SPECIAL PROJECT FINAL REPORT

Project Title:	High-Resolution Downscaled RCM-CMIP6 Simulations
Computer Project Account:	spienola
Start Year - End Year :	2022-2024
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Other Researchers (Name/Affiliation):	N/A

Summary of project objectives

The scientific objectives of the project are to dynamically downscale CMIP6 data to provide high resolution regional climate projections for Europe and Ireland using both standard atmosphere-only (WRF and COSMO-CLM) and coupled atmosphere-ocean-wave (COAWST) Regional Climate Models (RCMs). The resulting datasets will add to a larger ensemble of RCM data currently being produced at a national and European scale (EURO-CORDEX). The future climate is simulated under all four "tier-1" SSP (SSP1-2.6, SSP2-4.5, SSP3-7.0 and SSP5-8.5) scenarios.

Summary of problems encountered

The problems encountered were minimal. The implementation and running of the WRF & COSMO-CLM RCMs on the Atos system presented no issues. The only minor issues were the transferring of the large climate datasets from atos to local servers which resulted in some delays.

Experience with the Special Project framework

No issues to report; the administration and reporting procedures were efficient.

Summary of results

The future climate of Ireland (1981-2100) was simulated at high resolution using the WRF and COSMO-CLM Regional Climate Models (RCMs). The future climate was simulated under all four "tier-1" SSP (SSP1-2.6, SSP2-4.5, SSP3-7.0 and SSP5-8.5) scenarios.

The choice of CMIP6 data for downscaling was informed by CMIP6 validation studies (e.g. Bock et al., 2020; Eyring et al., 2021) and a careful review conducted by EURO-CORDEX partners (COSMO-CLM team, personal communication). This study identified an initial set of CMIP6 datasets based on many factors, e.g. model-level data availability, SSP–RCP coverage (SSP1-2.6, SSP2-4.5, SSP3-7.0 and SSP5-8.5), model resolution, equilibrium climate sensitivity (low, medium and high), model skill, e.g., transient climate response, June–August and December–February extratropical storm tracks, and circulation and sea surface temperature validations. Informed by this study, and with particular weight given to ensuring a plausible spread of equilibrium climate sensitivity (ECS), the CMIP6 datasets presented in Table 1 (first column) were chosen for initial downscaling over the Irish domain. ESM realisations result from running the same ESM with slightly different initial conditions, i.e. the starting date of historical simulations. The choice of CMIP6 data is corroborated by a separate 2021 study conducted by the Finnish Meteorological Institute (Ruosteenoja, 2021). This filtering of CMIP6 models resulted in a high-quality, representative and manageable ensemble for downscaling over Ireland.

An overview of the ensemble of RCM simulations is presented in Table 1. Data from a 30-year reference period (1981–2010) and three future 30-year periods (2021–2050, 2041–2070 and 2071–2100) were used for the analysis of projected changes in the Irish climate for each of the four RCP-SSP scenarios. The historical period was compared with the corresponding future period for all simulations within the same RCM–ESM realisation. This resulted in 10 future anomalies for each future 30-year time period and SSP–RCP, i.e. the difference between future and past. In this study, the ensemble members of the downscaled ESM simulations are treated as independent estimates of the climate system and are given equal weight. Only the differences between the simulations of the past and future climate for each model are used in the analysis (e.g. WRF–EC-Earth-Veg-r12i1p1f1 SSP1-2.6 is compared only with WRF–EC-Earth-Veg-r12i1p1f1 historical and WRF–EC-Earth-Veg-r14i1p1f1 SSP1-2.6 is compared only with WRF–EC-Earth-Veg-r14i1p1f1 historical). While model biases may not be invariant under future scenarios of greenhouse gas emissions, this approach may reduce the impact of model bias.

CMIP6 ESM	ESM ECS	ESM Ensemble Members	RCM Nesting Strategy	RCM
EC-Earth AOGCM $(\times 1)$	4.2	r11i1p1f1	20km → 4km	WRF
EC-Earth-Veg $(\times 2)$	4.31	r12i1p1f & r14i1p1f1	20km → 4km	WRF
MPI-ESM1-2-HR $(\times 2)$	2.98	r1i1p1f1 & r2i1p1f1	20km → 4km	WRF
EC-Earth-Veg $(\times 2)$	4.31	r12i1p1f & r14i1p1f1	12km → 4km	COSMO-CLM5
MPI-ESM1-2-HR $(\times 2)$	2.98	r1i1p1f1 & r2i1p1f1	12km → 4km	COSMO-CLM5
MIROC6 $(\times 1)$	2.61	r1i1p1f1	12km → 4km	COSMO-CLM5

Table 1. Details of the completed ensemble of RCM-CMIP6 simulations analysed as part of the current study. The columns present information on the CMIP6 ESM (number in bracket indicates number of separate ESM realisations downscaled), ESM Equilibrium Climate Sensitivity, ESM realization ensemble id's, nesting strategy.

The RCM configurations were validated by running simulations of the past Irish climate for the period 1981–2010, driven by both fifth-generation ECMWF atmospheric reanalysis of the global climate (ERA5) and the CMIP6 ESM datasets, and comparing the output against observational data. See Figures 1 & 2 for validations of 2m temperature and precipitation as resolved by the COSMO-CLM5-ERA5 and the downscaled CMIP6 simulations. It is noted that WRF has a cold bias and tends to be wetter compared to COSMO-CLM. For precipitation (see Figures 1a&b and Table 2), averaged over the country, the MAE ranges from 9.4% (COSMO-

CLM5-EC-Earth3-Veg r12i1p1f1) to 32% (WRF-MPI-ESM1-2-HR r1i1p1f1). While the WRF biases are generally larger, it is noted that the bias and MAE are similar (i.e., the sign of the bias is consistent). This is desirable for the bias-correcting that will be carried out as part of the Met Eireann TRANSLATE project. For temperature, averaged over the country (see Figures 1c&d and Table), the Mean Absolute Error (MAE) ranges from 0.24℃ (COSMO-CLM5-ERA5 4km) to 2.12℃ (WRF-EC-Earth r11i1p1f1; note that this GCM also has a large cold bias).

