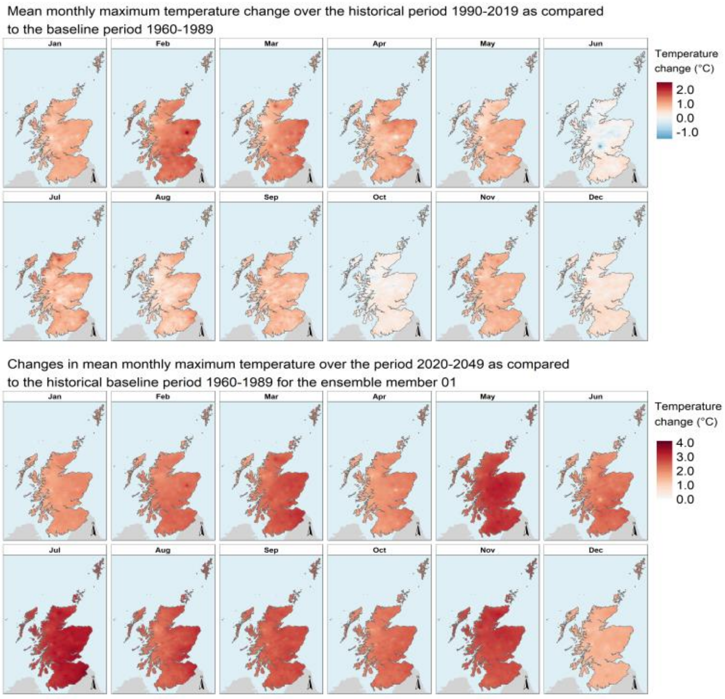
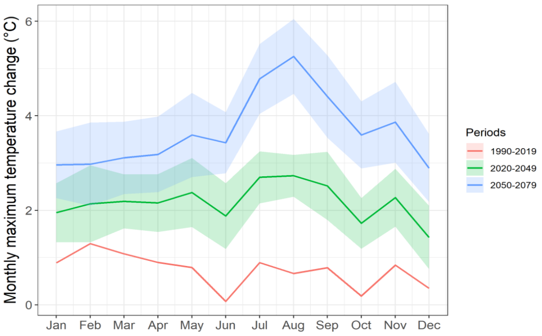
Climate Trends and Future Projections in Scotland.

Deliverable D2.1a for the

Project D5-2 Climate Change Impacts on Natural Capital

5th December 2022





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 how the climate has changed in Scotland since 1960 and is 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 trends of general summaries (means, totals etc.) to illustrate the temporal and spatial variability of changes to the climate. 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 these observed trends may change in the future. **The objective** of the research presented here is to illustrate a range of visualisation methods to establish the underpinning capabilities to support assessments of the impacts of climate change on Natural Capital assets.

To help set the context for climate changes in Scotland, we present descriptive summary information at a global and UK scale. This report does not cover extreme changes in weather phenomena, as this is the subject of an accompany report.

Observed changes:

The observed trends in precipitation, maximum and minimum temperature are derived by comparing data from 1990 – 2019 with a 1960 – 1989 baseline period, which can be summarised as:

Precipitation:

- There has been an overall increase in precipitation, with the area of Scotland experiencing higher precipitation being large 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 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 an general national trend of a positive increase (warming) in diurnal temperature range.

Projected future changes

Data from the UKCP18 climate projections (12 individual model simulations) for two time periods, 2020 – 2049 and 2050 – 2079, were 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.

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 2020 to 2049 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.

Water availability indicated using the Climatic Water Balance:

Changes in the Climatic Water Balance (precipitation – evapotranspiration) indicate potential differences in water availability. Observed trends and future projections in warming indicate an increased rate of evapotranspiration.

Observed trends:

- There has been an observed change in Climatic Water Balance, which is variable both spatially and temporally.

    - West coast areas have becoming water (increased surplus water) between December to April.
    - March to May have experienced a decrease (reduced water) in the east as has the whole of Scotland in September.
    - June to August have experienced an increase in Climatic Water Balance (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.

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.

Contents

Citation:

This report should be cited as:

Rivington M, Jabloun M (2022) Climate Trends and Future Projections in Scotland. Deliverable D2.1a for the Project D5-2 Climate Change Impacts on Natural Capital. The James Hutton Institute, Aberdeen. Scotland. DOI: 10.5281/zenodo.7657945 https://zenodo.org/record/7657945#.Y_OwnSbP2Uk

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Acknowledgements

This report has been produced by the D5-2 Climate Change Impacts on Natural Capital Project funded by the Scottish Government Rural and Environment Science and Analytical Services Strategic Research Programme (2022-2027). We also thank and acknowledge the UK Meteorological Office for use of the 1km gridded observed climate data and UKCP18 climate projections.

Introduction

The purpose of this report is to present spatial and temporal information on how the climate has changed in Scotland since 1960 and is projected to change in the future. The context is to build an understanding of what these observed trends and projected changes 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 general summaries (means, totals etc.) 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. Please note: a follow-on Deliverable (D2.1b) assesses issues of changes in extremes.

The objective is to illustrate, using a range of visualisation methods, how the climate has changed and is projected to change in the future. Here 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 later use climate data, these analysis and mapping in this report 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 these trends 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 and projections of the climate into risks to and opportunity for Natural Capital assets.

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).
- 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).

Online map visualisation tool

The increased analytical and visualisation capability has enabled the generation of hundreds of climate-based maps for Scotland (and the whole UK in many cases). This presents challenges in how to present such a large amount of information. Calculations of trends are based on use of daily data from 1960 – 2079 and aggregated to mean monthly values, plus there are 12 climate projections, for a large number of analytical and visualisation types. To address this, we have developed an online map visualisation tool that allows the user to explore observed trends and future projections.

The map visualisation tool is available here:

https://mjabloun.shinyapps.io/agmet-app/

It is a prototype website and so still under development, but it will be further developed during the project to display other map products.

Document structure

In Part 1, for context, we first provide a global overview of observed trends and future projections, followed by details of a 'snapshot' of the state of the UK climate for 2021. In Part 2 evidence is presented of observed trends in Scotland, by comparing data for 1990 – 2019 with a baseline period of 1960 - 1989. In Part 3, visualisations of climate change results are illustrated, along with details aimed to help understand the variation between the individual projections. An example of a site-specific trends and projection assessment is also provided. A key element in climate change impacts on Natural Capital is water availability, so in Part 4 we present estimated observed and future changes in the Climatic Water Balance (the difference between precipitation input and evapotranspiration output). Appendix A provides examples of additional map representations of analyses available, plus agrometeorological indicator products derived from the UKCP18 data. Appendix B sets out the methods used to produce the results in this report. Appendix C assess the climate model skill, a key aspect of any climate change impact assessment, as it is essential to understand the utility of the climate model data to enable meaningful interpretations of projections allowing for model error and biases and consequences on impacts assessment of Natural Capital assets.

Part1: Global and UK Perspective

Global observed climate trends

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*).

State of the UK Climate

The UK Meteorological Office provides an annual State of the UK Climate Report (Kendon et al 2022)[1]. These reports are 'snapshot' representations of what the climatic features have been for a year and places these within the context of long-term observation. The reports are useful indications of trends and how these align with future projections. The key findings for 2021 are summarised here:

- The UK's climate is continuing to change, recent decades have been warmer, wetter and sunnier than the 20th century.
- All of the UK's top 10 warmest years, in the time series from 1884, have occurred this century.
- While the year 2021 would be considered near normal compared to the last three decades, before 1990, a year like this would be the second warmest in the series.
- In 2021 specifically, UK temperatures and sunshine were near to the 1991 – 2020 average with rainfall slightly below.

Land temperature

- 2021 was 0.1°C warmer than the 1991–2020 average, and 18th warmest in the UK series from 1884. It was warmer than all but one year in this series prior to 1990.
- Winter and spring were colder than the 1991–2020 average. However, 2021 included the UK's ninth warmest summer and equal-third warmest autumn on record in series from 1884.
- All the top ten warmest years for the UK in the series from 1884 have occurred this century.
- The most recent decade (2012–2021) has been on average 0.2°C warmer than the 1991–2020 average and 1.0°C warmer than 1961–1990.
- The 21st century so far has been warmer than any period of equivalent length from the last three centuries as shown by the Central England temperature series.

Precipitation

- 2021 rainfall was 95% of the 1991–2020 average and 102% of the 1961–1990 average.
- 2021 included the UK's fifth driest April and second wettest May in monthly series from 1836.
- Five of the ten wettest years for the UK in a series from 1836 have occurred this century.
- Since 2009, the UK has had its wettest February, April, June, November and December on record in monthly series from 1836—five of 12 months—as well as its wettest winter.
- The most recent decade (2012–2021) has been on average 2% wetter than 1991–2020 and 10% wetter than 1961–1990 for the UK overall.

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[1] https://rmets.onlinelibrary.wiley.com/doi/10.1002/JOC.7787

- For the most recent decade (2012–2021) UK summers have been on average 6% wetter than 1991–2020 and 15% wetter than 1961–1990. UK winters have been 10%/26% wetter.

Air and ground frost

- The numbers of air and ground frosts in 2021 were above the 1991–2020 average.
- The numbers of air frosts and ground frosts in April 2021 were the highest on record for the UK in series from 1960.
- The most recent decade (2012–2021) has had 5% fewer days of both air and ground frost compared to the 1991–2020 average, and 21%/18% fewer compared to 1961–1990.

Energy demand and growing conditions indices

- Heating and cooling degree days in 2021 were near the 1991–2020 average. Growing degree days were seventh highest for the UK in a series from 1960.
- The most recent decade (2012–2021) has had 2% fewer heating degree days per year on average compared to 1991–2020 and 11% fewer compared to 1961–1990.
- The most recent decade (2012–2021) has had 2% more growing degree days per year on average compared to 1991–2020 and 17% more compared to 1961–1990.

Near-coast sea-surface temperature

- 2021 was ranked 20th warmest year for UK near-coastal sea-surface temperature (SST) in a series from 1870.
- The most recent decade (2012–2021) has been on average 0.1°C warmer than the 1991–2020 average and 0.7°C warmer than 1961–1990.
- Nine of the ten warmest years for near-coast SST for the UK have occurred this century.

Snow

- For a week in early February the UK experienced its most widespread and significant snow event since late February to early March 2018.
- In terms of overall snowiness, 2021 was a fairly average year when compared to the last 60 years, whereas in the last ten years 2012–2021, only 2013 and 2018 were snowier.
- Widespread and substantial snow events have occurred in 2021, 2018, 2013, 2010 and 2009, but their number and severity have generally declined since the 1960s.

Sunshine

- The UK 2021 annual sunshine total was 99% of the 1991–2020 average.
- April 2021 was the UK's equal-sunniest April on record in a series from 1919, shared with April 2020, and also the sunniest calendar month of the year.
- The most recent decade (2012–2021) has had for the UK on average 2% more hours of bright sunshine than the 1991–2020 average and 8% more than the 1961–1990 average.
- For the most recent decade (2012–2021) UK winters have been 3% sunnier than 1991–2020 and 13% sunnier than 1961–1990. UK springs have been 6%/15% sunnier.

Wind

- With the notable exception of storm Arwen, the year was less stormy than most other years in recent decades.
- There have been fewer occurrences of max gust speeds exceeding 40/50/60 Kt for the last two decades compared to the 1980s and 1990s.

- The UK annual mean wind speed for 2021 was second lowest in a series from 1969.
- The UK annual mean wind speed from 1969 to 2021 shows a downward trend, consistent with that observed globally. However, this series must be interpreted with some caution.

Sea-level rise

- The rate of sea-level rise in the UK is increasing, with selected locations recording a range from 3.0 ± 0.9 to 5.2 ± 0.9 mm·year−1 over the past 30 years when corrected for vertical land movement, compared to the 1.5 ± 0.1 mm·year−1 since 1900s.
- For the 20th century the rate of sea-level rise around the UK is close to the estimate of the global sea-level rise.
- Storm surges of over 1.5 m were seen during Storm Arwen, but extreme sea levels were avoided as this occurred during low water and a neap tide.
- A red warning was issued for storm Arwen on November 26–27, 2021, one of the most damaging winter storms of the latest decade. Unusually, the strongest winds were from a northerly direction.

Phenology

- First leaf dates in 2021 were earlier than the baseline (1999–2020) for species that leaf earlier in the season (e.g., Elder normally in March), but delayed by the cold April for later leafing species (e.g., Pedunculate Oak normally in April). This resulted in a mixed spring overall.
- Bare tree dates in 2021 were 2–5 days later than normal with Pedunculate Oak pushed back to early December.
- Overall, the 2021 leaf-on season was only 1–7 days longer than the 1999–2020 baseline because of the colder spring.

Part 2: Observed climate trends in Scotland

We present here trends for two time periods: 1960 – 1989 (the World Meteorological Organisation climate normal baseline period) and 1990- 2019 (the ’current climate’).

Summary of observed climate trends:

Precipitation:

- Between 1960 – 1989 and 1990 – 2019, there have been substantial changes on the spatial and temporal patterns of precipitation in Scotland:
    - December, January, March and May have become wetter in the west and drier in the eastern areas.
    - February and to a lesser extent Aril have become wetter, particularly in the west (up to 60%).
    - June, July, October and November have become wetter in the east.
    - September has become drier across all of Scotland with the exception of the north-east coastal area.
    - August has experienced variable change, with lowland areas generally becoming drier and upland areas wetter.
- Precipitation variability for each month over the two observed periods has changed and differs spatially and temporally.
    - February and December have the largest increased variability when it has become wetter in the west.
    - January, April, July and November have seen a decrease in variability in the west.
    - March, May and to some extent October have experienced a decrease in variability.
    - November has decreased variability in the north but increased in the south.

Maximum and minimum temperature:

- In all months there has been an increase in maximum and minimum temperatures, and this extends to all areas of Scotland.
    - The spatial extent of this warming has been uniform, with little variation by elevation.
- February experienced the most warming, up to 2°C for maximum and 1°C minimum for temperature, with other months seeing similar changes.
    - The only exceptions are some lower maximum temperatures in June and October in the Highlands and colder minimum temperatures in October (mostly in the west) and December (mostly in the central Highlands).

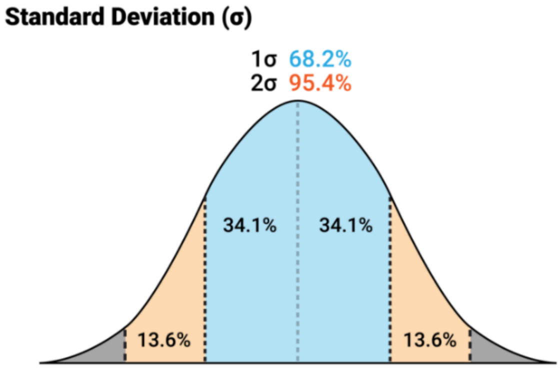
Text Box 1: Notes on observed data utility

It is important to highlight a key issue to understand is 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 in 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 concentration of observation stations in lowland areas, there are concerns on how representative the interpolated data is in 1km cells containing 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.

How to read the maps:

Figure 1 indicates the observed changes per month in precipitation between the 1960 – 1989 baseline period and the recent 1990 – 2019 period. Blue areas indicate an increase in precipitation, white (or very pale blue or red) indicate no or very little change. Red indicates a decrease in precipitation. Figure 2 presents information on the change in precipitation between the baseline and current climate as the percent relative change in precipitation, where blue indicates areas that have become wetter, red where it has become drier and white where there has been little or no change. For temperature (Figures 5 and 10) red indicates an increase and blue a decrease.

Figures 3, 6 and 11 show the change in standard deviation, indicating the amount of variability in monthly total precipitation (mm) and maximum and minimum temperature respectively within the two 30-year periods. In the precipitation example blue indicates an increase in the standard deviation, white (or very pale blue or red) indicate no or very little change, and red shows a decrease. A positive change on the map (blue) indicates increased variability, a negative (red) indicates decreased variability. One standard deviation (σ) represents 68.2% of observations (right).



In the temperature examples red indicates a shift towards variation becoming warmer, and blue colder.

Observed precipitation trends

Precipitation is a highly spatially (non-contiguous) and temporally variable weather feature, hence changes in climate over time can be problematic to identify. Comparing the changes in mean monthly precipitation between two time periods enables some change detection.

Scotland has a pronounced west to east precipitation gradient, with the west having higher rainfall. The mean monthly amount of precipitation and the steepness of the gradient varies per month (Figure 1).

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[2] HadUK-Grid Overview - Met Office

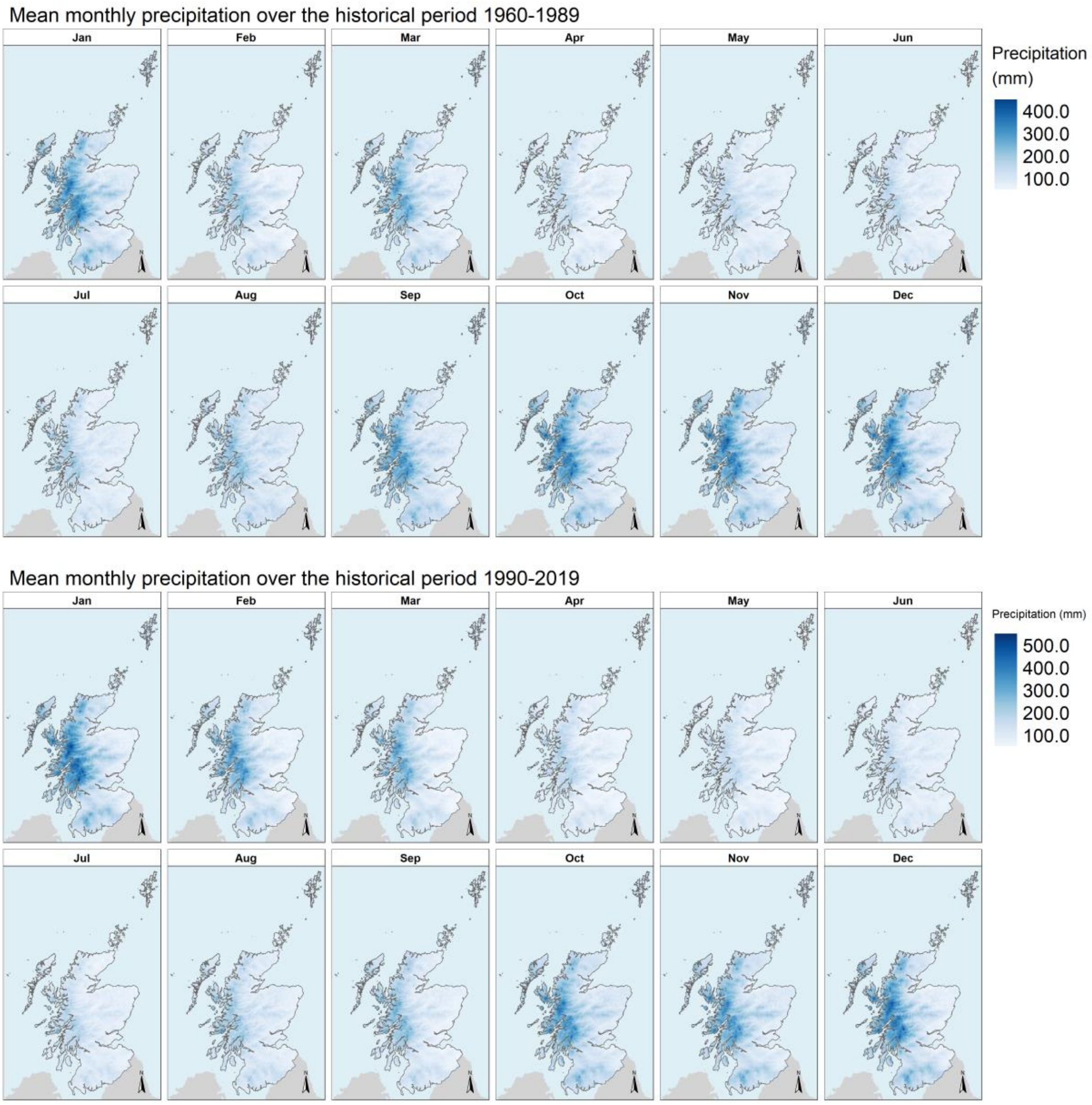


Figure 1. Mean total precipitation per month for the period 1960-1990 (top, base line period) and 1990 – 2019 (bottom). Note: the legend scales are different so direct comparisons here are not possible – instead, see Figure 2.

Precipitation changes:

Overall, there has been an increase in precipitation, with the area experiencing higher precipitation being large than that of decreases (Figure 2). There is a wide variation in spatial and temporal change, for example all of Scotland became drier in September, except the Moray and north Aberdeenshire coastal areas, but variability however shows an increase in the north but decrease in the south (Figure 3). The largest increases in precipitation occurred in February, which is also associated with an increase in variability (standard deviation). In the west of Scotland precipitation has increased from December to May, but either remained similar or decreased in July, August and October. In June the north-west became drier whilst in November the north became drier. Eastern Scotland became drier in January, March, May, August, September and December, but wetter in February, June, July, October and November. The following maps present the changes in mean monthly precipitation, relative change (%) and standard deviation between the 1960 – 1989 baseline and recent 1990 - 2019 period.

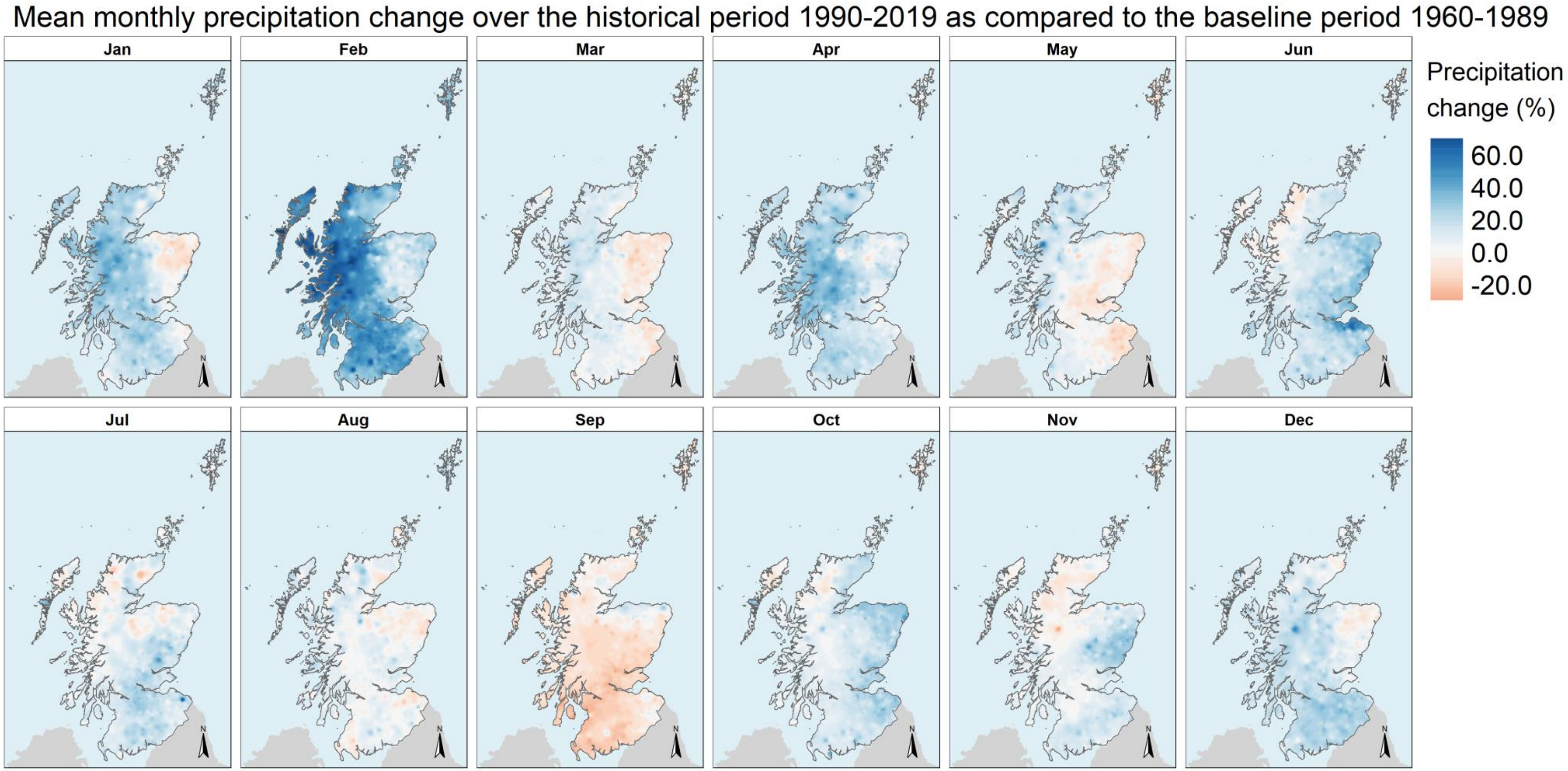


Figure 2. Relative change (%) in mean monthly precipitation between the 1960 – 1989 baseline period and 1990 – 2019 period.

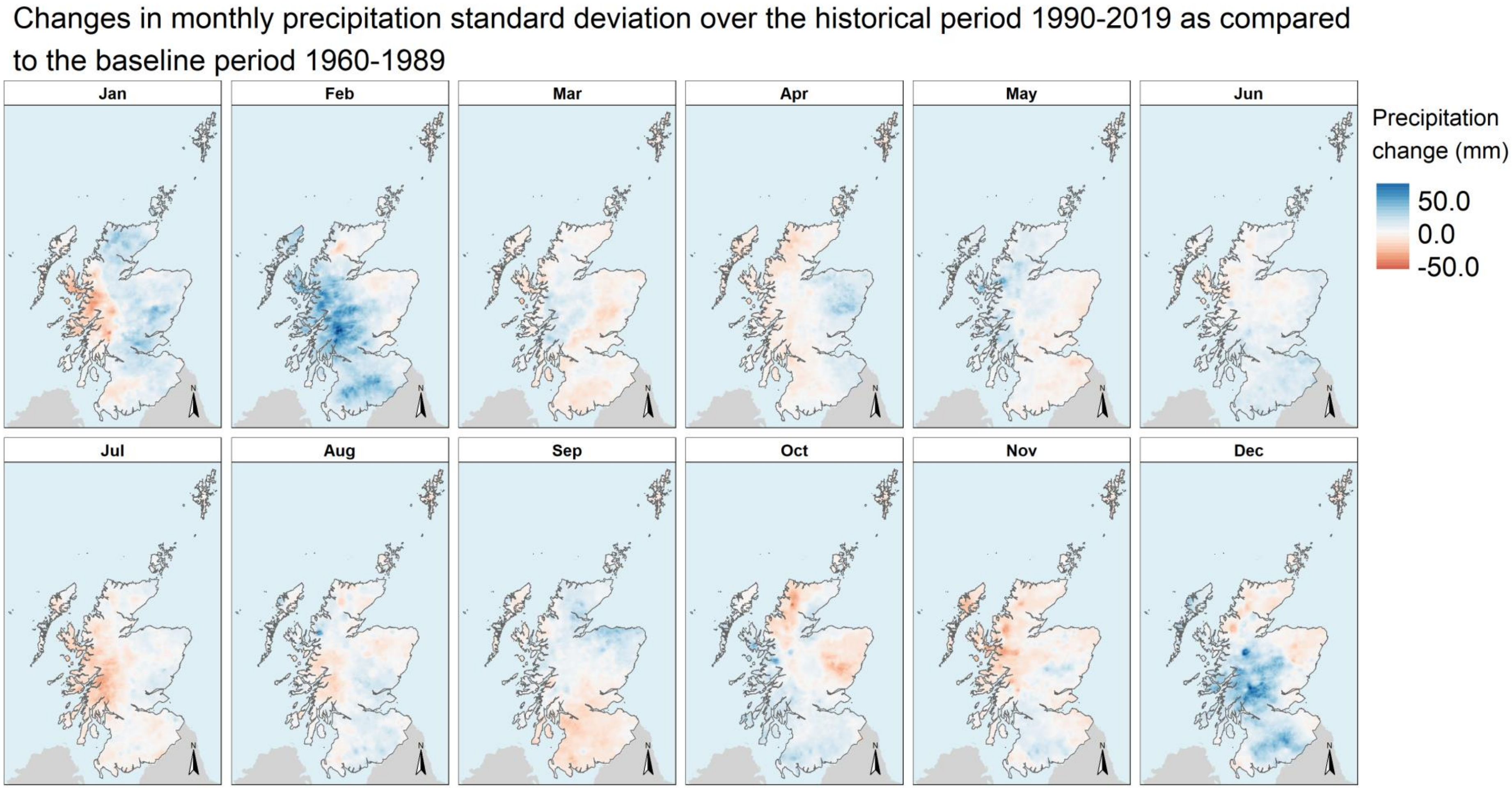


Figure 3. Changes in the standard deviation of mean monthly precipitation per month as an indication of variability between the baseline period (1960 – 1989) and recent period (1990 – 2019).

There has been a trend towards drier conditions in January, March, May and to a lesser extent in April in the east of Scotland. Conversely February has become substantially wetter in the west and in June, July, October and November in the east.

In terms of variability (Figure 3), there has been a mixed temporal and spatial patterns of change in precipitation. The increase seen in February's total precipitation is reflected in the increased variability shown by the standard deviation in the west. Conversely, January, April, July and November (and to a lesser extent August) have seen a decrease in variability in the west.

A primary explanation for the increase in precipitation amount and variability is likely associated with an increase in event intensity, is that air can hold more moisture as it becomes warmer, by about 7% for every 1°C rise in temperature (known as the Clausius-Clapeyron relationship). The changes in variability seen indicates increased intensity of precipitation events when they do occur, and more drying through evapotranspiration under warmer conditions (Figure 5). Hence in respect of total water availability and impacts on Natural Capital assets, it is important to consider the net Climatic Water Balance of precipitation minus evapotranspiration (see Part 4).

Observed temperature trends

Unlike precipitation, temperature is a more spatially contiguous weather variable, enabling change detection to be more feasible by comparing the differences in mean monthly maximum (Figure 5) and minimum (Figure 10) temperatures, and diurnal range (Figure 15).

Maximum temperature

The mean monthly maximum temperatures represent the daytime higher temperature values, but not the extremes of the individual hottest days. Figure 4 shows the observed mean monthly maximum temperature for the 1960 – 1989 baseline and recent 1990 – 2019 periods.

