SPECIAL PROJECT FINAL REPORT

All the following mandatory information needs to be provided.

Project Title:	HARMONIE Climate (HCLIM) Regional Downscaling Simulations for Ireland for SSP3-7.0
Computer Project Account:	spiemcgo
Start Year - End Year:	2022-2024
Principal Investigator(s)	John Hanley Markus Todt
Affiliation/Address:	Met Éireann, 65/67 Glasnevin Hill, Dublin 9, D09 Y921, Ireland
Other Researchers (Name/Affiliation):	Tido Semmler Enda O'Dea

The following should cover the entire project duration.

Summary of project objectives

(10 lines max)

The aim of the project is to produce and evaluate future climate projections for Ireland by downscaling global CMIP6 climate simulations from the EC-Earth model. Global simulations are dynamically downscaled using the regional climate model HCLIM, which is based on the NWP modelling system HARMONIE, by first downscaling to 12km spatial resolution using hydrostatic ALADIN physics in HCLIM and subsequently to 4km spatial resolution using non-hydrostatic AROME physics in HCLIM. Both 12km and 4km domains are shown in Figure 1.

This project takes a three-step approach, first downscaling ERA5 data for validation purposes, then downscaling a historical EC-Earth simulation for the period 1981-2015, and finally downscaling several future scenarios continuing from the EC-Earth historical simulation. Previously, two future scenarios were downscaled, a SSP2–4.5 simulation and a SSP5–8.5 simulation. A proposal for this special project was submitted in order to downscale a third future scenario, SSP3-7.0.

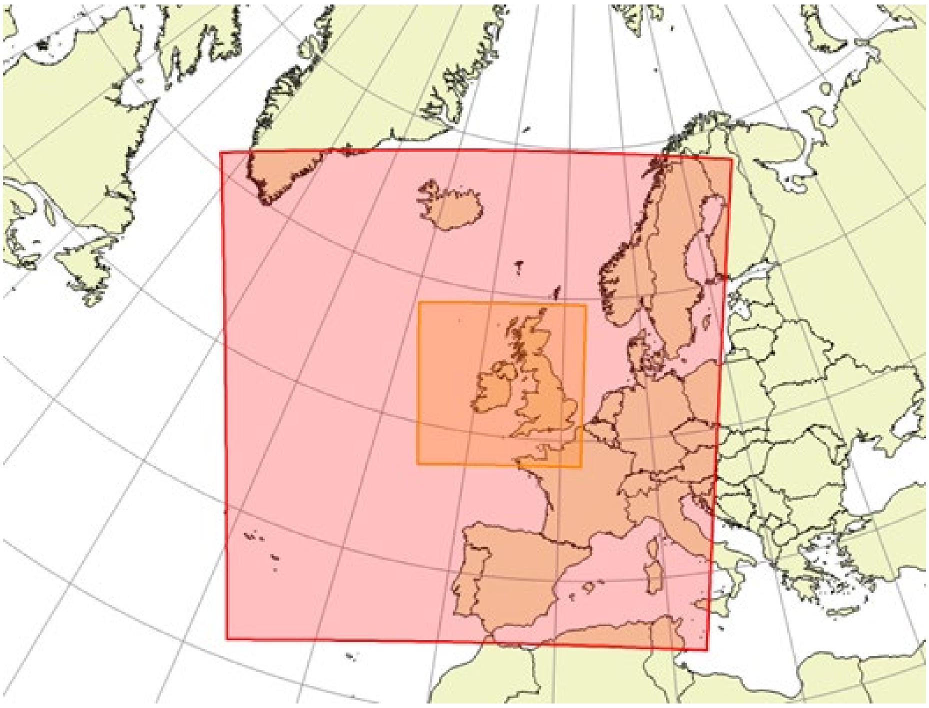

Figure 1 *Downscaling domains with the intermediate 12 km resolution domain shown in red and the inner 4 km resolution domain shown in orange.*

Summary of problems encountered

(If you encountered any problems of a more technical nature, please describe them here.)

No technical issues were encountered during the project, which was a successor project to the original Spiemcgo project. An extension project was necessary as two technical issues were experienced during the original project, namely difficulty in porting HCLIM cycle 38 from cca to Atos, which proved to be insurmountable within the timeframe of the project and so we simply moved to the next version of HCLIM, cycle 43, and the discovery of a very cold bias in the early part of the driving EC-Earth3 ensemble member, which was resolved by simply switching to an equivalent EC-Earth3-Veg ensemble member which became available around the same time. As a result of these issues, the SSP3-7.0 future scenario could not be completed as part of the original project, and so this project was created to add this final scenario to the completed SSP2–4.5 and SSP5–8.5 scenarios.

Experience with the Special Project framework

(Please let us know about your experience with administrative aspects like the application procedure, progress reporting etc.)

We had a very positive experience with all aspects of the special project administration and would like to thank Carsten Maas and Milana Vuckovic for their support.

Summary of results

(This section should comprise up to 10 pages, reflecting the complexity and duration of the project, and can be replaced by a short summary plus an existing scientific report on the project.)