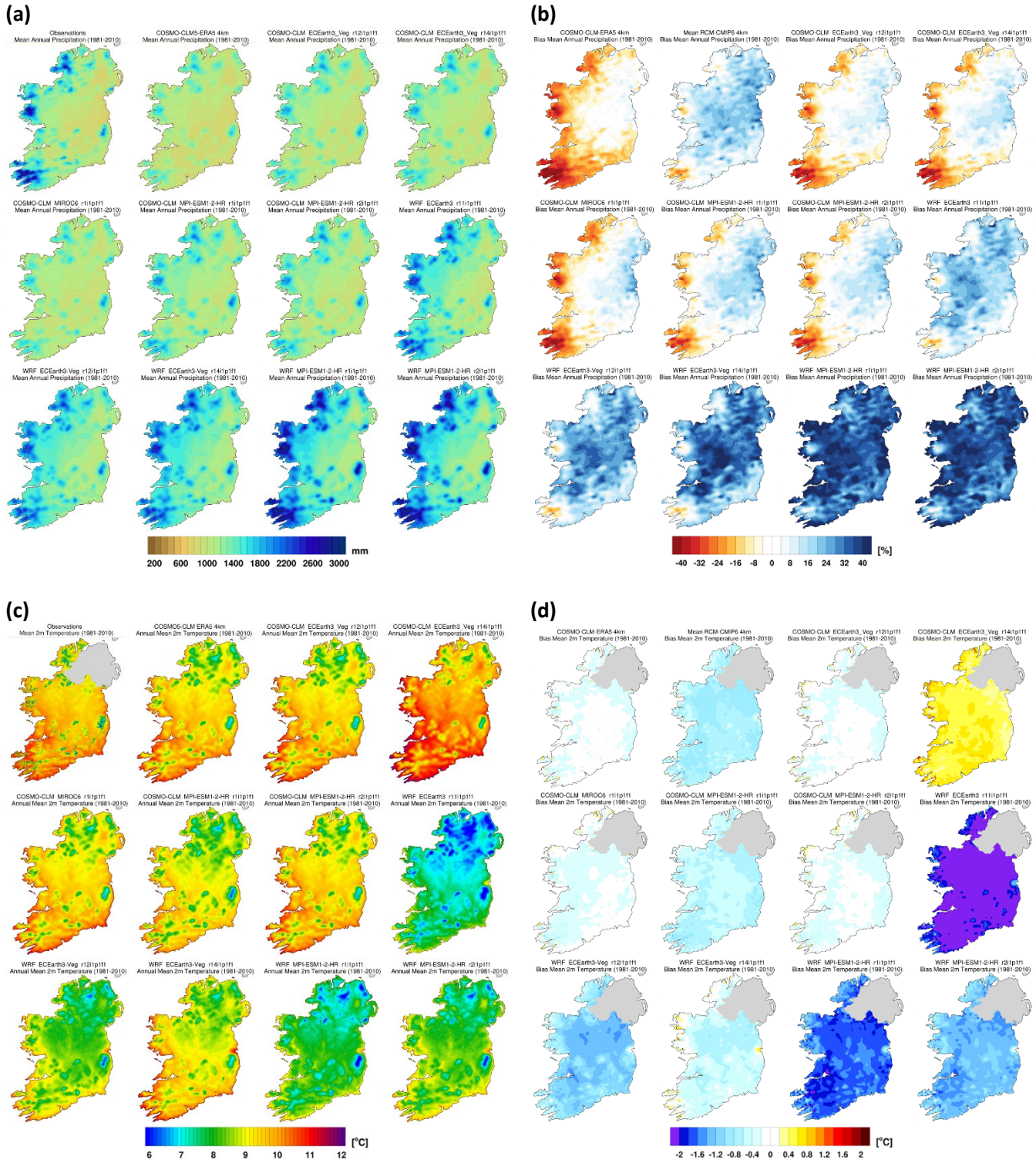


Figure 1. Annual 2m Temperature and Precipitation (1981-2010) for Observations, COSMO-CLM5-ERA5 and the RCM-CMIP6 ensemble members; **(a)** Mean Precipitation (mm) **(b)** RCM Precipitation Percentage Bias (%), **(c)** Mean 2m Temperature and **(d)** RCM 2m Temperature Bias (°C)

Mean Annual Validations 1981-2010	Precipitation Bias (%)	Precipitation MAE (%)	Temperature Bias (℃)	Temperature MAE (℃)
COSMO-CLM5 ERA5 4km	-11.42	12.80	**-0.14**	**0.21**
Mean RCM-CMIP6 4km	12.56	14.27	-0.72	0.73
COSMO-CLM5 ECEarth3_Veg r12i1p1f1	-3.25	**9.59**	-0.15	0.23
COSMO-CLM5 ECEarth3_Veg r14i1p1f1	-2.30	10.08	0.54	0.54
COSMO-CLM5 MIROC6 r1i1p1f1	-3.53	11.23	-0.21	0.27
COSMO-CLM5 MPI-ESM1-2-HR r1i1p1f1	4.16	11.31	-0.57	0.59
COSMO-CLM5 MPI-ESM1-2-HR r2i1p1f1	**1.55**	10.22	-0.18	0.24
WRF ECEarth3 r11i1p1f1	15.38	16.25	**-2.23**	**2.23**
WRF ECEarth3-Veg r12i1p1f1	20.03	20.83	-1.09	1.10
WRF ECEarth3-Veg r14i1p1f1	25.39	25.93	-0.43	0.50
WRF MPI-ESM1-2-HR r1i1p1f1	**34.21**	**34.23**	-1.64	1.64
WRF MPI-ESM1-2-HR r2i1p1f1	34.09	34.11	-1.26	1.26

