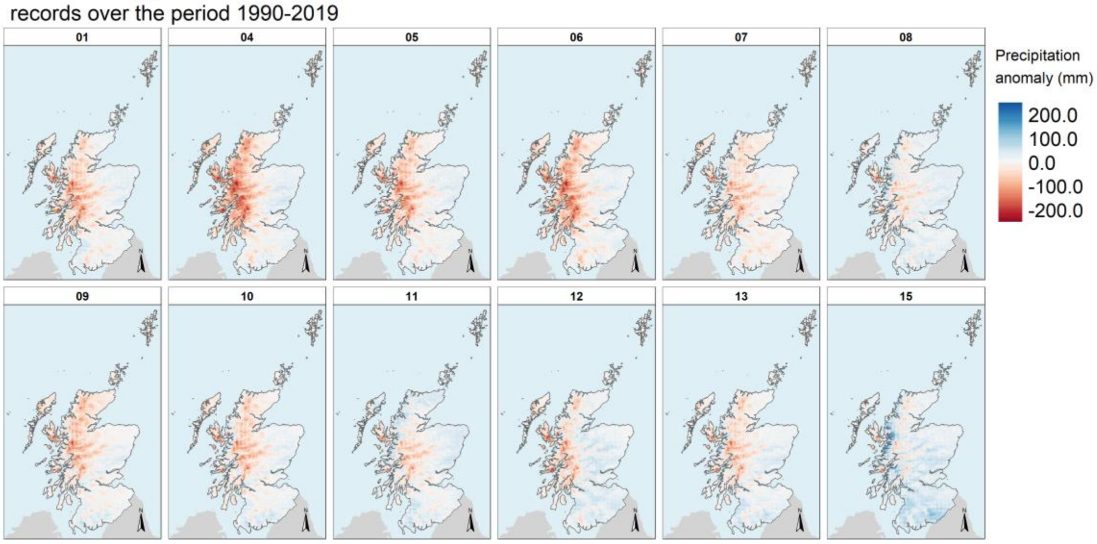
Precipitation:

Precipitation is a high spatially and temporally variable weather feature to model, being especially challenging in upland areas and in a maritime climate with a strong west to east rainfall gradient.

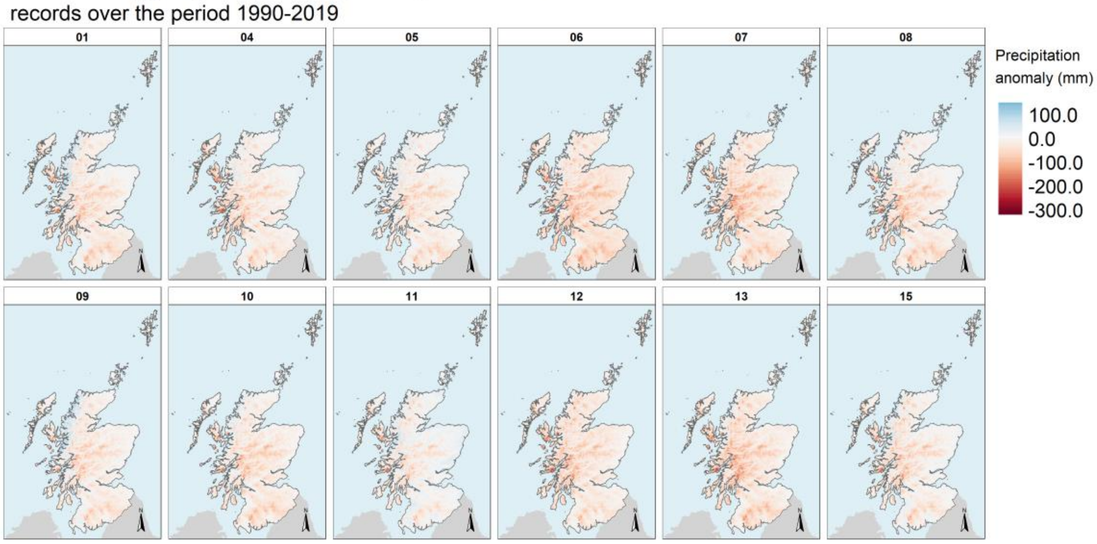
Mean monthly precipitation anomaly for January between the ensemble members and the historical records over the period 1990-2019



Mean monthly precipitation anomaly for March between the ensemble members and the historical records over the period 1990-2019



Mean monthly precipitation anomaly for August between the ensemble members and the historical records over the period 1990-2019



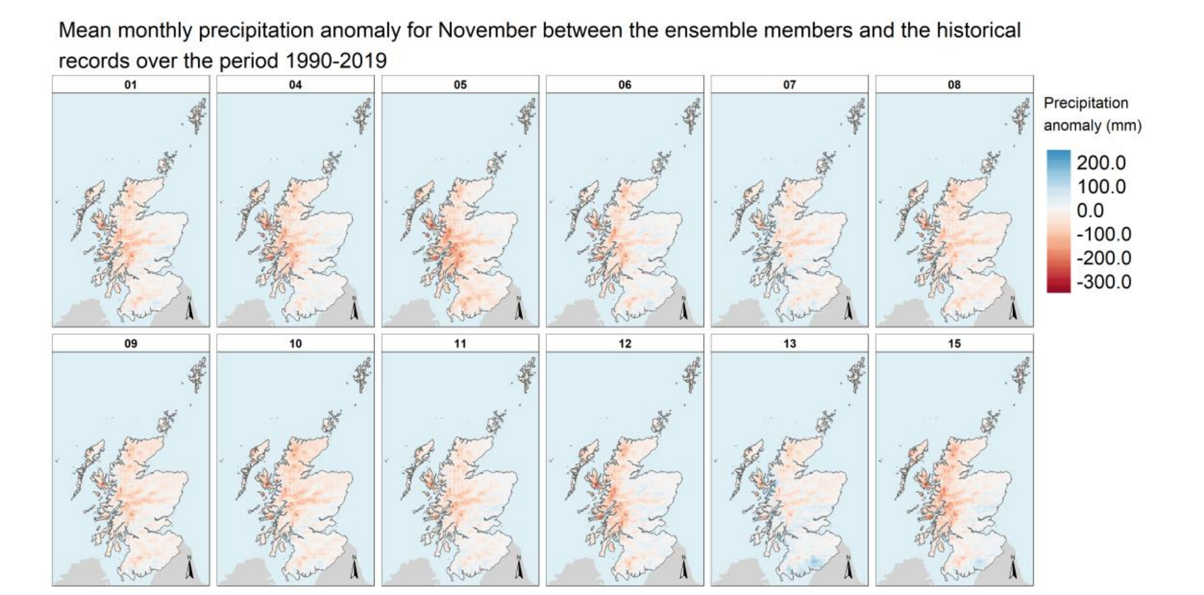


Figure 70. Climate model skill indicated by mean monthly precipitation anomaly between climate model estimates for the observed 1990 – 2019 period compared to observations for January, March, August and November.