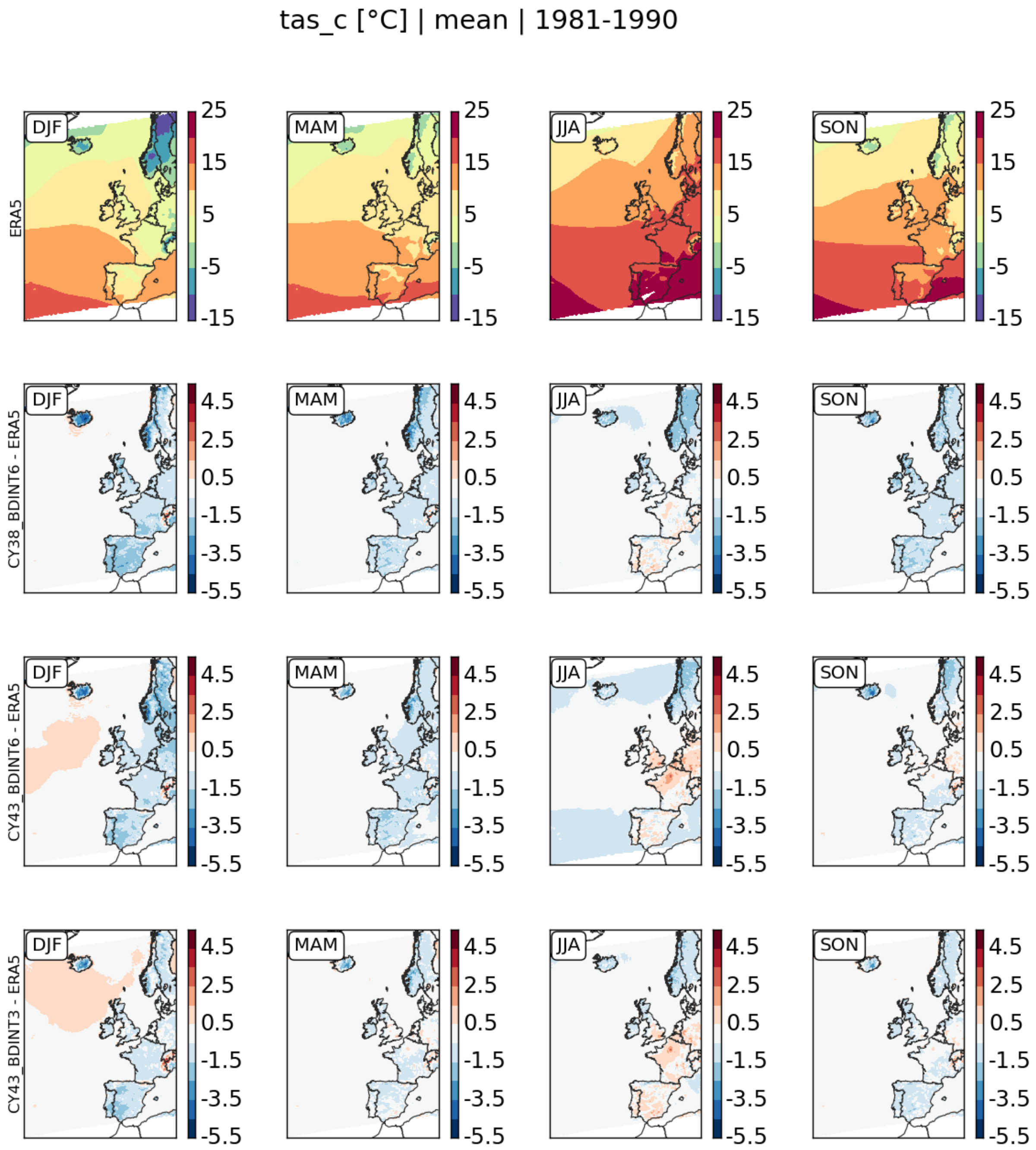

Figure 1 – Seasonal averages of 2m air temperature over the 12km-resolution domain and the period 1981-1990 for ERA5 (first row) and differences in seasonal averages between HCLIM cycle 38 and ERA5 (second row), between HCLIM cycle 43 with 6-hourly boundary forcing and ERA5 (third row), and between HCLIM cycle 43 with 3-hourly boundary forcing and ERA5 (fourth row). All fields are interpolated to the spatial resolution of ERA5 prior to comparison. This figure was created through the Regional Climate Analysis Tool (RCAT).

We downscaled ERA5 data with HCLIM cycle 43 (henceforth HC43) for comparison with the previous run that had used HCLIM cycle 38 (henceforth HC38), which covers the period 1981-2010 with ERA5 boundary forcing every 6 hours. This had been chosen to be in line with global model output from EC-Earth, which is available every 6 hours. However, ERA5 data has a higher frequency, so that we ran HC43 downscaling of ERA5 with both 6-hourly boundary forcing (over the period 1981-1990) and 3-hourly boundary forcing (over the period 1981-2010) for consistency in comparison.

While there are differences between the two HC43 simulations due to the differing boundary forcing intervals, differences between HCLIM versions are generally larger, as seen, for example, in seasonal averages of 2m air temperature for the 12km simulations with ALADIN settings in HCLIM (Figure 1). Nevertheless, all three HCLIM downscaling runs feature similar spatial patterns with temperatures after downscaling being lower than in ERA5 except over central/western Europe and the Iberian Peninsula during JJA. One feature that stands out as a difference between HC38 and HC43 are larger urban areas such as around London and Paris, which is more pronounced for measures of extreme temperatures such as 95th percentile of 3-hourly temperatures (Figure 2). High temperature extremes also show an effect of changing the boundary forcing frequency from 6-hourly to 3-hourly. Both average and extremes show generally higher temperatures in HC43 compared to HC38.

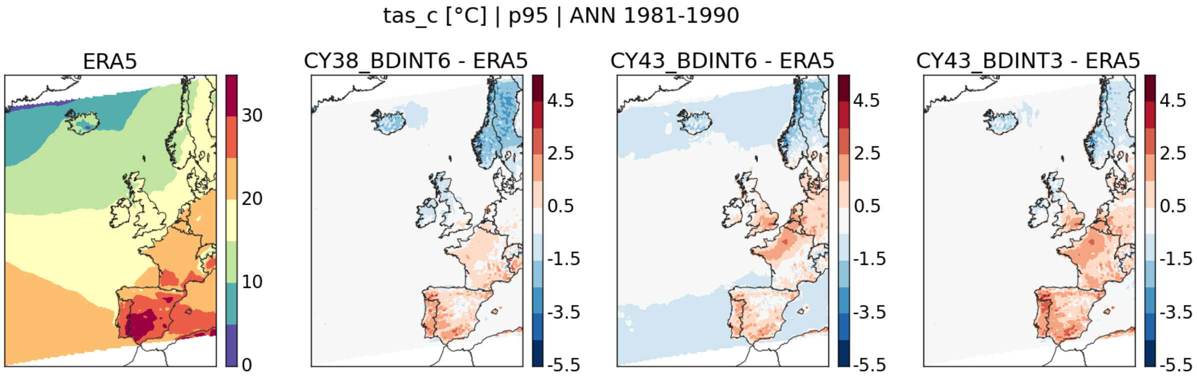

Figure 2 – 95th percentile of 3-hourly 2m air temperatures over the 12km-resolution domain and the period 1981-1990 for ERA5 (left panel) and differences in 95th percentile of 2m air temperatures between HCLIM cycle 38 and ERA5 (centre-left panel), between HCLIM cycle 43 with 6-hourly boundary forcing and ERA5 (centre-right panel), and between HCLIM cycle 43 with 3-hourly boundary forcing and ERA5 (right panel). All fields are interpolated to the spatial resolution of ERA5 prior to comparison. This figure was created through the Regional Climate Analysis Tool (RCAT).

As an example of the impact of downscaling, 99th percentiles of 3-hourly precipitation are shown in Figure 3 for the 4km simulations with AROME settings focused on Ireland. Resolving orographic features increases precipitation in HCLIM across versions compared to ERA5, with higher precipitation in HC43 than in HC38 and only small differences between the HC43 runs with different boundary-forcing frequencies. Note that maps of standard deviation in 3-hourly precipitation are also similar across HCLIM downscaling runs and do not show differences between boundary-forcing frequencies (not shown here for brevity).

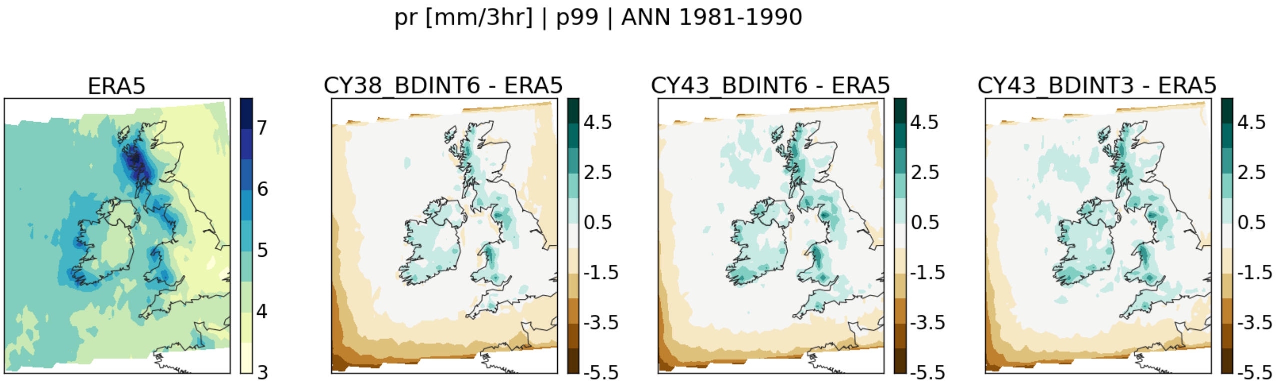

Figure 3 – 99th percentiles of 3-hourly precipitation over the 4km-resolution domain and the period 1981-1990 for ERA5 (left panel) and differences in 99th percentiles of precipitation between HCLIM cycle 38 and ERA5 (centre-left panel), between HCLIM cycle 43 with 6-hourly boundary forcing and ERA5 (centre-right panel), and between HCLIM cycle 43 with 3-hourly boundary forcing and ERA5 (right panel). All fields are interpolated to the spatial resolution of ERA5 prior to comparison. This figure was created through the Regional Climate Analysis Tool (RCAT).

