SPECIAL PROJECT PROGRESS REPORT

Reporting year	2023
Project Title:	High-Resolution Downscaled RCM-CMIP6 Simulations
Computer Project Account:	spienola
Principal Investigator(s):	Paul Nolan
Affiliation:	Irish Centre for High-End Computing (ICHEC), IT Building, South Campus, National University of Ireland Galway (NUIG), Galway, Ireland
Name of ECMWF scientist(s) collaborating to the project (if applicable)	N/A
Start date of the project:	Jan 2022
Expected end date:	Dec 2024

Computer resources allocated/used for the current year and the previous one

(if applicable)

Please answer for all project resources

		Previous year		Current year	
		Allocated	Used	Allocated	Used
High Performance Computing Facility	(units)	60 million	60 million	70 million	70 million
Data storage capacity	(Gbytes)	30,000	20,000	30,000	20,000

Summary of project objectives (10 lines max)

The scientific objectives of the project are to dynamically downscale CMIP6 data to provide high resolution regional climate projections for Europe (Euro-CORDEX) 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 (10 lines max)

The problems encountered were minimal. The implementation and running of the WRF & COSMO-CLM RCMs on the new Atmos system presented no issues.

Summary of plans for the continuation of the project (10 lines max)

The PI will continue to run the simulations outlined in Tables 1 & 2 during year 3. In addition, the COAWST RCM will be run. Furthermore, the RCM work will contribute to the CORDEX project by running the required outer domain of selected RCM simulations on the Euro-CORDEX domains, conforming to the CORDEX standards, and extending the simulation period to 1950-2100 (for the outer domain).

List of publications/reports from the project with complete references

No publications – A number are in preparation.

Summary of Results

The Regional Climate Modelling (RCM) research involves downscaling CMIP6 data to provide high resolution (4km) climate projections for Ireland using the COSMO-CLM and WRF RCMs for the period 1980-2100. The future climate is simulated under all four 'tier-1' CMIP6 SSP (SSP1-2.6, SSP2-4.5, SSP3-7.0 and SSP5-8.5) scenarios. The outer domain (used to drive the inner 4km domain) was run at 12km (COSMO-CLM) and 20km (WRF), and roughly corresponds to the Euro-CORDEX domain.

The choice of CMIP6 data for downscaling was informed by a careful review carried out by Euro-CORDEX partners. This study identified an initial set of CMIP6 datasets based on many factors, e.g., model level data availability, SSP coverage (SSP1-2.6, SSP2-4.5, SSP3-7.0 & SSP5-8.5), model resolution, Equilibrium Climate Sensitivity (ECS; low, medium & high), model skill, e.g., JJA/DJF Extratropical Storm Track, Transient Climate Response, circulation and sea surface temperature validations. Informed by this study, and with particular weight given to ensuring a plausible spread of ECS, the CMIP6 datasets presented in Table 1 (white shading) were chosen for initial downscaling over the Irish domain. The choice of CMIP6 data is further confirmed by a separate 2021 study carried out by the Finnish Meteorological Institute (Ruosteenoja, K., 2021). This filtering of CMIP6 models results in a high-quality, representative, and manageable ensemble for downscaling over Ireland.

CMIP6 Model	Ensemble id	ECS	# 4km Simulations (4 x SSPs)	Atmospheric resolution
MIROC6	r1i1p1f1	2.61	1 COSMO-CLM	200 km
MPI-ESM1-2-HR	r1i1p1f1 r2i1p1f1	2.98	4 COSMO-CLM & WRF	100 km
EC-Earth3	r11i1p1f1	4.2	1 WRF	79 km
EC-Earth3-Veg	r12i1p1f1 r14i1p1f1	4.31	4 COSMO-CLM & WRF	79 km
CMCC-CM2-SR5	r1i1p1f1	3.52	COSMO-CLM	100 km
NorESM2-LM	r1i1p1f1	2.54		250 km
MPI-ESM1-2-LR	r1i1p1f1	3		250 km
CMCC-ESM2	r1i1p1f1	??		100 km
ACCESS-ESM1-5	r1i1p1f1	3.87		250 km
CNRM-ESM2-1	r1i1p1f1	4.76		110 km

Table 1. Initial CMIP6 data selected for downscaling over Ireland (white shading). The datasets shaded in blue are currently running while orange are CMIP6 datasets highlighted for future downscaling.