Figure 70 Illustrates the spatial and temporal variability in model skill in estimating mean monthly precipitation. Areas of white, light red or blue indicate good skill, darker colours represent less skill.

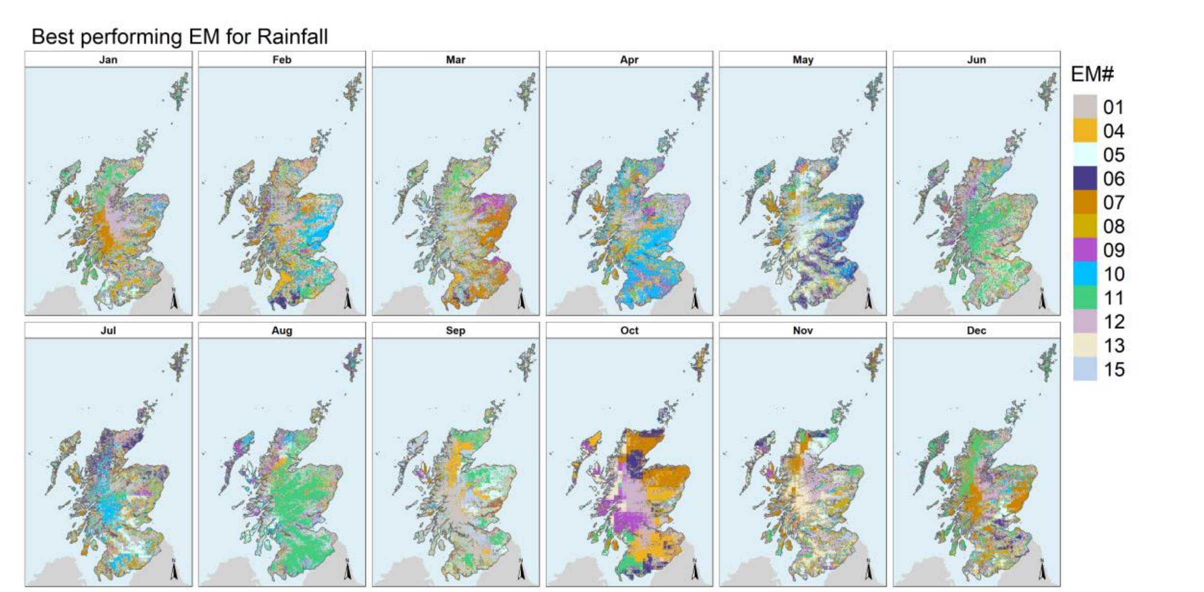


Figure 71. Spatial distribution of the best performing ensemble member per month for precipitation.

There is no clear one ensemble member that produces estimated precipitation that fits with the observations for all months. Instead, there is a spatial and temporal range of skill. For example, EM11 performs well for a large area of Scotland in August. This range means that it is not feasible to use just one ensemble member as a best representative projection.