For further analysis of the two different HCLIM cycles, we compare simulations with AROME settings over the 4km domain to gridded observational datasets for daily maximum and minimum temperature as well as for daily precipitation, which have been created by Met Éireann from station data. Differences between the simulations and observations are shown for daily maximum temperature in Figure 4. The simulation with HC38 shows little bias except for an underestimation across the country in spring. Both simulations with HC43 show a substantially stronger cold bias that is highest in summer. In contrast, daily minimum temperature shows a cold bias in the HC38 simulation across seasons, which is substantially reduced in HC43 (not shown here for brevity). The precipitation comparison shows a dry bias in all three HCLIM simulations mainly over the mountains along the west coast, where precipitation is highest overall, and a dry bias across the country in summer. Going from HC38 to HC43 reduces this dry bias, in particular for summer, but HC43 still features a dry bias over the mountains (not shown here for brevity).

To fully understand the temperature biases seen in the HCLIM simulations, we finally compare ERA5 with the gridded observations from Met Eireann over 1981-1990. The differences in daily maximum temperature display a spatial pattern of ERA5 being colder than gridded observations across most of the country except for mountainous areas, which is seen across seasons but with highest differences in summer (Figure 5). The magnitude of these differences is similar to the bias seen in HC43 simulations, suggesting that this apparent bias may at least partially be inherited from the driving data. It would also suggest that HC 38 might feature a warm bias that is masked by the driving data. In contrast to daily maximum temperature, ERA5 shows higher daily minimum temperatures across seasons and across most of the country compared to gridded observations, with highest differences in autumn (Figure 6). The differences in daily minimum temperature are higher than for daily maximum temperature. These differences suggest that HC 43 might not simulate daily minimum temperature as well as indicated by the above evaluation. However, the bias in daily minimum temperature would nonetheless be decreased by going from HC38 to HC43.

We subsequently ran nested downscaling simulations of EC-Earth3-Veg CMIP6 ensemble member r14i1p1f1 with HC43 (EC-Earth to 12km ALADIN to 4km AROME). The historical simulation was downscaled over the period 1981-2014, with 4 future CMIP6 emission scenarios downscaled over the period 2015-2100, namely:

- **SSP1-2.6:** This scenario represents an "early action" scenario with substantial and rapid reductions in global greenhouse gas emissions leading to a stabilized climate. It is characterized by low global emissions and a focus on sustainable development.

- **SSP2-4.5:** This scenario represents a "middle of the road" scenario where global society continues on its current trajectory, with gradual reductions in greenhouse gas emissions but not enough to prevent significant climate change. It is characterized by moderate emissions and a focus on gradual technological and economic development.
- **SSP3-7.0:** This scenario represents a future of regional rivalry and fragmentation, leading to high global emissions, a significant increase in global temperatures and climate impacts.
- **SSP5-8.5:** This scenario represents a “late action” scenario where rapid economic growth and accompanying increased fossil fuel use leads to a high-emissions trajectory and a significant increase in global temperatures.

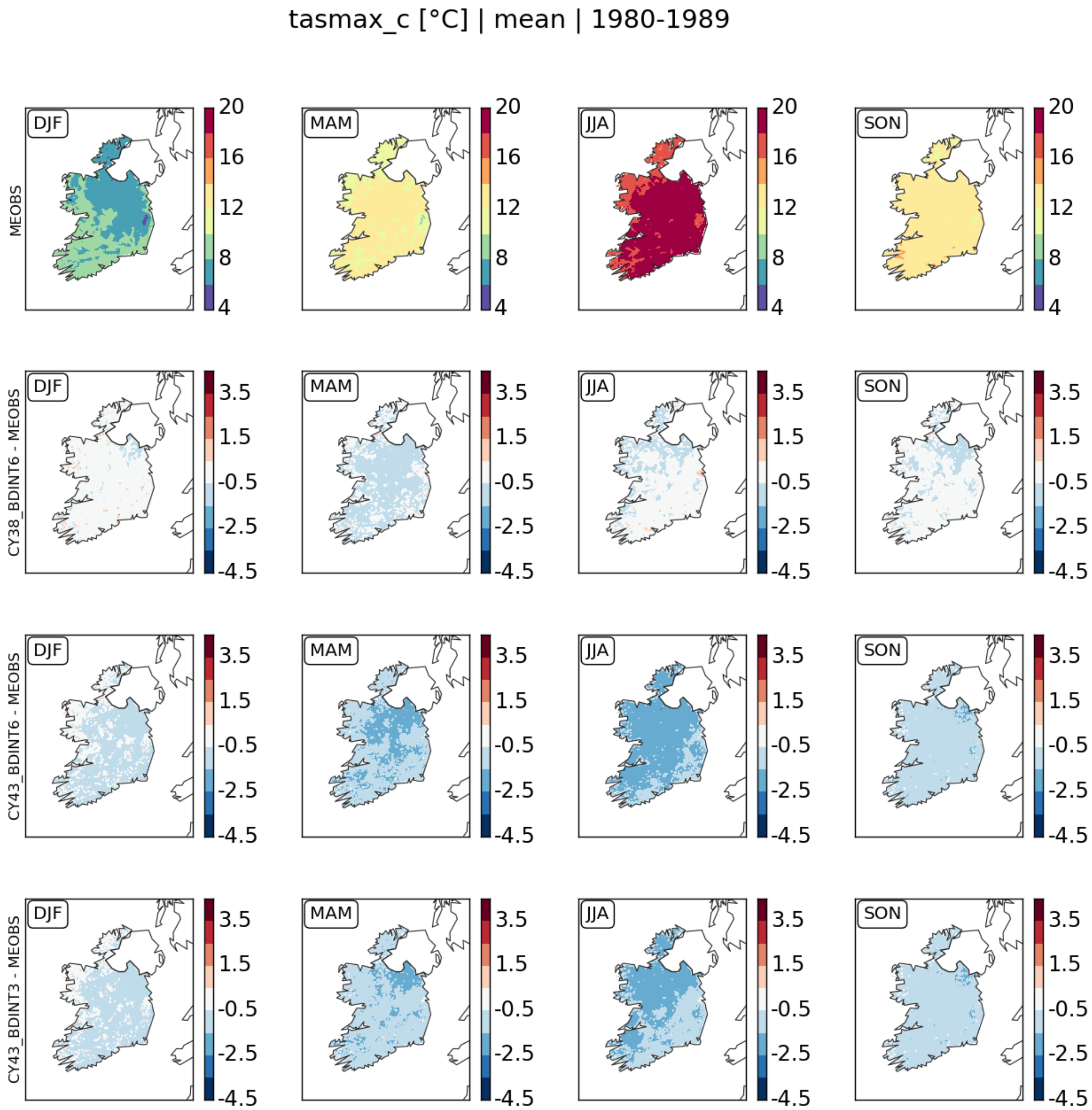

Figure 4 – Seasonal averages of maximum daily 2m air temperature over the Republic of Ireland and the period 1981-1990 for gridded observations (first row) and differences in seasonal averages between HCLIM cycle 38 and observations (second row), between HCLIM cycle 43 with 6-hourly boundary forcing and observations (third row), and between HCLIM cycle 43 with 3-hourly boundary forcing and observations (fourth row). All fields are interpolated to the spatial resolution of ERA5 prior to comparison. This figure was created through the Regional Climate Analysis Tool (RCAT).