Table 2. Precipitation (%) and 2m Temperature (℃) uncertainty estimates for COSMO-CLM5-ERA5, each RCM-CMIP6 ensemble member and mean of the RCM-CMIP6 ensemble, through comparison with Met Éireann gridded observations (1981-2010). For each metric, the best- and worst-performing scores are highlighted in blue and red text, respectively.

Projections of numerous variables (e.g., temperature, precipitation, 10m wind, snowfall, specific & relative humidity, MSLP, surface solar radiation, cloud cover, air density, 10cm soil temperature) and derived products (e.g., heatwaves, frost & ice days, growing & grazing season, growing degree days for crops & pests, heavy rainfall days, dry days, turbine height wind power, solar photovoltaic (see Figure 1a) power, heating degree days, driving rain, evapotranspiration (calculated using see Figure 1b) were analysed. To quantify the uncertainty in the projections, the 33rd, 50th and 66th percentiles of the ensemble of projections are calculated. To highlight areas of uncertainty, for each figure, hatching is included where the P33 & P66 projections have different signs. Figure An overview of the preliminary projections can be seen in Nolan (2024) EPA report.

Examples of the RCM climate projections for Ireland include:

- 2m temperatures are projected to increase by up to 3℃ by the end of the century for the SSP585 scenario. There is a clear west to east gradient in the temperature projections with the largest increases in the east. The temperature projections are enhanced for summer and autumn and extremes (Figure 2).
- The number of frost and ice days are projected to decrease substantially.
- Precipitation projections shows small changes (~0%) over the full year. The future winter & autumn months are projected to be wetter, while summer is projected to be dryer. A mixed signal is noted for spring (Figure 3; note the "hatching" highlighting areas of uncertainty)
- The precipitation climate is projected to be more variable with more very wet and dry events
- Snowfall is projected to decrease substantially
- 10m wind speed is projected to decrease over the full year and for all seasons. The decreases are largest for the summer months.
- Specific humidity is projected to increase substantially over the full year and for all seasons. Relative Humidity projections show no change (~0%) or small increases over the full year The largest increases are noted for the summer months.
- Solar photovoltaic power is projected to decrease over the full year (Figure 4a) and for all seasons. The decreases are largest for the summer months.
- Evapotranspiration, as derived using the FAO Penman-Monteith method, is projected to increase (Figure 4b). However, there is uncertainty in the projections for the lower SSPs and earlier time periods.