Maximum Temperature

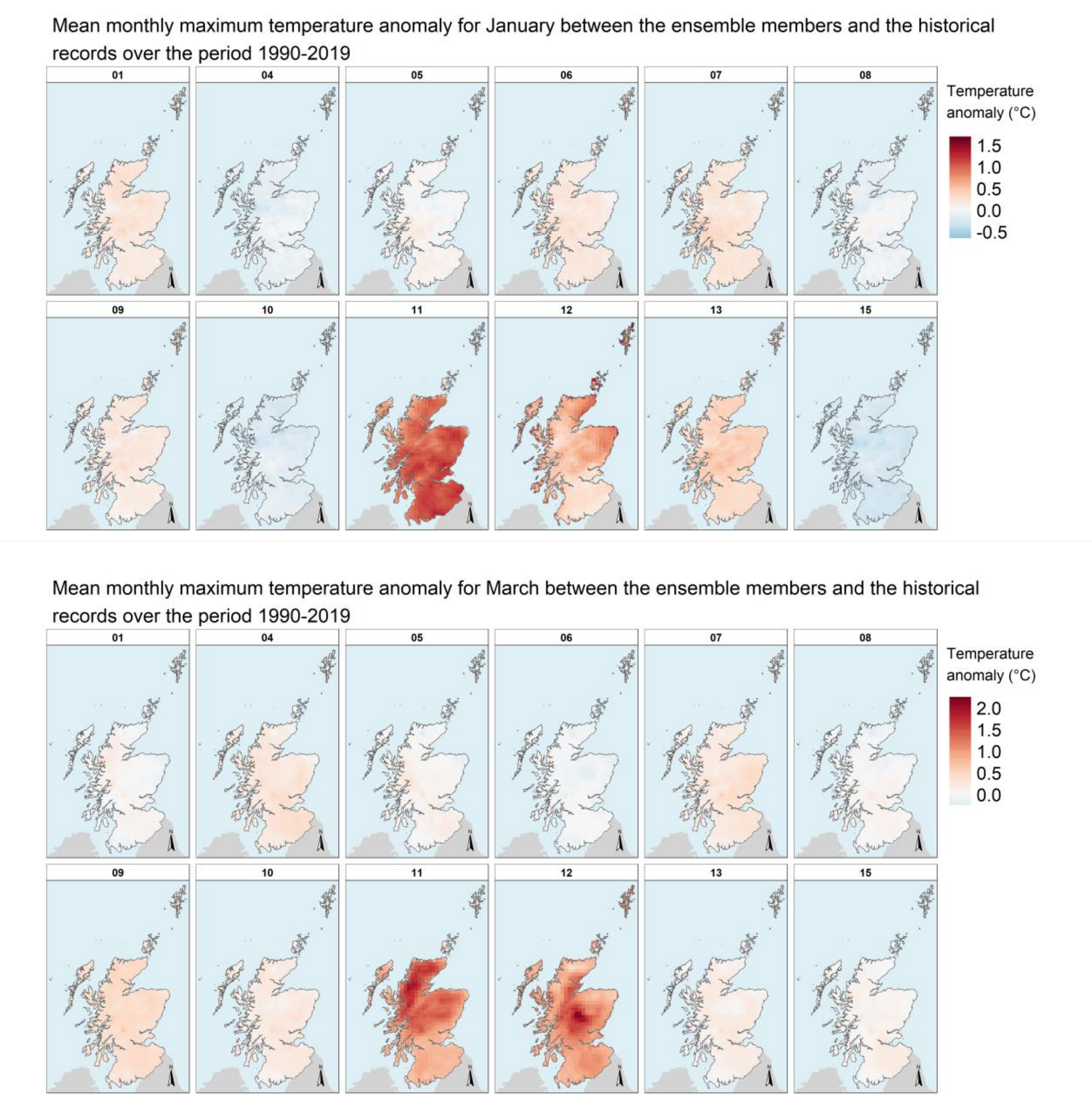


Figure 72a. Climate model skill indicated by mean monthly maximum temperature anomaly between climate model estimates for the observed 1990 – 2019 period compared to observations for January, March.

Figure 72a illustrates the range in ensemble member skill in representing the mean monthly maximum temperature in January and March. EMs 11 and 12 clearly have the largest anomaly and therefore lower skill. Conversely, EMs 01, 05, 06, 08 and 15 have relatively good skill.

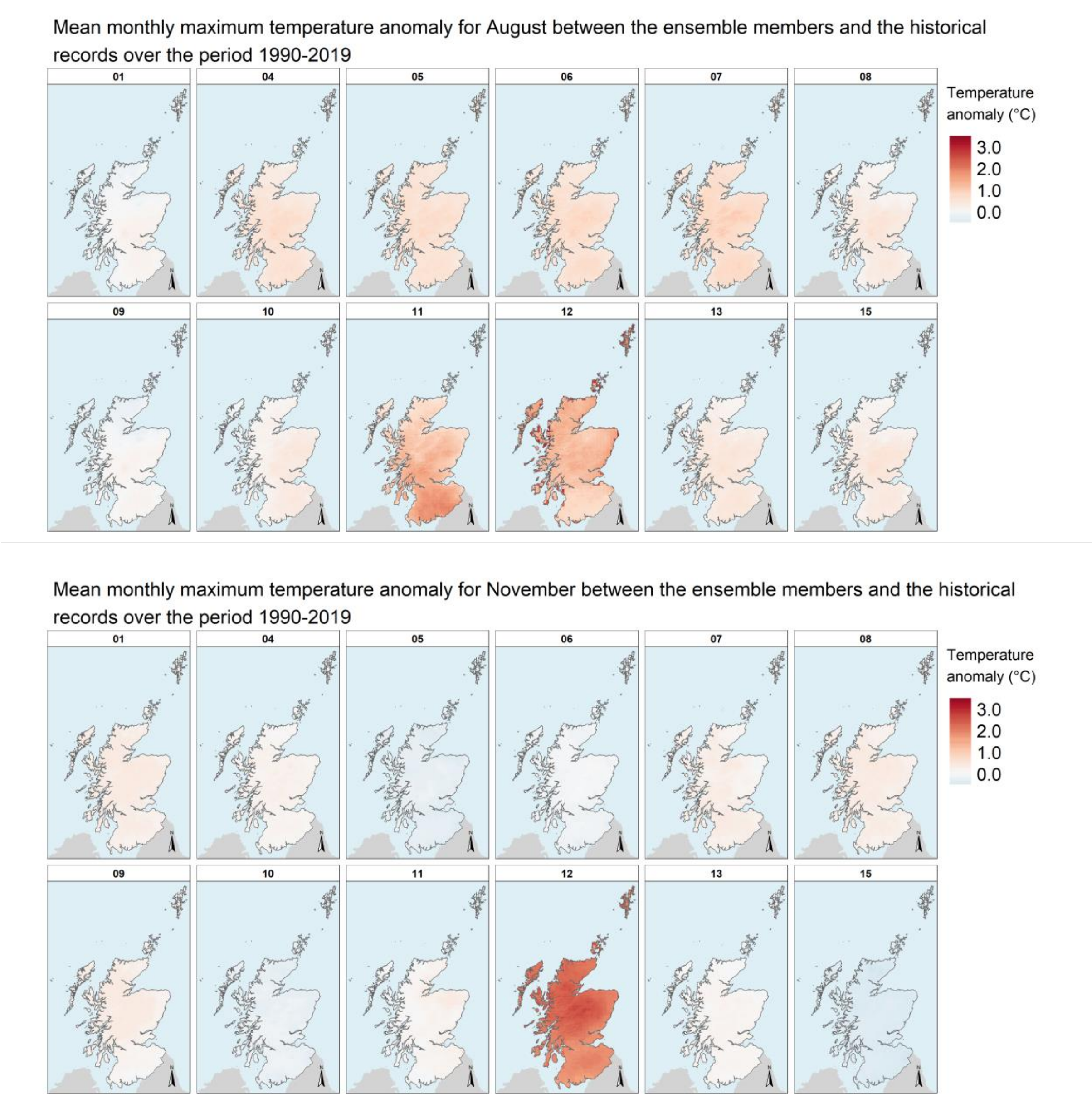


Figure 72b. Climate model skill indicated by mean monthly maximum temperature anomaly between climate model estimates for the observed 1990 – 2019 period compared to observations for August and November.

The level of skill in representing the mean monthly maximum temperature changes in August and November (Figure 72b), with all EMs except EM11 performing relatively well.