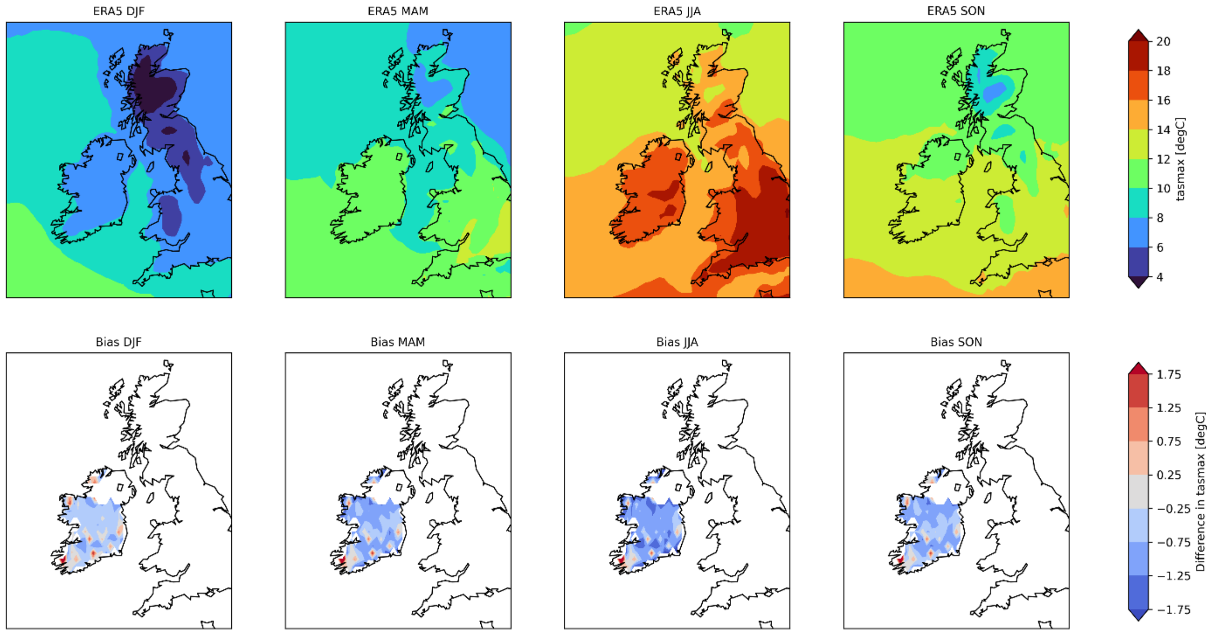

Figure 5 – Seasonal averages of maximum daily 2m air temperature over the period 1981-1990 for ERA5 (top row) and differences between ERA5 and Met Éireann's gridded observations (bottom row).

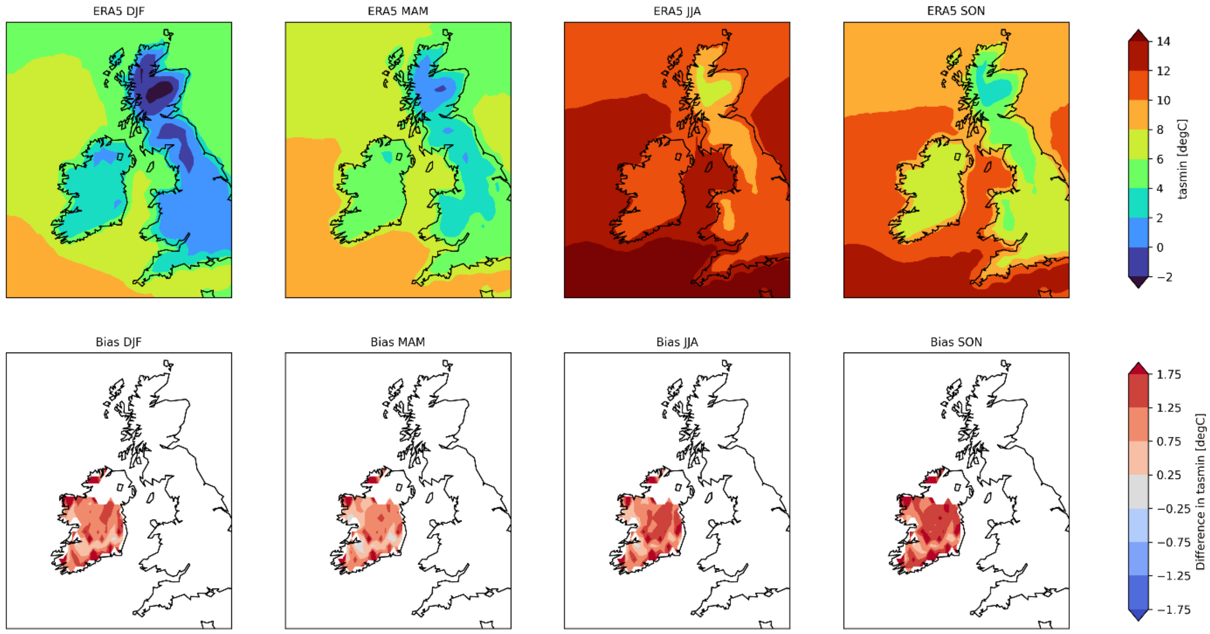

Figure 6 – Seasonal averages of minimum daily 2m air temperature over the period 1981-1990 for ERA5 (top row) and differences between ERA5 and Met Éireann's gridded observations (bottom row).