The RCM configurations were validated by downscaling the European Centre for Medium-Range Weather Forecasts (ECMWF) ERA5 reanalyses for multi-decadal time periods and comparing the output with Met Eireann observational data. See Figures 1-4 for preliminary 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 temperature, averaged over the country, 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). For precipitation, 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.

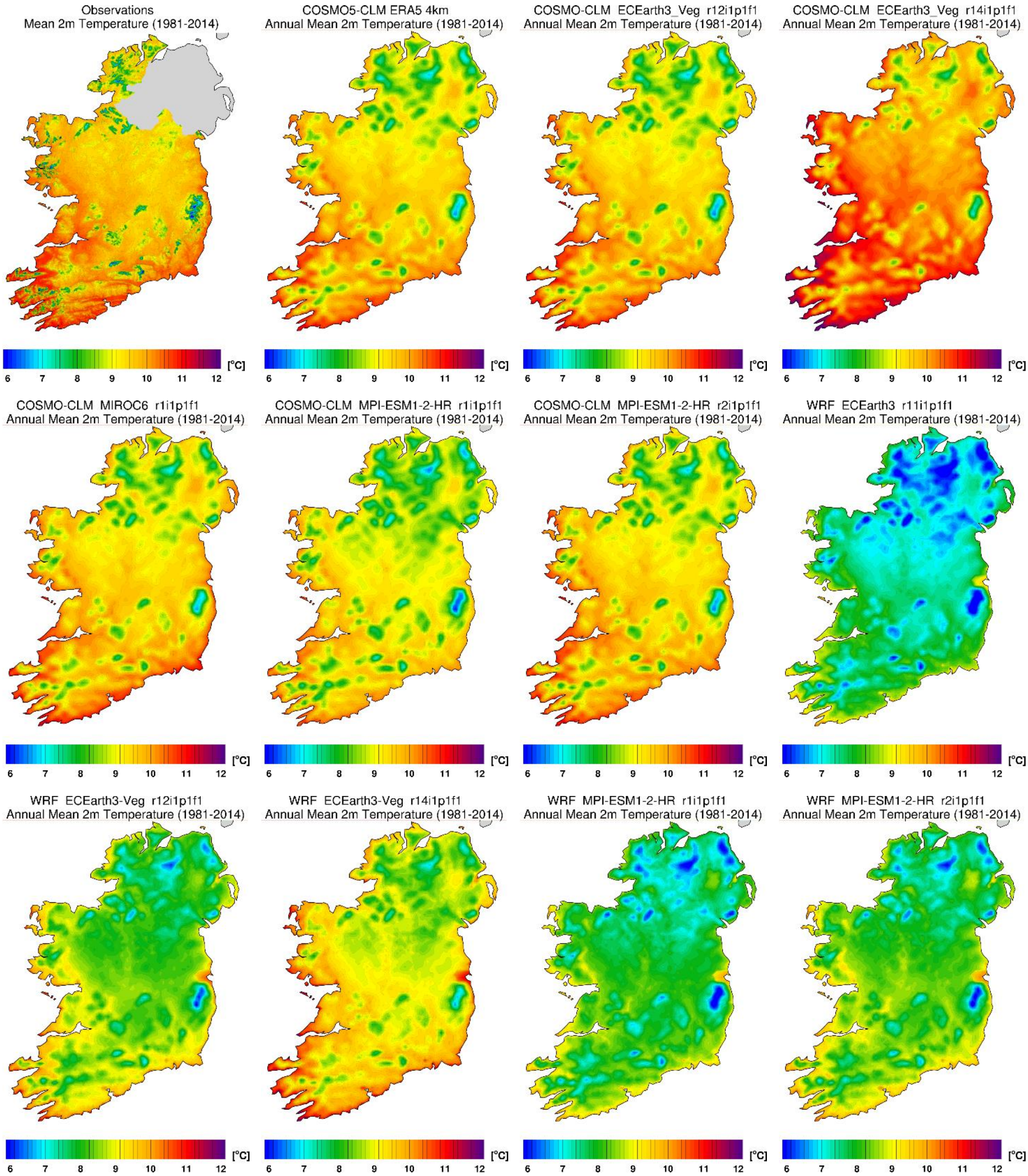

Figure 1. Observations, COSMO-CLM5-ERA5 and RCM-CMIP6 Mean 2m Temperature (1981-2014)