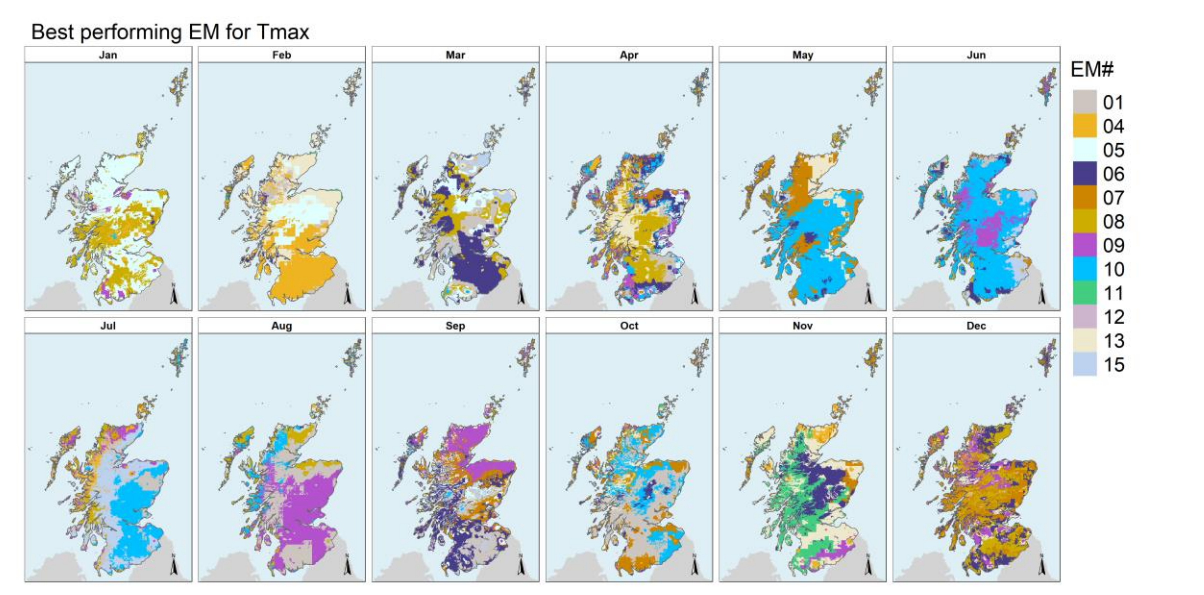


Figure 73. Spatial distribution of the best performing ensemble member per month for maximum temperature.

As with precipitation, no one EM is the best performing for all months, with large spatial and temporal variations in the EM with the best performance.

Minimum Temperature

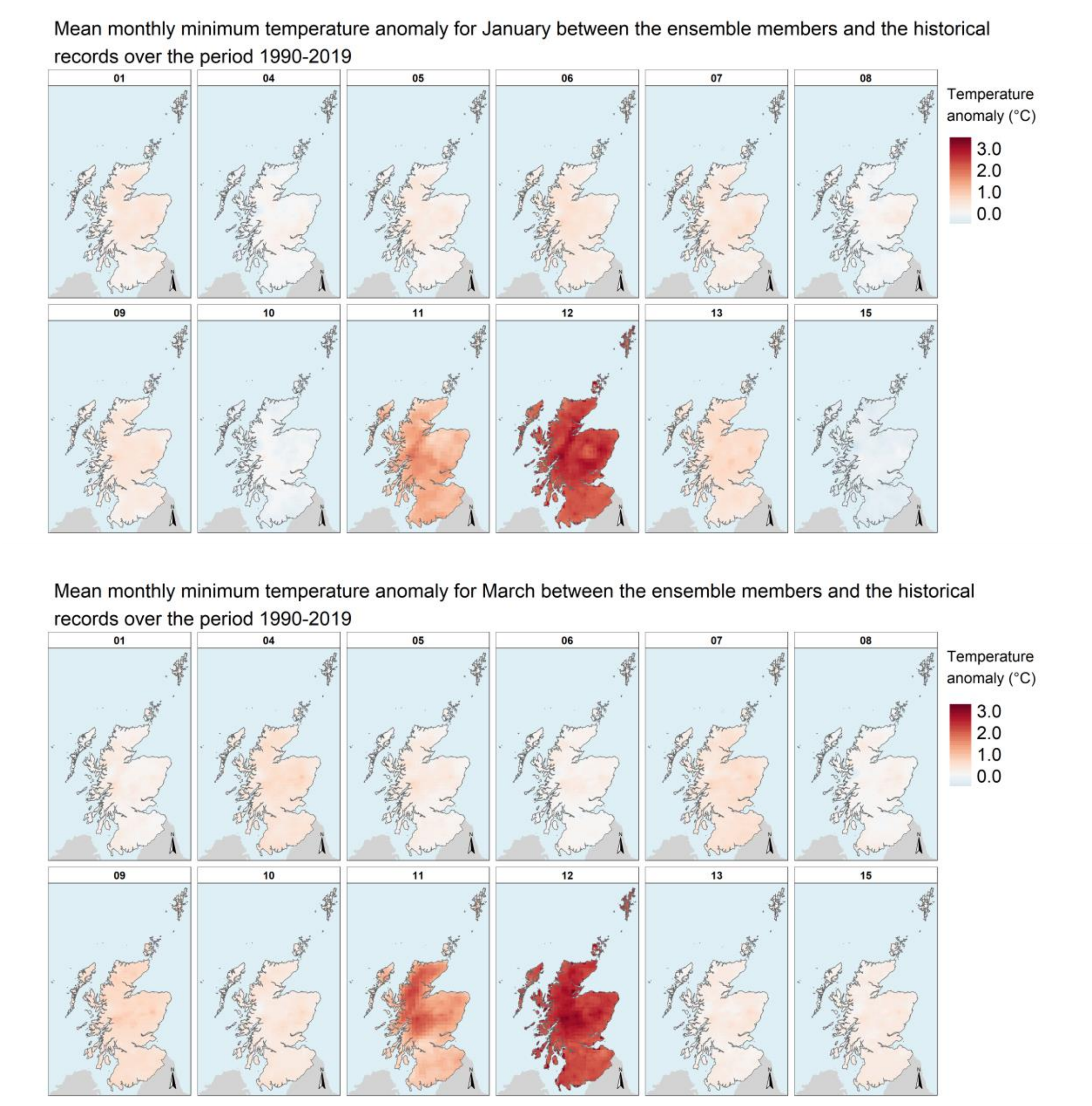
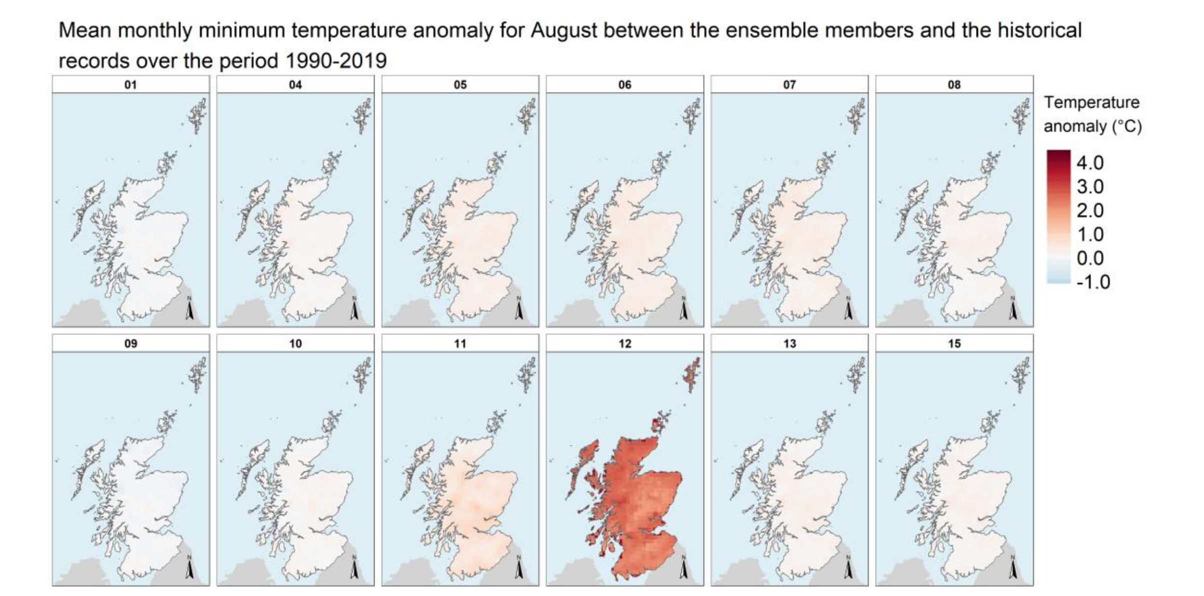