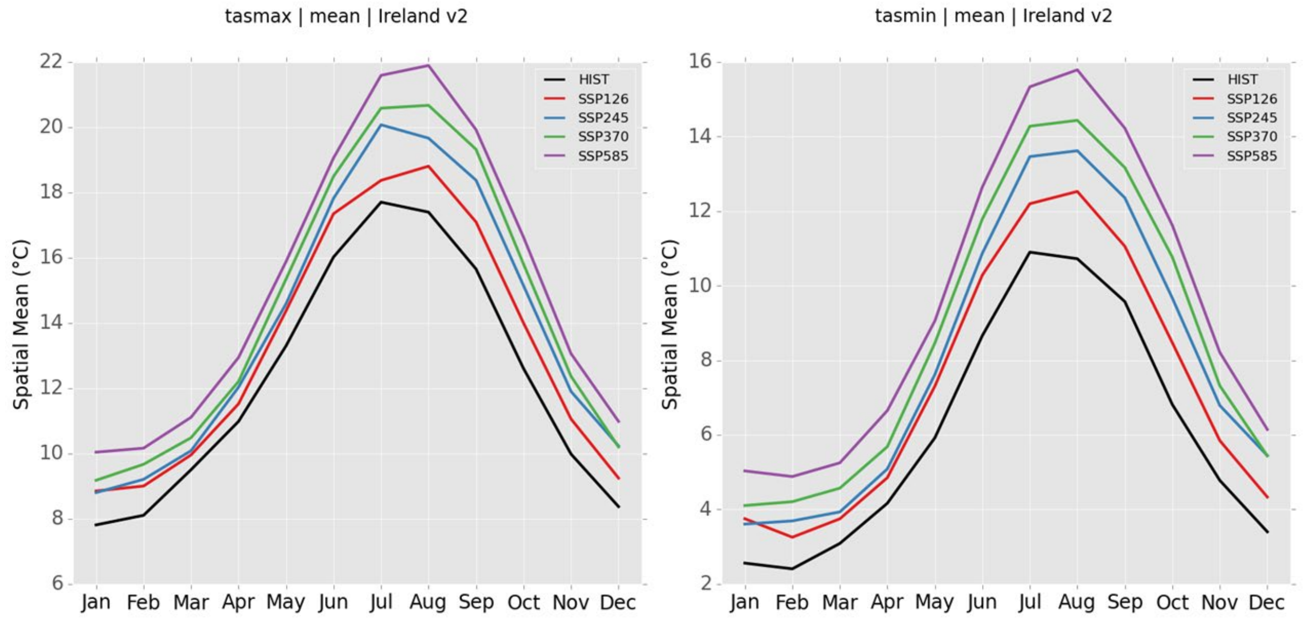

Figure 7 – Seasonal cycles of daily maximum (left panel) and daily minimum (right panel) 2m air temperature averaged over the island of Ireland for the period 1981-2010 in the historical simulation (black lines) and the period 2071-2100 in future scenarios (coloured lines). This figure was created through the Regional Climate Analysis Tool (RCAT).

Changes in daily maximum and minimum temperatures are shown as spatially averaged seasonal cycles for the different simulations (Figure 7). Both show a gradual, substantial increase across future scenarios with largest differences between scenarios in summer. Even for the intermediate scenario SSP2-4.5, average maximum and minimum temperatures increase by about 2°C in summer. An interesting aspect is that temperature changes are similar for SSP1-2.6 and SSP2-4.5 over January to May but diverge later in the year.

Changes in seasonal cycles of temperature illustrate the impact of climate change on growing-season length. This becomes even more evident when looking at the low end of the temperature distribution, here shown as 5th-percentile daily minimum temperatures (Figure 8). Even in the low emission scenarios SSP1–2.6 and SSP2–4.5, wintertime temperatures are substantially increased and consequently, frost days are substantially reduced.

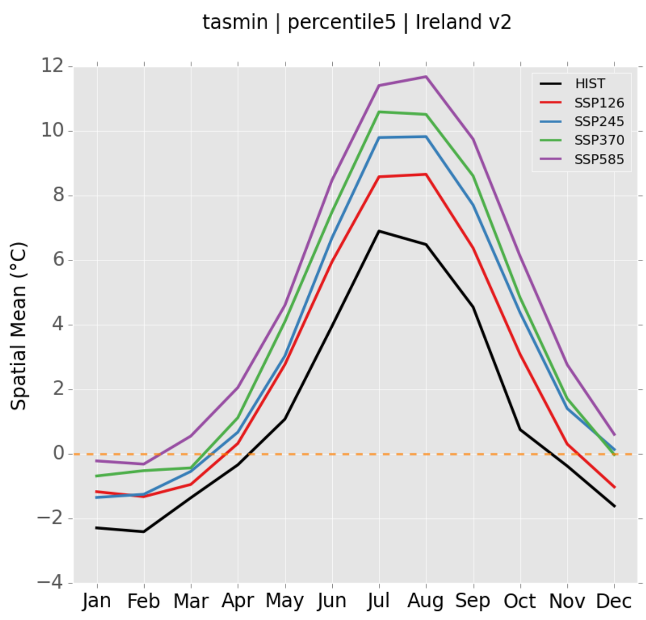

Figure 8 – Seasonal cycles of 5th-percentile daily minimum 2m air temperature averaged over the island of Ireland for period 1981-2010 in the historical simulation (black line) and period 2071-2100 in future scenarios (coloured lines). This figure was created through the Regional Climate Analysis Tool (RCAT).

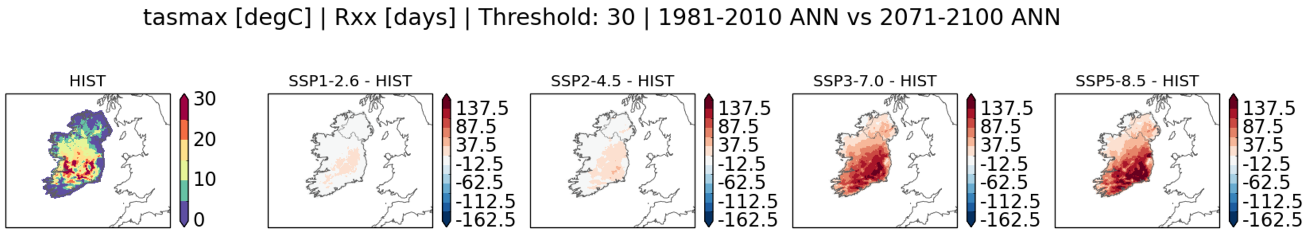

Figure 9 – Number of days with maximum 2m air temperatures above 30°C over the period 1981-2010 in the historical simulation and differences between future scenarios over 2071-2100 and historical simulations.

On the other end of the temperature distribution, the number of days with daily maximum temperatures above 30°C in the different simulations is shown in Figure 9. Ireland historically experiences these temperatures only very rarely, and the historical simulation shows highest values of about 1 day per year on average over central areas. In scenarios SSP1-2.6 and SSP2-4.5, these values roughly double or triple. However, there is a step change for this threshold-based index between SSP2-4.5 and SSP3-7.0, with about a week per year of daily maximum temperatures above 30°C in SSP3-7.0 and even more in SSP5-8.5. A comparison of the downscaled historical simulation (henceforth ECE-HCLIM) with downscaled ERA5 (henceforth ERA5-HCLIM) and gridded observations over the same period shows that ECE-HCLIM is overall warmer than ERA5-HCLIM but both simulations have colder average daily maximum temperatures than observations over the historical period 1981-2010 (not shown here for brevity). While ERA5-HCLIM is colder than observations across percentiles, ECE-HCLIM shows warmer daily maximum temperatures than observations at both tail ends of the distribution, indicating a different shape of the temperature distribution compared to ERA5-HCLIM and observations, which leads to the (unrealistically) high number of days with daily maximum temperatures above 30°C in ECE-HCLIM. It should also be noted here that the EC-Earth3-Veg simulation used to drive HCLIM is the second-warmest of the 11 available EC-Earth3-Veg CMIP6 simulations over Ireland for the period 1981-2010, which likely contributes to the high temperature extremes.