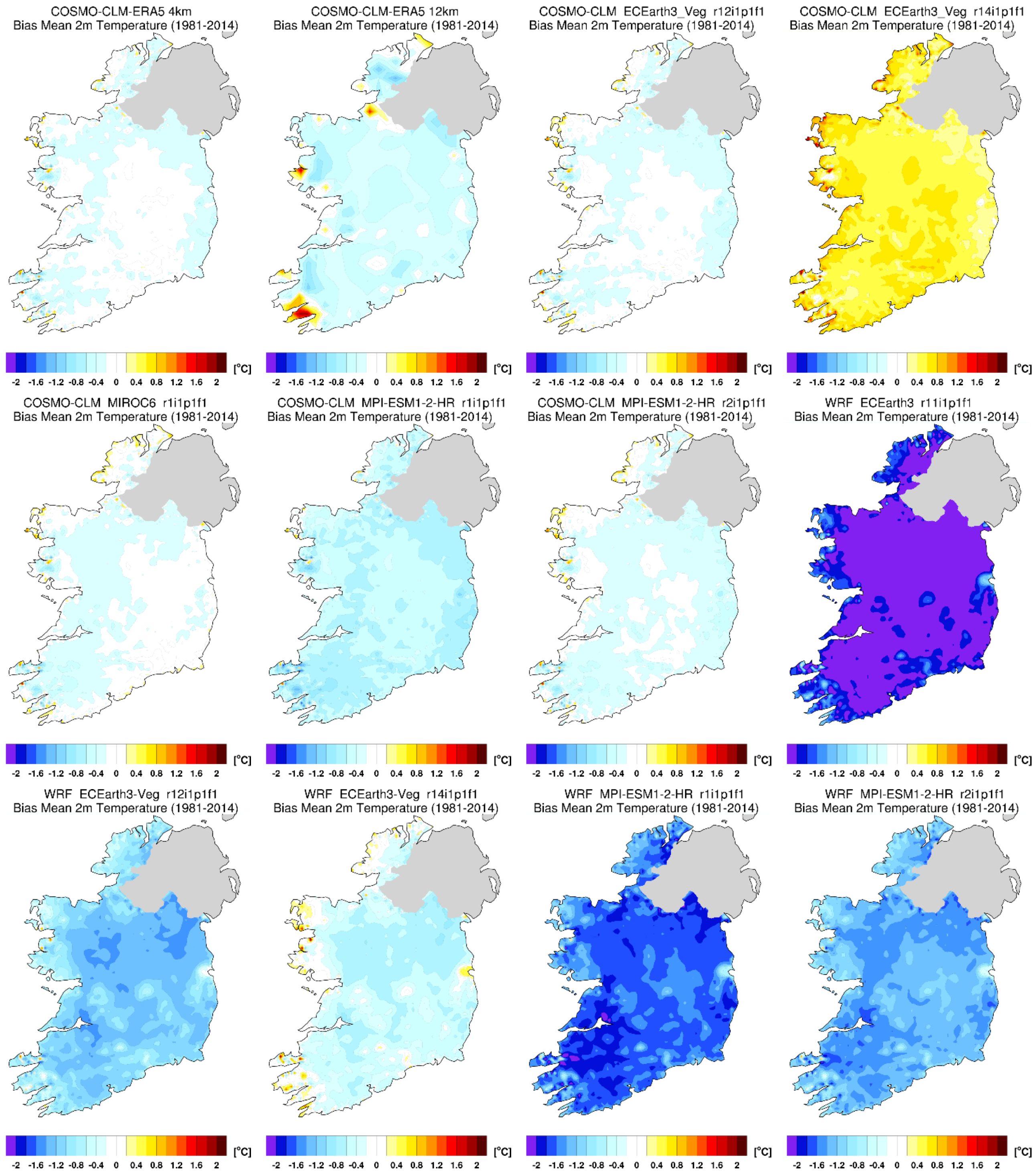

Figure 2. COSMO-CLM5-ERA5 and RCM-CMIP6 Mean 2m Temperature Bias (1981-2014)