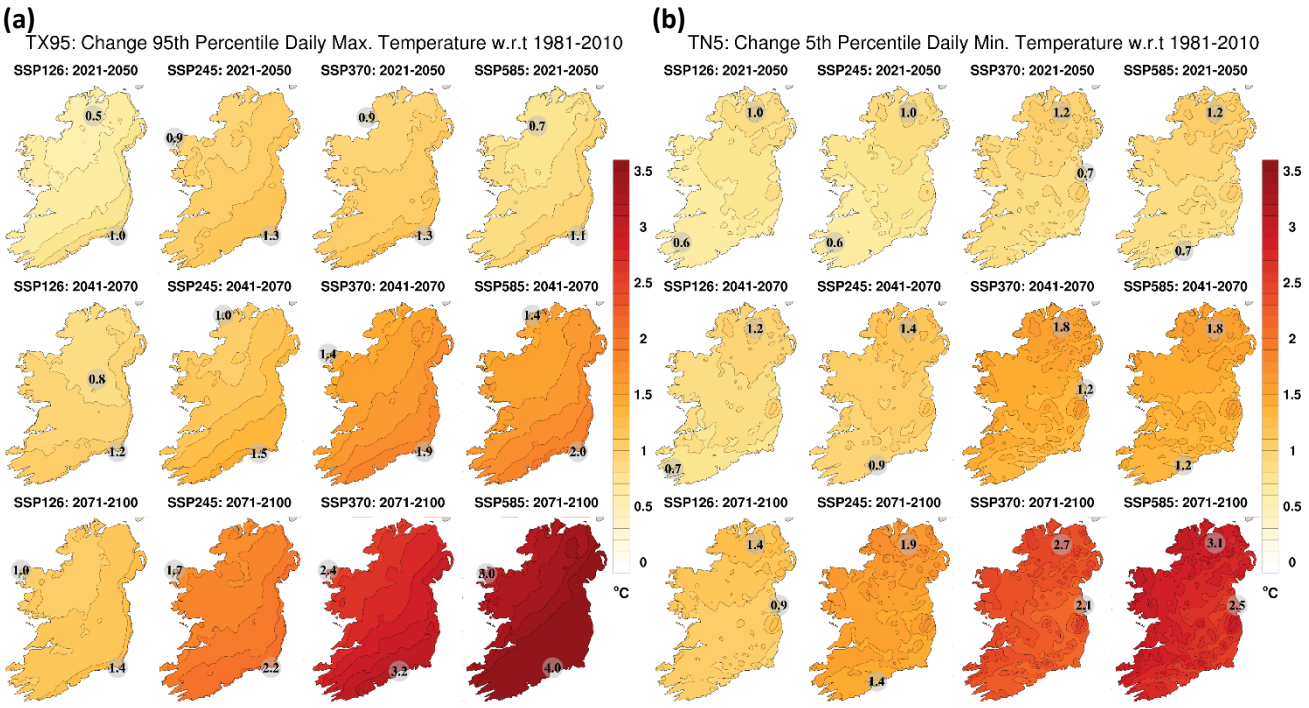
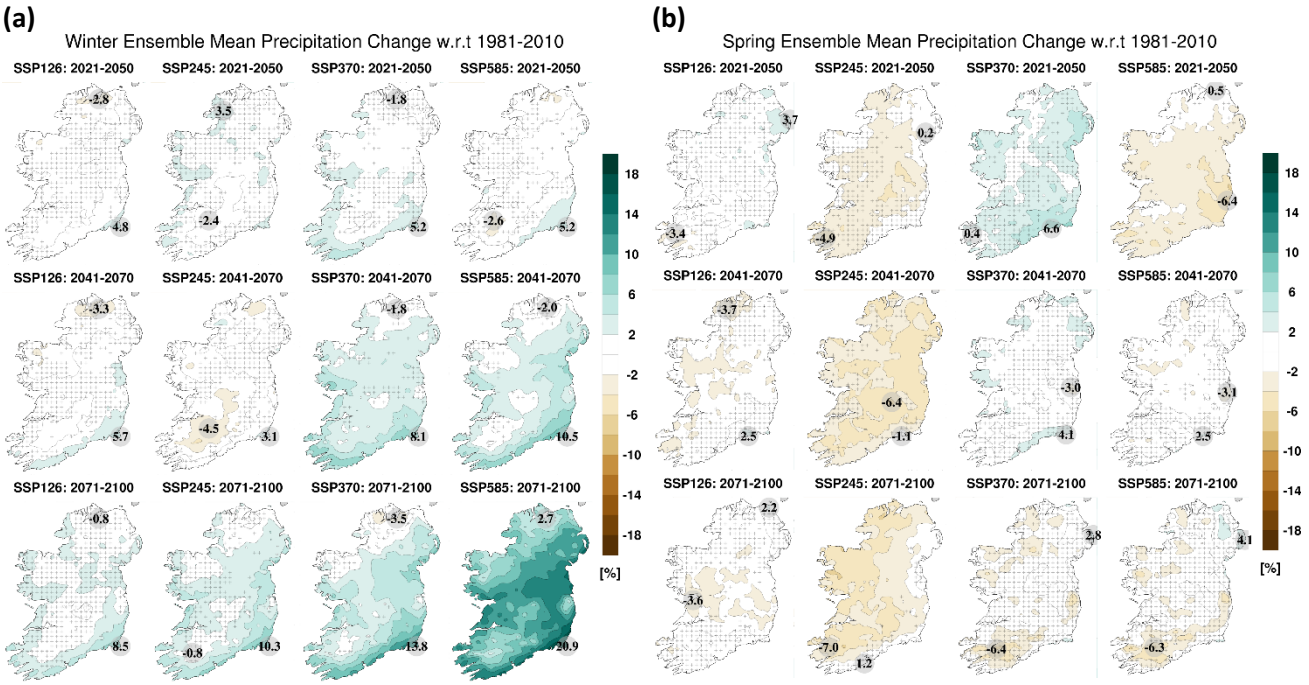


Figure 2. Projected changes in extreme 2-m temperature: **(a)** top 5% of daily maximum temperatures (warm summer days) and **(b)** bottom 5% of daily minimum temperatures (cold winter nights). In each case, the future 30-year period is compared with the past period, 1981–2010. The numbers included on each plot are the minimum and maximum projected changes, displayed at their locations.