Changes in average daily precipitation from 1981-2010 (historical simulation) to the end of the 21st century in the various scenarios are shown in Figure 10. From an Irish perspective, summer is the only season showing consistent changes across scenarios with a substantial drying (apart from spring showing consistently little to no changes). This drying is even more substantial on a relative scale, as precipitation is lowest in summer. Precipitation in autumn and winter (storm season) is only increasing in the highest-emission scenario over Ireland, which is in contrast to consistent increases in precipitation over the West of Scotland and, to a lesser degree, of England and Wales.

Changes in 95th-percentile daily precipitation from 1981-2010 to the end of the 21st century in the various scenarios are shown in Figure 11, which do not mirror changes in mean precipitation. Generally, extreme precipitation is projected to increase for all seasons except summer with higher increases for higher emission scenarios during autumn and winter. Even in summer, there is less decrease in extreme precipitation than in mean precipitation on a relative scale, suggesting an increase in variability (widening of distribution).
Comparing different annual high-precipitation percentiles further illustrates this (Figure 12). While 95th-percentile precipitation only shows a clear increase for the high-emission scenarios, 99th-percentile precipitation shows an increase across all scenarios that also increases from low-emission to high-emission scenarios. On the other end of the precipitation distribution, we can see a decrease in days with more than 1 mm of precipitation – i.e. an increase in the number of dry days – further indicating an increase in variability of precipitation (Figure 13).

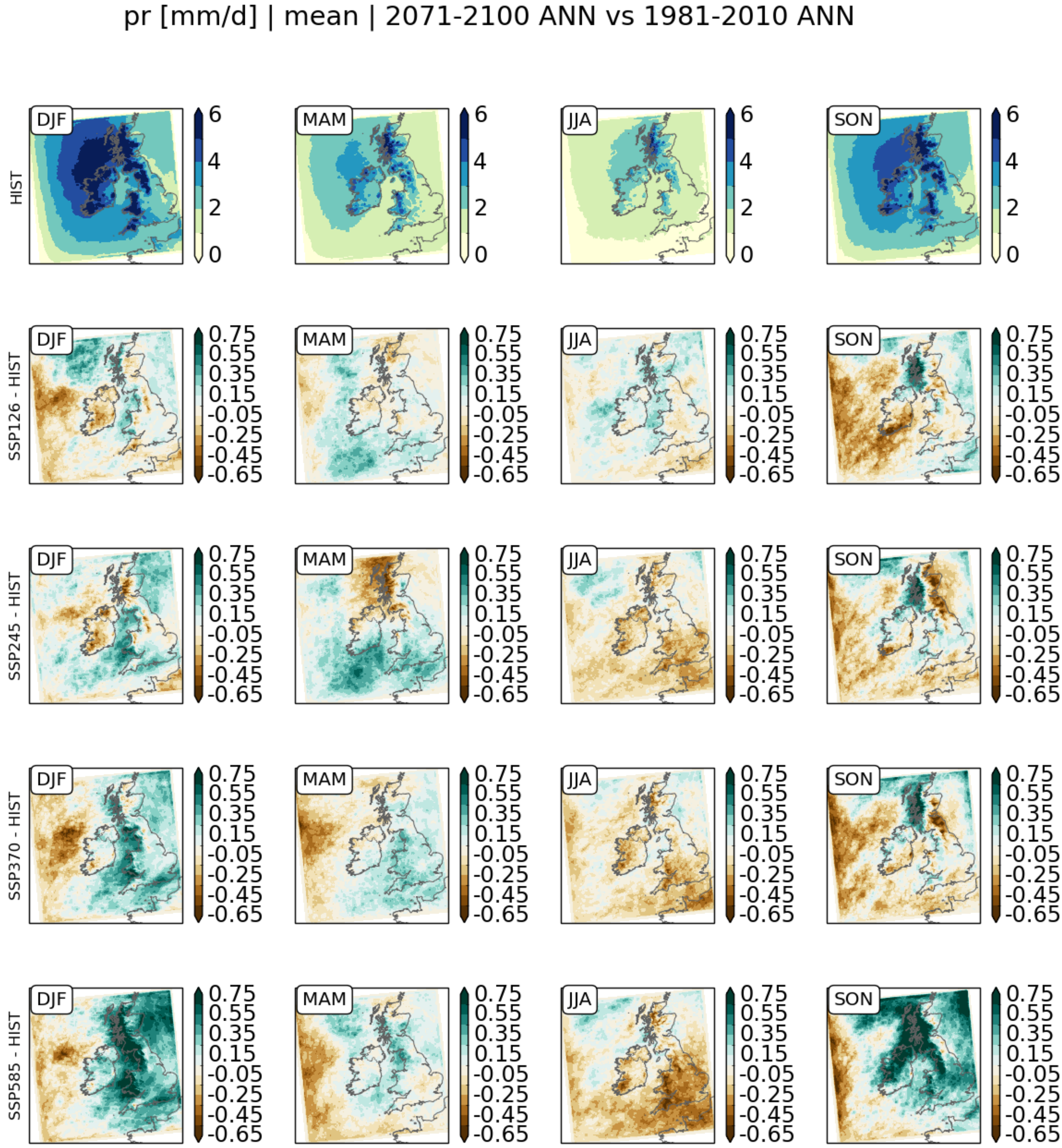

Figure 10 – Seasonal averages of daily precipitation over the 4km-resolution domain and the period 1981-2010 in the historical simulation (first row) as well as differences in seasonal averages between future scenario SSP1-2.6 and the historical simulation (second row), between future scenario SSP2-4.5 and the historical simulation (third row), between future scenario SSP3-7.0 and the historical simulation (fourth row), and between future scenario SSP5-8.5 and the historical simulation (fifth row). This figure was created through the Regional Climate Analysis Tool (RCAT).