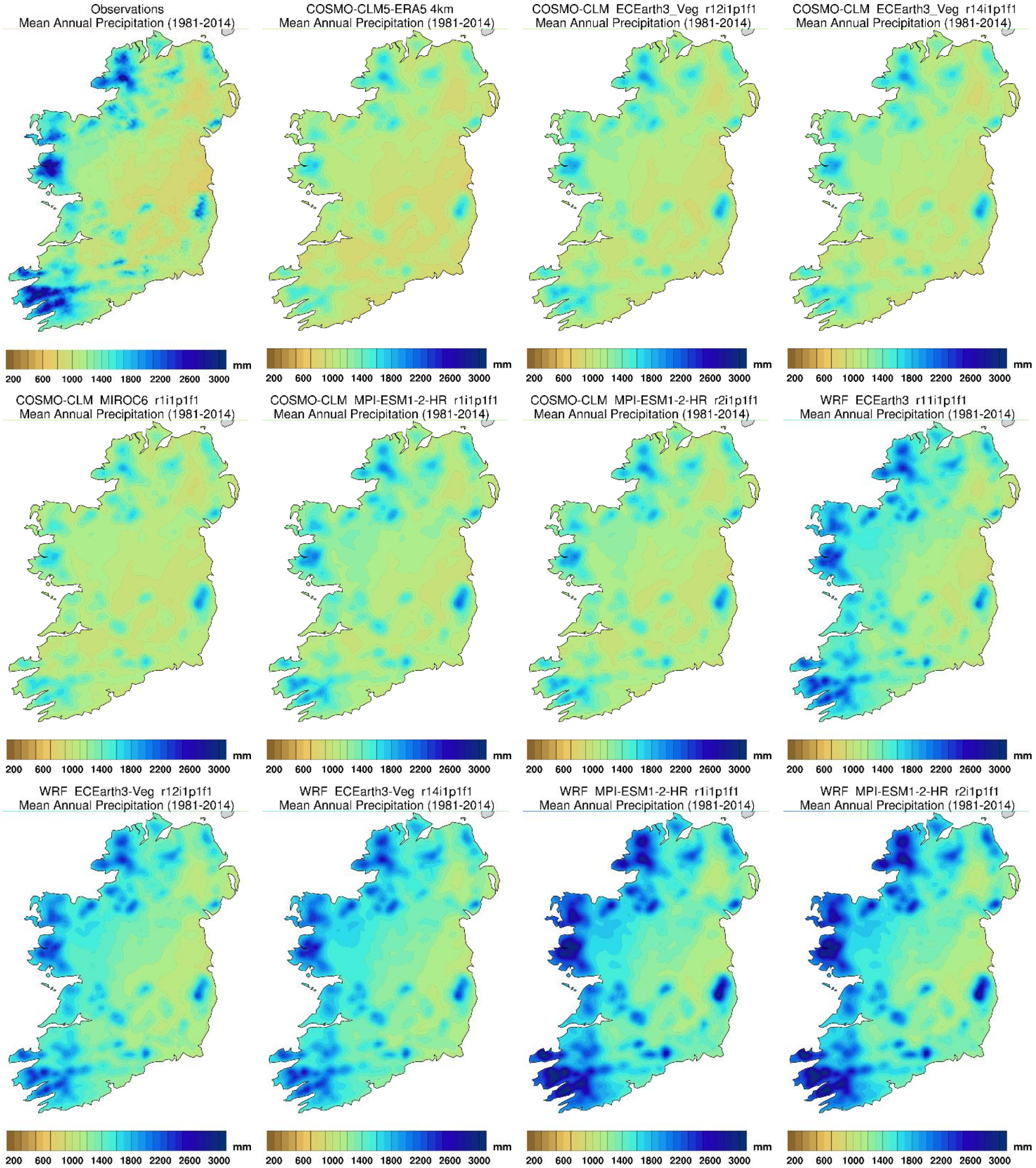

Figure 3. Observations, COSMO-CLM5-ERA5 and RCM-CMIP6 Mean Annual Precipitation (1981-2014)