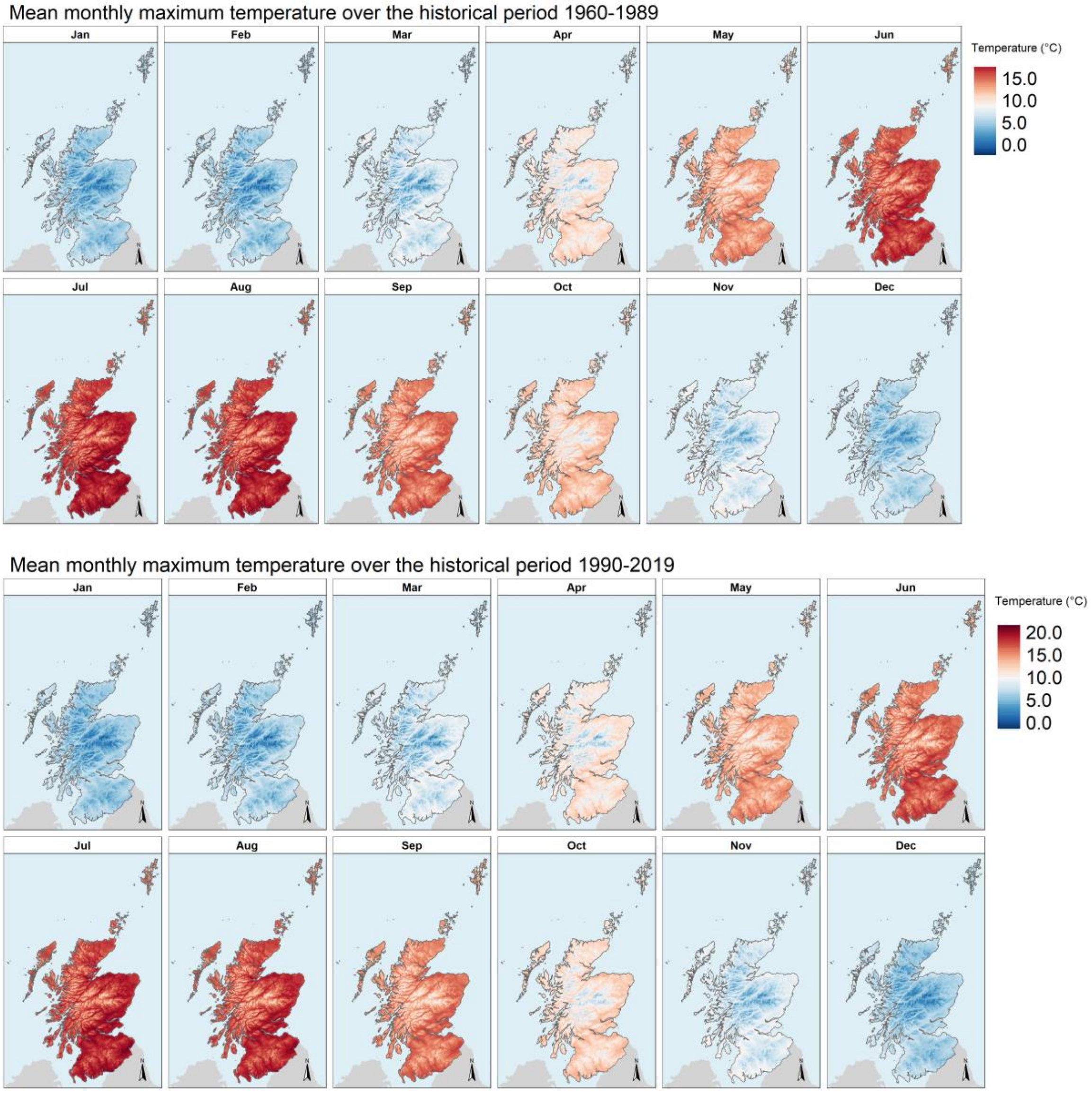


Figure 4. Mean monthly maximum temperature for the 1960 – 1989 baseline (top) and recent 1990 – 2019 period (bottom). Note: the legend scales are different so direct comparisons here are not possible – instead, see Figure 5.

The following maps present the relative changes (%) in mean monthly maximum temperature and standard deviation between the 1960 – 1989 baseline and recent 1990 - 2019 period.

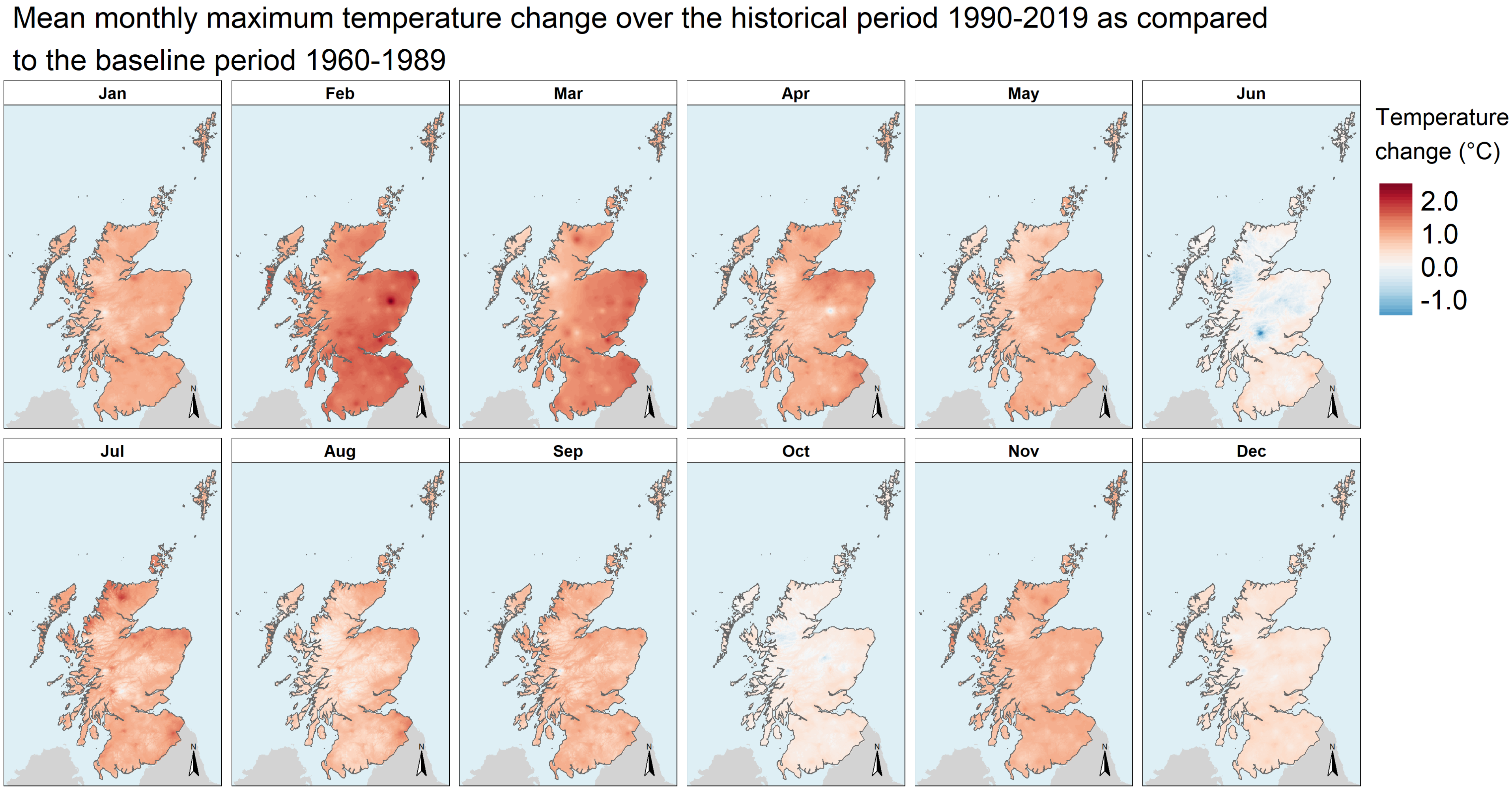


Figure 5. Change in mean monthly maximum temperature change between the 1960 – 1989 baseline period and 1990 – 2019.

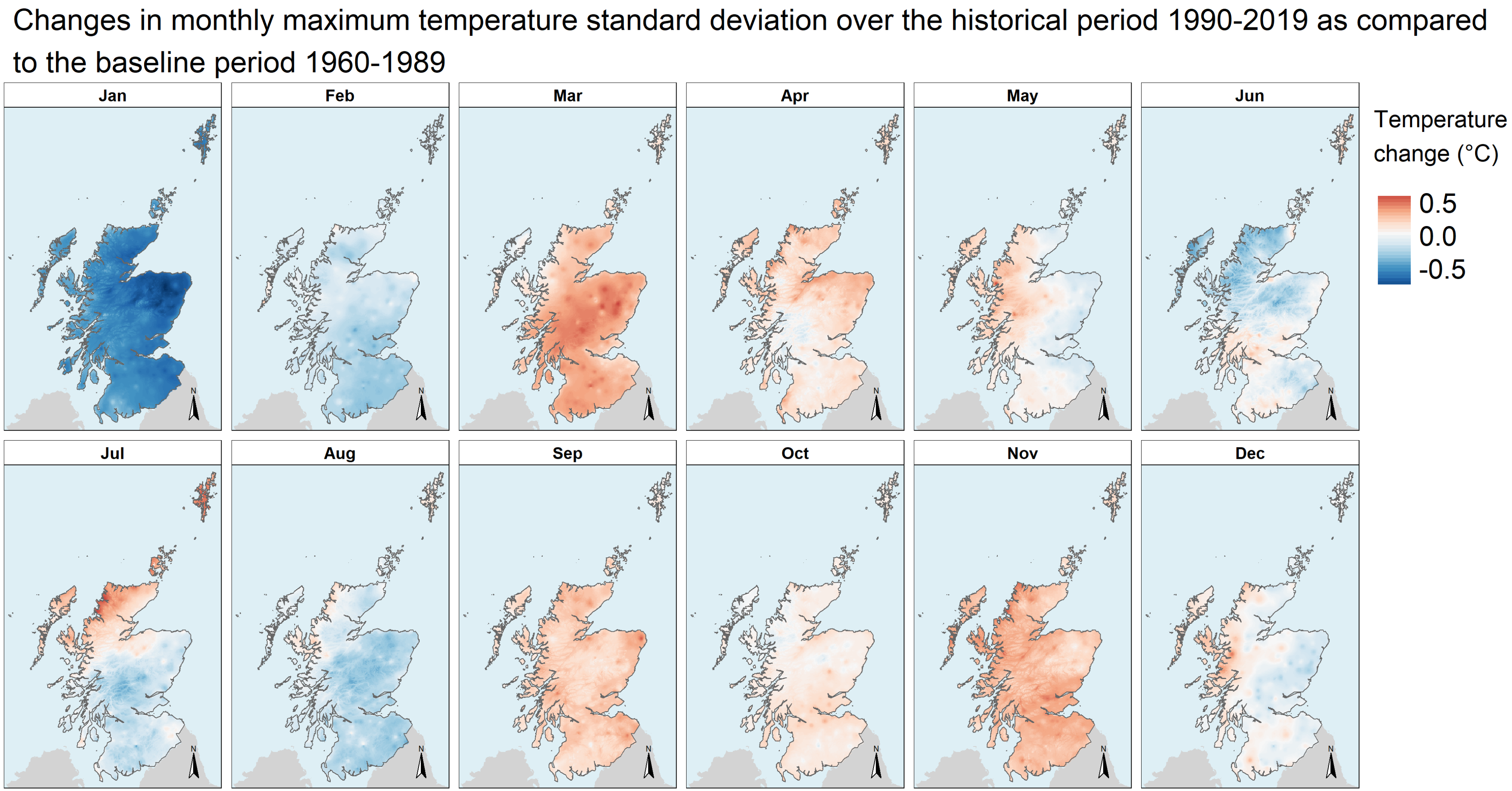


Figure 6. Changes in the standard deviation of mean monthly maximum temperature per month as an indication of variability between the baseline period (1960 – 1989) and current climate period (1990 – 2019).

For all months there is an overall increase in maximum temperature, except in June and to a lesser extent October, confined to some mountain areas, most notably the Cairngorms, Torridon and Loch Lomond areas, where there has been come cooling (Figures 5 and 7). 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, i.e. it doesn't reflect the topographical differences, though for some locations there has been little or no change from the 1960 – 1989 baseline period.

In terms of variability (Figure 6), January, February and August have seen an almost nationwide shift towards reduced standard deviation, whilst March, April (except the Lochaber and northern Argyll areas), September, October and November have seen a widespread increase.

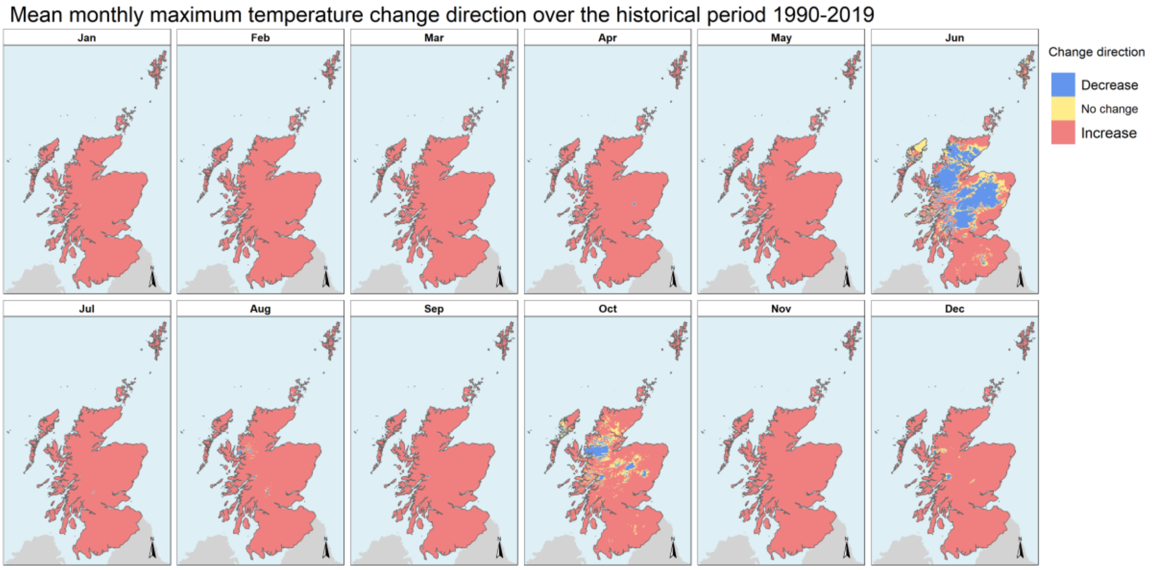


Figure 7. Maximum temperature change direction per month between the 1960-1989 baseline and 1990 – 2019. Red = increase, yellow = no change (+/1 0.5 °C) and blue = decrease.

The direction of change is almost uniformly an increase in maximum temperature (Figure 7), the exceptions being some upland areas in June and October.

This is reflected in the area proportion of change (Figure 8), presented as an alternative form of result visualisation, which illustrates that all but June and October have had a mean monthly temperature increase. This means that, despite the changes in variation, the whole of Scotland has experienced warming except the blue areas in June and October.

This analysis has not assessed why there has been a decrease in maximum temperature in these locations, but it may be associated with an increase in cloud and precipitation (Figure 2).

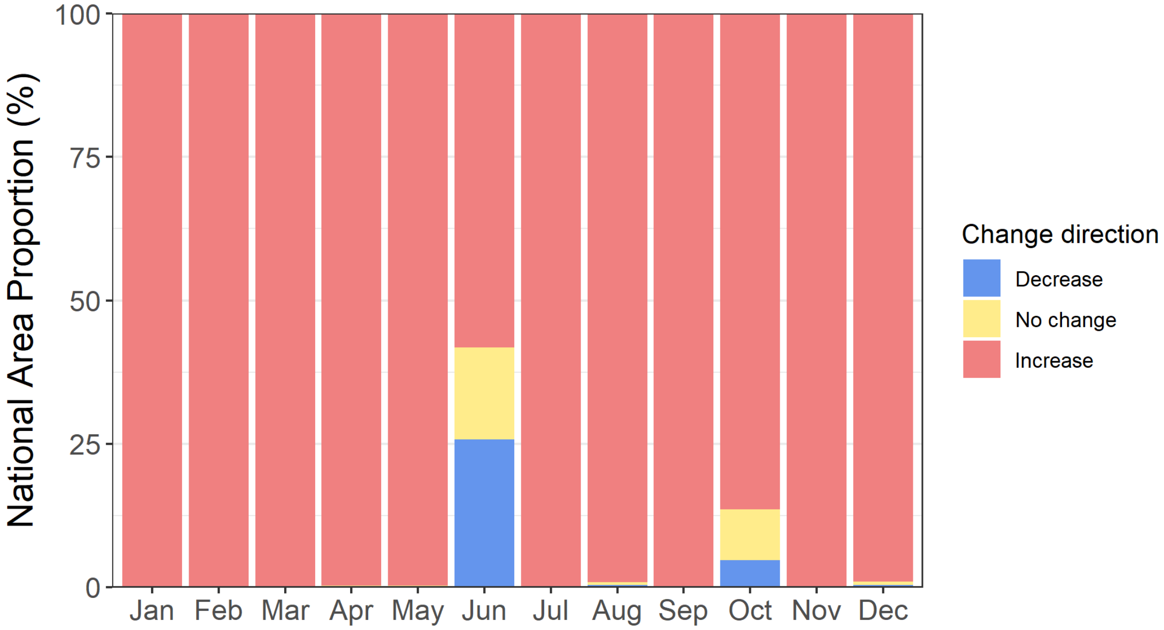
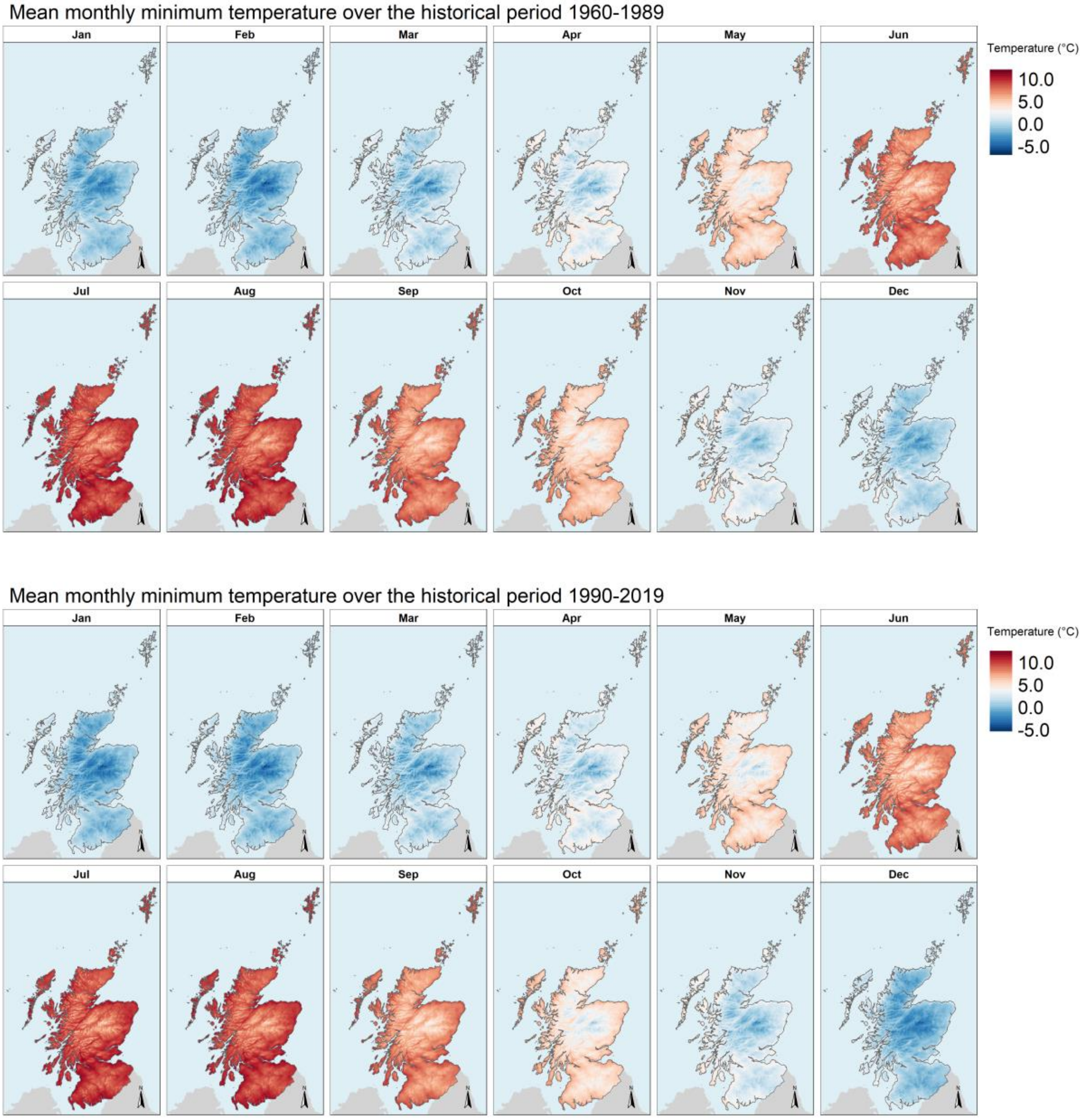


Figure 8. Maximum temperature change direction for the national land area proportion (%). Red = increase, yellow = no change (+/1 0.5 °C) and blue = decrease.

Additional analysis (see Figure 39) assessed the rate of change per decade in the baseline period (1960 – 1989). This shows that the highest rate of change of mean monthly maximum temperature per decade has been in July (up to 1°C), followed by December, November, August and then May. Other months have experienced slower warming and for some months (March, April, June, September, October) some slight lowering of mean monthly maximum temperature (-0.5°C).

Minimum Temperature

The mean monthly minimum temperature represents night-time values, but not extreme lows. Figure 9 shows the mean monthly minimum temperature for the 1960 – 1989 baseline and 1990 – 2019 periods and Figure 10 shows the differences between them to illustrate the observed change.



Mean monthly minimum temperature over the historical period 1960-1989

Mean monthly minimum temperature over the historical period 1990-2019

Figure 9. Mean monthly minimum temperature for the 1960 – 1989 baseline (top) and recent 1990 – 2019 period.

Minimum temperature values are closely linked to Scotland’s topography, with upland areas being cooler. The results of the observed change in minimum temperature are similar to those of maximum temperature. All months except October and December have seen higher (warmer) minimum temperatures, with February experiencing the largest increase (Figure 10). The spatial range of change is relatively uniform, again with little visible effect of topography.

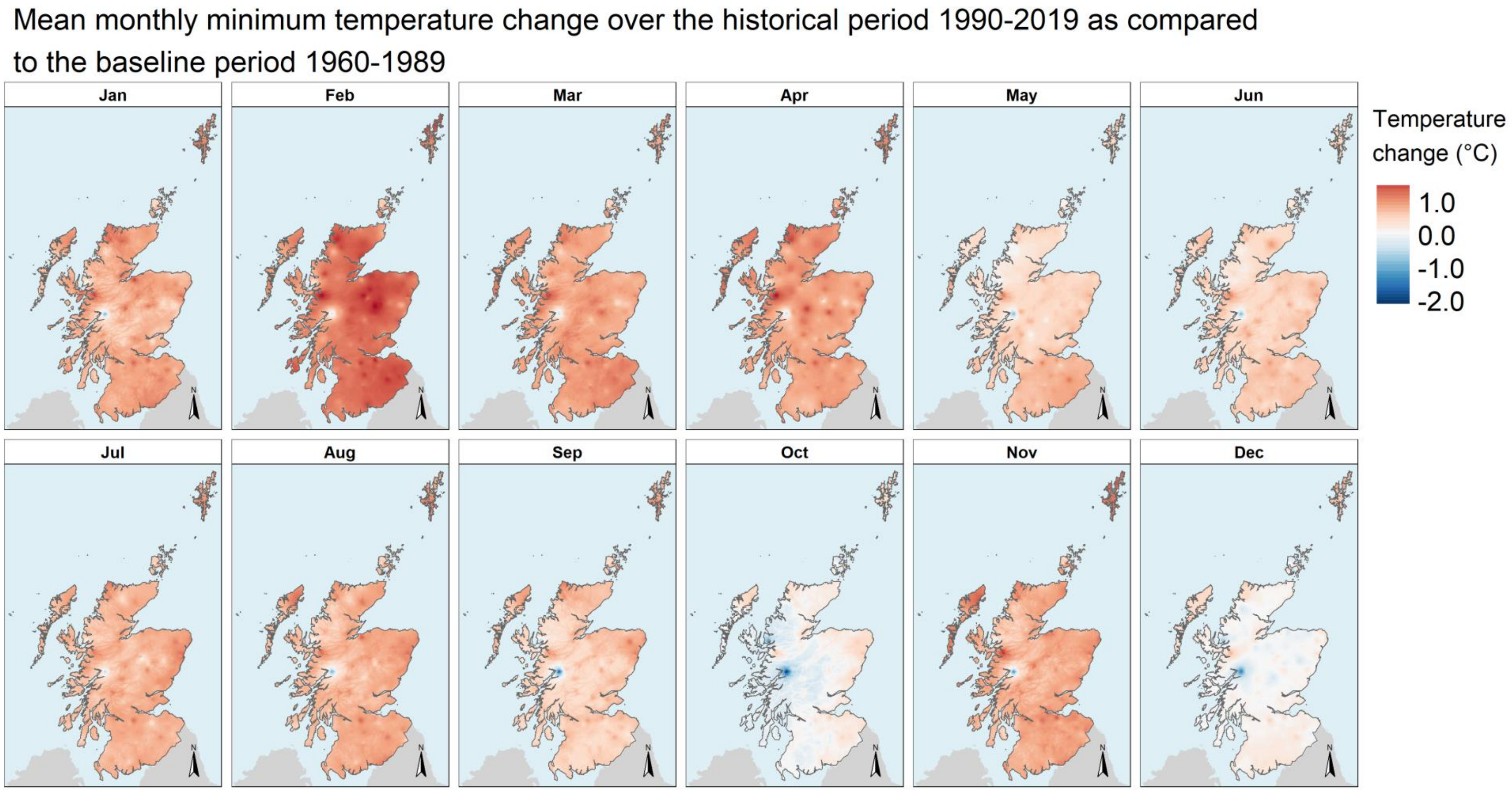


Figure 10. Change in mean monthly minimum temperature change between the 1960 – 1989 baseline period and 1990 – 2019.

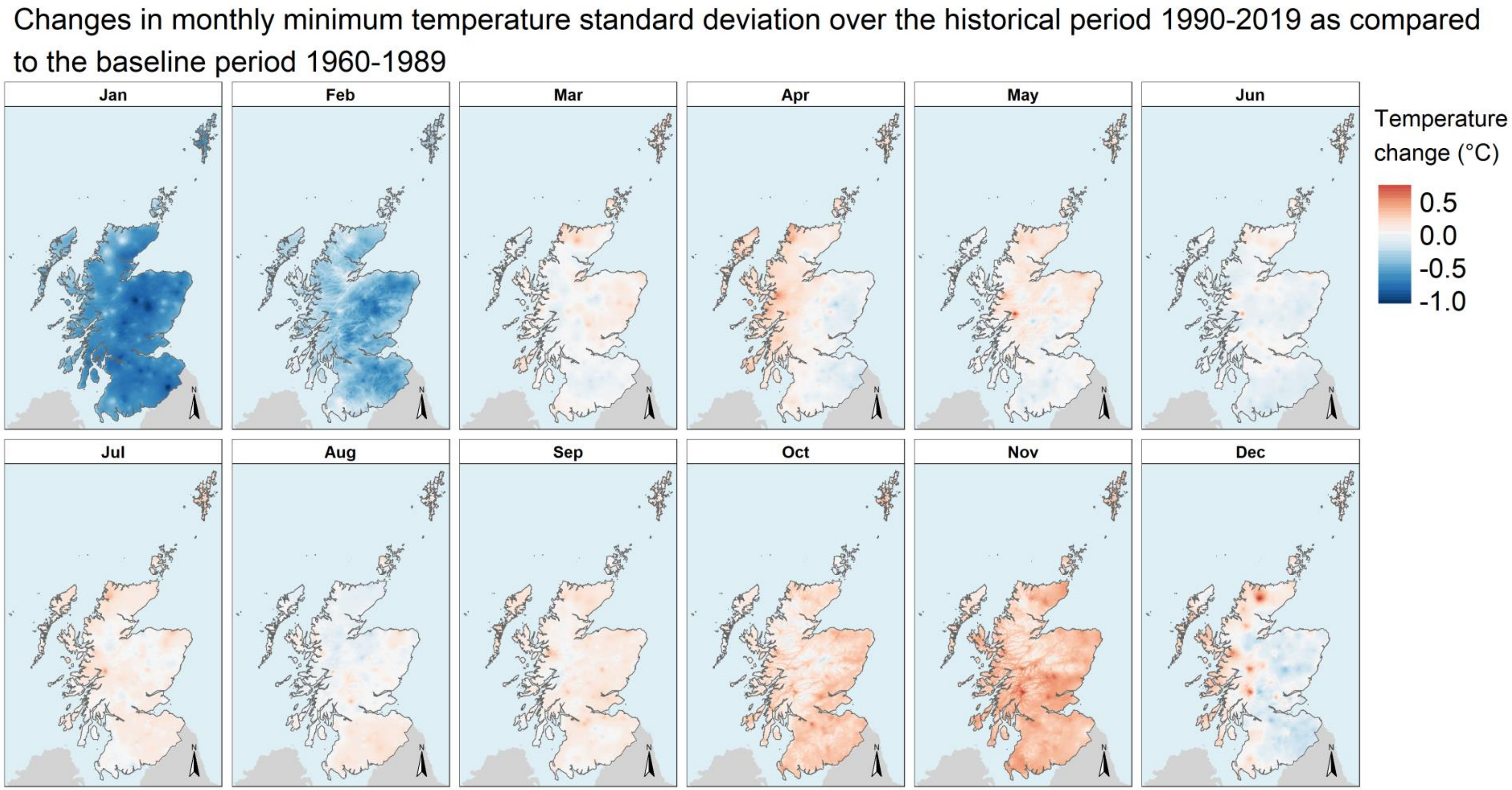


Figure 11. Changes in the standard deviation of mean monthly minimum temperature per month as an indication of variability between the baseline period (1960 – 1989) and current period (1990 – 2019)

In terms of variation (Figure 11), January and February have experienced a reduction in variability, by up to 1°C, and July, September, October and November having an increase, with the other months having a mixed response

As with maximum temperature, the direction of change is consistently towards warmer minimum temperatures, but in this case the exceptions are October and December.