Figure 74a. Climate model skill indicated by mean monthly minimum temperature anomaly between climate model estimates for the observed 1990 – 2019 period compared to observations for January, March.

In estimating the mean monthly minimum temperature, as with for precipitation and maximum temperature, there is a broad range of skill. For January and March, EM12 makes large errors, by up to 3°C (Figure 74a).



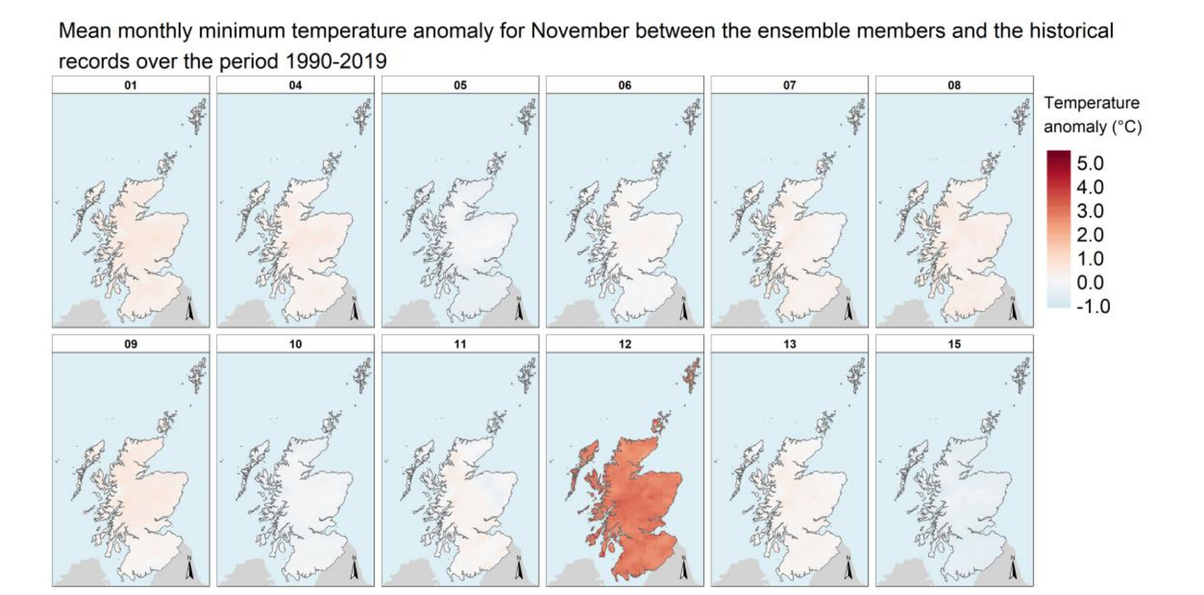


Figure 74b. Climate model skill indicated by mean monthly minimum temperature anomaly between climate model estimates for the observed 1990 – 2019 period compared to observations for August and November.

Figure 74b again highlights EM12 as a poorly performing estimate of mean monthly minimum temperature, this time in August and November. Other EMs perform relatively well, with anomalies being c. +/- 1°C.

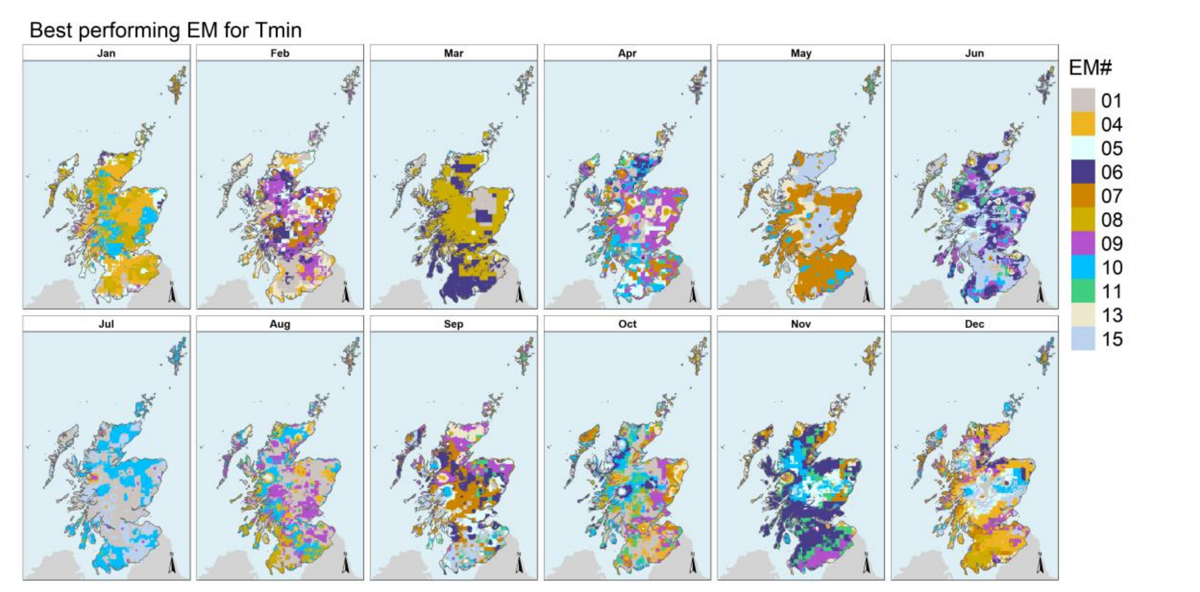


Figure 75. Spatial distribution of the best performing ensemble member per month for minimum temperature.