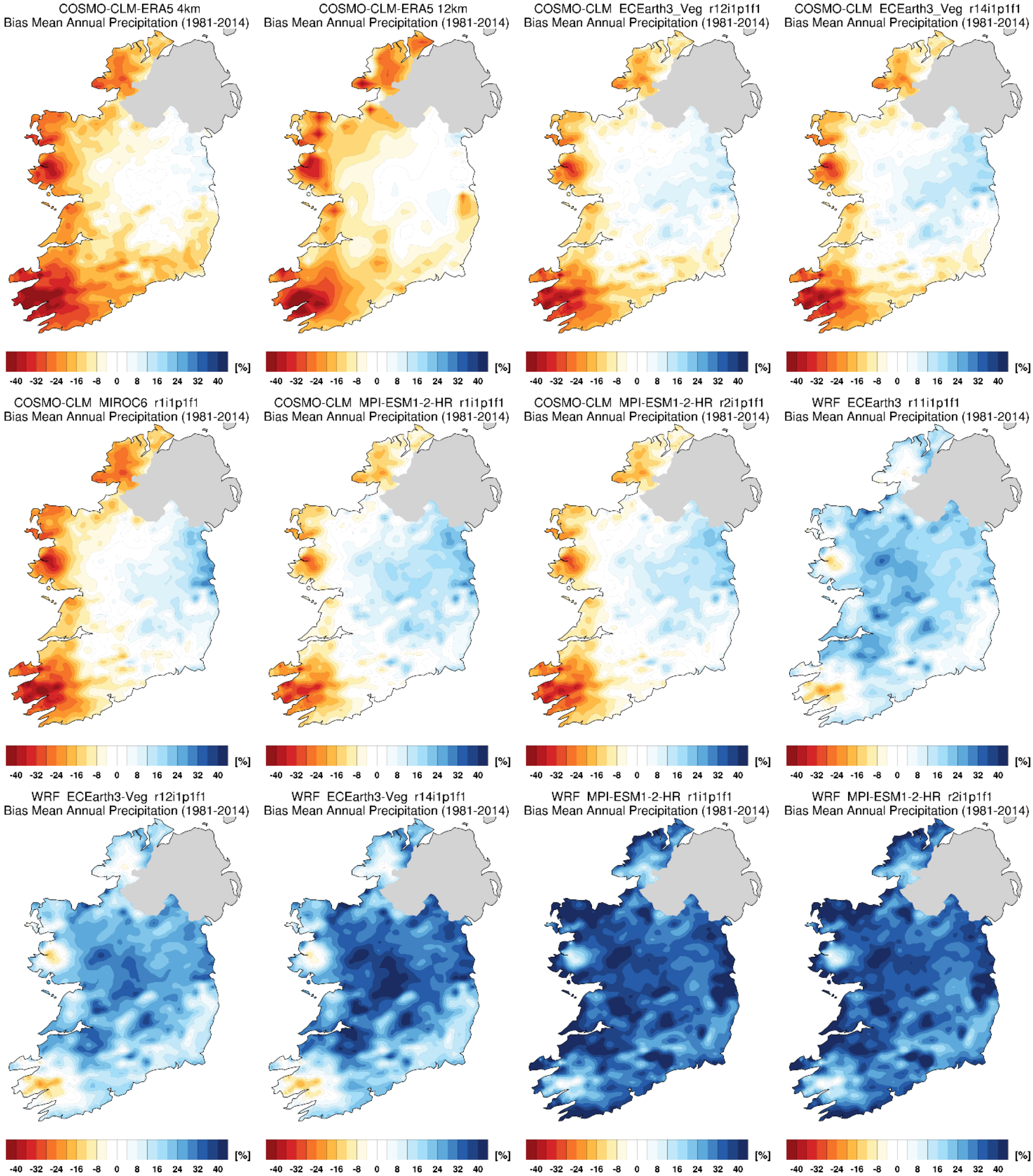

Figure 4. COSMO-CLM5-ERA5 and RCM-CMIP6 Mean Annual Precipitation Bias (1981-2014)

RCM	CMIP6 ESM Ensemble id	Historical 1980-2014 Progress	SSP1-2.6 2015-2100 Progress	SSP2-4.5 2015-2100 Progress	SSP3-7.0 2015-2100 Progress	SSP5-8.5 2015-2100 Progress
WRF (20 & 4km)	EC-Earth AOGCM r11i1p1f1	Complete	Complete	Complete	Complete	Complete
WRF (20 & 4km)	EC-Earth-Veg r12i1p1f1	Complete	Complete	Complete	Complete	Complete
WRF (20 & 4km)	EC-Earth-Veg r14i1p1f1	Complete	Complete	Complete	Complete	Complete
COSMO-CLM5 (12 & 4km)	EC-Earth-Veg r12i1p1f1	Complete	Complete	Complete	Complete	Complete
COSMO-CLM5 (12 & 4km)	EC-Earth-Veg r14i1p1f1	Complete	Complete	Complete	Complete	Complete
COSMO-CLM5 (12 & 4km)	MPI-ESM1-2-HR r1i1p1f1	Complete	Complete	Complete	Complete	Complete
COSMO-CLM5 (12 & 4km)	MPI-ESM1-2-HR r2i1p1f1	Complete	Complete	Complete	Complete	Complete
WRF (20 & 4km)	MPI-ESM1-2-HR r1i1p1f1	Complete	Complete	Complete	Complete	Complete
WRF (20 & 4km)	MPI-ESM1-2-HR r2i1p1f1	Complete	Complete	Complete	Complete	Complete
COSMO-CLM5 (12 & 4km)	MIROC6 r1i1p1f1	Complete	Complete	Complete	Complete	Complete
COSMO-CLM5 (12 & 4km)	CMCC-CM2-SR5 r1i1p1f1	Running	Running	Running	Running	Running

Table 2. Details of the progress of the initial ensemble of RCM-CMIP6 simulations. The rows present information on the RCM used, nesting strategy, CMIP6 ESM ensemble id, historical (1980-2014) simulation progress, future (2015-2100) simulation progress for each SSP.

The completed RCM simulations presented in Table 2 comprise over 4000 years of simulated data (~200 TB) and are currently being analysed. Preliminary results are in line with previous RCM-CMIP5-RCP projections for Ireland (EPA report 339) which adds a measure of confidence to the projections.

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 power, heating degree days, driving rain, evapotranspiration) 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. Other methods such as investigating if |mean| - std > 0 will be returned to when the ensemble size is larger.

Examples of the analysed projections include:

- 2m temperatures are projected to increase by up to 3°C by the end of the century for the SSP585 scenario (Figure 5). 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 (Figure 6) and extremes (Figure 7).
- The number of frost and ice days are projected to decrease substantially (Figure 8).
- Precipitation projections shows small changes (~0%) over the full year (Figure 9)
- 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 10; note the "hatching" highlighting areas of uncertainty)
- The precipitation climate is projected to be more variable with more very wet (Figure 11) and dry events (Figure 12)
- Snowfall is projected to decrease substantially (Figure 13)
- 10m wind speed is projected to decrease over the full year (Figure 14) and for all seasons (Figure 15). The decreases are largest for the summer months. Note that the PhD student assisted with the analysis of wind fields and derived renewable energy products.