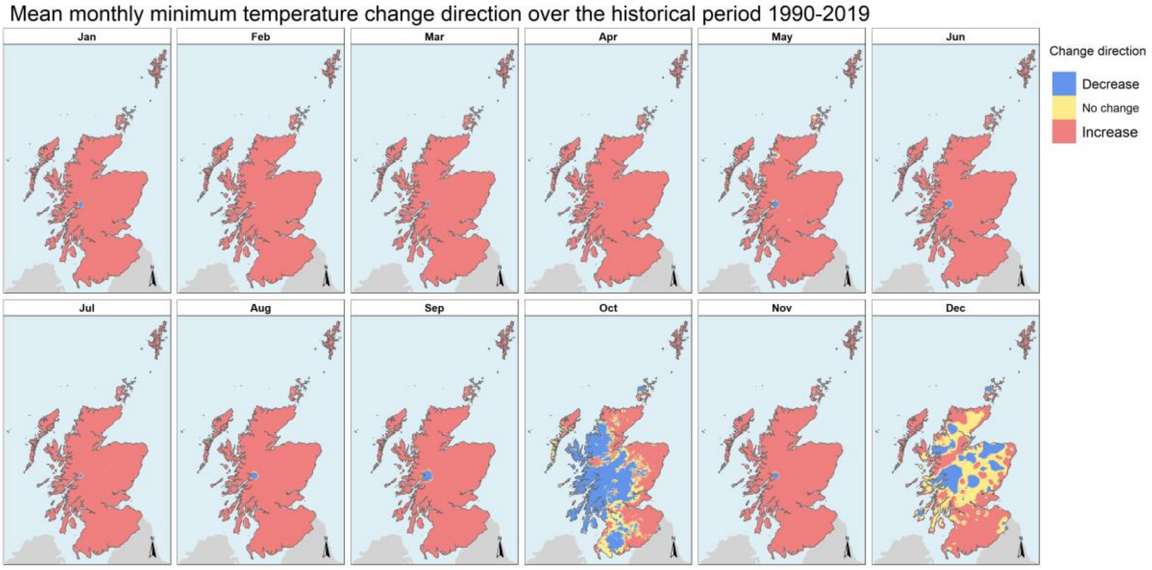


Figure 12. Minimum temperature change direction per month between the 1960-1989 baseline and 1990 – 2019. Red = increase, yellow = no change (+/1 0.5 °C) and blue = decrease.

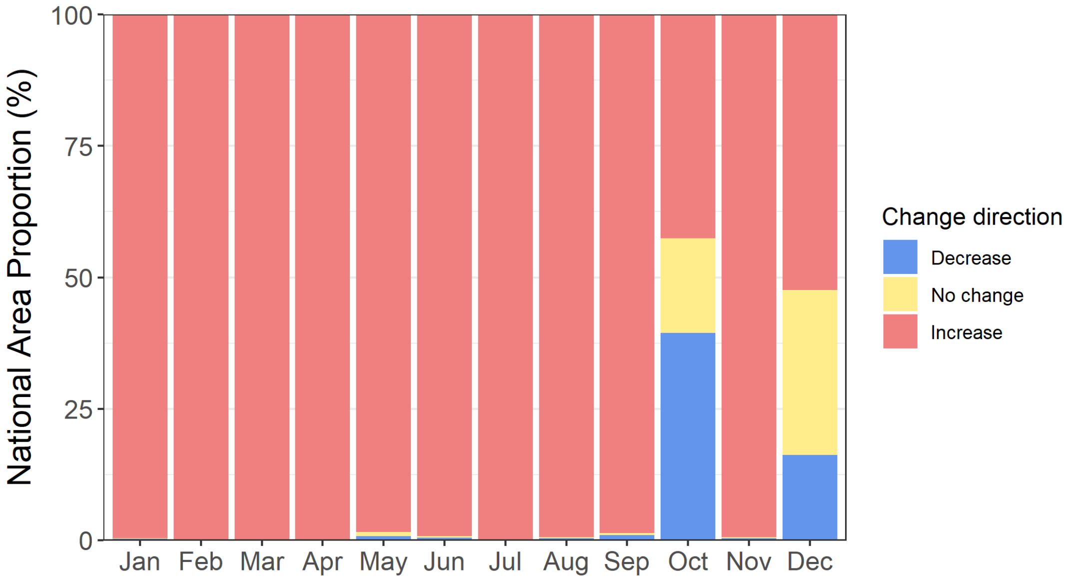
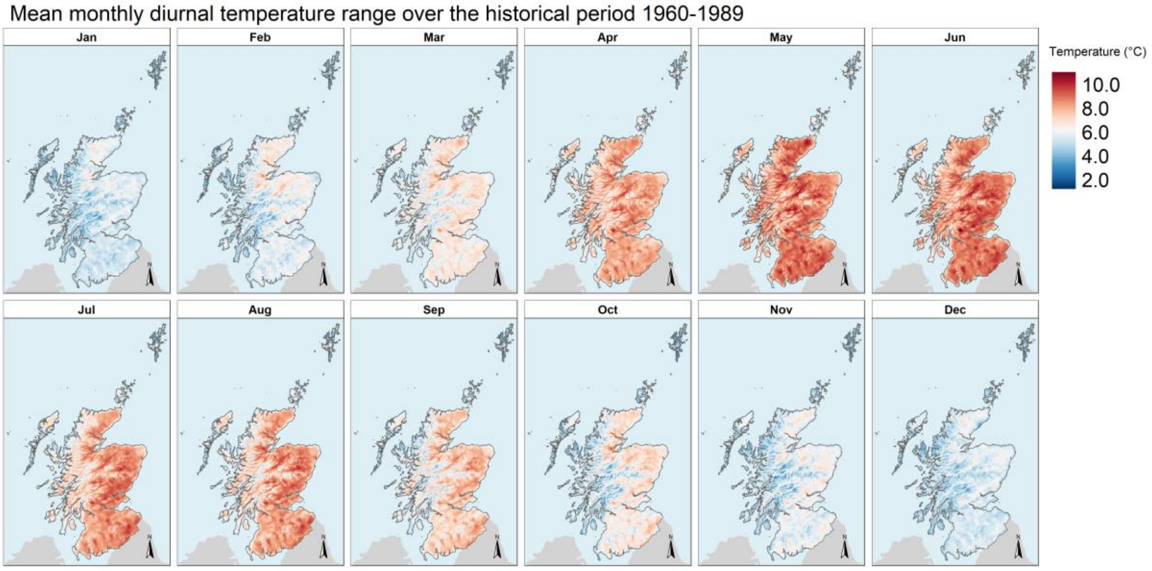


Figure 13. Minimum temperature change direction for the national land area proportion (%). Red = increase, yellow = no change (+/1 0.5 °C) and blue = decrease.

Diurnal Temperature Range

The diurnal temperature range is the difference between minimum and maximum temperature per day. It is a useful indication of warming or cooling trends and reflects the total energy input into an ecosystem, affecting phenology. Figure 14 illustrates the diurnal temperature per month for the two observed time periods, whilst Figure 15 shows the observed change.



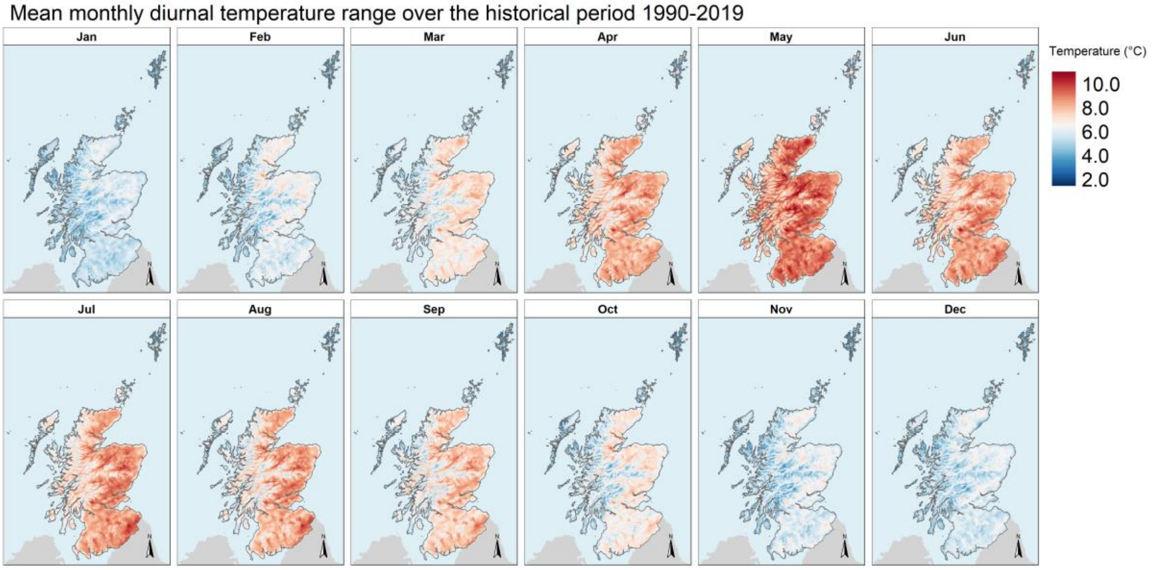


Figure 14. Mean monthly diurnal temperature range for the 1960 – 1989 baseline (top) and recent 1990 – 2019 period.

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. Whilst maximum and minimum temperature have increased, this result indicates that the difference between the two have also increased. June has experienced a decrease in diurnal range, which also aligns with the observed decreases in maximum and minimum temperature. The overall increases in temperature and diurnal range aligns with observed changes in plant and insect phenology (through more rapid thermal time accumulation).

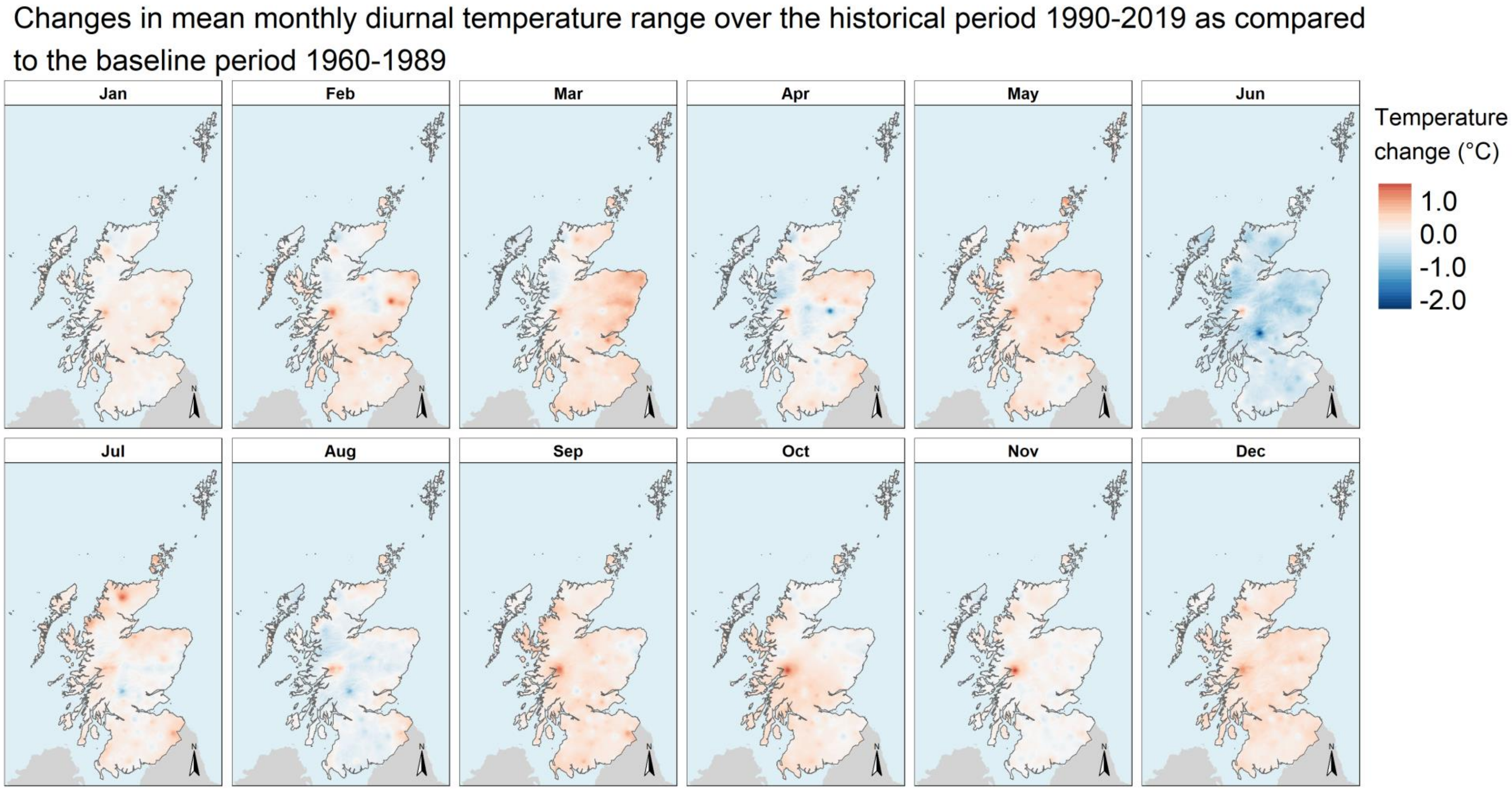


Figure 15. Change in mean monthly diurnal temperature range change between the 1960 – 1989 baseline period and 1990 – 2019.

Observed change summary:

The observed trends in precipitation, maximum and minimum temperature can be summarised as:

Precipitation:

- There has been an increase in precipitation, with the area experiencing higher precipitation being large 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 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 an general national trend of a positive increase (warming) in diurnal temperature range.

Part 3: Climate change projections

This section details a set of twelve climate projections generated as part of the UK Climate Projections (UKCP18).

UK Climate Projection Summary:

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.

Climate Change Projections for Scotland

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

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 16 (and 44-45 in Appendix B), 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 16 details the precipitation and temperature anomaly for each projection, that is, the change between each future projection and the observed 1960-1989 baseline. Figure 16 (and similarly 44-45 in Appendix B) 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 C** (Assessing climate model utility and uncertainty) provides details of the skill of the climate models' by assessing their ability to simulate observations.

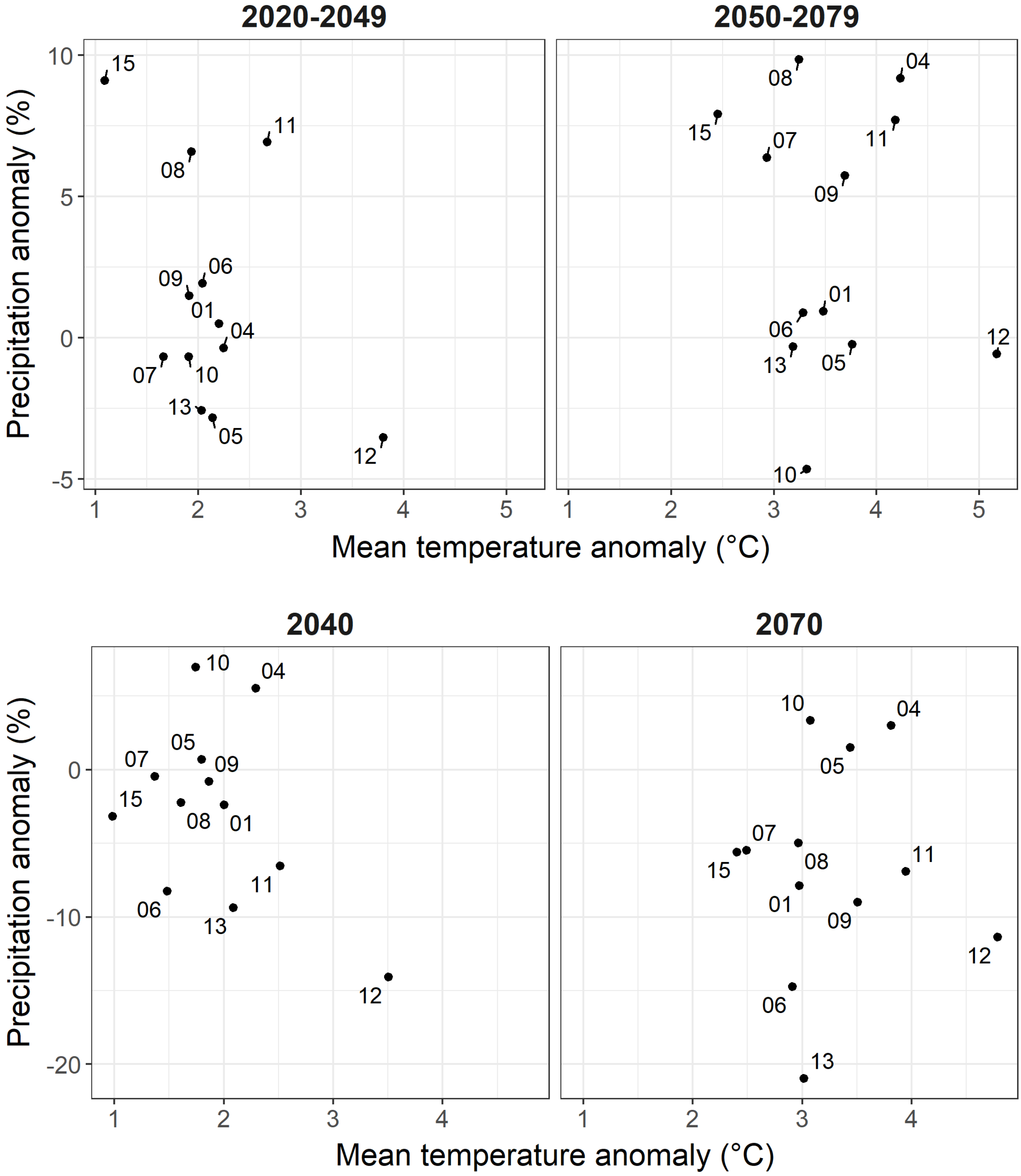


Figure 16. Climate change signal for the 12 projections used. Top: Annual precipitation and temperature anomaly under RCP8.5 for 2030-2049 ('2040') and 2060-2079 ('2070') with respect to 1994-2015 baseline. Bottom: Comparison of the Scotland arable area-wide mean climate change signal in the growing season only (March to September).

Figure 16 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

In this section, results are presented either as:

- Climate signal: projection anomaly plots.
- Mean monthly plots for observed and future periods.
- Change maps: the differences between the baseline and future projection periods (Note: we have provided one example, EM01, but there are the other 11 projections also available).
- Agreement maps: where there is agreement when multiple projections are used.
- Change direction maps: an increase or decrease in precipitation or temperature.
- National area proportion plots: showing the % of Scotland's land area projected to experience an increase of decrease in precipitation and temperature per month for each of the 12 projections.

Projected Changes in Precipitation

The national monthly precipitation anomaly (Figure 17) 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. May to July show little signs of future change but do not align well to the observed changes. 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.

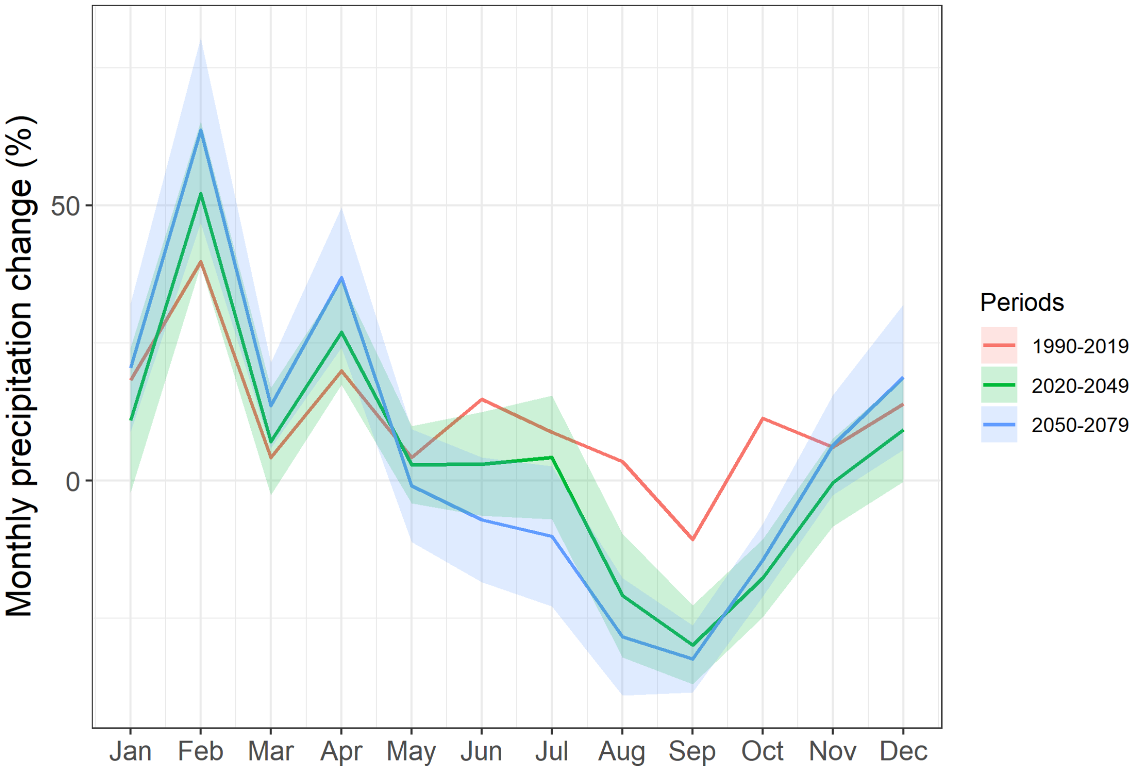


Figure 17. Percent change in the national mean monthly precipitation compared to the 1960-1989 baseline for three time periods. Solid lines: 1990 – 2019 (red, observed data); 2020 – 2049 (green) and 2050 – 2079 (blue) mean of the 12 climate projections. Shaded areas represent the variation between the 12 projections. Note: the 0 line represents the baseline.

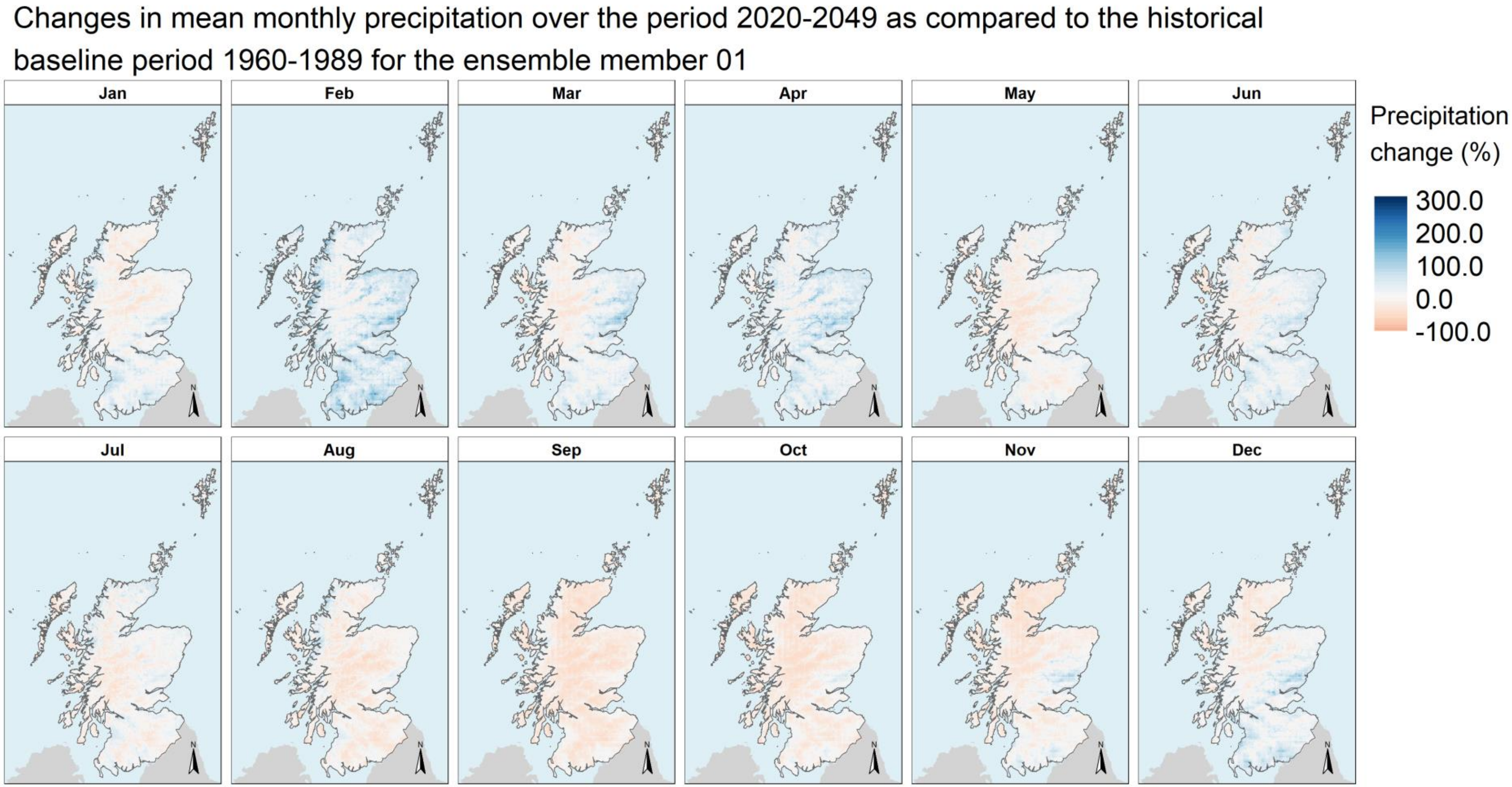


Figure 18a. Ensemble Member 01 projection of change in precipitation (%) for the 2020 – 2049 period compared to the 1960 - 1989 baseline. Notes: there is a difference in scale to that in Figure 18b; There are a further 11 Ensemble Member projections.

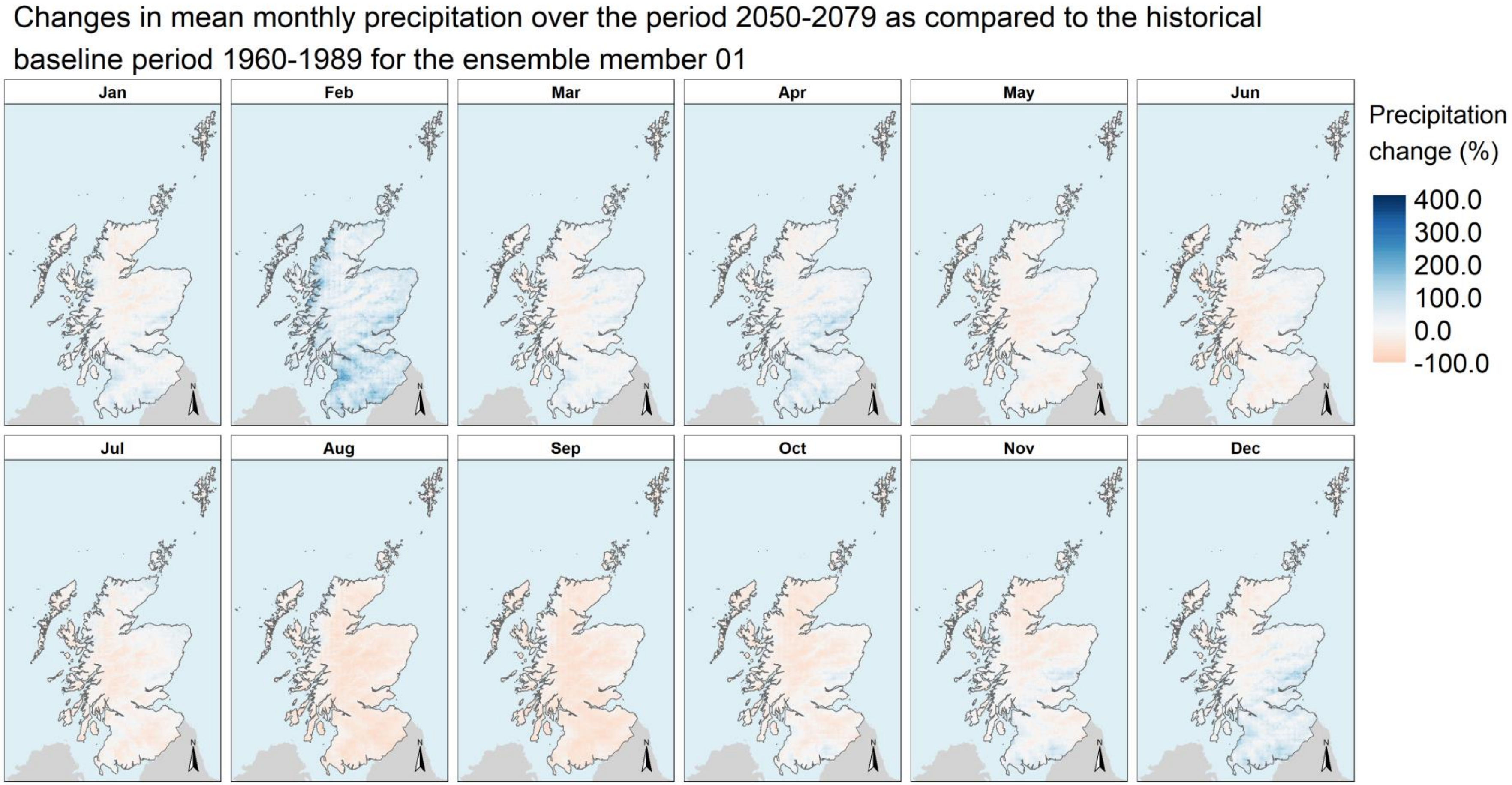
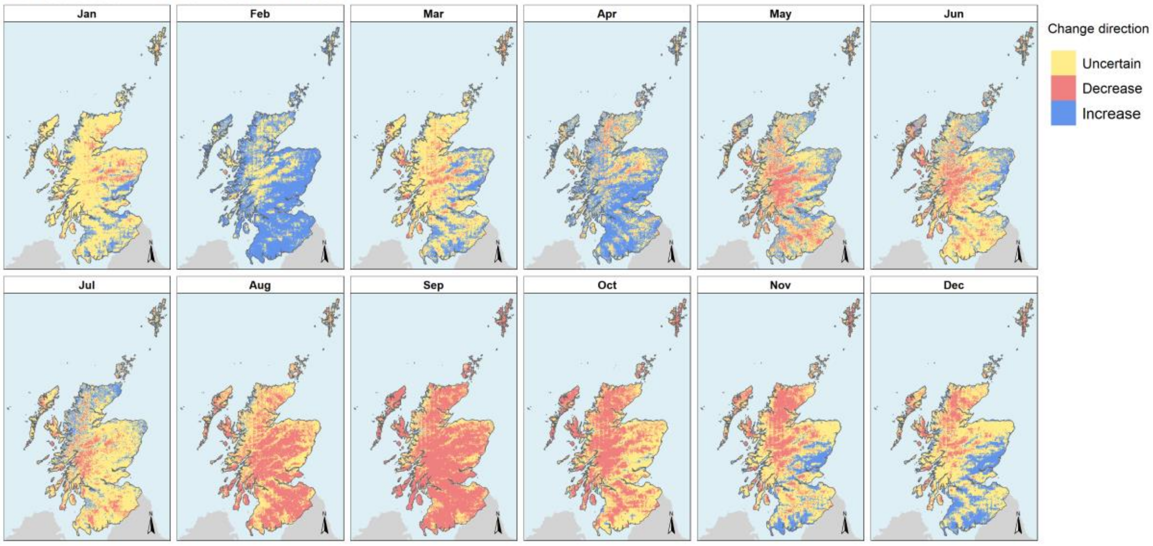


Figure 18. Ensemble Member 01 projection of change in precipitation (%) for 2050 – 2079 period compared to the 1960 - 1989 baseline. Notes: there is a difference in scale to that in Figure 18a; There are a further 11 Ensemble Member projections.