As with levels of skill for precipitation and maximum temperature, no one EM shows consistently good skill for estimating mean monthly minimum temperature.

References:

Rivington, M., Miller, D., Matthews, K.B., Russell, G., Bellocchi, G. and Buchan, K. (2008a). Evaluating Regional Climate Model estimates against site-specific observed data in the UK. Climatic Change, 88, 157-185.

Rivington, M., Miller, D., Matthews, K.B., Russell, G., Bellocchi, G. and Buchan, K. (2008b) Downscaling Regional Climate Model estimates of daily precipitation, temperature and solar radiation data. Climate Research 35, 181-202.

Appendix E: Example Additional Maps

The following are examples of the range of additional map products available to aid the analysis of climate trends and to support the research outputs from the D5-2 Risk and Opportunities Assessment Framework on climate change impacts on Natural Capital assets.

Agrometeorological Indicators

Another parallel area of research within the Scottish Government Strategic Research Programme (2016 – 2021) has used the same input climate projection data, and therefore complementary to the climate trends analysis, is the production of Agrometeorological Indicators. These are things like the length of growing season, occurrences of frosts in spring and autumn, the date when soil water falls below field capacity etc. These have been estimated at a 1km resolution for the whole UK, enabling comparison of impacts in Scotland in a wider context. An example, Plant Heat Stress, is illustrated in Figures 76 (two historical baseline periods) and 77 (projections for three ensemble members).

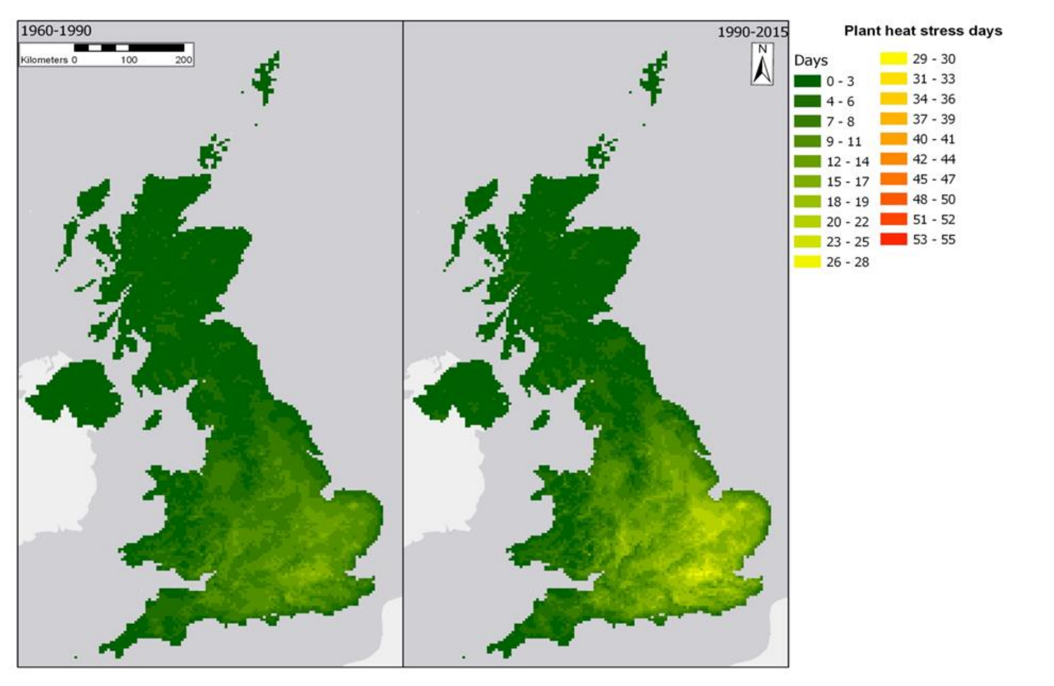


Figure 76. Observed changes in the mean Plant Heat Stress Indicator (number of days in a year when the maximum temperature is greater than 25°C) between 1960 – 1990 and 1990 – 2015.

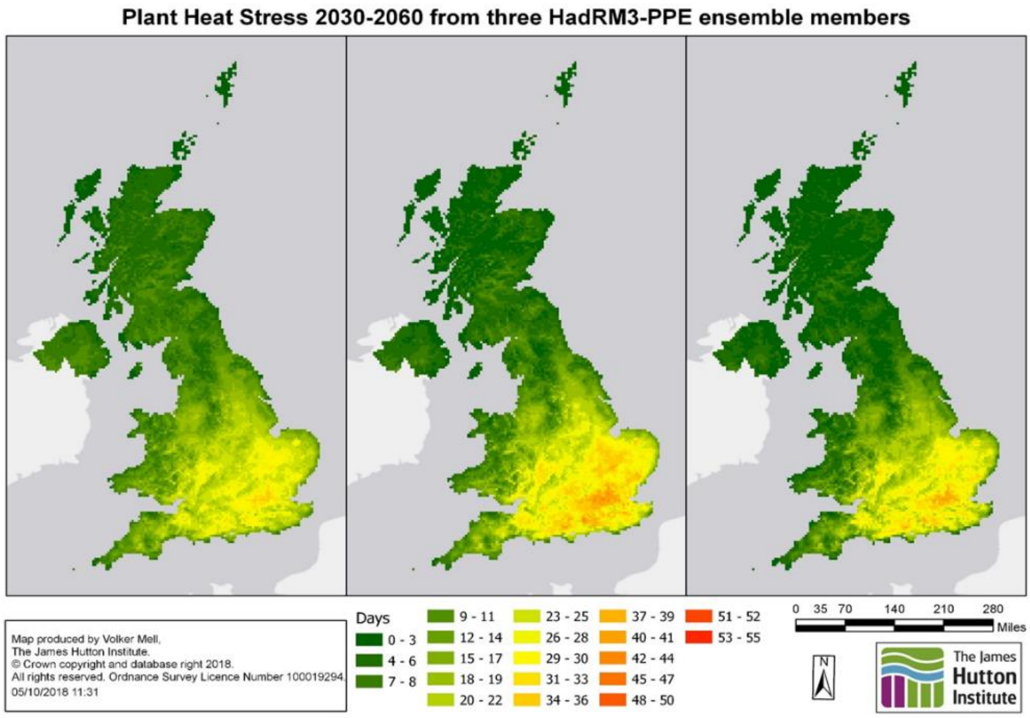


Figure 77. Projected changes in the mean Plant Heat Stress Indicator (number of days in a year when the maximum temperature is greater than 25°C) for the 2030 - 2060 period for three ensemble members.