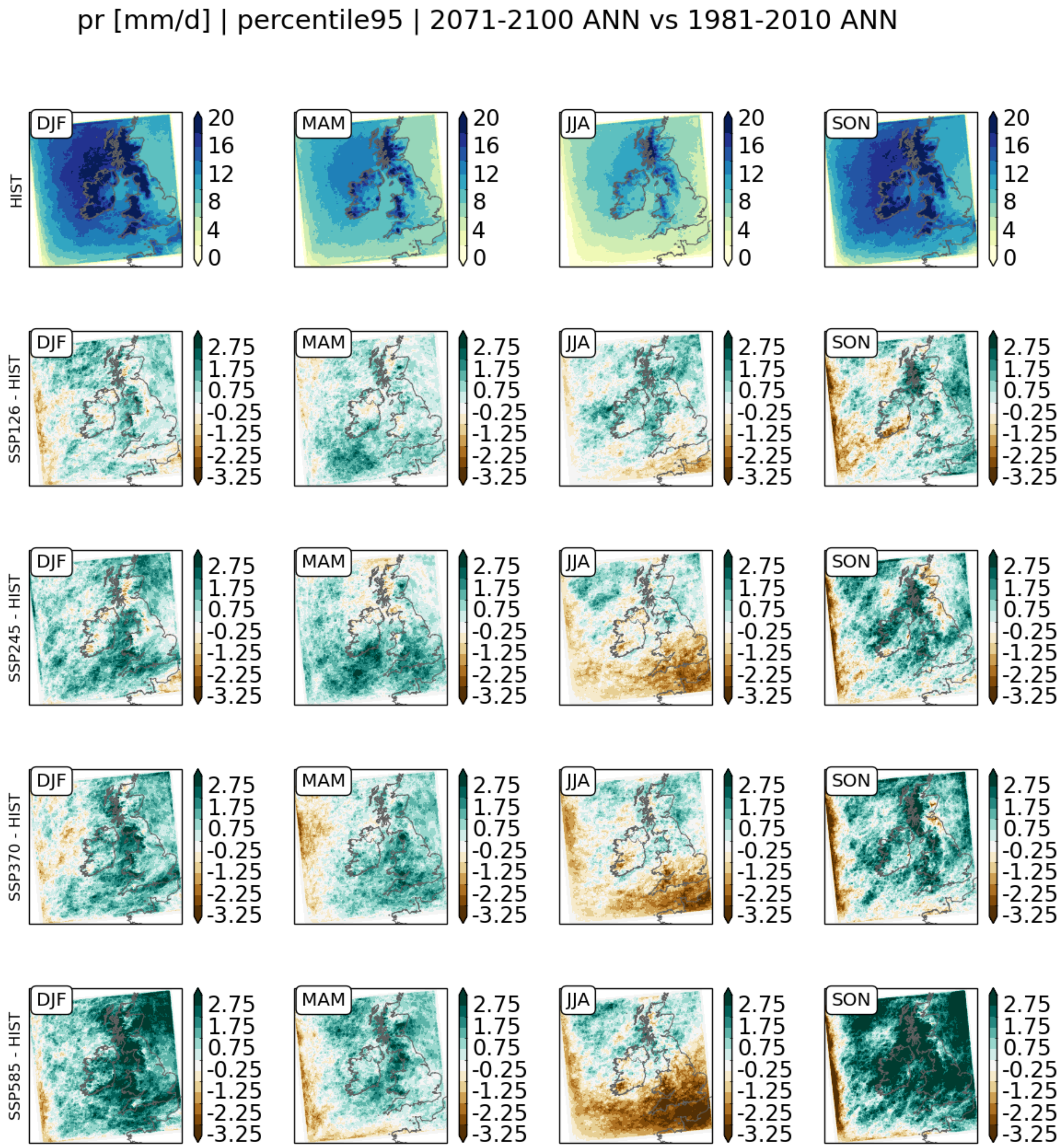

Figure 11 – Seasonal averages of 95th-percentile daily precipitation over the 4km-resolution domain and the period 1981-2010 in the historical simulation (first row) as well as differences in seasonal averages between future scenario SSP1-2.6 and the historical simulation (second row), between future scenario SSP2-4.5 and the historical simulation (third row), between future scenario SSP3-7.0 and the historical simulation (fourth row), and between future scenario SSP5-8.5 and the historical simulation (fifth row). This figure was created through the Regional Climate Analysis Tool (RCAT).

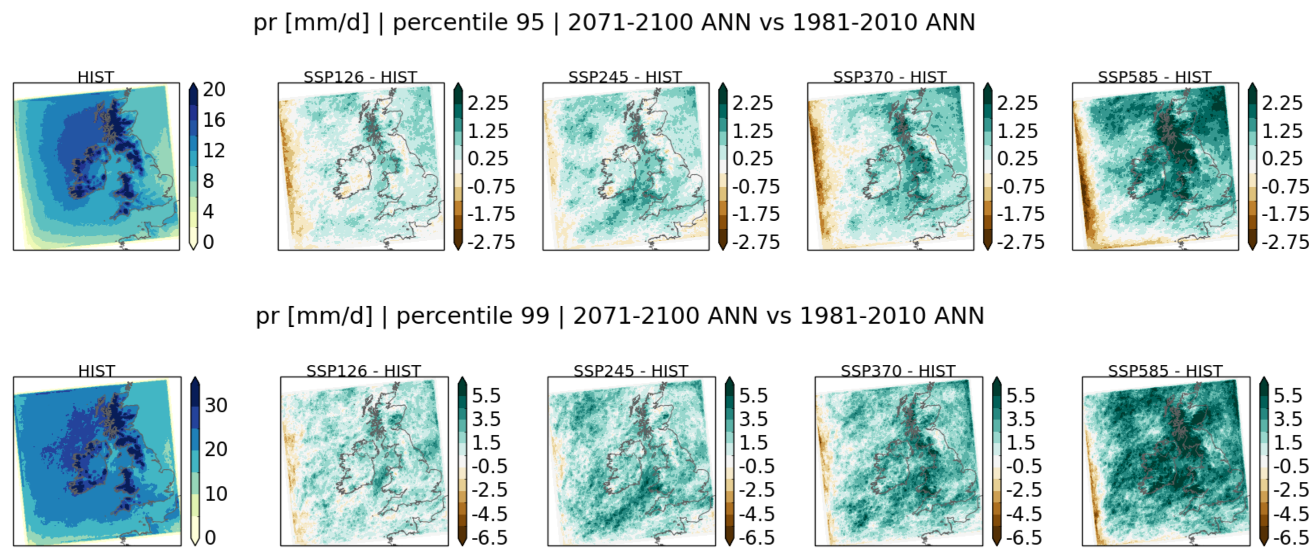

Figure 12 – Percentiles 95 (top row) and 99 (bottom row) of daily precipitation for the period 1981-2010 in the historical simulation and differences between the period 2071-2100 of the future scenarios and the historical simulation. This figure was created through the Regional Climate Analysis Tool (RCAT).

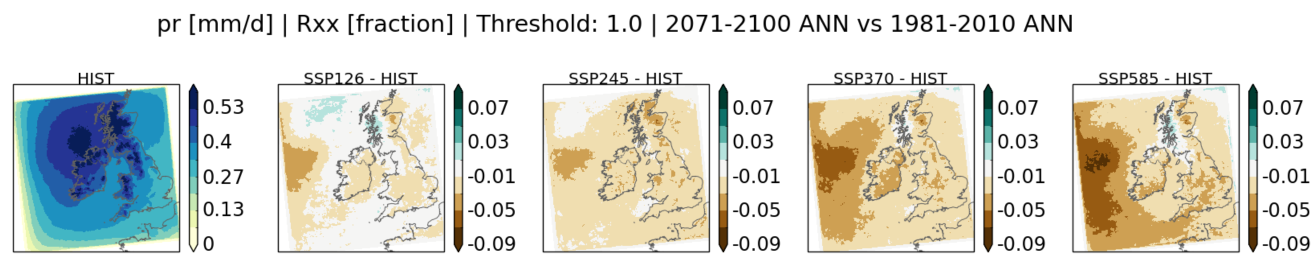

Figure 13 – Number of days with precipitation above 1 mm as a fraction of the 30-year periods for the historical simulation and differences between future scenarios and historical simulation. This figure was created through the Regional Climate Analysis Tool (RCAT).

Changes in daily maximum wind speed from 1981-2010 to the end of the 21st century in the various scenarios are shown in Figure 14. Wind speeds are generally projected to decrease over the domain. Strongest decreases are seen for summer, which is the season with the lowest wind speeds. Wind-speed extremes are also projected to decrease (Figure 15). However, decreases are smaller in relative terms for extremes than for mean wind speeds.