The example provided in Figure 18a and b is for one projection (EM01), which has a c. 2°C temperature increase in the 2020 – 2049 period and a similar precipitation total to the current climate. This example indicates that in the future February and April will generally become wetter, June becomes drier in the west and wetter in the east, whilst July to November become drier. December and January show drier conditions in the north but wetter in the south. We can see from Figure 17 that this temporal pattern is generally consistent with the other projections. The next step in the analysis is to then assess the spatial consistency of the projections.

Agreement between projections

Rather than provide here maps for all 12 projections (they have been mapped and archived), we have instead produced 'agreement maps' showing where the projections produce the same or similar results.


Change direction agreement for mean monthly precipitation over the period 2020-2049 for at least 12 ensemble members

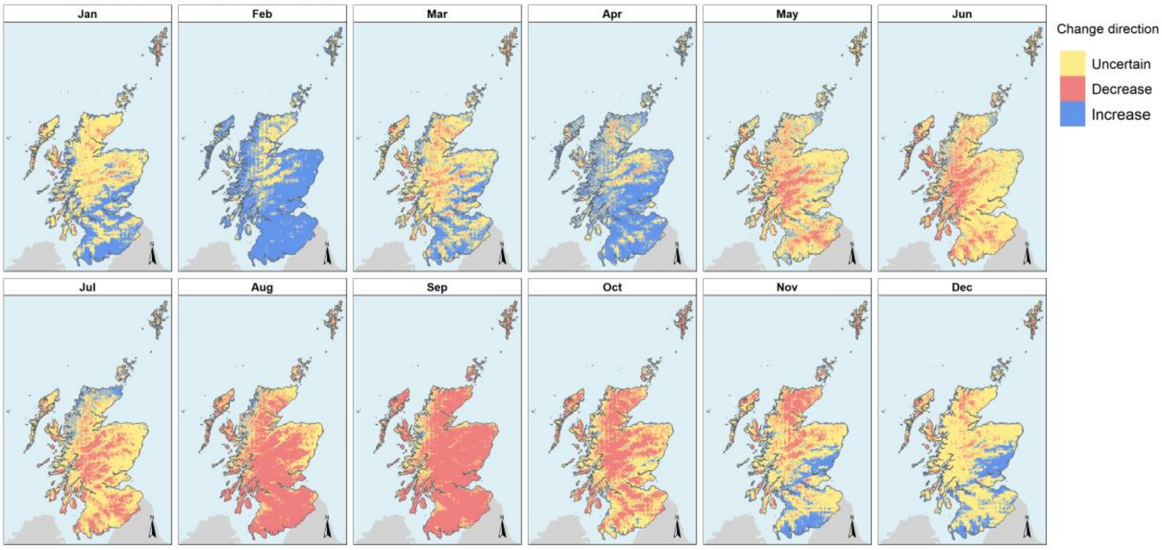

Change direction agreement for mean monthly precipitation over the period 2050-2079 for at least 12 ensemble members

Figure 19. Agreement maps for all 12 projections on the direction of change in mean monthly precipitation for the 2020 – 2049 (top) and 2050 – 2079 (bottom) periods.

Figure 19 shows the agreement in either having an increase or decrease in precipitation for all 12 projections (Note: we have agreement maps for 12 to 7 projections and have the potential to select combinations based on overall projected anomaly and or model skill). This approach gives us more confidence in the probabilities of estimated future climates. From Figure 19, there is general agreement for most of Scotland that September may experience a decrease in precipitation. Similarly, February is likely to see an increase. Yellow areas in Figure 19 represent locations where there is no agreement between the projections (e.g. some indicate increases, other decreases). For January, there are few areas where there is agreement for the 2020 – 2049 period, but this shifts towards agreement that southern Scotland is likely to see an increase in precipitation.

It is worth noting that the level of agreement between projections increases in the 2050 – 2049 period for some months, e.g. the ‘uncertain’ (yellow) areas in August and September in Figure 19 are less than for the 2020 – 2049 period, but decreases for others (e.g. June).

Changes in variability

Climate change projections indicate an increase in temporal (UKMO 2019) and spatial variability (UKCP18), however, the climate models have a varying level of skill in simulating observed variability.

To illustrate variation, we also produce maps of the changes in Standard Deviation (σ). Figure 20 shows the changes for EM01, where blues areas represent an increase in σ meaning more variability, and red where σ decrease and variability is reduced. Whilst not an ideal form of variance illustration, it does provide useful indications of possible directions of change.

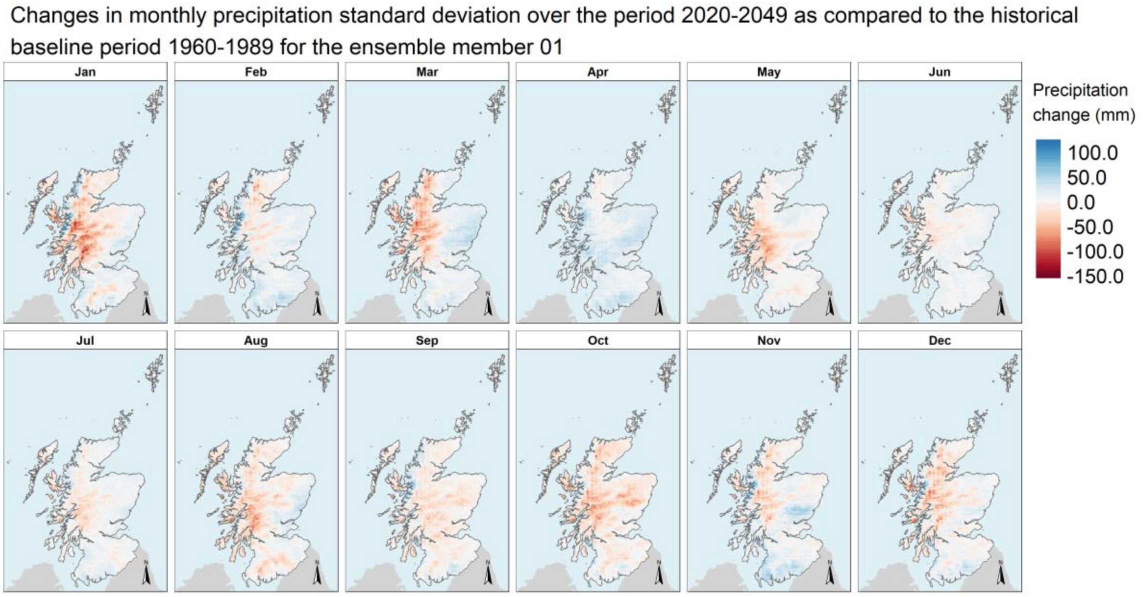

Changes in monthly precipitation standard deviation over the period 2020-2049 as compared to the historical baseline period 1960-1989 for the ensemble member 01

Figure 20. Ensemble Member 01 projection of change in the standard deviation of precipitation (mm) compared to the 1960 - 1989 baseline.

From the EM01 example in Figure 20, there is a possible reduction in variability in the higher elevation upland areas, and an increase in eastern and southern areas. April is projected to see a general increase, whilst September may have a decrease in σ. To date we have not produced agreement maps for the standard deviation mapping, but this is feasible. As noted earlier, a related Deliverable (D2.1b) will be produced detailing changes in extremes, and a further Deliverable (D2.1c) with detail changes in event return period.

Figure 21 plots the percent of the national land area where there may be an increase, decrease or no change in mean monthly precipitation per month for all 12 projections. The results for EM01 seen in Figures 18a and b, and 20 can be put int context of the other projections, which also indicate a temporal pattern of increased precipitation in the winter and a decrease in the summer to early autumn.

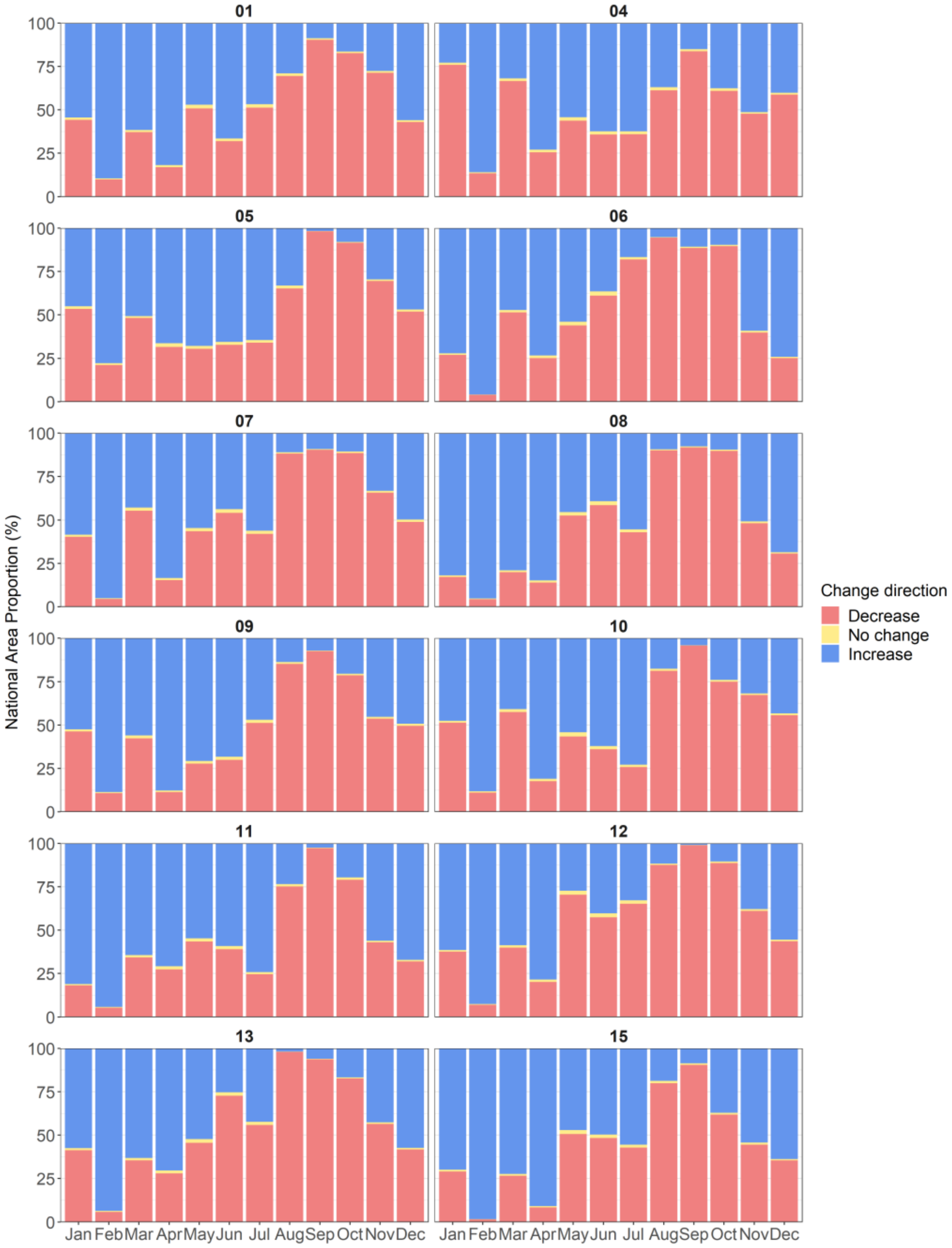


Figure 21. Scotland's land area proportion projected to experience either an increase (blue) no change (yellow) or decrease (red) in mean monthly precipitation for the 2040's period.

There is a high level of consistency between the projections that February may experience an increase in precipitation across the whole of Scotland, whereas August and September may see decreases.

Projected Changes in Temperature

The national mean monthly observed and projected maximum and minimum temperature changes are shown in Figure 22. As seen in Part 2, 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.

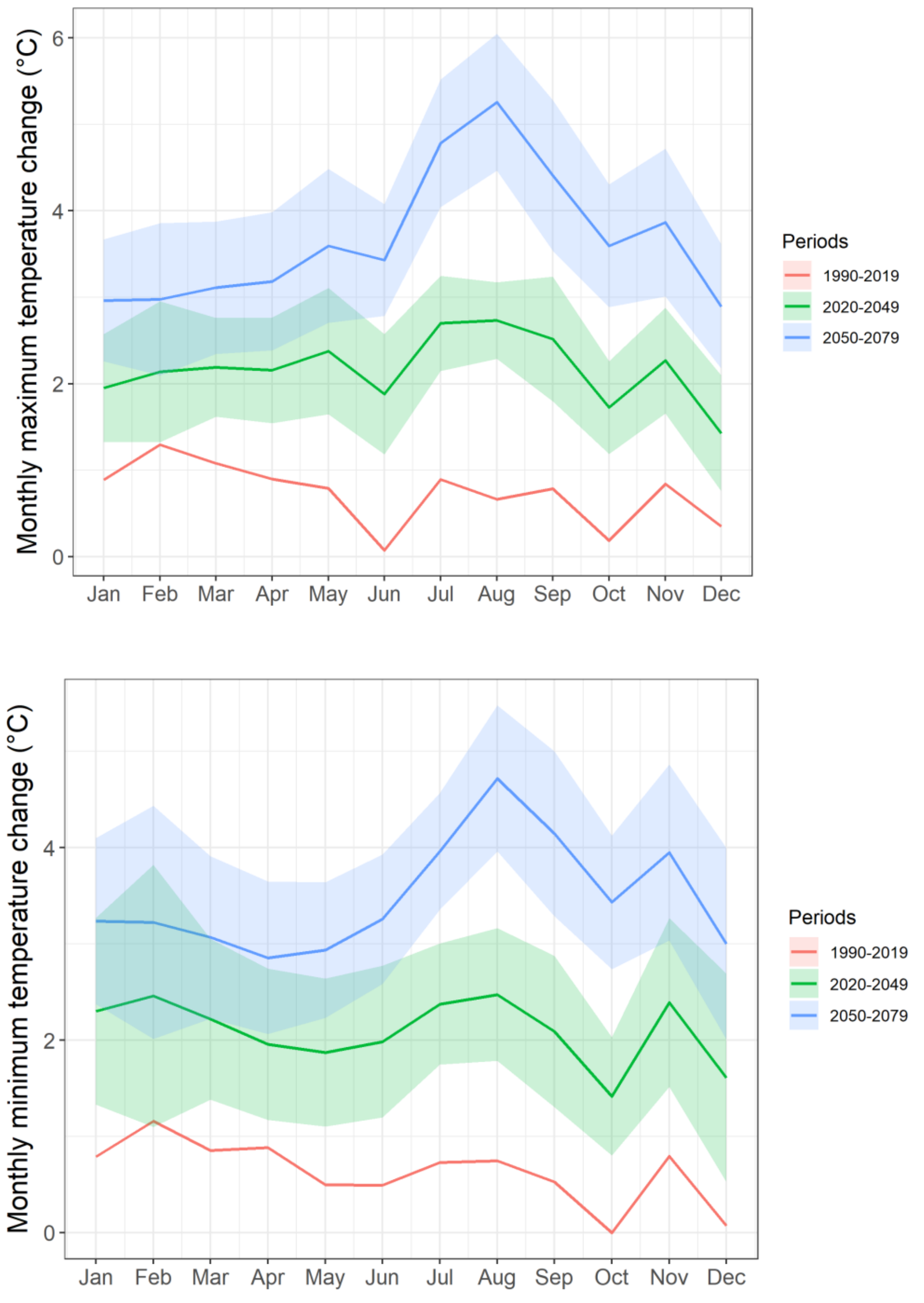


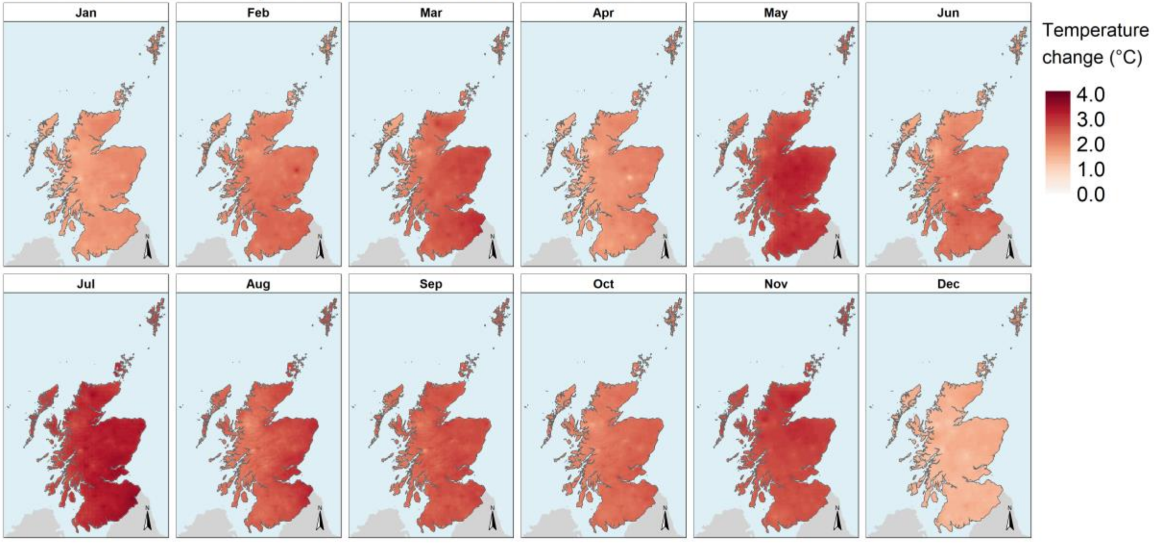
Figure 22. Percent change in the national mean monthly maximum (top) and minimum temperature (bottom) compared to the 1960-1989 baseline for three time periods. Solid lines: 1990 – 2019 (red, observed data); 2020 – 2049 (green) and 2050 – 2079 (blue) mean of the 12 climate projections). Shaded areas represent the variation between the 12 projections. Note: the 0 line represents the baseline.

Maximum Temperature

The observed trend in maximum temperature is projected to continue through the 2020 – 2049 and 2050 – 2079 periods (Figure 22). For the initial future period to 2050 the ensemble mean increase is approximately 2°C, but higher especially in February, July, August and November. October and December are estimated to have less of an increase. The overall projection mean increase, particularly in the summer months may increase to in excess of 4°C warmer.

For the change maps, as with precipitation, here we present one example projection (EM01) to illustrate possible changes in maximum temperature.

Changes in mean monthly maximum temperature over the period 2020-2049 as compared to the historical baseline period 1960-1989 for the ensemble member 01



Changes in mean monthly maximum temperature over the period 250-2079 as compared to the historical baseline period 1960-1989 for the ensemble member 01

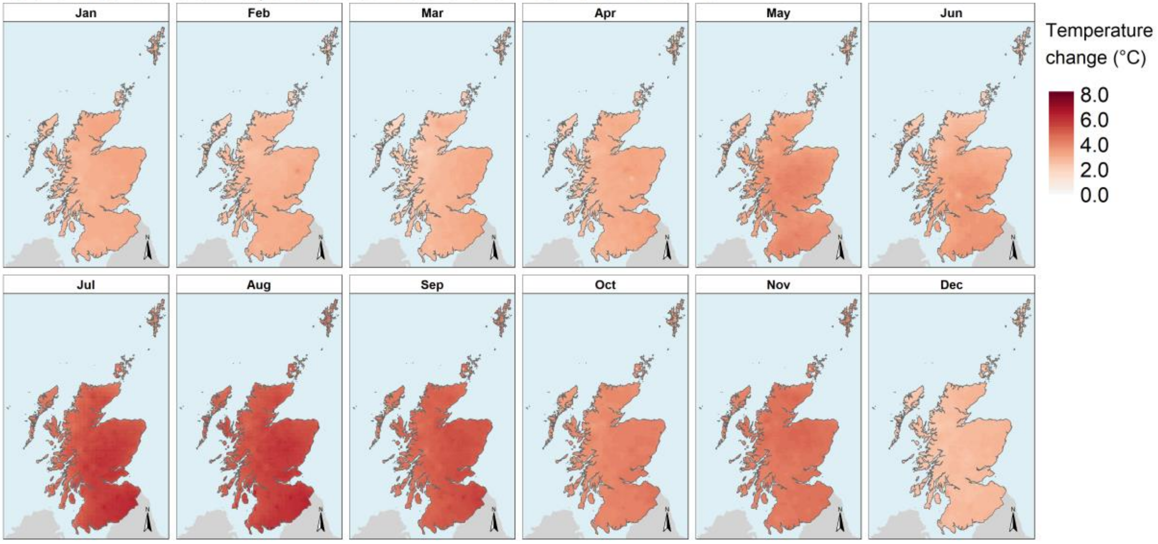
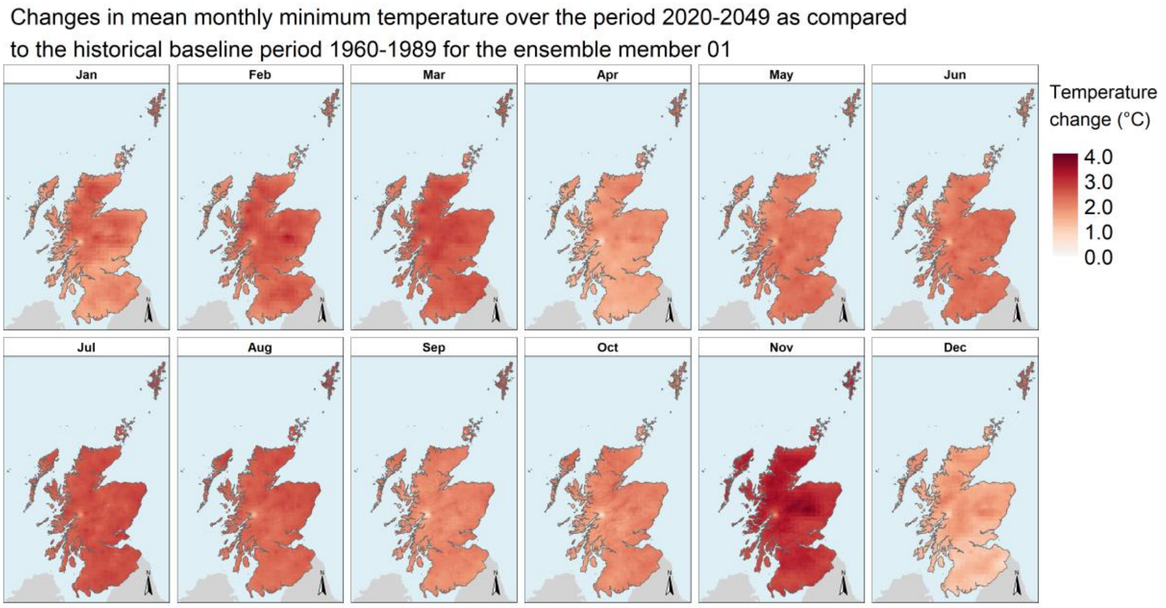


Figure 23. Ensemble Member 01 projection of change in mean monthly maximum temperature (°C) for 2020 – 2049 (top) and 2050 – 2079 (bottom) periods compared to the 1960 - 1989 baseline. Notes: 1). There are differences in scales between the two maps. 2). There are a further 11 Ensemble Member projections.

The maximum temperature increase is estimated to be uniform across Scotland, and does not reflect the effects of topography and elevation (Figure 23). There is some variation between projections as to how much individual months warm, the general pattern is for more warming in the summer months except June. In respect of the change direction maps, and area proportion plots for mean monthly maximum temperature, **all** projections show an increase in maximum temperature (one exception is EM15 which shows a possible decrease in December for the Ben Nevis area). Hence, we have not shown the maps here.

Minimum Temperature

As with precipitation and maximum temperature, here we present one example projection (EM01) to illustrate possible changes in maximum temperature.


Changes in mean monthly minimum temperature over the period 2020-2049 as compared to the historical baseline period 1960-1989 for the ensemble member 01

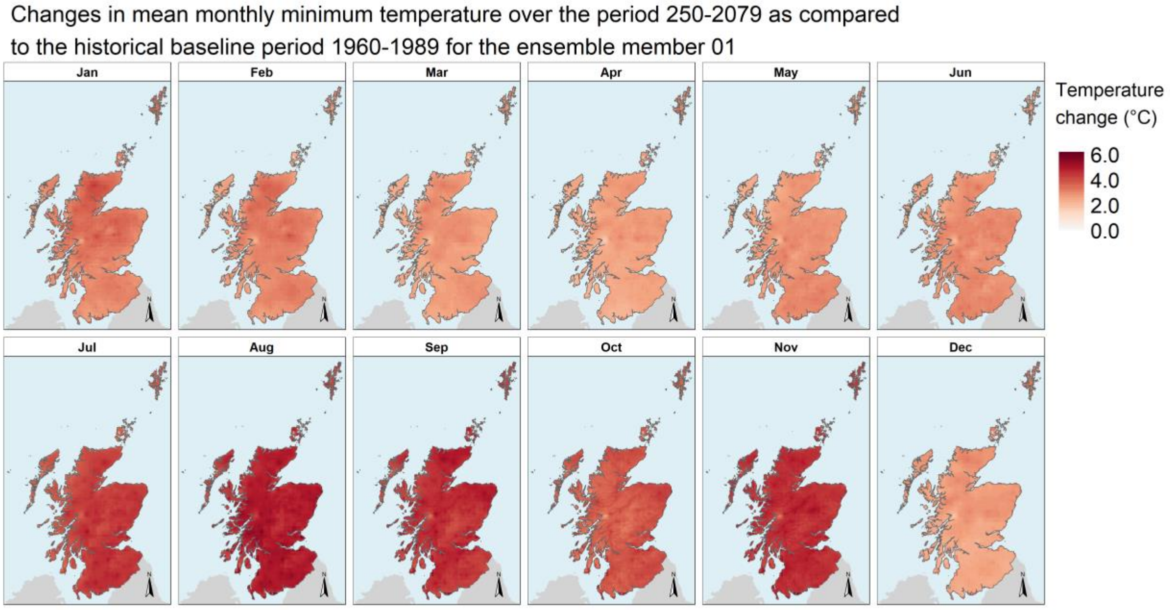

Changes in mean monthly minimum temperature over the period 250-2079 as compared to the historical baseline period 1960-1989 for the ensemble member 01

Figure 24. Ensemble Member 01 projection of change in mean monthly minimum temperature (°C) for 2020 – 2049 (top) and 2050 – 2079 (bottom) periods compared to the 1960 - 1989 baseline. Notes: 1). Differences in scales. 2). There are a further 11 Ensemble Member projections.

The minimum temperature increase is estimated to be relatively uniform across Scotland but unlike maximum temperature does show some relationship with topography and elevation amongst some of the 12 projections (Figure 24). As with maximum temperature, there is some variation between projections as to how much individual months warm, but the general pattern is more mixed with some projections showing greater warming in the winter months. In respect of the change direction maps, and area proportion plots for mean monthly maximum temperature, **all** projections show an increase in maximum temperature. The only exception is EM15 which shows a possible decrease in December for most of the upland areas of Scotland.

Note: we have not presented the agreement maps for the 12 projections of maximum and minimum temperature, as there is a high level of agreement between them.

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.

Location specific case study: Balmoral winter.

As an example of location specific trends and future projections, we present here details of observed and projection data for Balmoral. Balmoral has a long and good quality data record from 1918 to 2018, enabling a detailed assessment of the past trends for maximum and minimum air temperature and precipitation at a specific location. Results presented here are a summary of a study assessing past and future snow cover change, hence focussed on the winter months (Rivington et al 2019).

Table 1: Changes in Balmoral winter period monthly precipitation and temperature between 1918 and 2018

	Precipitation (mm)	Maximum Temperature (°C)	Minimum Temperature (°C)
November	↑ 17	↑ 1.64	↑ 0.85
December	↓ -111	↑ 0.64	↓ -0.34
January	↓ -24	↑ 1.34	↑ 1.20
February	↑ 45	↑ 0.98	↑ 0.37
March	↑ 47	↑ 1.23	↑ 1.28
April	↑ 33	↑ 1.90	↑ 0.82
May	↓ -117	↑ 1.34	↑ 0.81

Table 1 and Figures 25 - 26 show there has been a substantial warming trend per month since 1918. The rate of increase is greater for maximum temperature (the winter average is 1.30°C) than for minimum (average of 0.71°C). However, December minimum temperature has decreased by c. 0.34°C.

Substantial increases in maximum temperature have occurred in April (1.90°C), indicating an increase in melting effects on snow. However average minimum temperatures have not increase as much as the maximum temperatures. Precipitation has seen decreases in December, January and May, but increases in the other winter months; yet it remains highly variable over time and between years.