All of the indicators detailed in Table 2 have been estimated and mapped for the whole UK, including map animations as a time series from 1960 – 2098. A prototype website is currently under construction.

Table 2. Agrometeorological Indicators and definitions. S/M indicates whether a single or multiple weather variable is used to calculate the metric.

Type	Metric Name	Units	Definition	S / M
Date	Start Growing Season	day of year	Day when 5 consecutive days T_{avg} > 5.6 °C (from Jan 1st)	S
	Start of Field Operations		Day when $\sum T_{avg}$ from Jan 1st > 200°C (T_{sum}200)	S
	End of Field Capacity		Day when Soil Moisture Deficit (SMD) > 5 mm (from Jan 1st)	M
	Last Air Frost (Spring)		Day when T_{min} < 0.0 °C (from Jan 1st)	S
	Last Grass Frost (Spring)		Day when T_{min} < 5.0 °C (from Jan 1st)	S
	Date of Maximum SMD		Day when SMD at maximum	M
	First Grass Frost		Day when T_{min} < 5.0 °C (from July 1st)	S
	First Air Frost		Day when T_{min} < 0.0 °C (from July 1st)	S
	Return to Field Capacity		Day when SMD < 5 mm (after date of max SMD)	M
	End Growing Season		Day when 5 consecutive days T_{avg} < 5.6 °C (from July 1st)	S
Count	Air Frost	days	Days when T_{min} < 0.0 °C	S
	Growing Season Range		Days between Start Growing Season and End Growing Season	S
	Growing Season Length		Days when T_{avg} > 5.6 °C between Start and End of Growing Season	S
	Access Period Range		Days between Return to FC – End of FC	M
	Access Period Length		Days when soil moisture < field capacity	M
	Plant Heat Stress		Days when T_{max} > 25.0 °C	S
Degree Days	Accumulated Frost	day deg	∑ day degrees where T_{min}< 0.0 °C	S
	Growing Degree Days		∑ T_{avg} > 5.6 °C	S
	Heating Degree Days		∑ 15.5 °C - T_{avg} where T_{avg} < 15.5 deg °C	S
Water	*Excess Winter Rainfall*	*mm*	∑ P when soils at field capacity for period 1st October to 31st March	S
	Minimum soil water		Max Soil Moisture Deficit	M
Waves	*Heat Wave*	Count	Maximum count of consecutive days when T_{max} >Avg T_{max} (baseline year) + 3.0 °C (minimum 6 days)	S
	Cold Spell		Maximum count of consecutive days when T_{min} < Avg T_{min} (baseline year) - 3.0 °C (minimum 6 days)	S
Indices	P seasonality	Index	S = winter P – summer P / total P	S
	P heterogeneity		Modified Fournier Index $MFI = \sum_{i=1}^{12} \frac{P_i^2}{P_t}$	S

Note: ongoing research is developing further Indicators and producing a public facing website to display the Agrometeorological Indicators and climate summaries for the whole UK from 1060 to 2098.

Appendix F: Climate Anomalies for 2022

The summer of 2022 heatwave provides an opportunity to compare the observations of climatic variables with the anomaly from the 1961–1990 baseline (camparable with the 1960-1989 we have used) and the future projections. For example, in August 2022 the maximum temparature increase above the baseline for eastern Scotland was between 2.5 and 3.5°C, and between 0.5 and 1.5°C across the majority of the country. These values are comparable to a number of the climate projections for the 2020-2049 period.