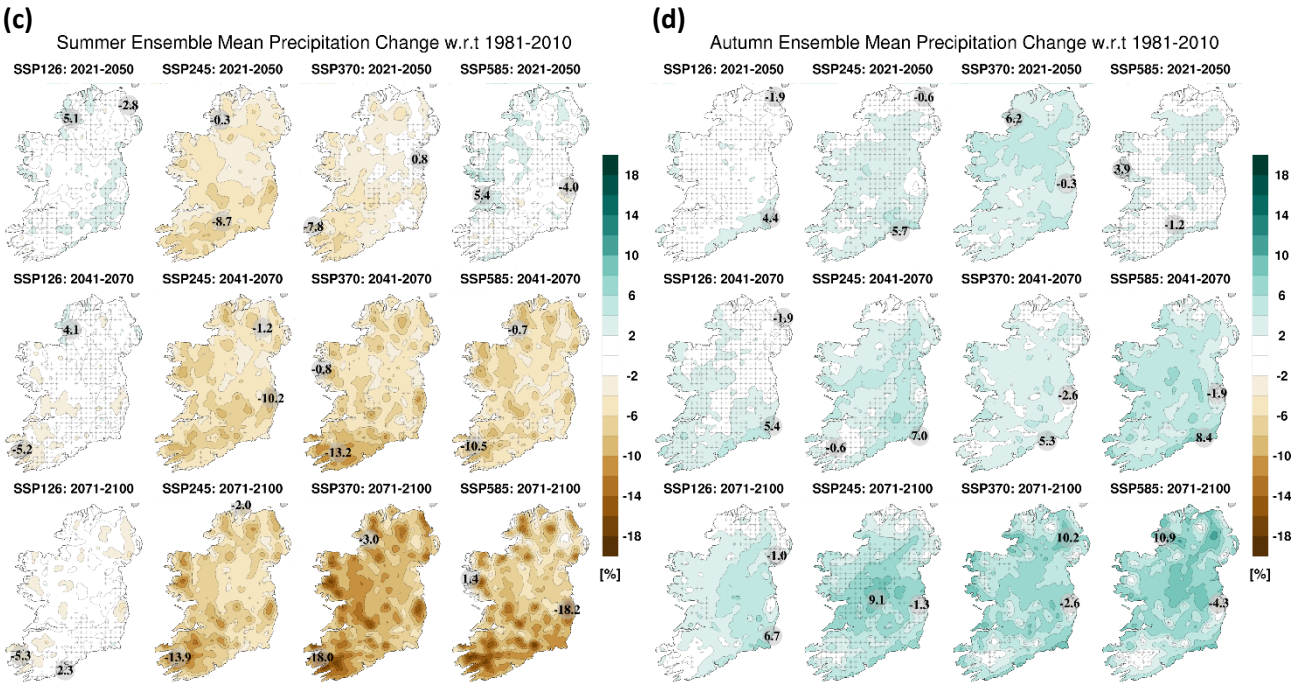


Figure 3. Seasonal RCM ensemble projections of mean precipitation (%); **(a)** winter, **(b)** spring, **(c)** summer and **(d)** autumn. In each case, the future 30-year period is compared with the past period, 1981–2010. The numbers included on each plot are the minimum and maximum projected changes, displayed at their locations.

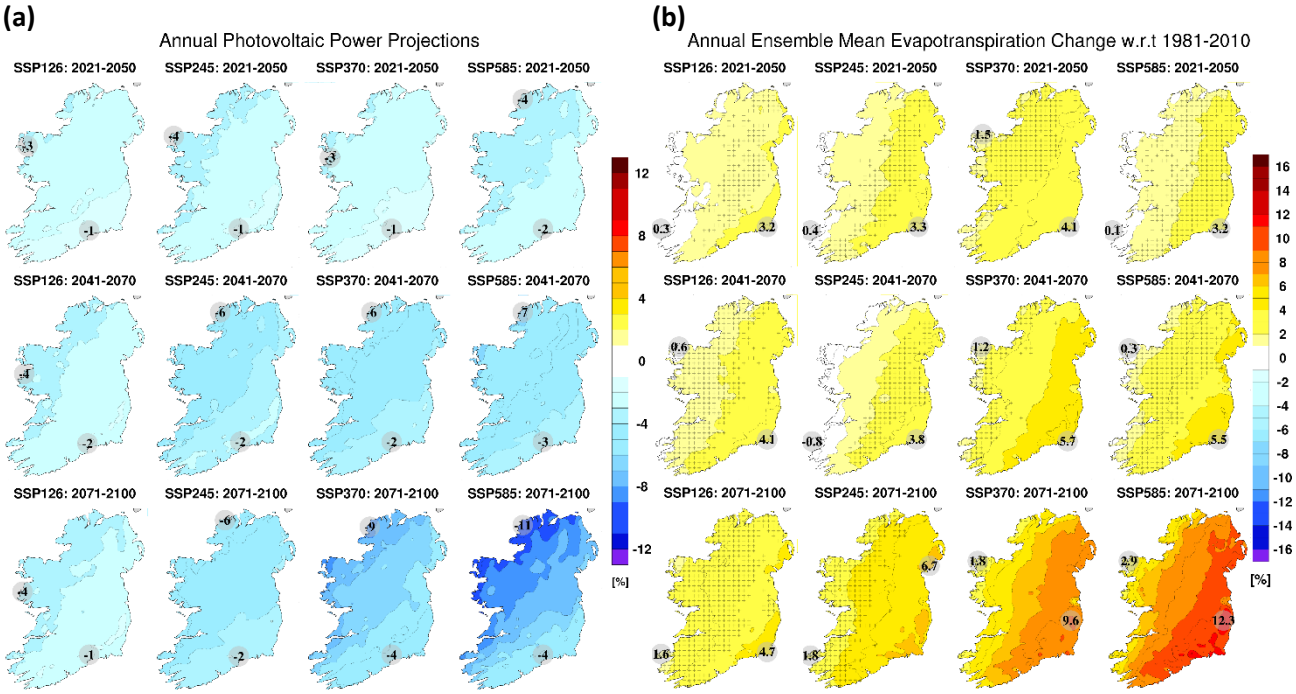


Figure 4. Projected changes (%) in mean annual **(a)** photovoltaic and **(b)** evapotranspiration. In each case, the future 30-year period is compared with the past period, 1981–2010. The numbers included on each plot are the minimum and maximum projected changes, displayed at their locations.

The SSP-RCP scenario-based RCM projections were supplemented with global warming threshold (GWT) scenario projections. Figure 5 presents 2m temperature projections for Ireland for various GWTs (1.5, 2, 2.5, 3, 3.5 and 4°C). For example, the projections under the "2°C GWT Scenario" show temperature projections over Ireland in a world which is 2°C warmer with respect to 1850-1900. The GWT scenario projections were assessed using the RCM-CMIP6-SSP scenario projections of Table 1 as well as the ensemble of RCM-CMIP5-RCP projections of Nolan and Flanagan (2020). As such, the ensemble size is considerably larger (at the time

of writing, up to 58 members) and allows for a better quantification of uncertainty. This increased ensemble size allows for the IPCC AR6 "Approach C" to be implemented where robustness/certainty is based on both model agreement (≥80% agreement of ensemble members in the sign of projected change) and significance (in this case, the 'signal to noise ratio' test). Furthermore, the enhanced ensemble size allows for assessment of a larger range of "likelihood" projections. Figure 6 presents various percentiles of the ensemble of projections of annual 2m temperature for five GWT scenarios; the 10th (very likely), 33rd (likely), 50th (as likely as not), mean, 66th (unlikely) and 90th (very unlikely) projections. Some sample GWT scenario projections for precipitation (%), presented in Figure 7 (seasonal) and Figure 8 (annual likelihood projections), show substantial less areas of uncertainty (compared to the SSP-based projections), underpinning the importance of analysing large ensembles in the assessment of climate change.