The downscaled EC-Earth simulations shown here are planned to be included in TRANSLATE (https://www.met.ie/science/translate), which is a Met Éireann-led project to standardise climate projections for Ireland. This project uses an ensemble of downscaled global climate simulations from different sources; however, the simulations shown here are the only ones contributed by Met Éireann and therefore represent a substantial achievement.

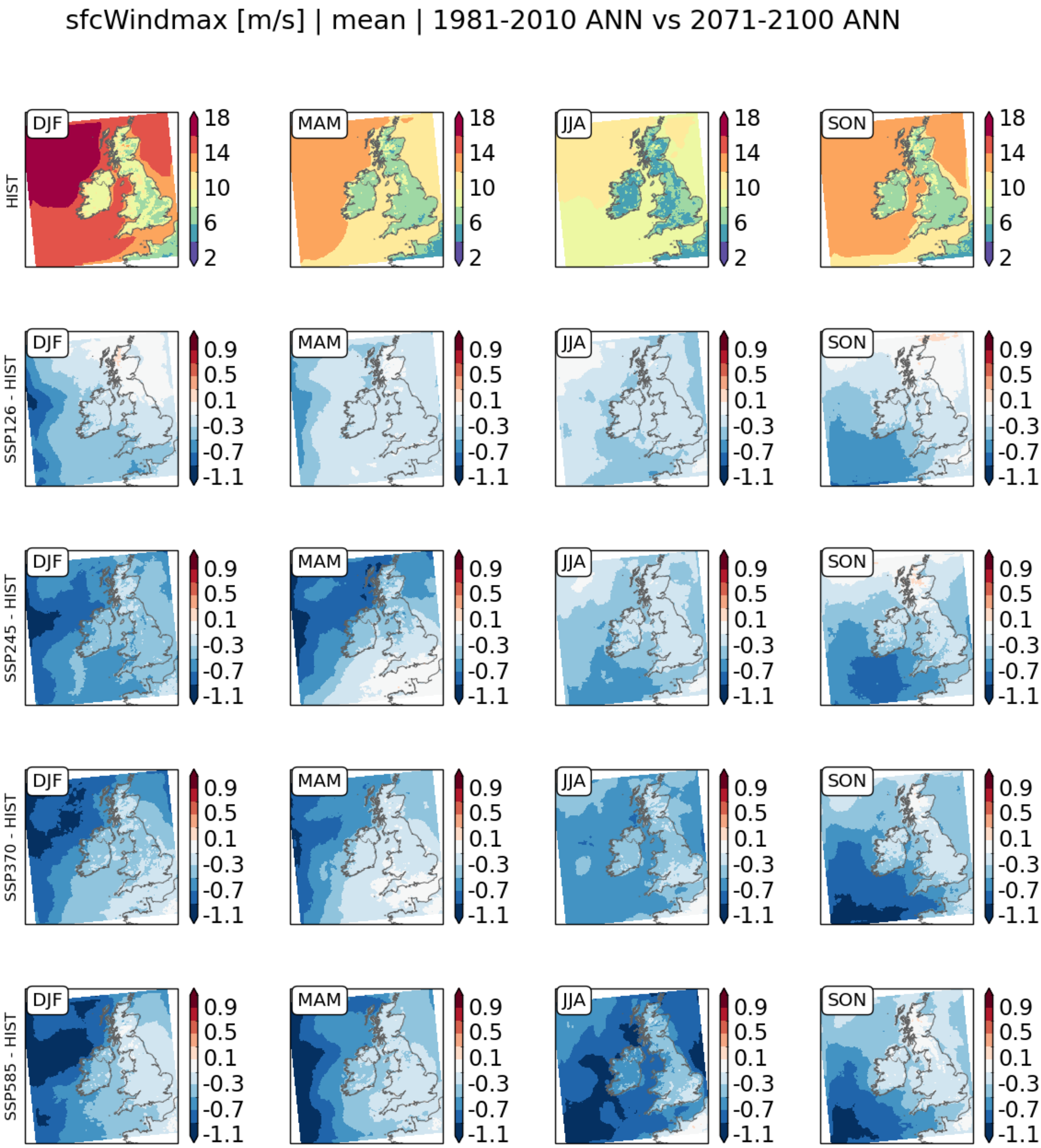

Figure 14 – Seasonal averages of daily maximum wind speed over the 4km-resolution domain and the period 1981-2010 in the historical simulation (first row) as well as differences in seasonal averages between future scenario SSP1-2.6 and the historical simulation (second row), between future scenario SSP2-4.5 and the historical simulation (third row), between future scenario SSP3-7.0 and the historical simulation (fourth row), and between future scenario SSP5-8.5 and the historical simulation (fifth row). This figure was created through the Regional Climate Analysis Tool (RCAT).

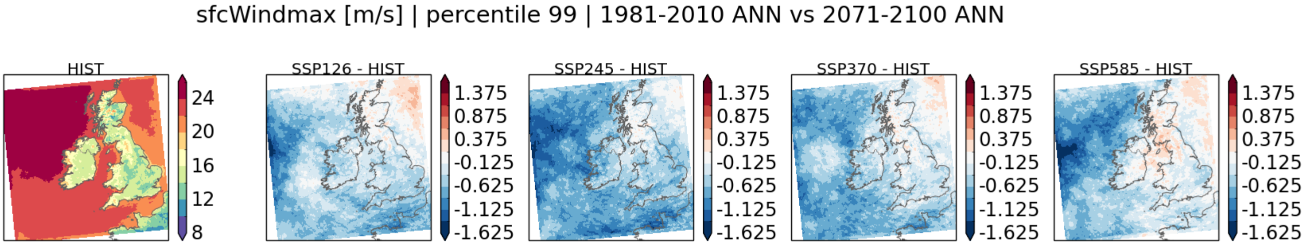

Figure 15 – Percentile 99 of daily maximum wind speed for the period 1981-2010 in the historical simulation and differences between period 2071-2100 of the future scenarios and the historical simulation. This figure was created through the Regional Climate Analysis Tool (RCAT).

List of publications/reports from the project with complete references

N/A

Future plans

(Please let us know of any imminent plans regarding a continuation of this research activity, in particular if they are linked to another/new Special Project.)

There will be no direct continuation of this project, but we will continue to use HCLIM for dynamical downscaling and might need more resources than we have in our national allocation. For example, we are currently running global AWI-CM simulations with a high resolution over the North Atlantic to better represent future changes in the Atlantic Meridional Overturning Circulation (AMOC), and we will downscale those simulations with HCLIM. We are further looking at potential AMOC storyline simulations (low-likelihood, high-impact scenarios), which we might downscale with HCLIM. If we choose several of those experiments, we will likely need to apply for a special project. More generally, we are thinking about extending our downscaling simulations to ensembles, which would also require more resources than we usually have. However, we are currently testing the next version of HCLIM (cycle 46), which is more efficient than HCLIM cycle 43 (mainly due to using single precision). We are also currently coordinating a set of pan-European experiments within the HCLIM consortium to explore key topics of interest, including the ability of HCLIM to correct biases in GCM data, in particular in the position of the North Atlantic storm track, as well as determining optimal model physics configurations. Based on the results of these experiments, we may run additional experiments in the future which would benefit from special project resources.