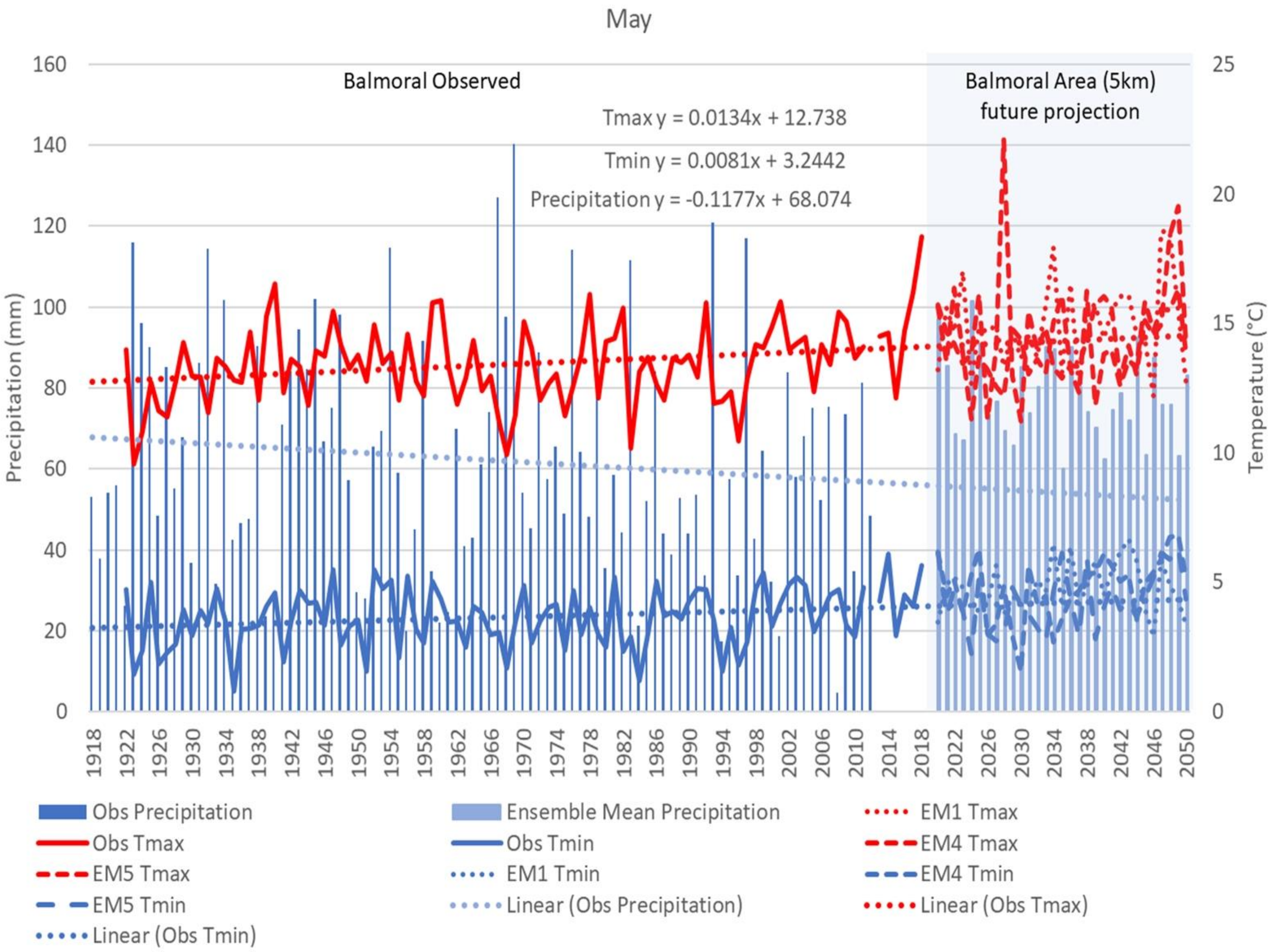


Figure 25. Weather data (maximum and minimum daily temperature, total daily precipitation) trends for May, Balmoral 1918-2018 and estimated future 2020-2050 (RCP8.5)

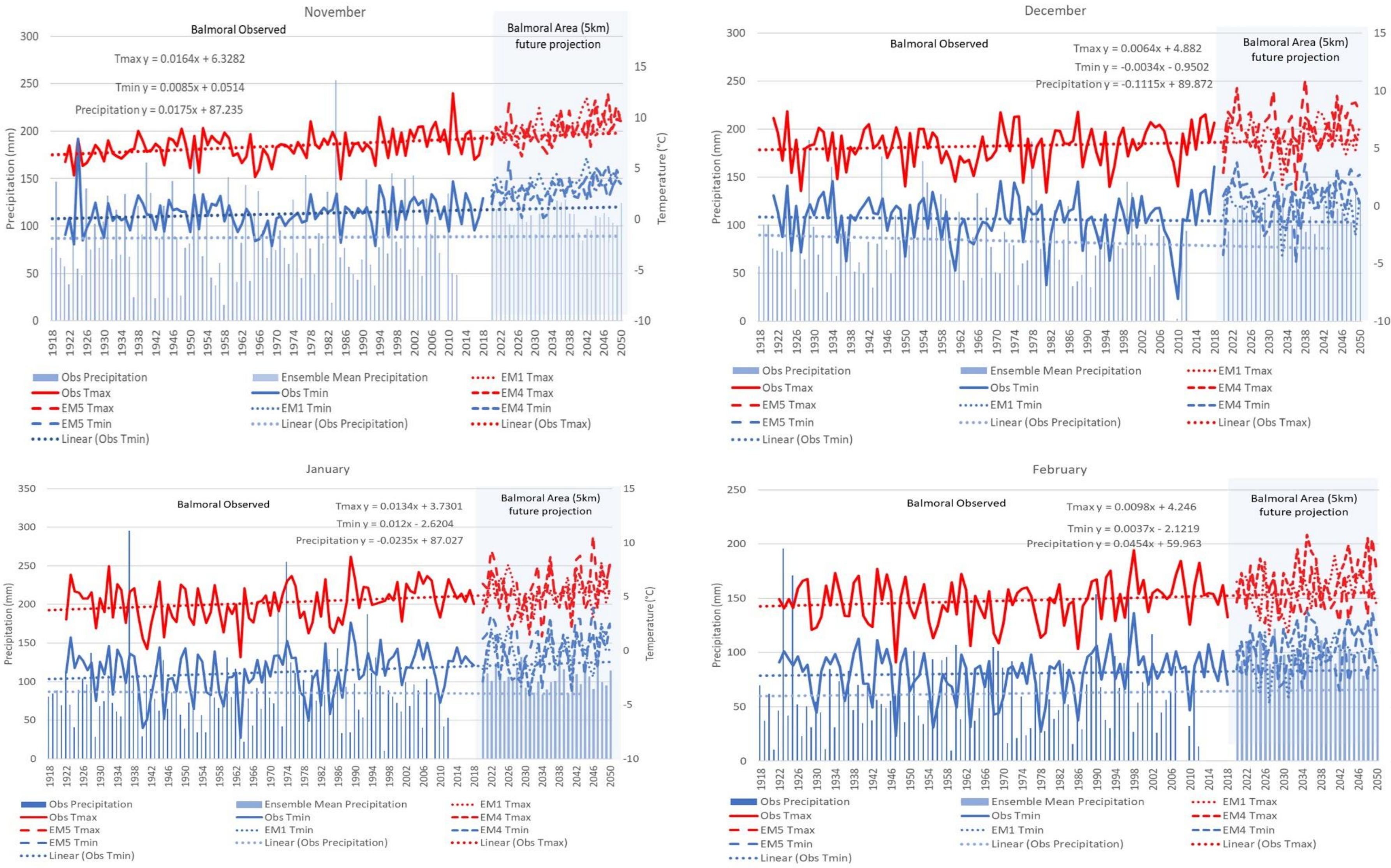


Figure 26. Weather data (maximum and minimum daily temperature, total daily precipitation) trends for November, December, January, and February, Balmoral 1918-2018 and estimated future 2020-2050 (RCP8.5)

Whilst there has been large annual variability in precipitation, some months (May in Figure 25, December in Figure 26) have seen a decrease in mean monthly total.

Data presented in Figures 25 and 26 also shows that there has been an observed warming trend for all winter months, except minimum temperature in December. These are likely to continue in the future. Precipitation however has remained highly variable but with no clear observed trend across all winter months.

The estimated linear trend lines (dotted lines in Figures 25 and 26) have been extended to 2050 to show how the observed trends relate to the future projections. In the May example in Figure 25 the maximum and minimum temperature trends matches well to the climate model projections. Here only three climate model estimates are shown from the available 12, but these are representative of the range. For other months, the projected future minimum temperatures are greater than indicated by the extended observed trend. This may be due to systematic climate model error over-estimating minimum temperature (Rivington et al 2008a).

Part 4: Changes in Climatic Water Balance

This section assesses the combined impacts of changes in temperature and precipitation on the Climatic Water Balance (CWB): this is the difference between precipitation input and evapotranspiration output. Evapotranspiration is the total amount of moisture returned to the atmosphere from evaporation from surfaces and water transpired from plants. We used the Priestly-Taylor method using precipitation, maximum and minimum temperature and solar radiation.

Here we present the estimated CWB for the two observed periods and the differences between them to indicate trends, followed by an example of a future projection (EM01) and changes in the two future periods from the 1960 – 1989 baseline. Change direction agreement maps are shown (Figures 32 and 36) for the two future periods for projection EM01, along with the area proportions of change direction for all 12 projections (Figures 33 and 37). Also provided are change direction maps indicating whether the CWB shifts in the future from surplus to a deficit (meaning switching from an excess of water to a shortage), remains at a surplus or deficit (hence the same as the baseline) or shifts from a deficit to a surplus (Figures 31 and 35). Note: whilst these two maps show areas that remain at surplus or deficit, it is possible that the amount of deficit or surplus and also increase or decrease.

Observed trends in Climatic Water Balance

The 1960 – 1989 (Figure 28) and 1990 – 2019 (Figure 29) shows that Climatic Water Balance is in surplus (precipitation is greater than evapotranspiration out) in upland areas from September through to March (blue areas on the maps). In September to October and February to March, lowland areas are generally in low surplus (precipitation is marginally higher than evapotranspiration). Between April and August, with the exception of elevated areas of the west coast, there is a CWB deficit (reddish – orange areas on the maps).

There has been an observed change in CWB from the 1960-1989 baseline (Figure 29), with the west coast upland areas in December through to April becoming wetter and hence increased surplus (but less so in March). In the east March through to May have experienced a decrease as has the whole of Scotland in September (more so in the west). June to August have experience an increase in CWB (precipitation > evapotranspiration).

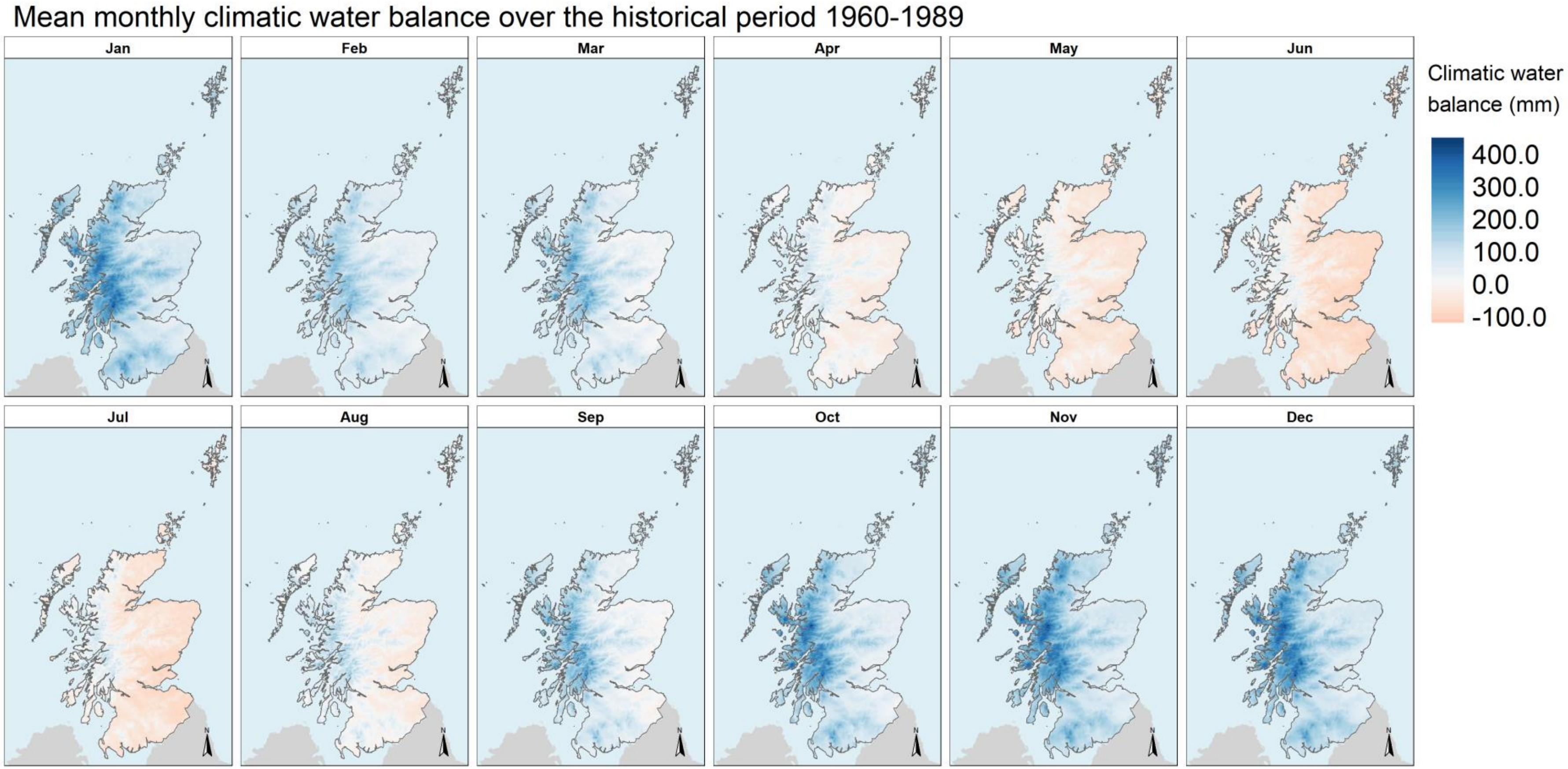


Figure 27. Climatic Water Balance (precipitation – evapotranspiration) per month for the 1960 – 1989 baseline period. Blue areas indicate a water surplus, red areas indicate a water deficit.

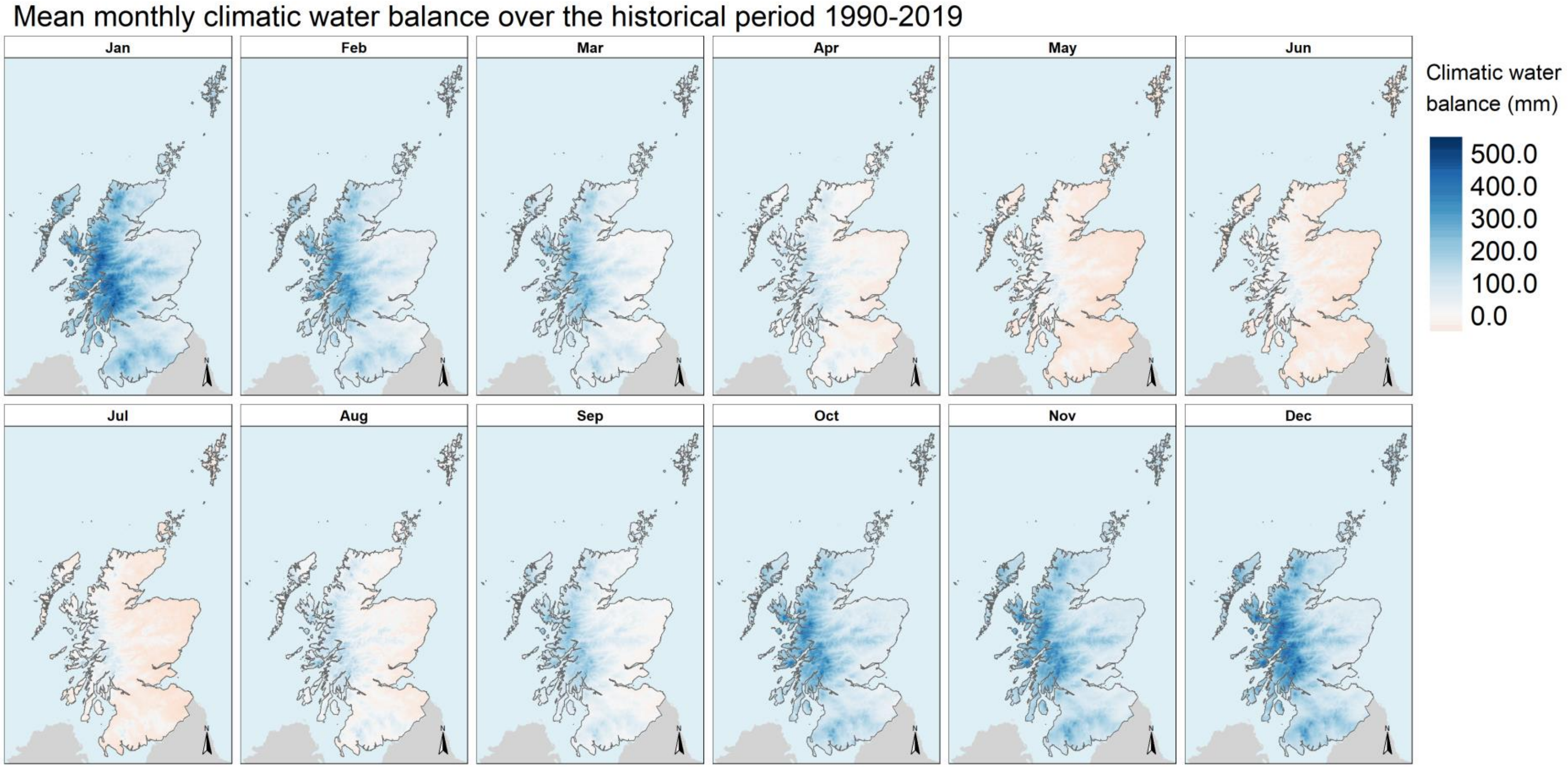


Figure 28. Climatic Water Balance (precipitation – evapotranspiration) per month for the 1990 – 2019 current climate period. Note: scales are different from those in Figure 27 (baseline). Blue areas indicate a water surplus, red areas indicate a water deficit.

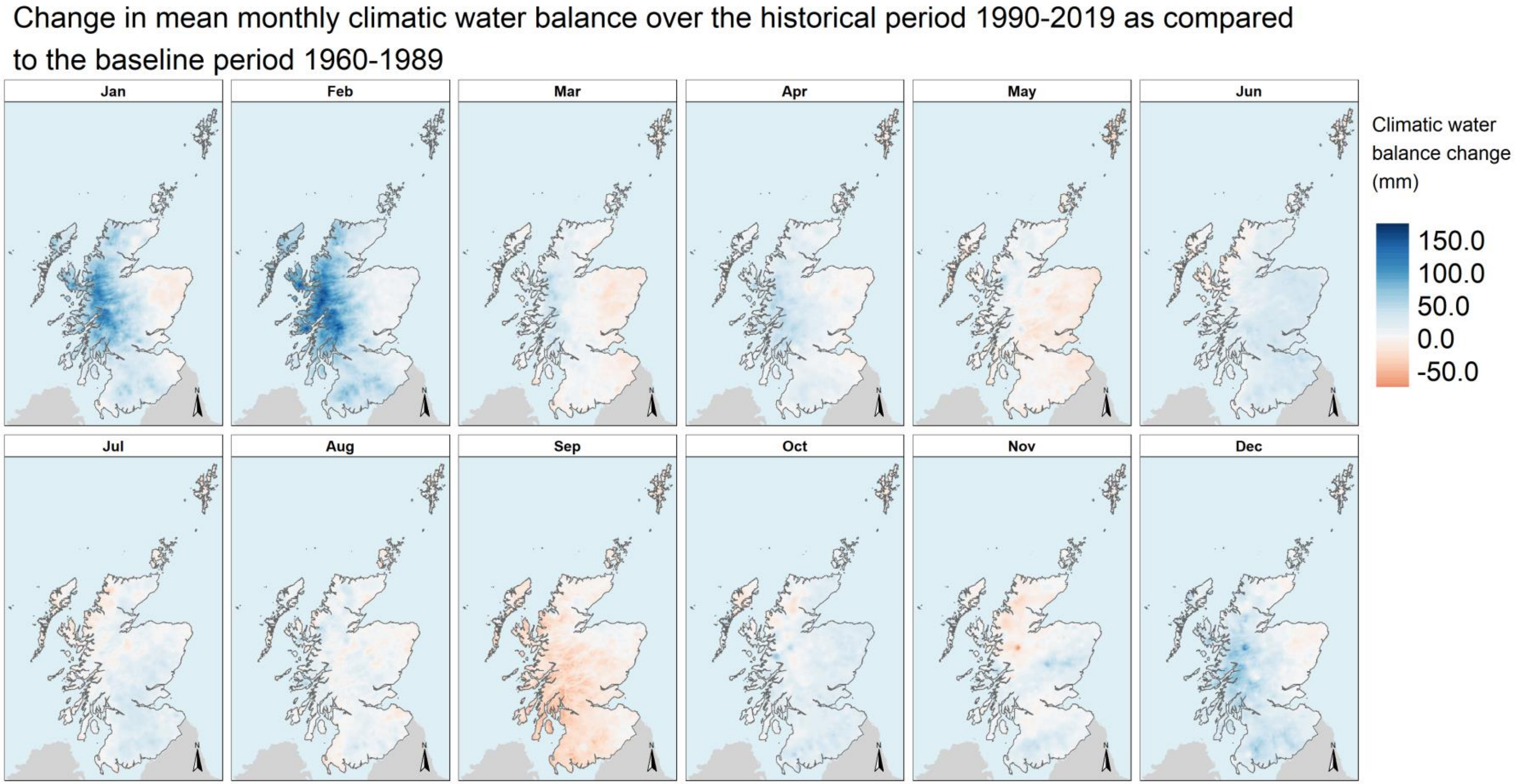


Figure 29. Change in the Climatic Water Balance (precipitation – evapotranspiration) per month between the 1960 – 1989 baseline and 1990 – 2019 current climate period.

Future projections in the Climatic Water Balance

This section assesses the two future projection periods of the estimated Climatic Water Balance (CWB). As previously, we have illustrated potential change with a single projection (ensemble member 01) and agreement maps for all projections. We re-emphasis here that there are large variations in the projections (Figure 16) hence there will be an associated large range in potential CWB responses, which are illustrated in the land area proportion graphs.

2020 – 2049 Climatic Water Balance

Using projection EM01 as an example (Figure 30), there is a projected overall change in the mean monthly CWB trending towards negative values (red areas on the maps, meaning less water available). There are however increases in February for most areas, and in the east in March, April and June, plus southern areas in December and January.

The change direction map for projection EM01 (Figure 31) shows October to March as remaining in CWB surplus (precipitation > evapotranspiration), but importantly there are areas between May and September that might experience a shift from surplus to a deficit. In this example April has areas down the central (south to north) parts where there may be a shift to an observed period deficit to a future surplus.

Figure 32 shows where there is agreement between all 12 climate projections for these shifts in CWB. 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 > evapotranspiration. There is also high agreement that the east will remain in deficit between May and August.

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. In September eastern lowland areas shift from surplus to deficit, whilst there is also a lack of agreement across the 12 projections as to the type of change the central (north to south) parts of the country may experience.

This and results for precipitation indicate a possible change in the west to east precipitation gradient and associated water availability, with the consequence that where the neutral point is (on a north to south axis) between surplus and deficit is moving westwards.

Note: Of concern if this shift from surplus to deficit occurs in peatland areas, as seen in Figures 31 and 32 for several of the summer months (and Figures 35 – 36 for the 2050 – 2079 period), is there may be an increased probability of peat becoming a source of carbon due to drying (reduction in anaerobic conditions), rather than a sink (if remaining wet and maintaining ecological functions), whilst also impacting on restoration efforts. The implication of the projections of CWB is a reduced amount of water available, however the impact on peatlands will also depend on broader hydrological process such as the water table height (also see report: [Moderating extremes in water availability: a review of the role of functioning wetlands | CREW | Scotland's Centre of Expertise for Waters]()). This important aspect will be a focal issue to assess further within the Climate Change Impacts on Natural Capital project.

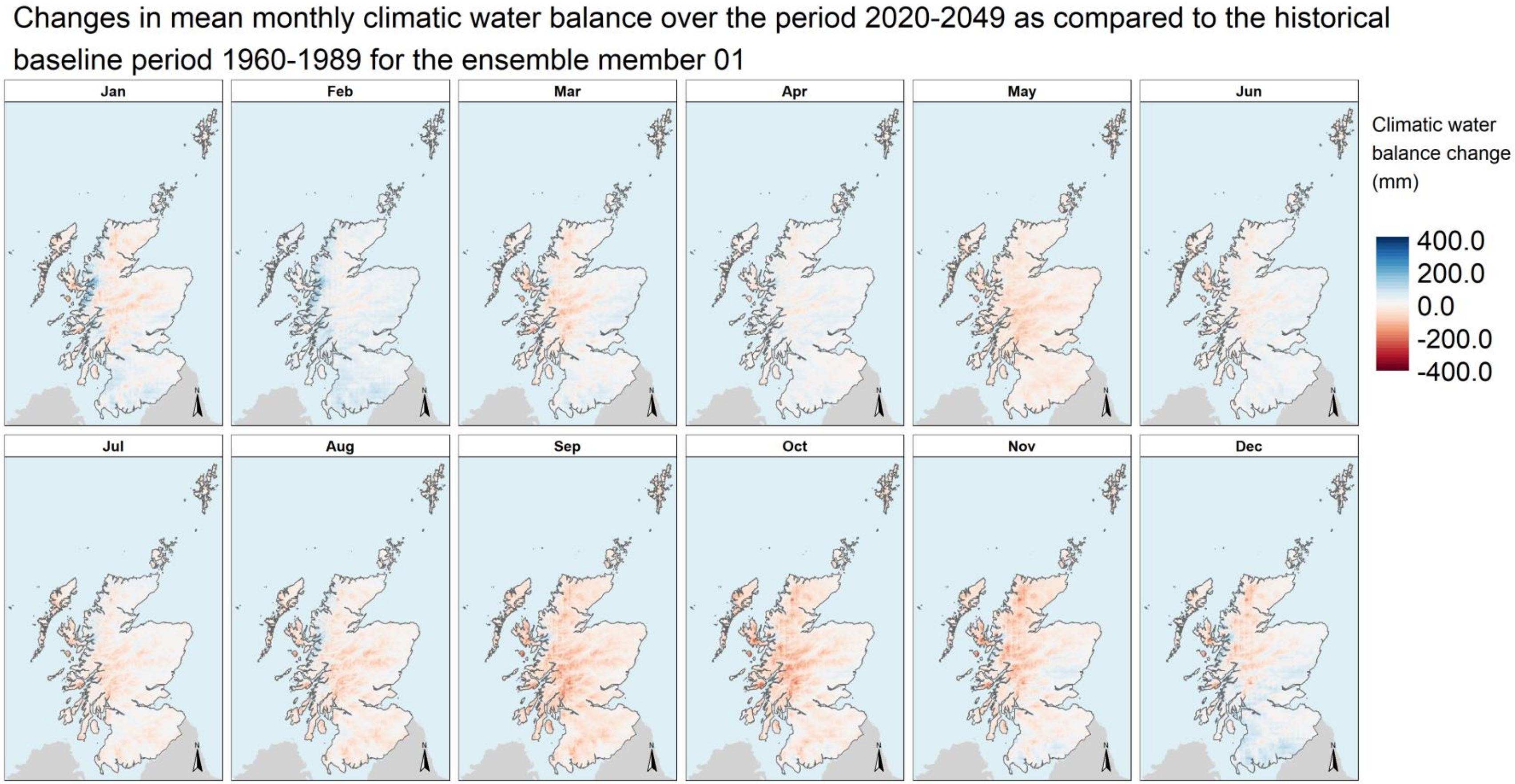


Figure 30. Projected changes in the Climatic Water Balance (precipitation – evapotranspiration) between the 1960 – 1989 baseline period and 2020 – 2049 period for ensemble member 01. Blue areas indicate a water surplus, red areas indicate a water deficit.

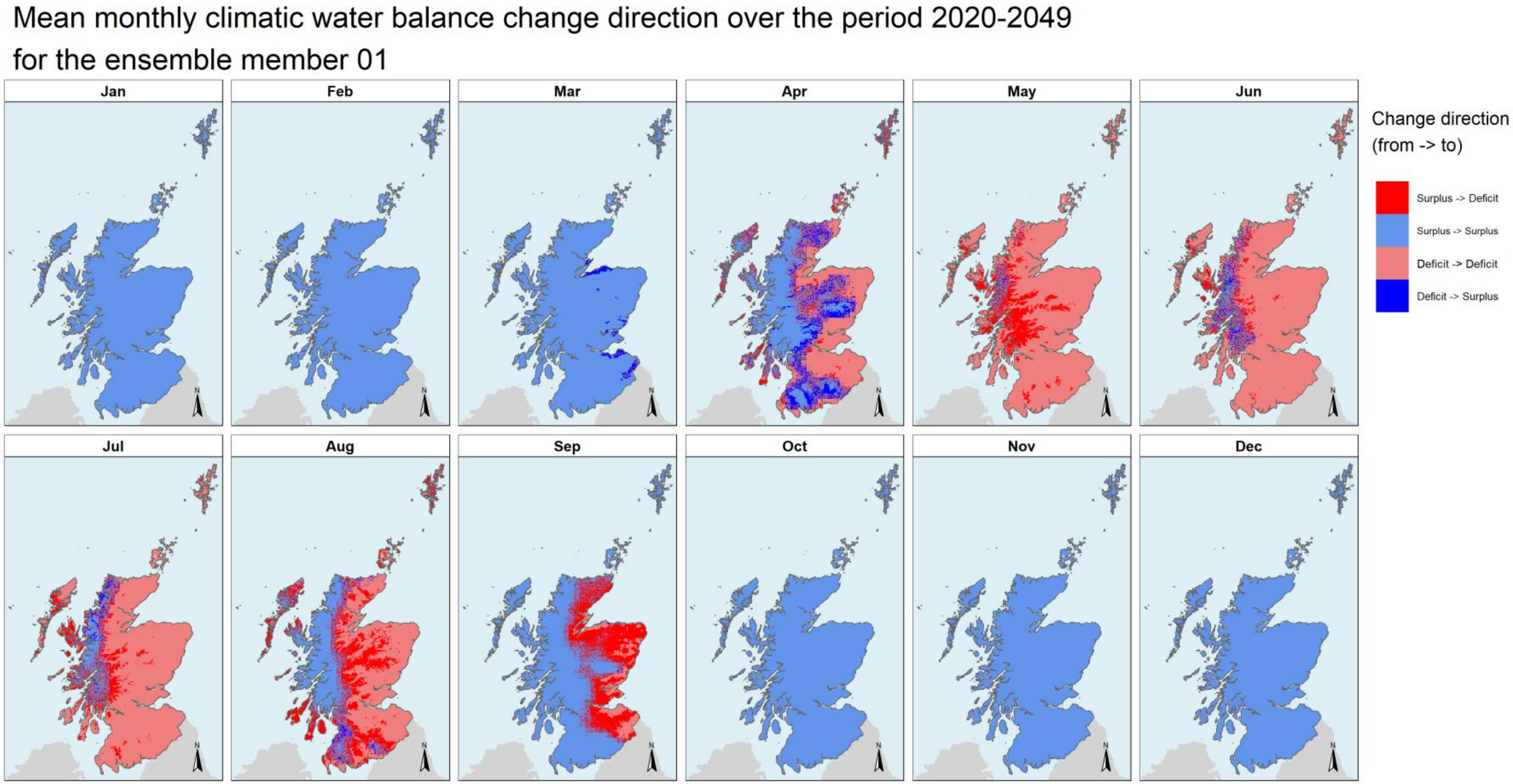


Figure 31. Climatic Water Balance change direction for 2020 – 2049 for ensemble member 01. Dark red: surplus to deficit; light red: deficit to deficit (remains a deficit); light blue: Surplus to surplus (remains a surplus); dark blue: deficit to surplus. Note: other maps provide details of the quantity of the surplus or deficit change.