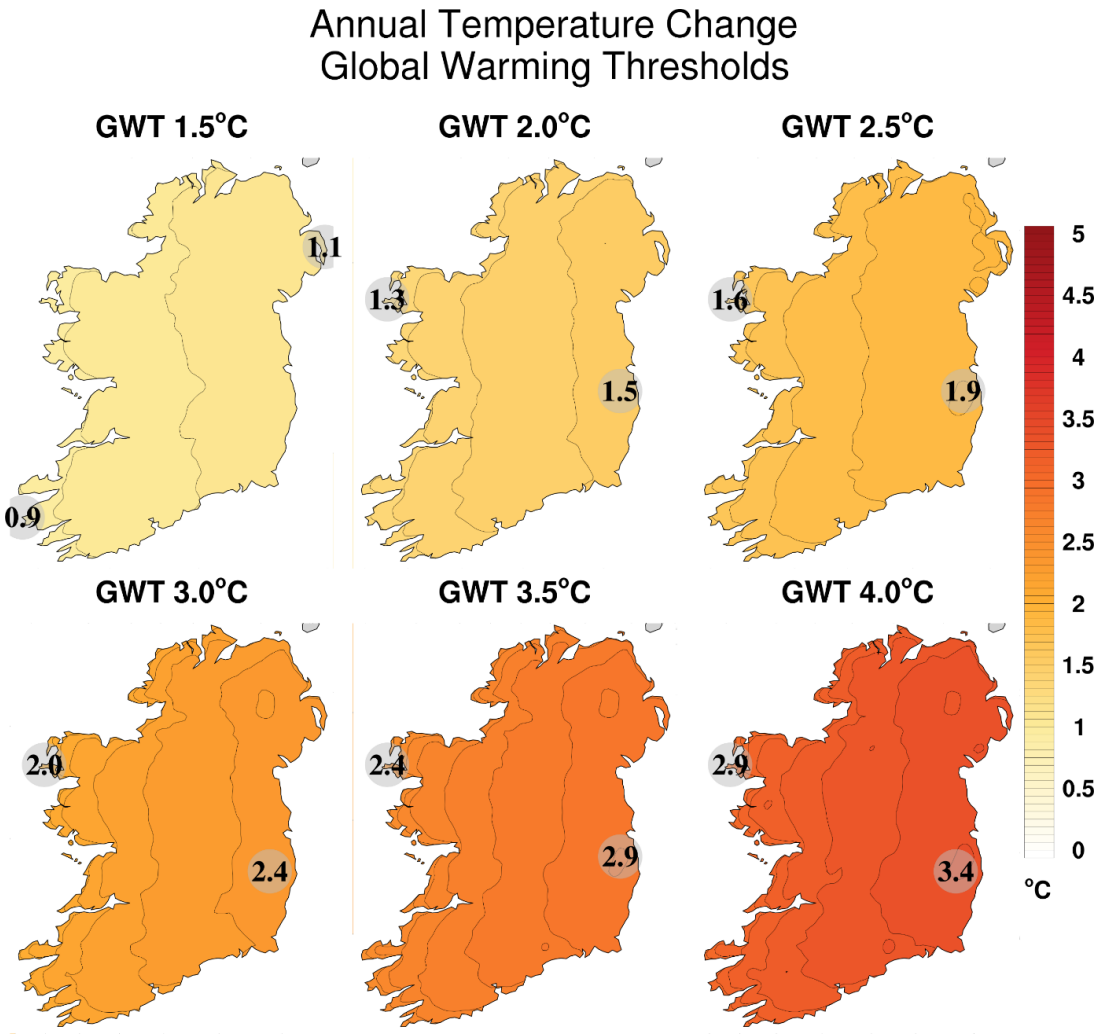


Figure 5. RCM 2m Temperature Projections for Ireland for Global Warming Thresholds (GWTs) w.r.t. 1850-1900; GWT = 1.5°C (58 ensemble members), GWT = 2.0°C (49 members), GWT = 2.5°C (40 members), GWT = 3.0°C (31 members), GWT = 3.5°C (22 members), GWT = 4.0°C (13 members). The projections were produced using an ensemble of high-resolution (4km) downscaled CMIP5-RCP and CMIP6-SSP GCMs. Hatchings are included to highlight areas of 'uncertainty'; "+" highlights areas where $|\mu_{ensemble}| - \sigma_{ensemble} < 0$, "×" highlights areas where the 20th and 80th percentile of ensemble projections have different signs and "✱" highlights areas where both conditions occur[1].

[1] Note that for the annual and seasonal temperature projections, no such areas of uncertainty were identified over Ireland.