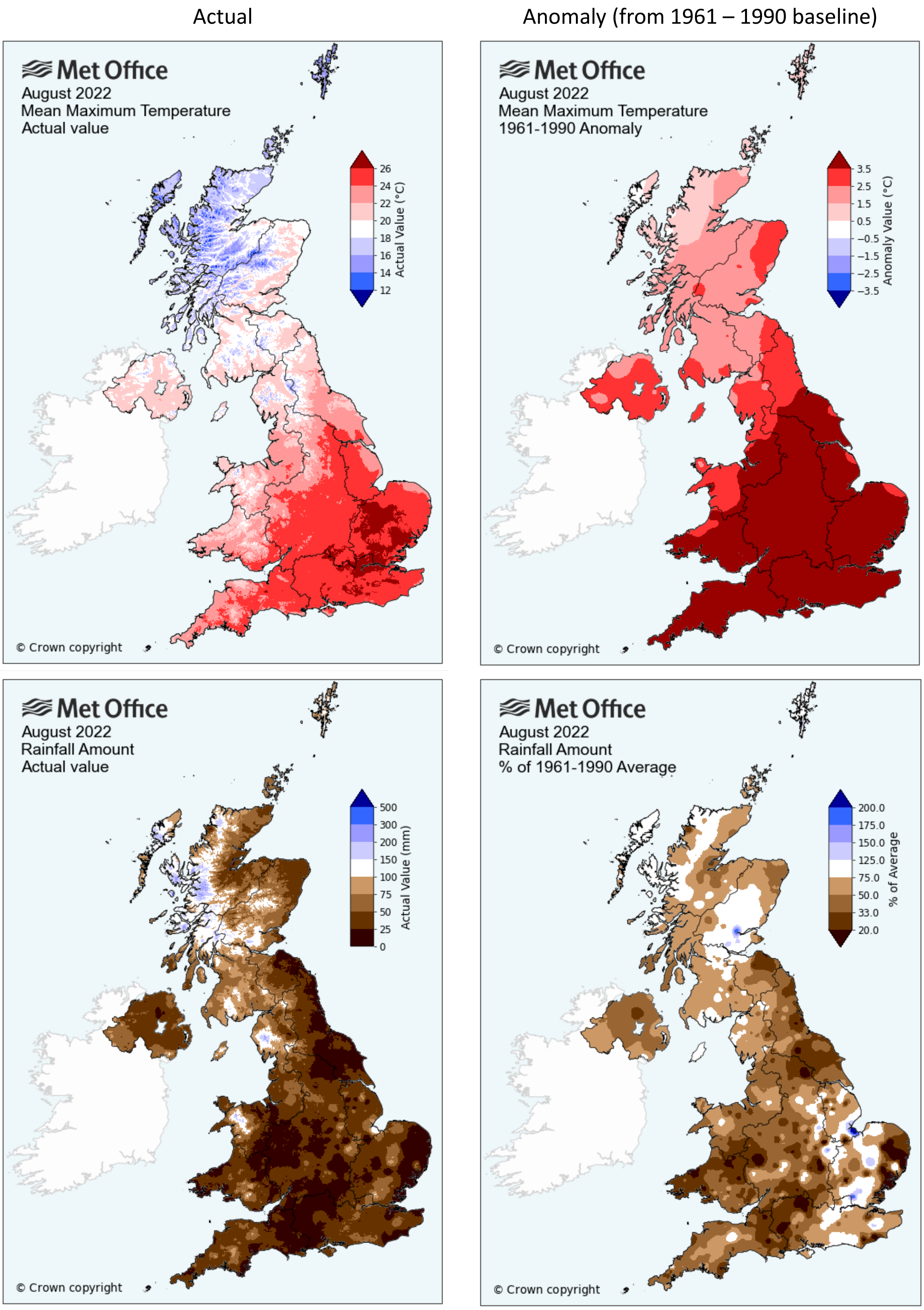


Figure 78. Actual mean maximum temperature (top) and rainfall amount (bottom) values for August 2022 and their anomaly from a 1961-1990 baseline.

For precipitation, Parts of eastern Scotland and the north-west were about average, but the East Lothian area to the east of Edinburgh experience just 20-30% of the average.

The number of days with rainfall greater or equal than 10mm was either about average or only 1-3 days below average (Figure 79). For vitually the whole of Scotland, mean minimum temparature was between 0.5 and 1.5°C warmer.

Actual Anomaly (from 1961 – 1990 baseline)

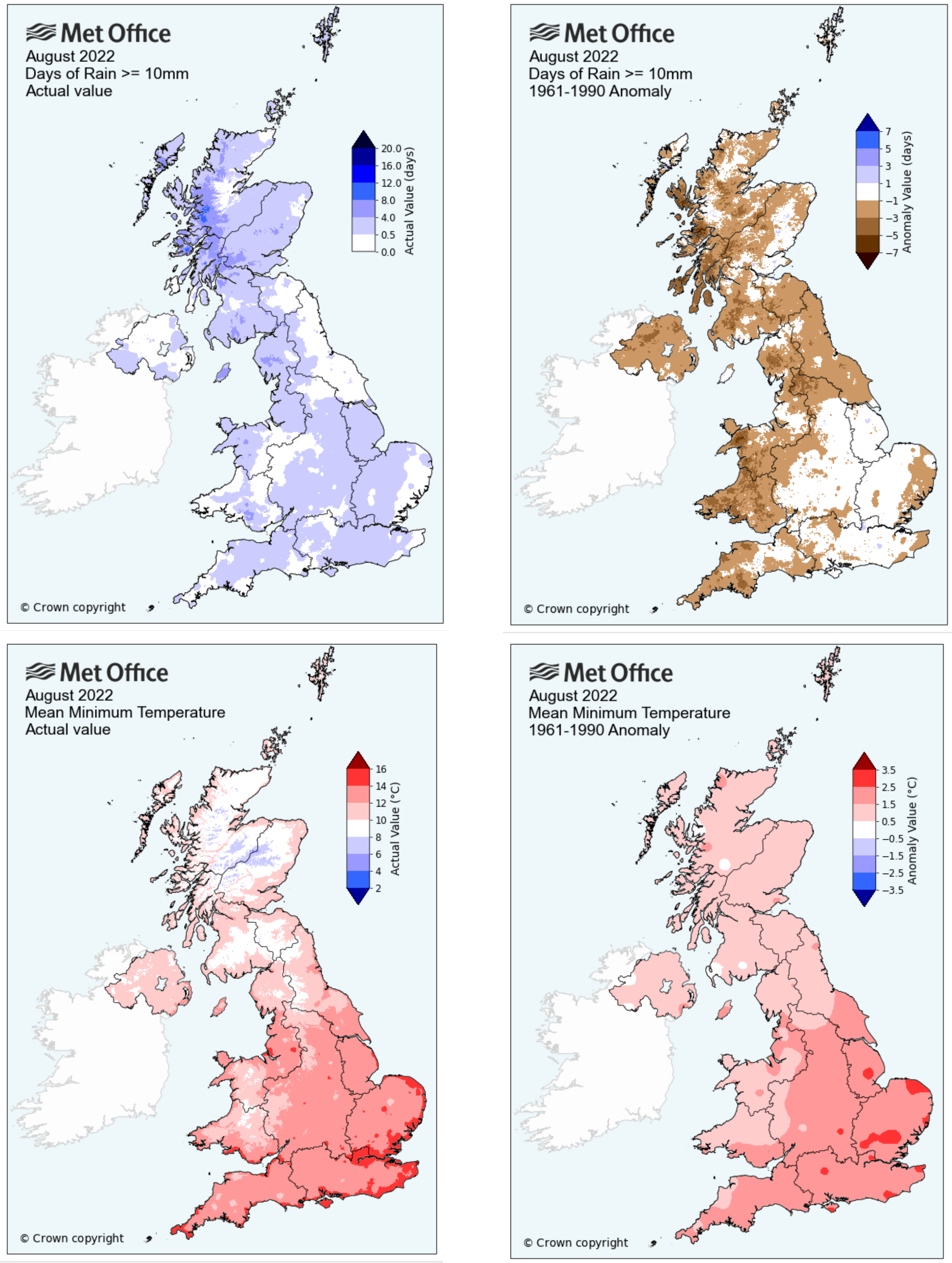


Figure 79. Actual number of days when rain is greater than or equal to 10mm (top) and mean minimum temperature (bottom) values for August 2022 and their anomaly from a 1961-1990 baseline.

The James Hutton Institute