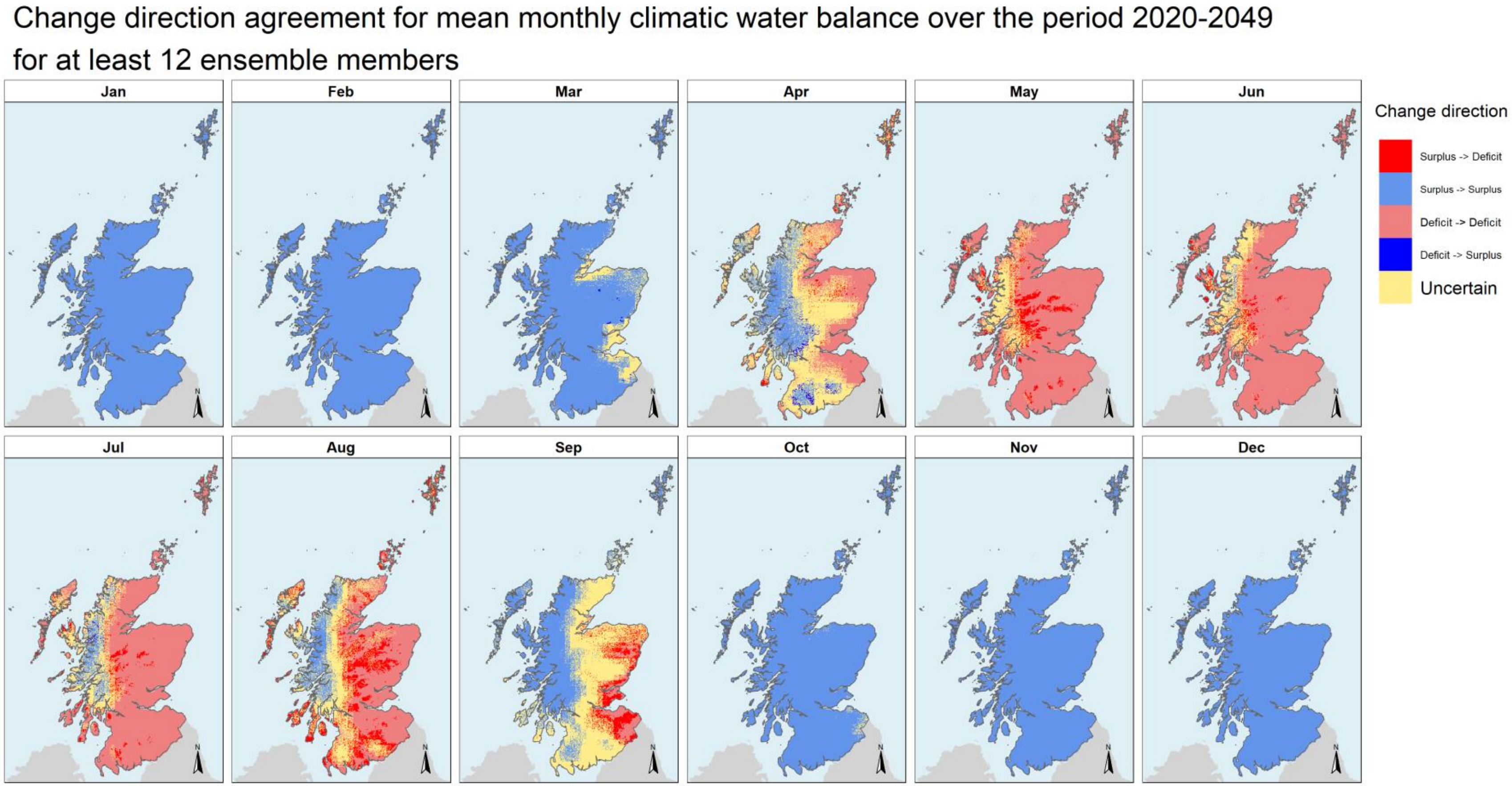


Figure 32. Agreement maps for the change direction (increase: blue, or decrease: red) of the Climatic Water Balance for the period 2020 – 2049 for all 12 climate projections (ensemble members). Yellow areas indicate no agreement between projections.

The pattern of area proportions of land projected to experience changes from surplus to deficit (and *vice versa* and remaining the same) is consistent between the 12 projections, but with variations in amount between them (Figure 33). August and September show consistently large areas shifting from surplus to deficit CWB. The changes from deficit to surplus seen in April indicates a potential increased risk of flooding events.

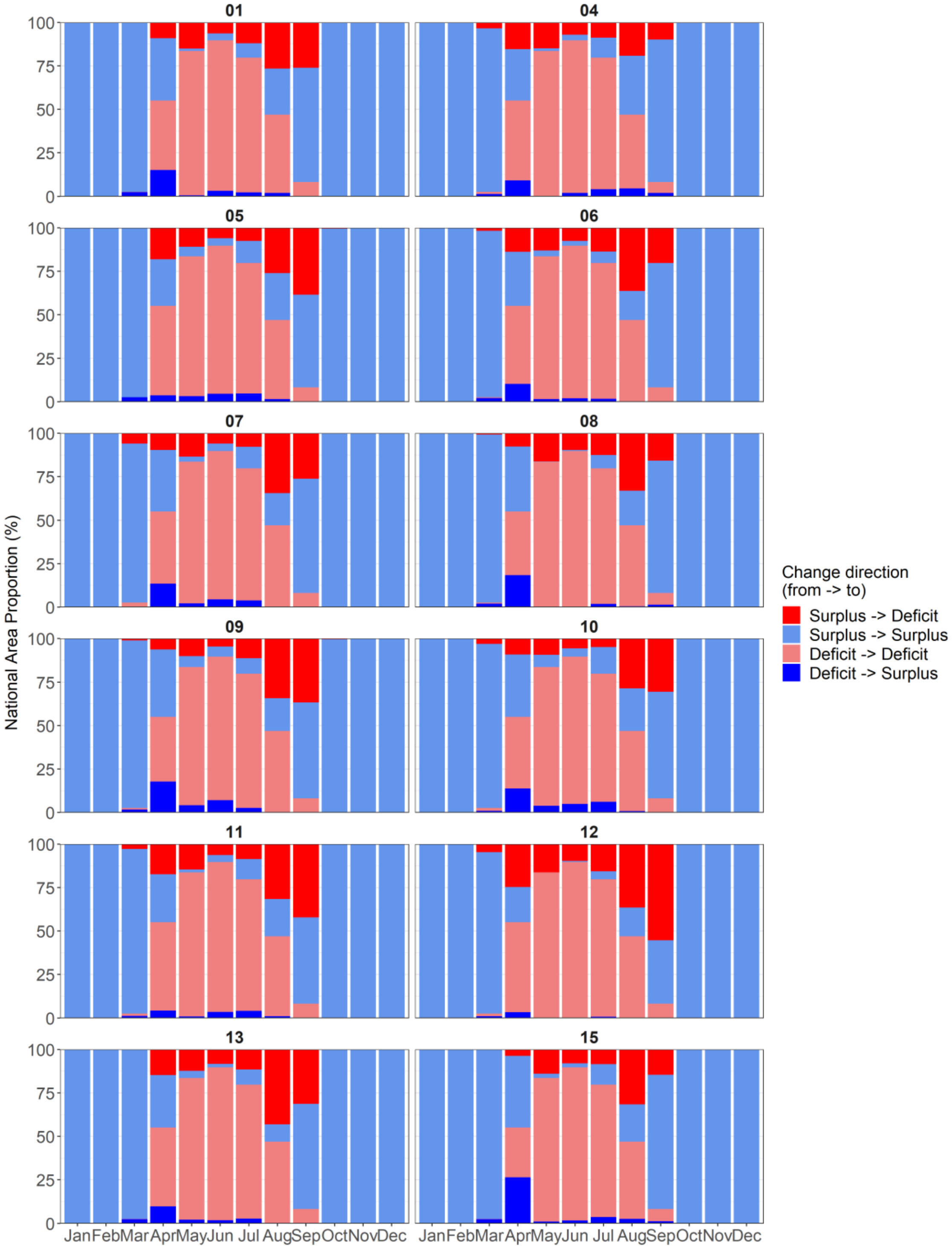


Figure 33. Area proportions for the change direction in Climatic Water Balance per month for all 12 climate projections for the period 2020 - 2049.

2050 – 2079 Climatic Water Balance

As per the 2020 – 2049 period we illustrate potential change in the Climate Water Balance with the EM01 projection, change direction, along with agreement maps and land area proportion graphs for all 12 projections.

The spatial pattern of projected changes of CWB for EM01 in the 2050 – 2079 period are similar to those of 2020 – 2049, however the extent and amount of change towards negative values (red areas in Figure 34) is larger. This reflects the increased warming seen in Part 2 driving higher rates of evapotranspiration, resulting in an increased reduction of water availability. February is estimated to continue having a positive increase in CWB (precipitation > evapotranspiration), as are southern parts of the country in December and January.

The mean monthly CWB change direction for 2050 – 2079 is again similar to the 2020 – 2049 period, however the boundary between remaining at a surplus (light blue in Figure 35) and shifting to a deficit (dark red) moves further to the west between June to September. In September more than half of the country in the east shifts from surplus to deficit. In April the south-west and Angus glens area are estimated to see a shift from deficit to surplus, as is a small section of the north-east coast in March.

Figure 36 indicates a high level of agreement of the change direction, with small areas of uncertainty as to where the boundary between remaining at surplus to shifting to deficit is (yellow areas, on a north-south line). Only April shows large uncertainty. These results imply a projected trend towards negative CWB with drying in the east (evapotranspiration > precipitation), with the gradient shifting westwards.

The pattern of land area proportion estimated to experience change (Figure 37) is similar to that of the 2020 – 2049 period (Figure 33), but with an increased proportion potentially shifting from surplus to deficit, indicating that water availability will decrease.

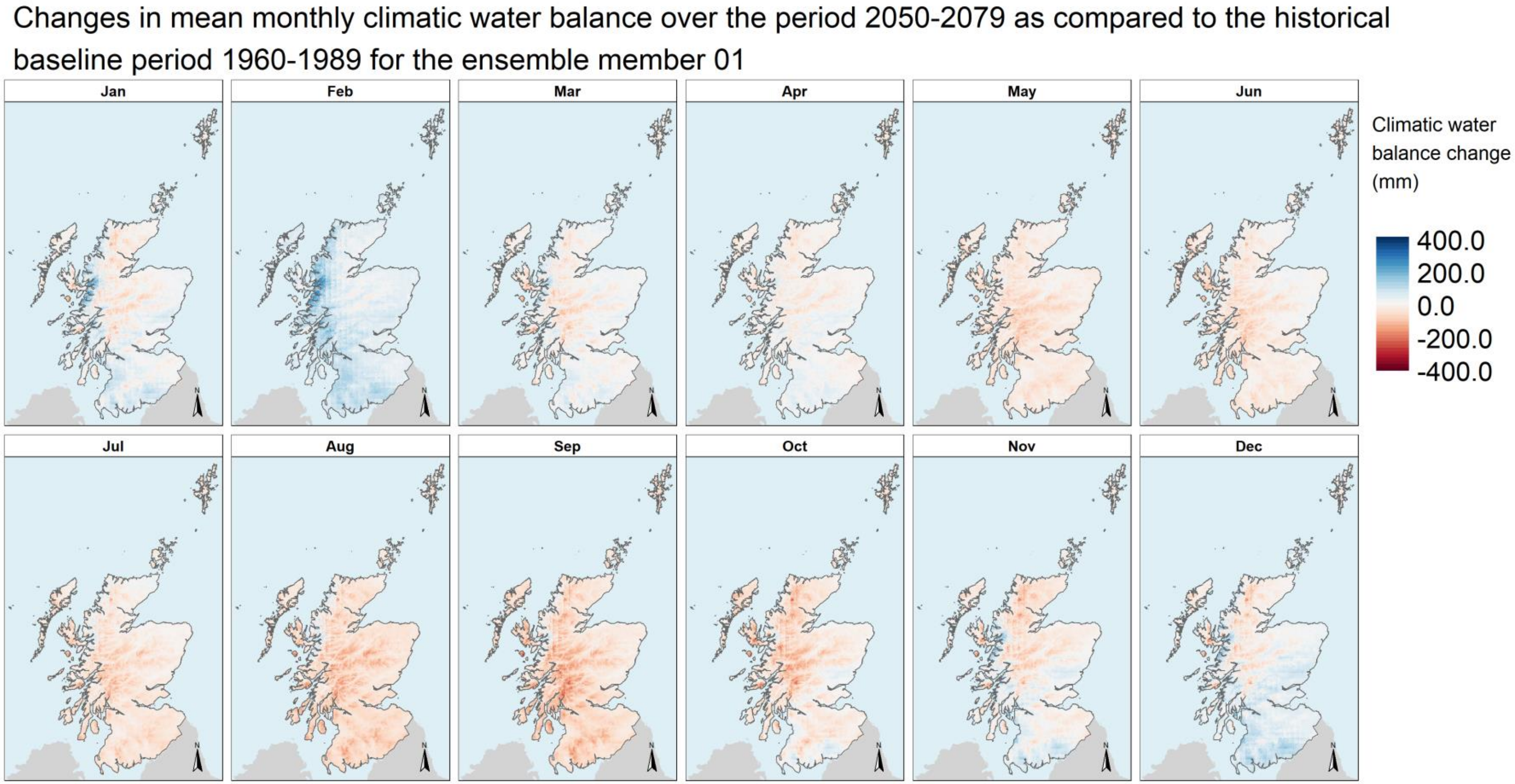


Figure 34. Projected changes in the Climatic Water Balance (precipitation – evapotranspiration) between the 1960 – 1989 baseline period and 2050 – 2079 period for ensemble member 01. Blue areas indicate a water surplus, red areas indicate a water deficit.

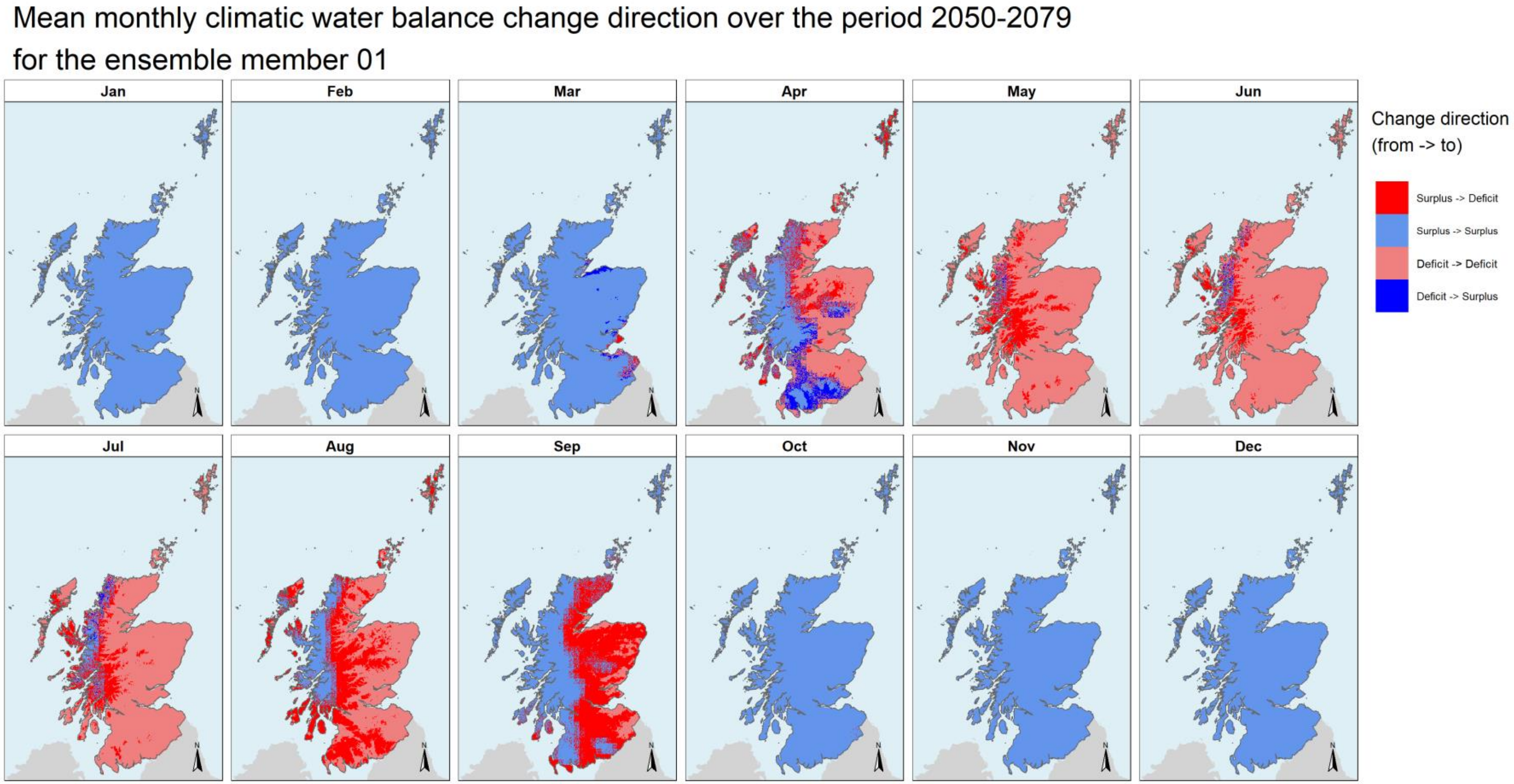


Figure 35. Climatic Water Balance change direction for 2050 – 2079 for ensemble member 01. Dark red: surplus to deficit; light red: deficit to deficit (remains a deficit); light blue: Surplus to surplus (remains a surplus); dark blue: deficit to surplus. Note: other maps provide details of the quantity of the surplus or deficit change.

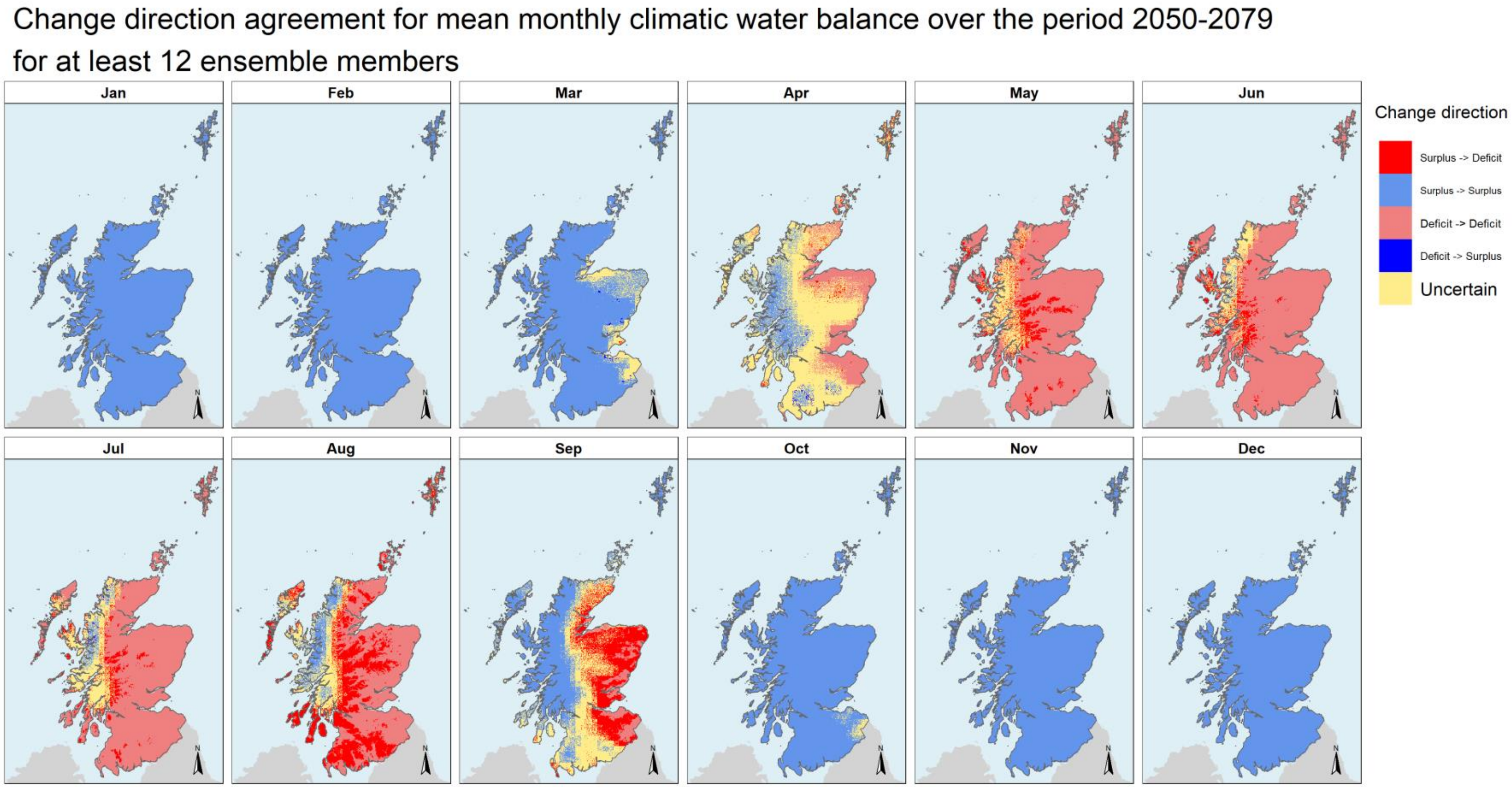


Figure 36. Agreement maps for the change direction (increase: blue, or decrease: red) of the Climatic Water Balance for the period 2050 – 2079 for all 12 climate projections (ensemble members). Yellow areas indicate no agreement between projections.

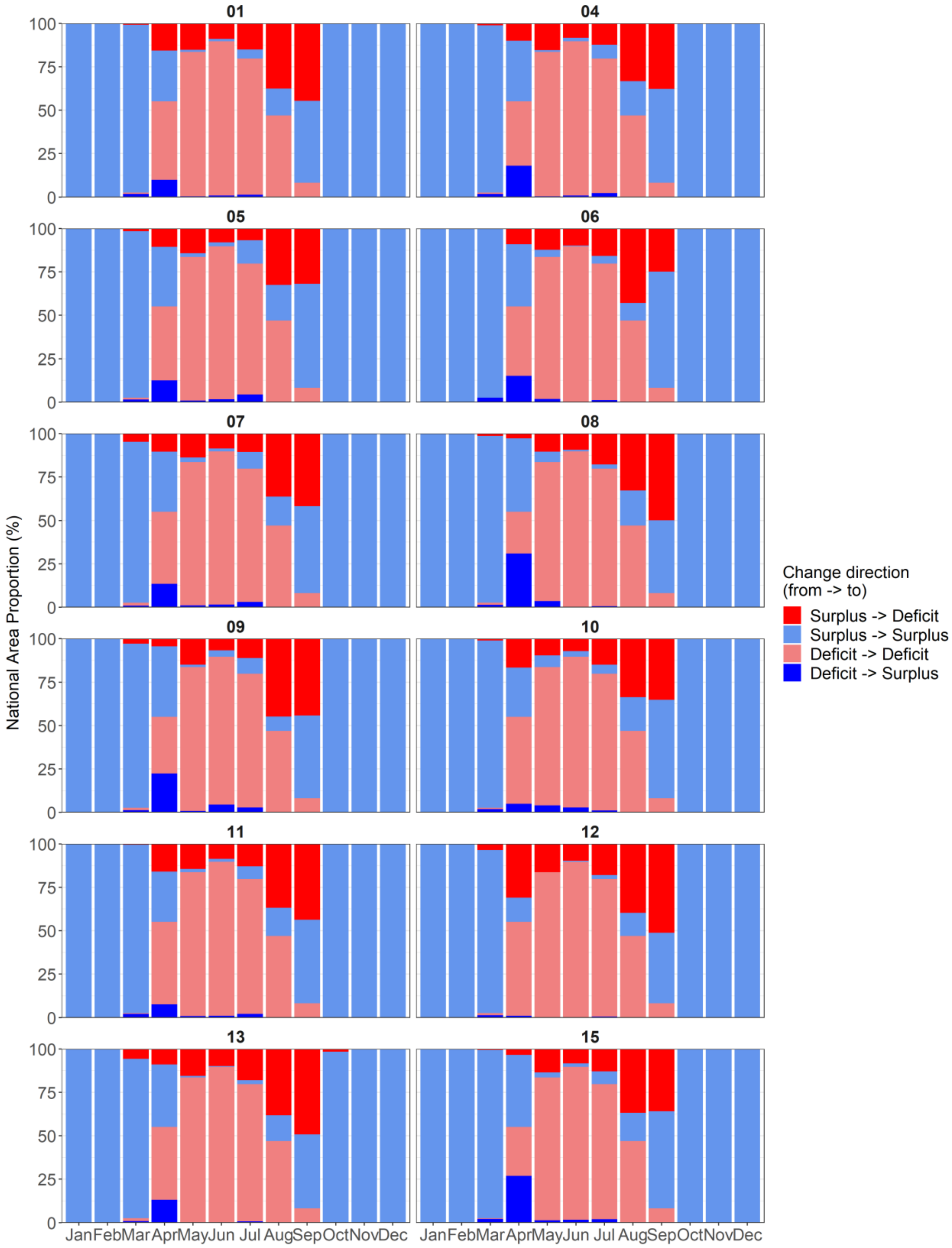


Figure 37. Area proportions for the change direction in Climatic Water Balance per month for all 12 climate projections for the period 2050 - 2079.

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 water (increased surplus water) between December to April.
    - March to May have experienced a decrease (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.

Next Steps

Having identified the observed trends and potential future climate changes, 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.

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WMO (2022) State of the Global Climate 2021. World Meteorological Organisation. WMO-No.1290. ISBN 978-92-63-11290-3. https://mcusercontent.com/e35fa2254c2a4394f75d43308/files/3d2f5b01-11a6-dee2-a42a-13ad5002dc33/1290_Statement_2021_en_1_.pdf

Appendix A: Example 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.