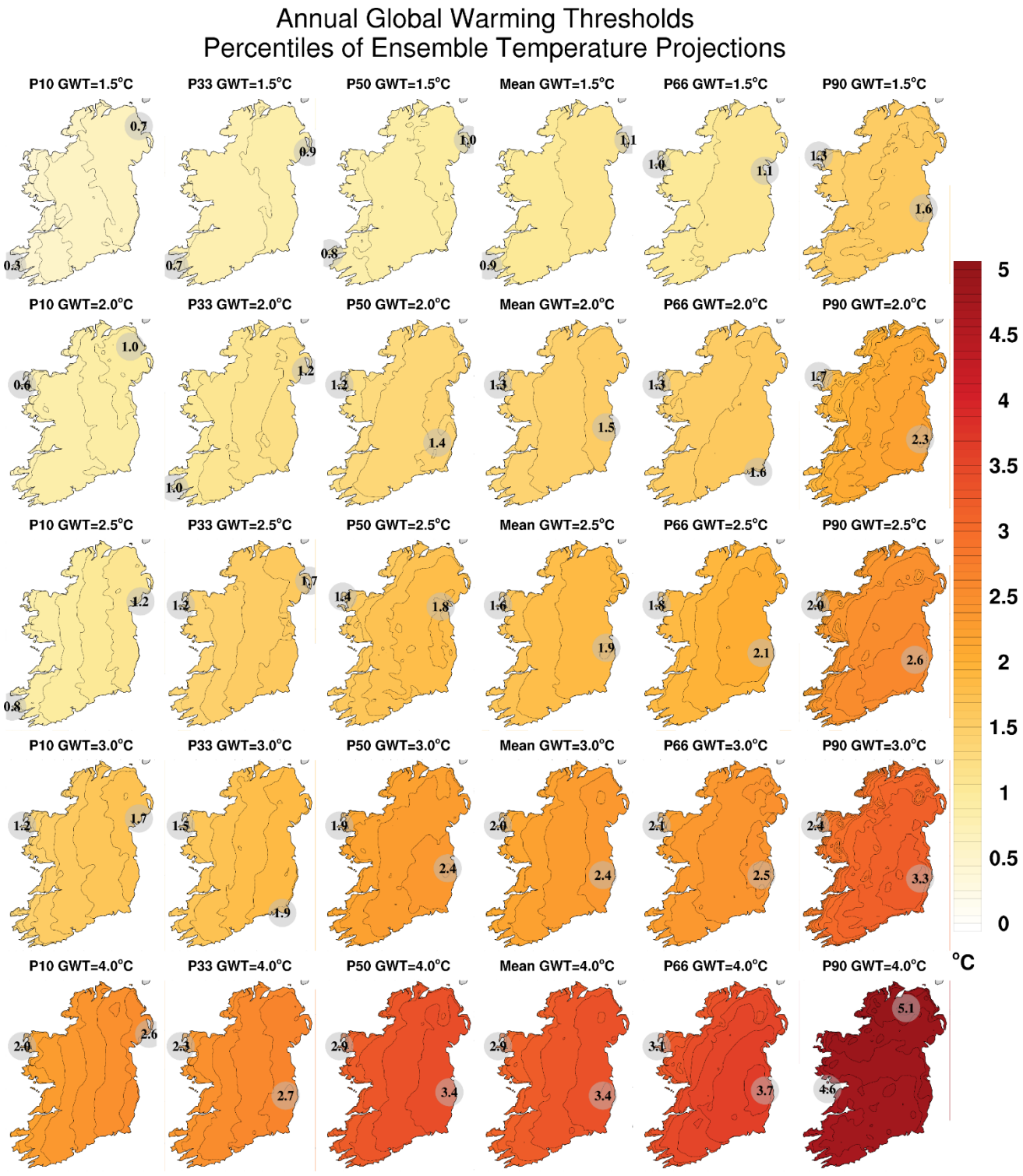


Figure 6. Percentiles of Ensemble of RCM Annual 2m Temperature GWT Projections (℃) w.r.t. 1850-1900; GWT = 1.5℃ (58 ensemble members), GWT = 2.0℃ (49 members), GWT = 2.5℃ (40 members), GWT = 3.0℃ (31 members) and GWT = 4.0℃ (13 members). The projections were produced using an ensemble of high-resolution (4km) downscaled CMIP5-RCP and CMIP6-SSP GCMs.