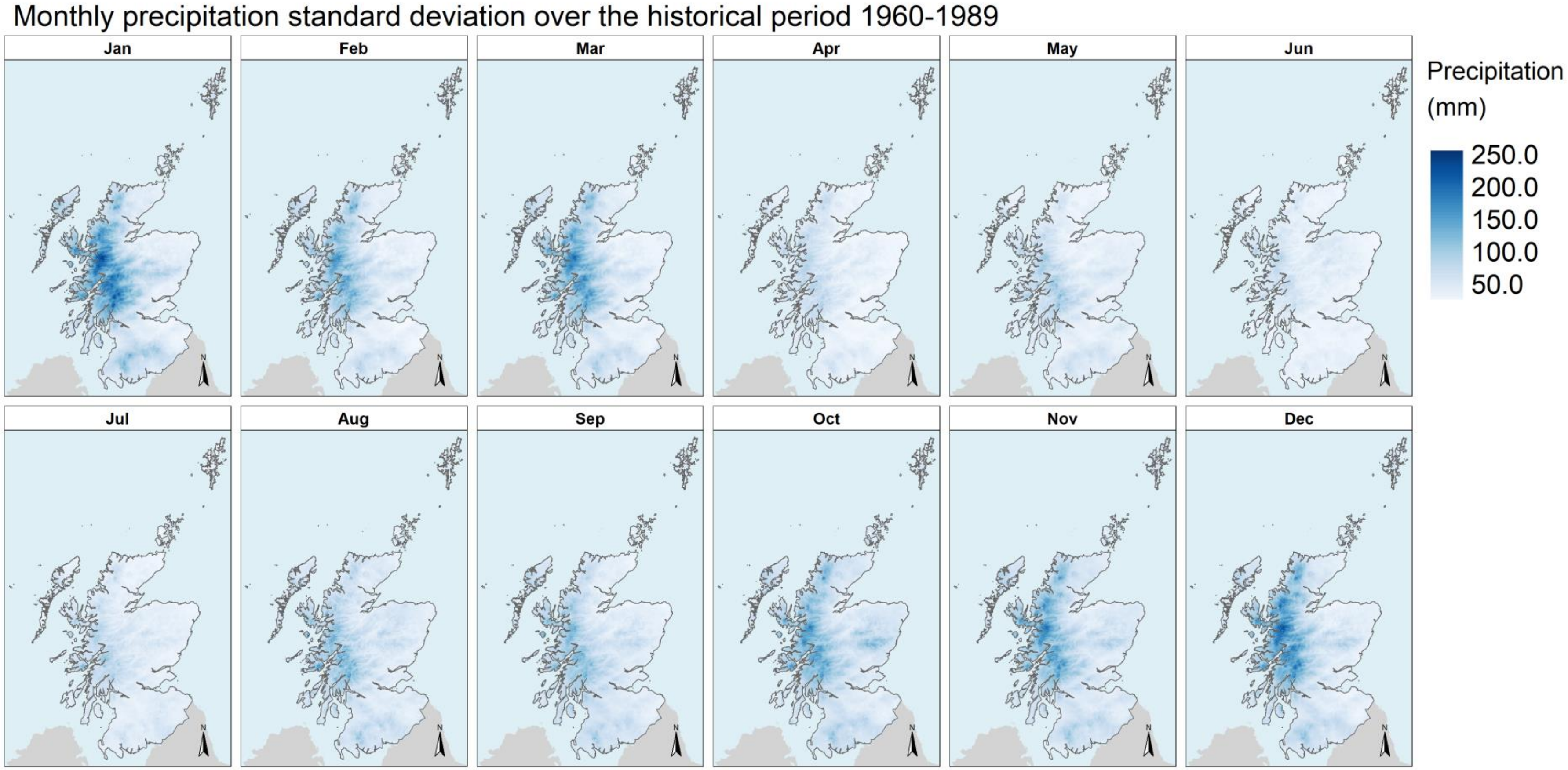

Figure 38. Standard deviation (mm) of monthly precipitation for the period 1960 - 1989

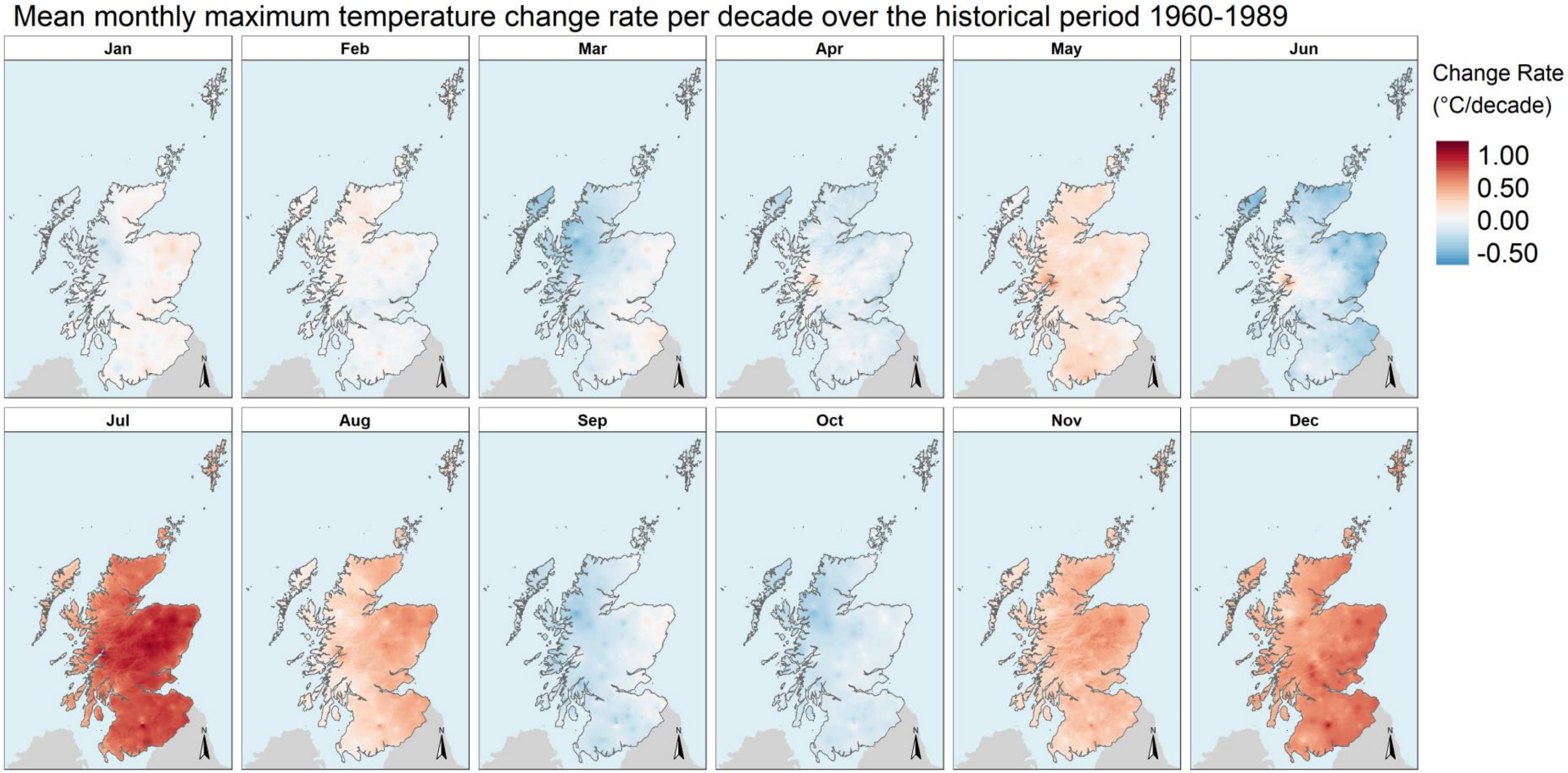

Figure 39. The rate of change in maximum temperature per month in the baseline period of 1960 – 1989.

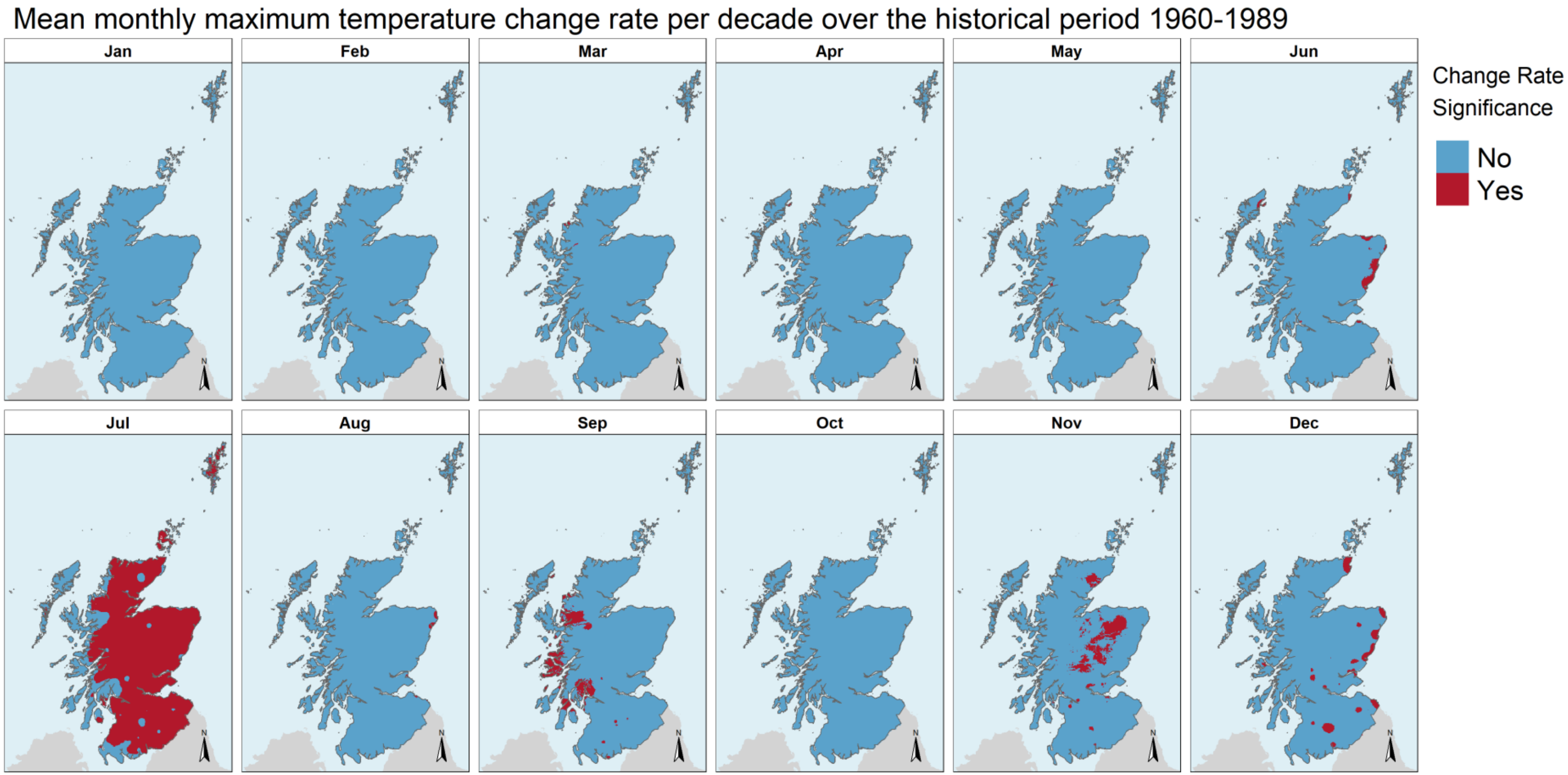

Figure 40. The significance of the rate of change in maximum temperature per month in the baseline period of 1960 – 1989.

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 42 (two historical baseline periods) and 43 (projections for three ensemble members).

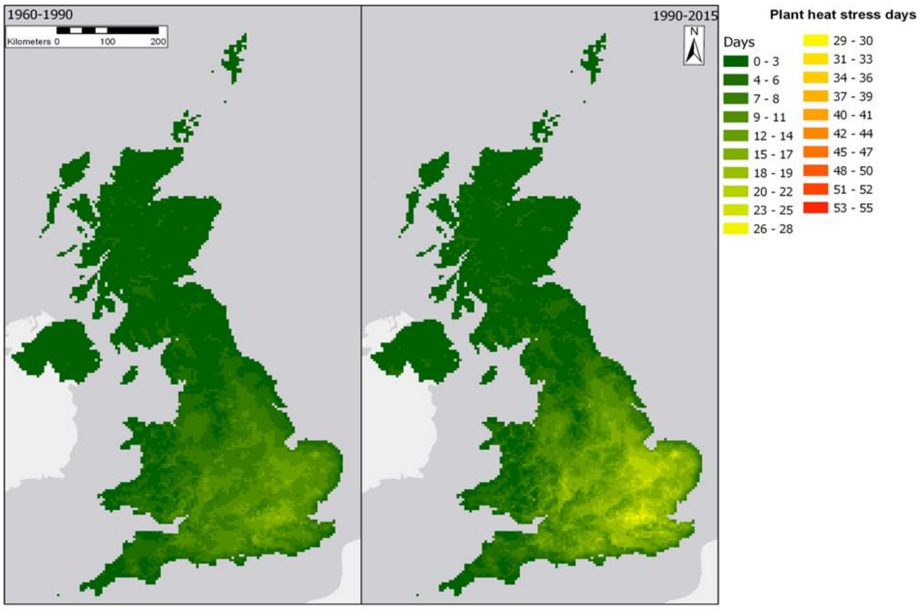

Figure 42. Observed changes in the mean Plant Heat Stress Indicator (number of days in a year when the maximum temperature is greater than 25°C) between 1960 – 1990 and 1990 – 2015.

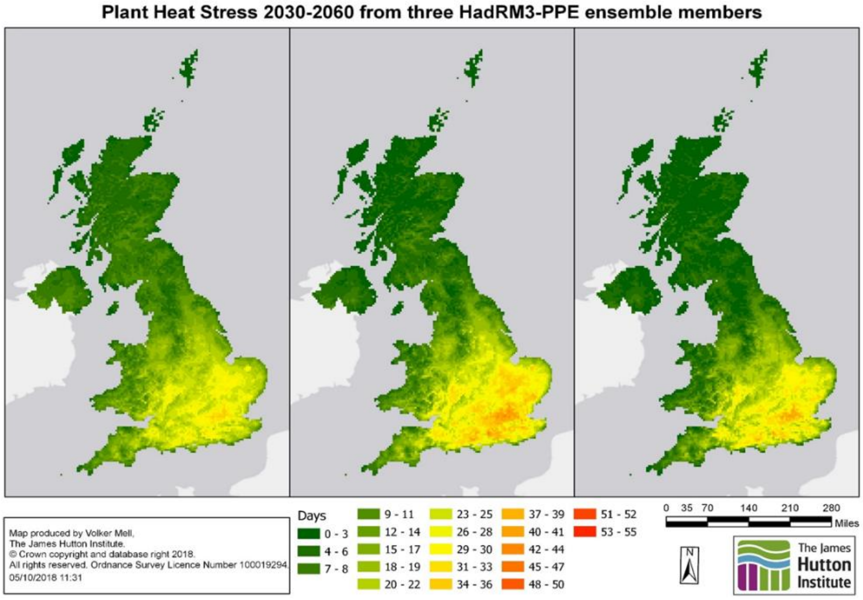

Figure 43. Projected changes in the mean Plant Heat Stress Indicator (number of days in a year when the maximum temperature is greater than 25°C) for the 2030 - 2060 period for three ensemble members.

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		$\sum T_{avg} > 5.6$ °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.

Appendix B: 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)[3]. 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 16 and 44 - 47, 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 44 and 45 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.

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

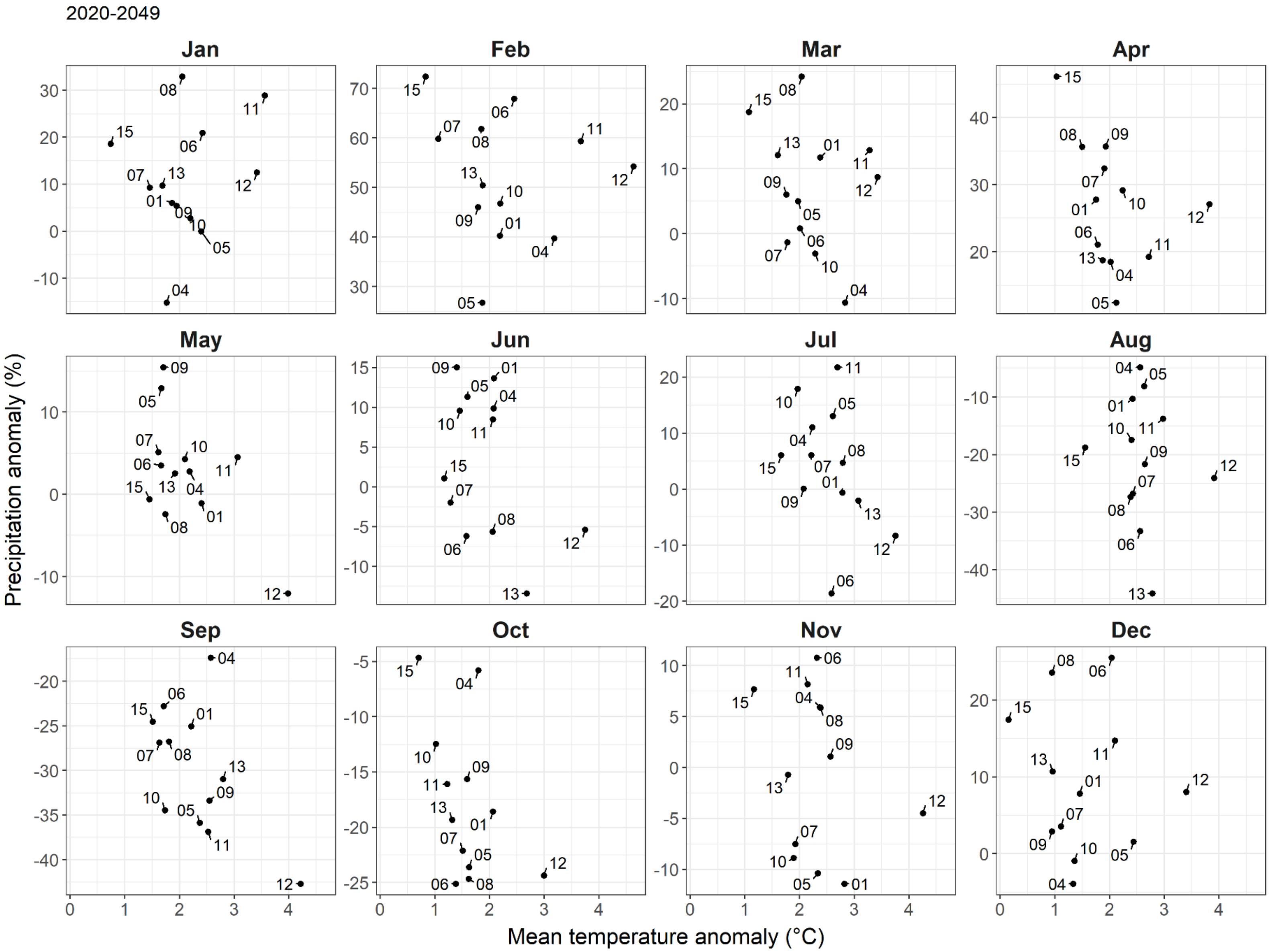


*Figure 44. Climate change signal per ensemble member and monthly anomaly under RCP8.5 for 2020-2049 ('2040') with respect to 1994-2015 baseline. **Please note** different axis scales per month.*

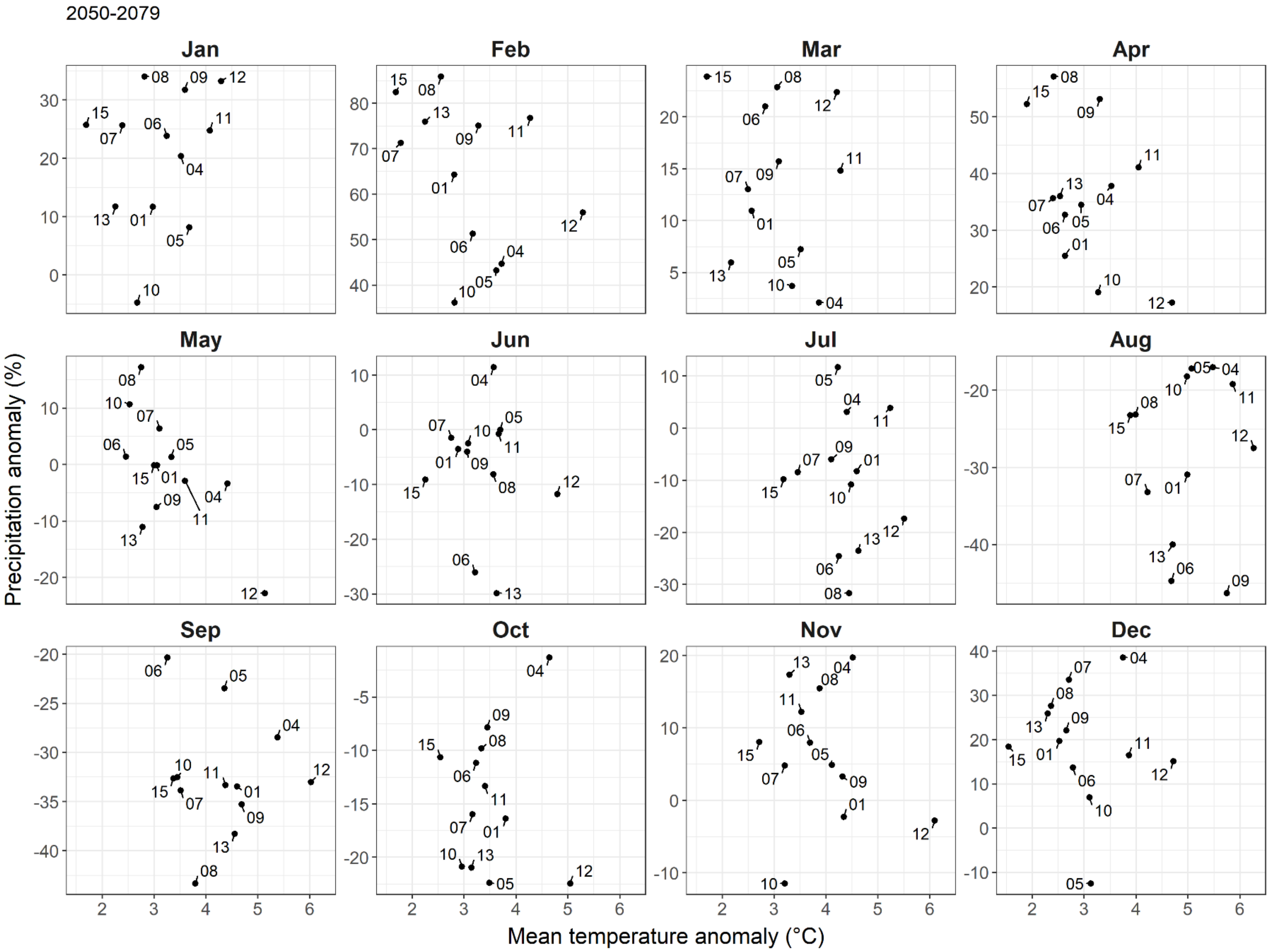


Figure 45. Climate change signal per ensemble member and monthly anomaly under RCP8.5 for 2050-2079 ('2070') with respect to 1994-2015 baseline. ***Please note*** *different axis scales per month.*

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 C: 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.

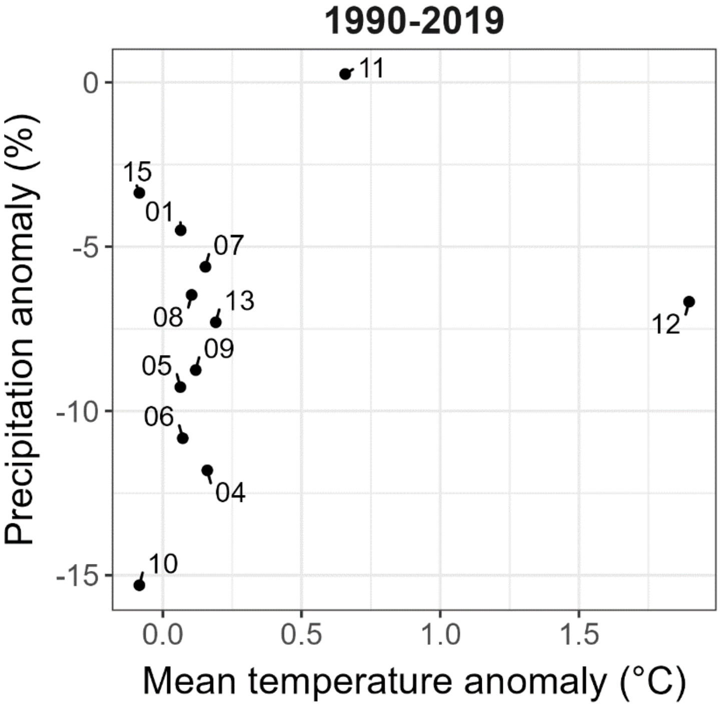


Figure 46. National scale comparison of the ability of the climate model per ensemble member to simulate annual observed climate indicated by the mean temperature and precipitation anomaly between each Ensemble Member and the 1990 – 2019 baseline. The 0 lines represent the baseline.

Figure 46 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 47).

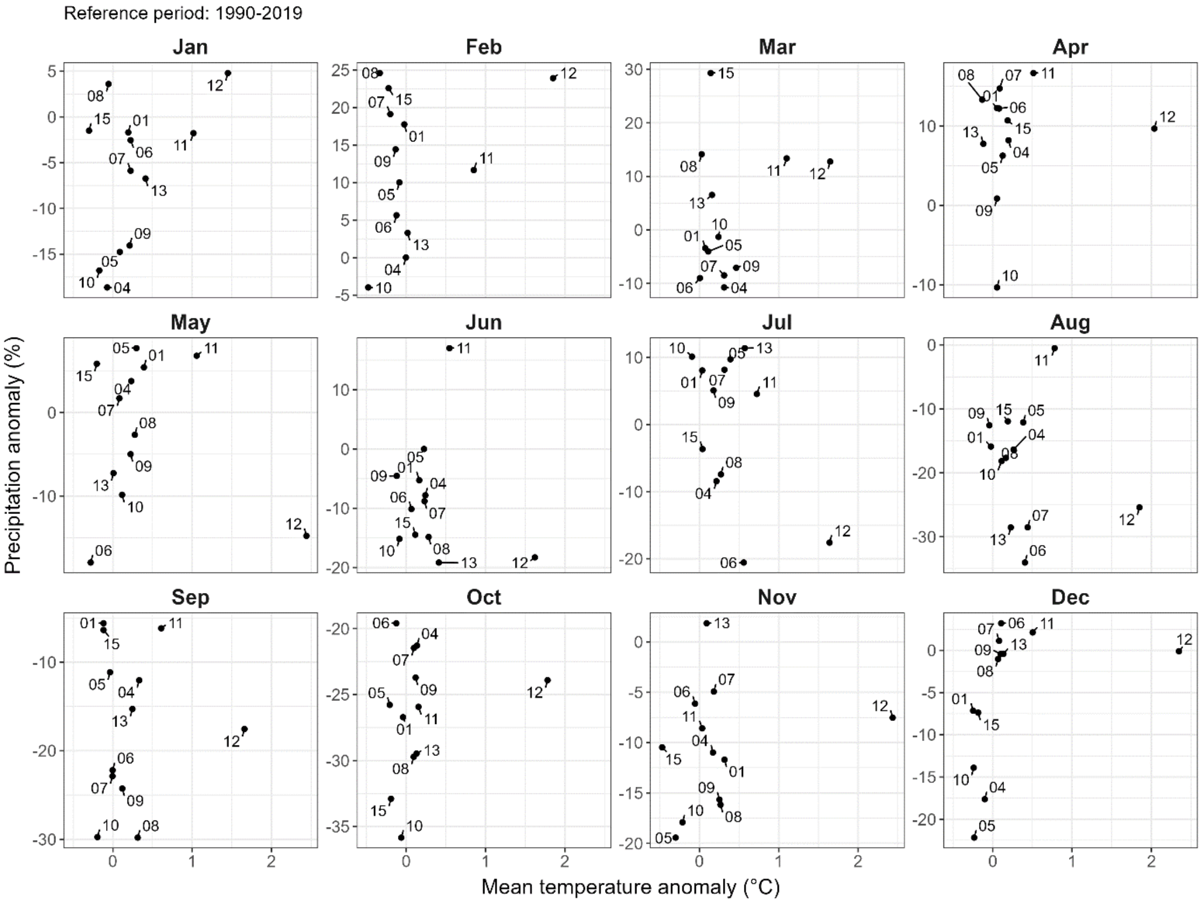


Figure 47. National scale comparison of the ability of the climate model per ensemble member to simulate monthly observed climate indicated by the mean temperature and precipitation anomaly between each Ensemble Member and the 1990 – 2019 baseline. The 0 lines represent the baseline.

Some ensemble members show good skill at simulating observed mean temperature per month (Figure 47), 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

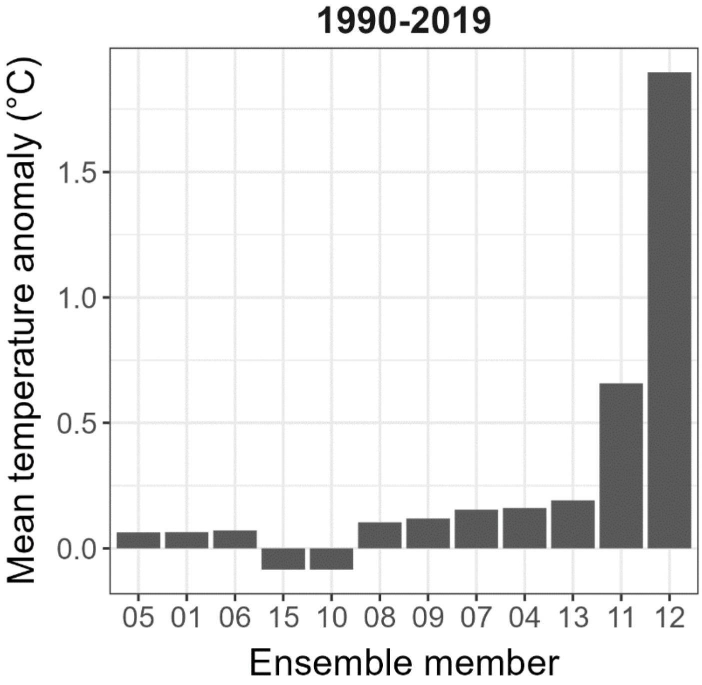


Figure 48. Ranking of climate model skill to represent the 1990 – 2019 baseline mean temperature per ensemble member

For the annual mean temperature anomaly (Figure 48), the EMs are ranked as follows (best -> worst): 05, 01, 06, 15, 10, 08, 09, 07, 04, 13, 11, 12.

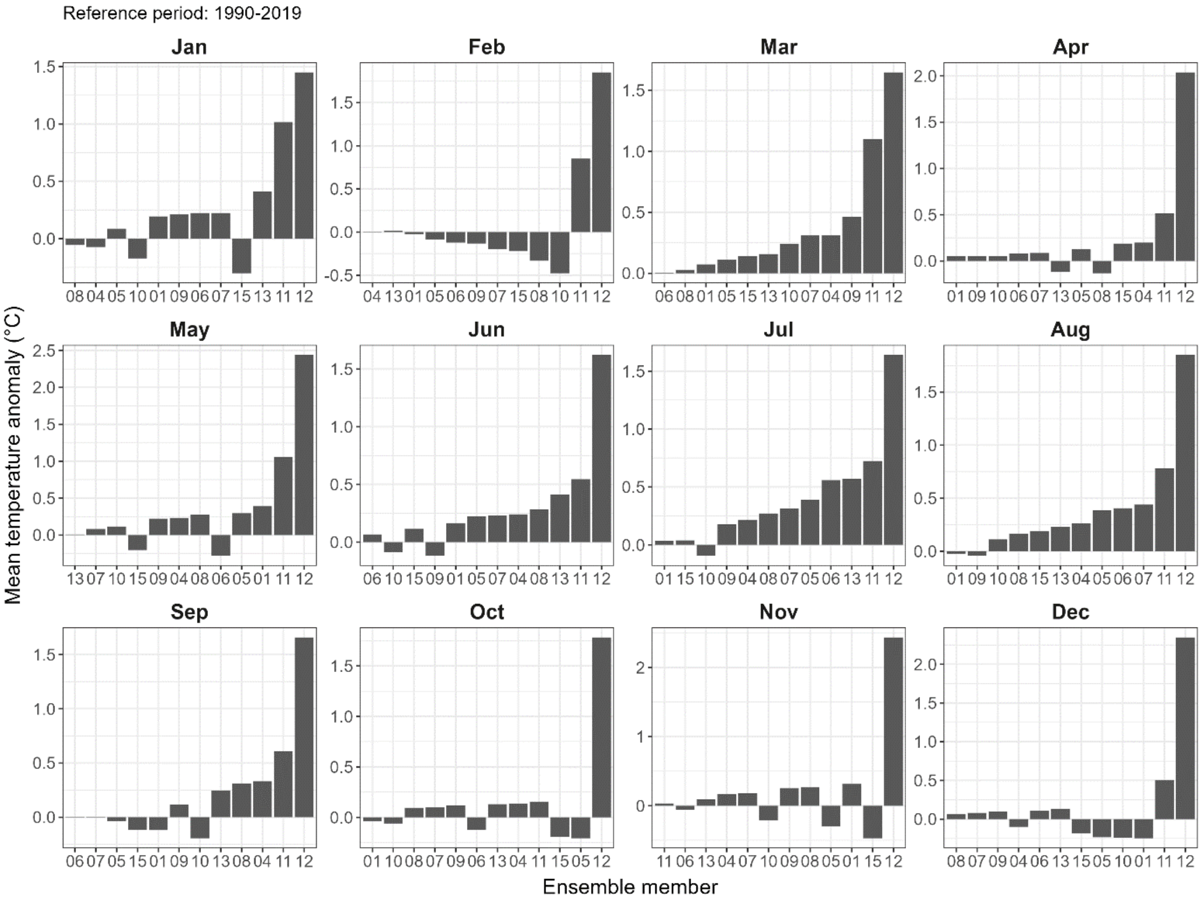


Figure 49. Ranking of climate model skill to represent the 1990 – 2019 baseline mean monthly temperature per ensemble member

Some ensemble members, particularly EM12, show consistent low skill in representing the past climate (Figure 49).

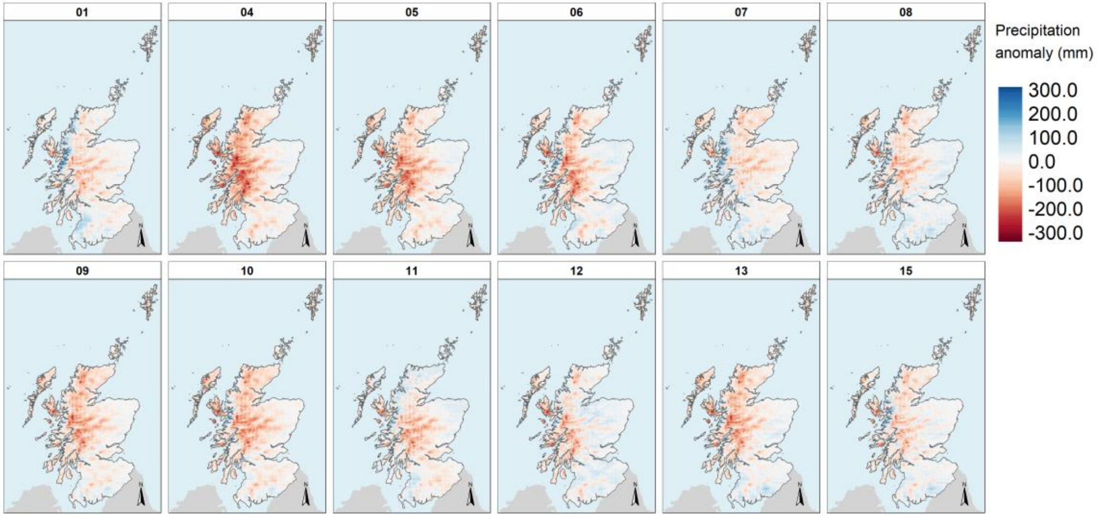
Spatial variability in model skill

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.

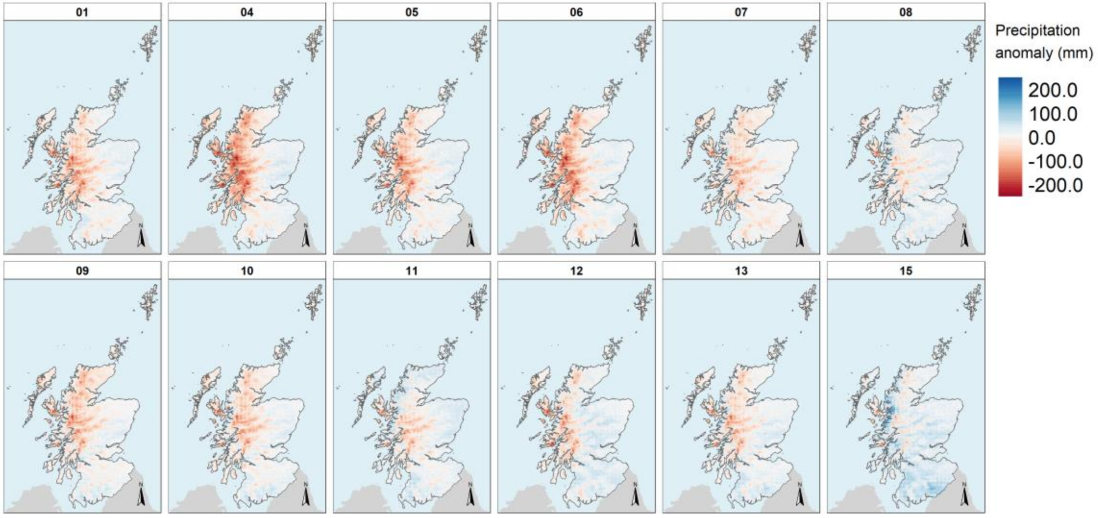
Precipitation:

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.

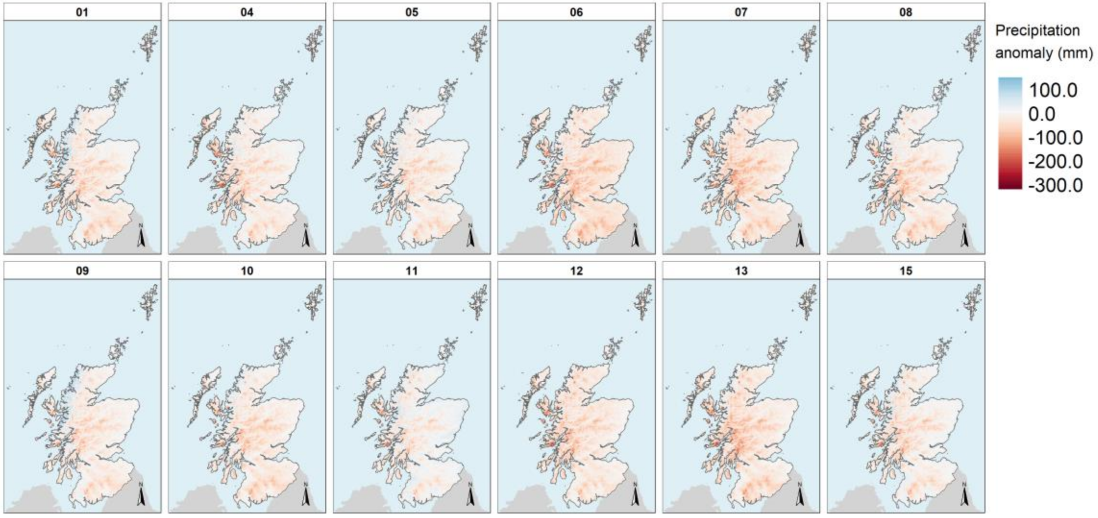
Mean monthly precipitation anomaly for January between the ensemble members and the historical records over the period 1990-2019



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



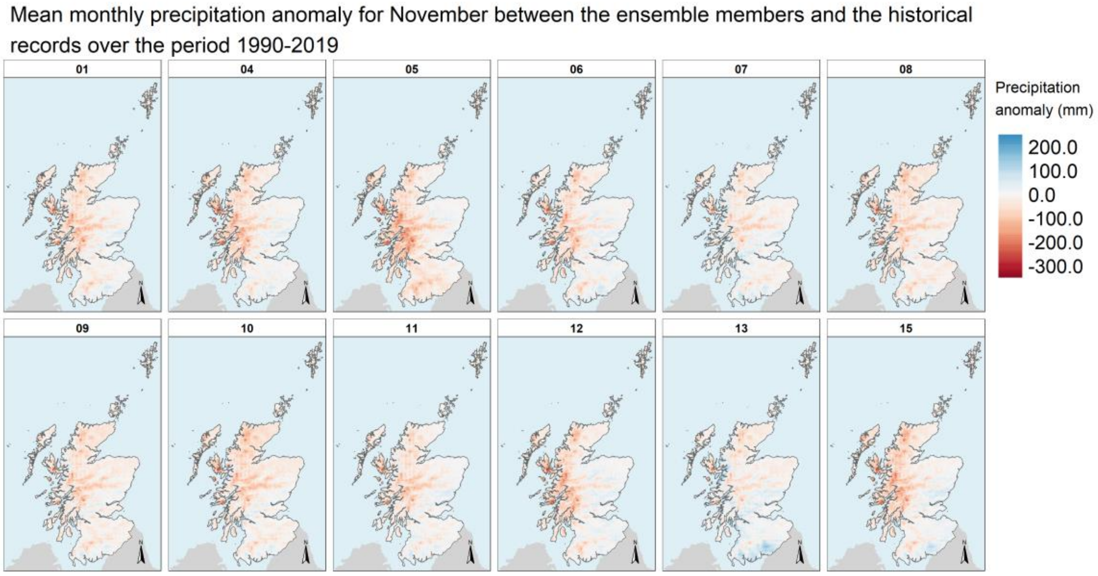


Figure 50. Climate model skill indicated by mean monthly precipitation anomaly between climate model estimates for the observed 1990 – 2019 period compared to observations for January, March, August and November.

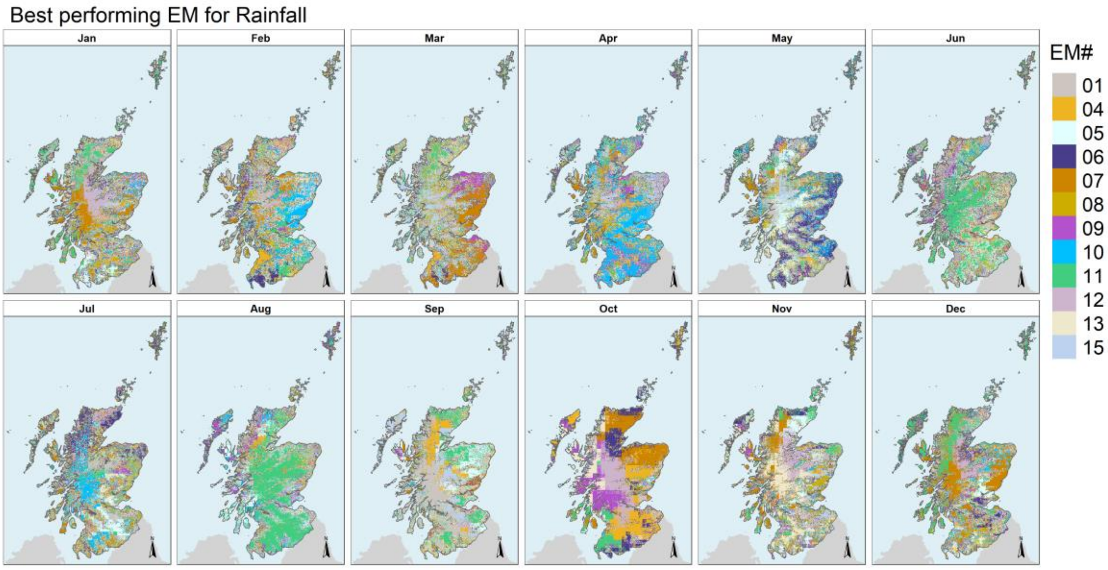
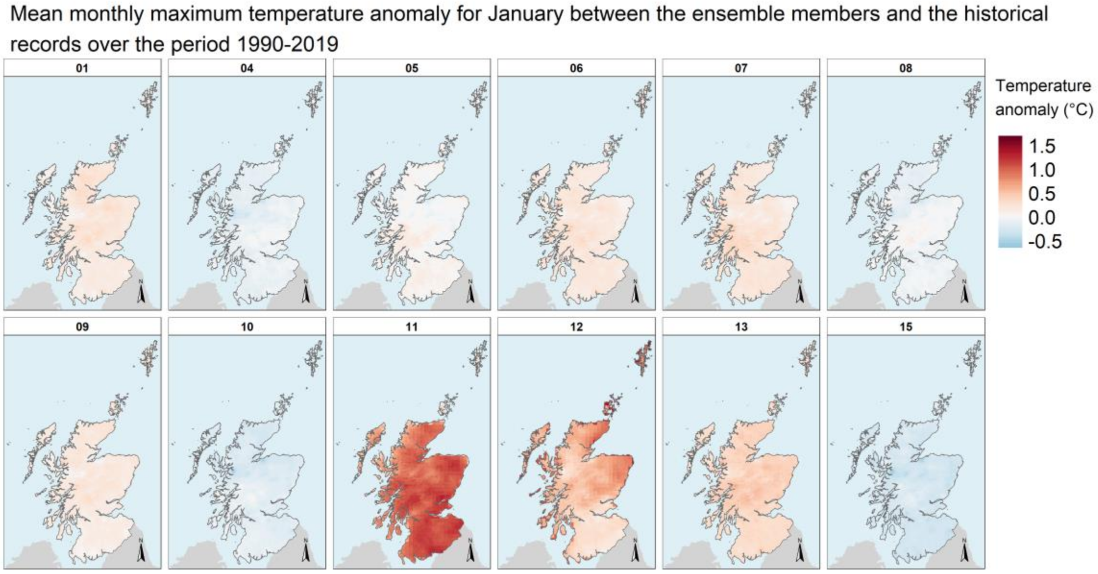


Figure 51. Spatial distribution of the best performing ensemble member per month for precipitation.

Maximum Temperature


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

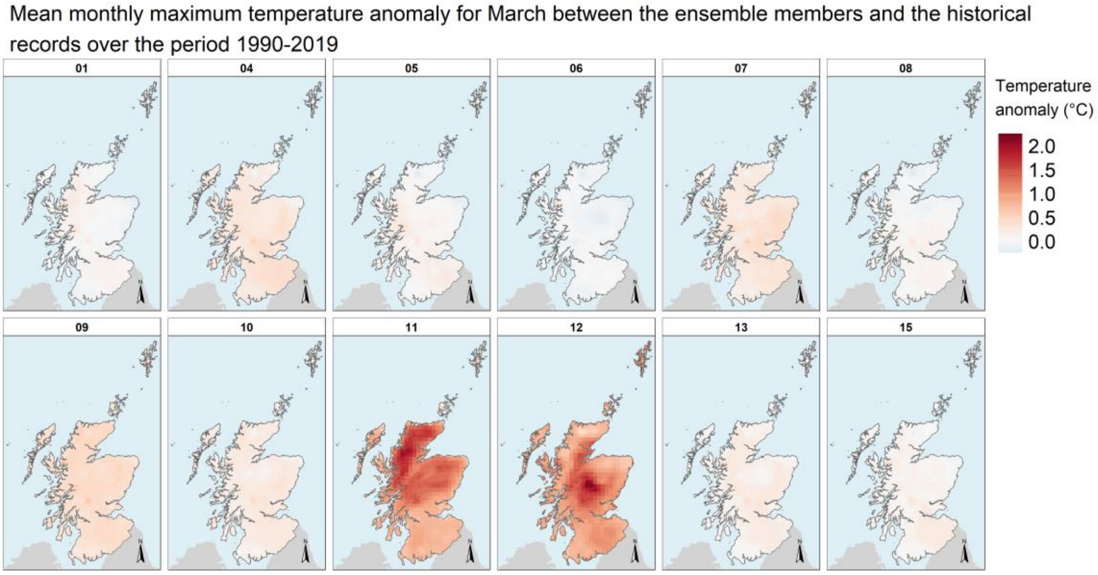
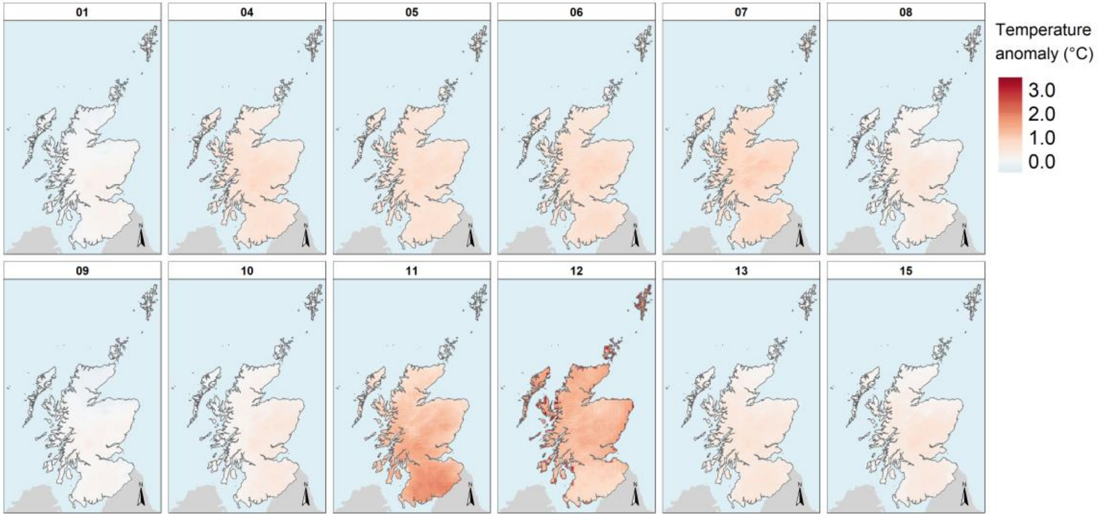

Mean monthly maximum temperature anomaly for March between the ensemble members and the historical records over the period 1990-2019

Figure 52a. 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.


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

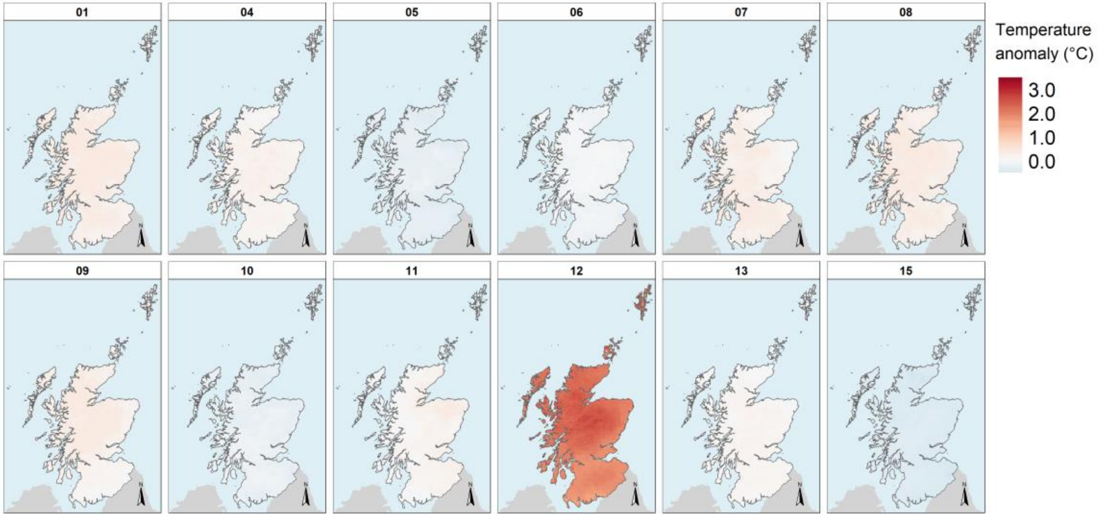

Mean monthly maximum temperature anomaly for November between the ensemble members and the historical records over the period 1990-2019

Figure 52b. 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.

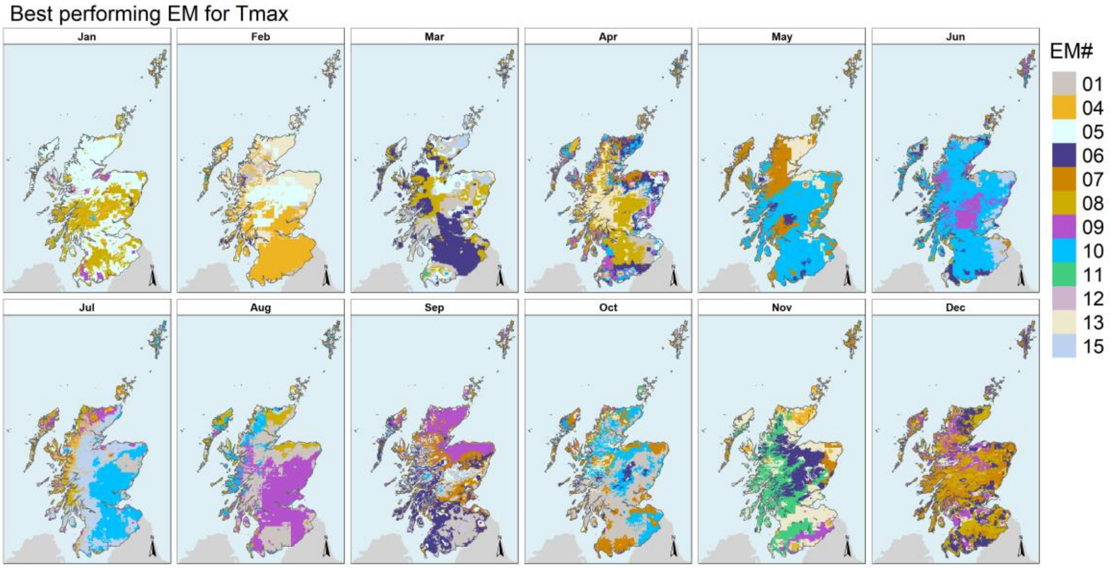
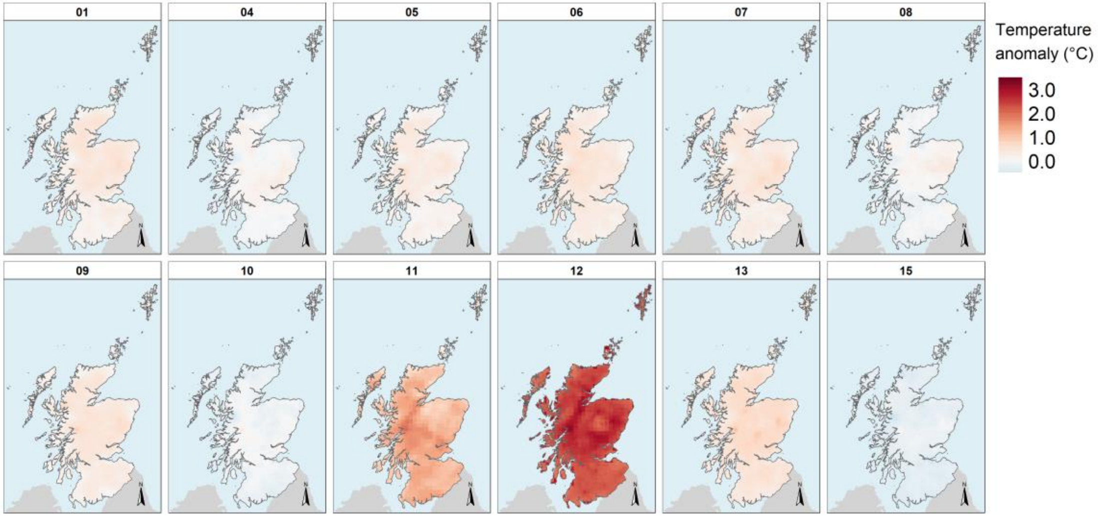


Figure 53. Spatial distribution of the best performing ensemble member per month for maximum temperature.

Minimum Temperature


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

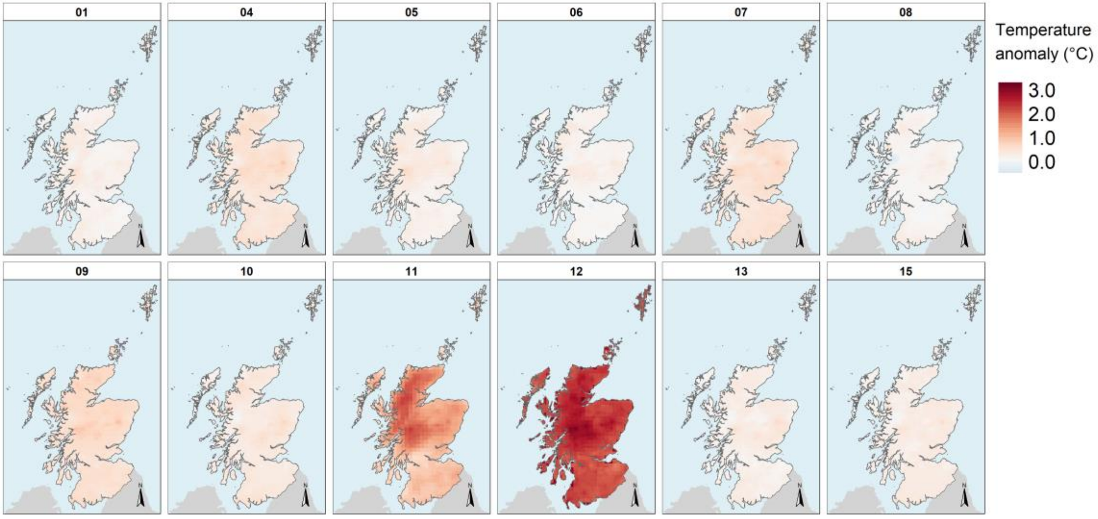
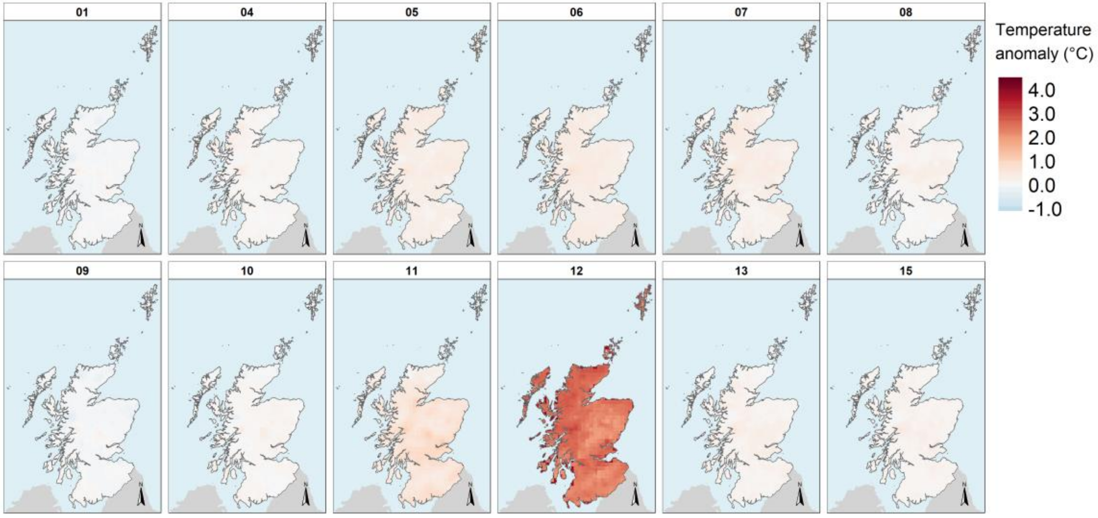

Mean monthly minimum temperature anomaly for March between the ensemble members and the historical records over the period 1990-2019

Figure 54a. 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.

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



Mean monthly minimum temperature anomaly for November between the ensemble members and the historical records over the period 1990-2019

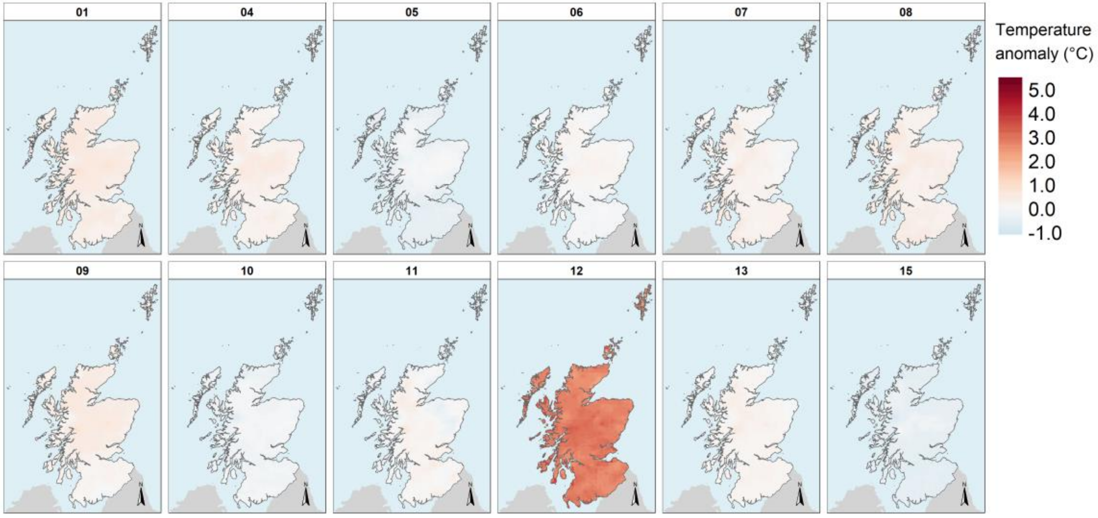


Figure 54b. Climate model skill indicated by mean monthly minimum temperature anomaly between climate model estimates for the observed 1990 – 2019 period compared to observations for August and November.

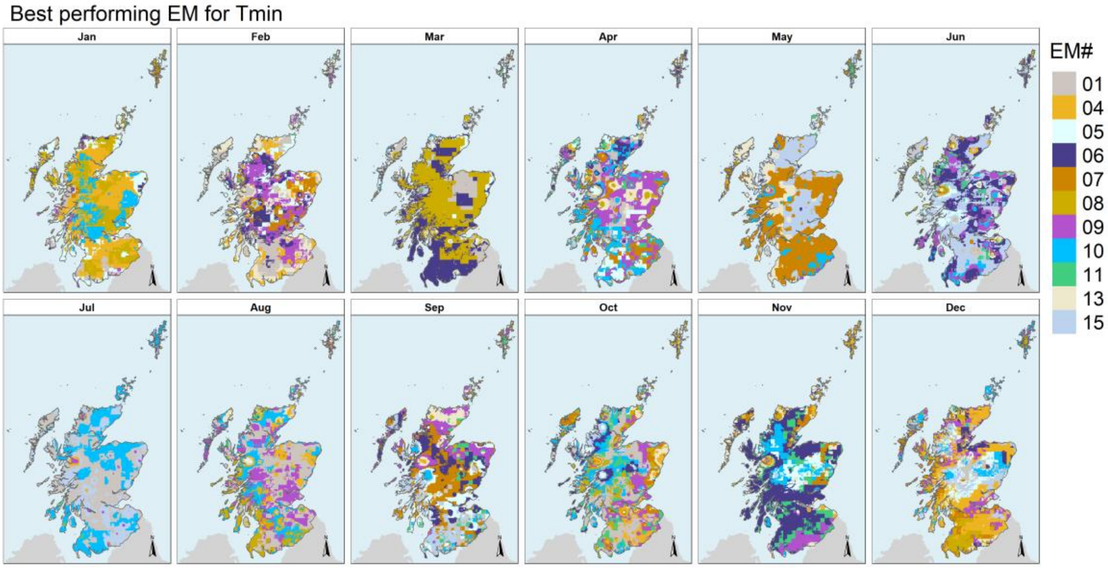


Figure 55. Spatial distribution of the best performing ensemble member per month for minimum temperature.

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.

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