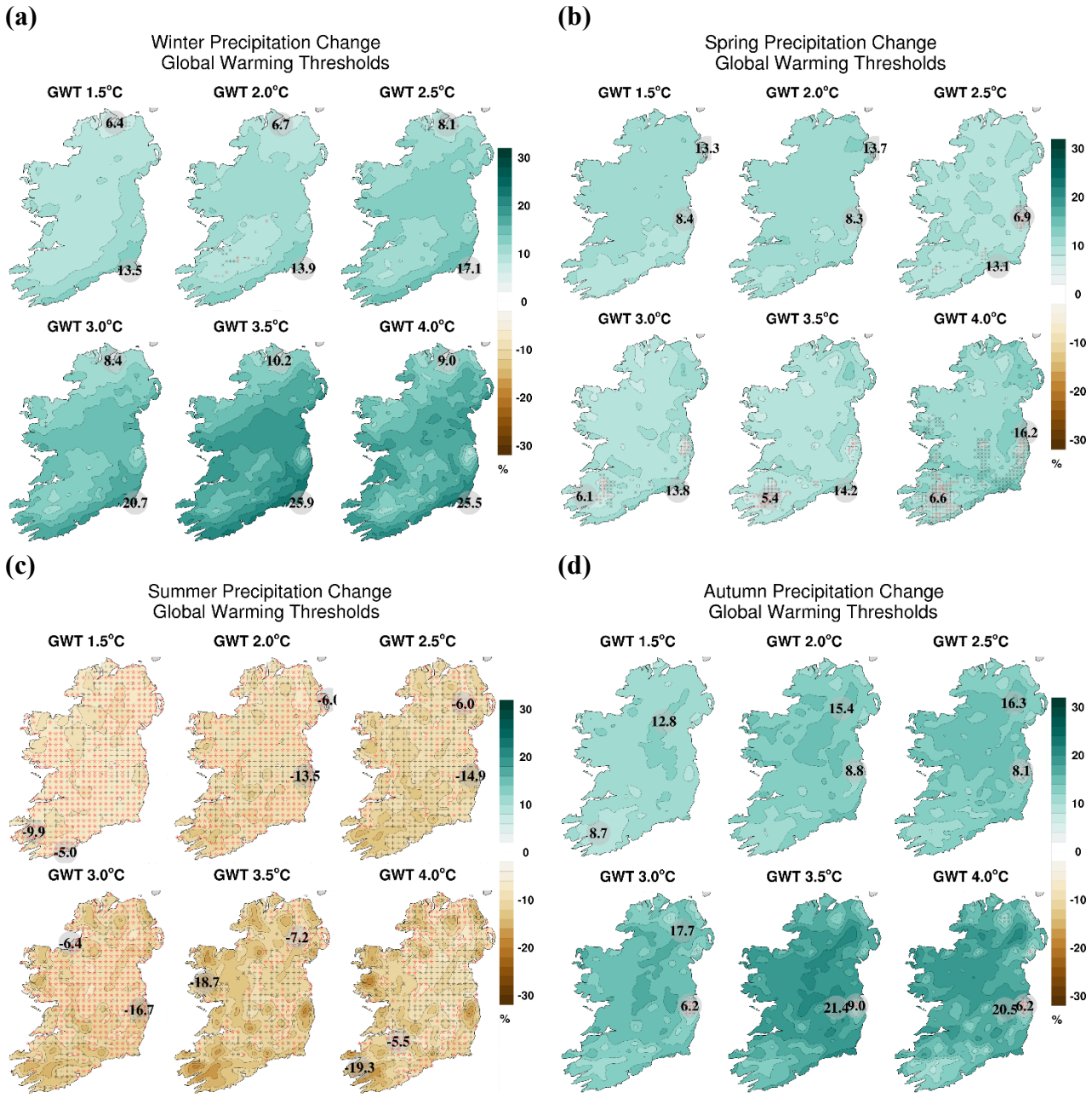


Figure 7. Seasonal RCM Precipitation GWT Projections (%) for Ireland w.r.t. 1850-1900; GWT = 1.5℃ (58 ensemble members), GWT = 2.0℃ (49 members), GWT = 2.5℃ (40 members), GWT = 3.0℃ (31 members), GWT = 3.5℃ (22 members), GWT = 4.0℃ (13 members). The projections were produced using an ensemble of high-resolution (4km) downscaled CMIP5-RCP and CMIP6-SSP GCMs. Hatchings are included to highlight areas of 'uncertainty'; "+" highlights areas where $|\mu_{ensemble}| - \sigma_{ensemble} < 0$, "×" highlights areas where the 20th and 80th percentile of ensemble projections have different signs and "✱" highlights areas where both conditions occur.

Figure 8. Percentiles of Ensemble of RCM Annual Precipitation GWT Projections (%) w.r.t. 1850-1900; GWT = 1.5°C (58 ensemble members), GWT = 2.0°C (49 members), GWT = 2.5°C (40 members), GWT = 3.0°C (31 members) and GWT = 4.0°C (13 members). The projections were produced using an ensemble of high-resolution (4km) downscaled CMIP5-RCP and CMIP6-SSP GCMs.

Ref: Nolan, P. and Flanagan, J., 2020. High-resolution climate projections for Ireland–a multi-model ensemble approach. *Environmental Protection Agency*, pp.978-1.

List of publications/reports from the project with complete references

- O'Brien, E. and Nolan, P., 2023. TRANSLATE: standardized climate projections for Ireland. *Frontiers in Climate*, *5*, p.1166828.
- Murphy, C., Heaphy, L., Quinn, T., O'Brien, E. and Nolan, P., 2023. Ireland's Climate Change Assessment. Volume 3: Being Prepared for Ireland's Future Climate.
- Nolan, Paul. "Updated high-resolution climate projections for Ireland." (2024). EPA Ireland, https://www.epa.ie/publications/research/epa-research-2030-reports/Research_Report-471-1.pdf
- O'Brien, E., Griffin, S., Duffy, C. and Nolan, P., 2025. Resolving the Dry Period Projection Paradox: Treat 'Consecutiveness' as a Nonlinearity. *International Journal of Climatology*, *45*(4), p.e8745.
- O'Brien, E., Ryan, P., Holloway, P., Wang, J., Nowbakht, P., Phillips, C., Fitton, J., O'Dwyer, B. and Nolan, P., 2024. TRANSLATE Research Report. *Prepared for Met Éireann by University of Galway, Irish Centre for High-End Computing. University College Cork, and MaREI, the SFI Research Centre for Energy, Climate, and Marine ISBN*, pp.978-1.
- Thorne, P., Boucher, J., Caulfield, B., Daly, H., Deane, P., Gallagher, D., Heaphy, L., McClean, D., McDonagh, S., McElwain, J. and McGookin, C., 2023. Ireland's Climate Change Assessment Synthesis Report.

Future plans

The number of RCM ensembles of Table 1 will be increased to allow for a more robust quantification of the uncertainty in the climate projections. The fully coupled atmosphere-ocean-wave (COAWST) RCMs simulations are ongoing and are expected to provide enhanced projections of the Irish climate.