- Specific humidity is projected to increase substantially over the full year (Figure 16) and for all seasons (Figure 17). 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 18) and for all seasons (Figure 19). The decreases are largest for the summer months (Figure 19).
- Evapotranspiration, as derived using the FAO Penman-Monteith method, is projected to increase (Figure 20). However, there is uncertainty in the projections for the lower SSPs and earlier time periods.

2.2 Technical Work

The PI spent a large proportion of the period under review implementing and testing the RCMs on the atos HPC platforms. Specifically, the PI:

- Installed, tested and scale-tested the COSMO-CLM & WRF RCMs on the new ECMWF atos machine. The results show that the RCMs run approximately 2 & 1.5 times faster compared to the older ECMWF (cca) and ICHEC machines, respectively.
- Careful scale-testing on atos showed that WRF performance is optimal using intel compilers, hybrid OpenMP/MPI, classic netcdf and adaptive time stepping. The performance of COSMO-CLM is enhanced using intel compilers with enhanced memory per node. This is achieved by decreasing the number of cores per node from 128 to 64.

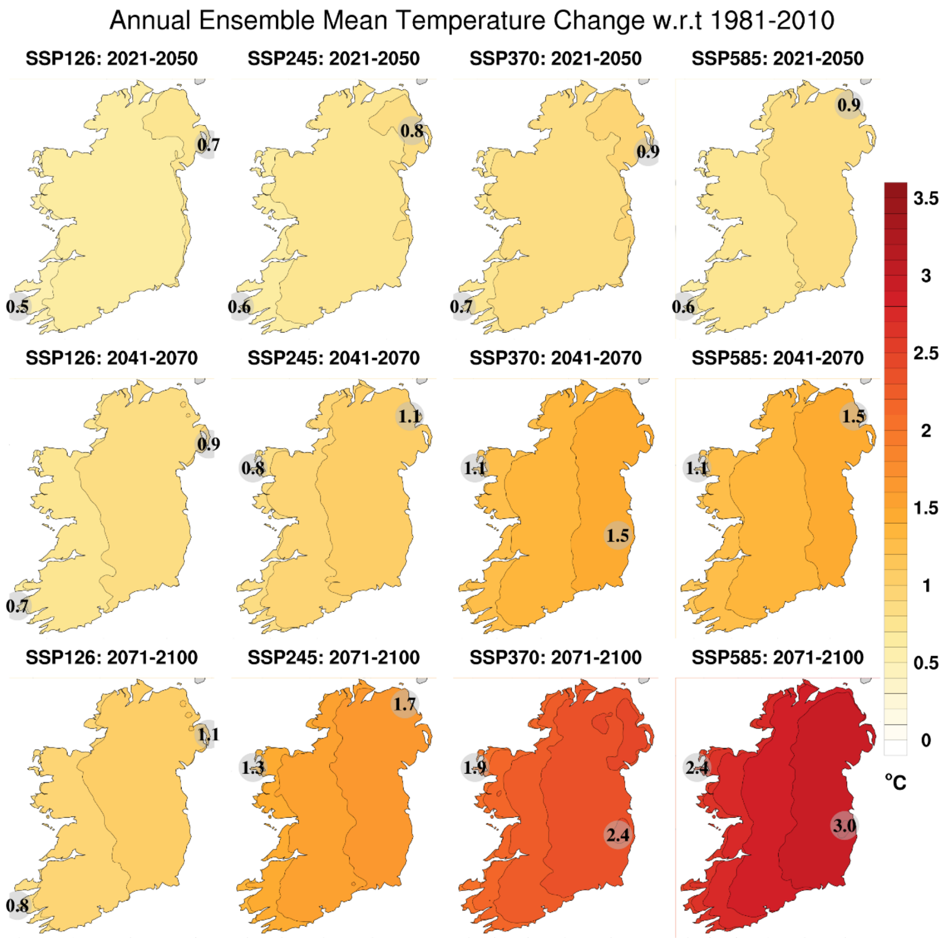

Figure 5 RCM-CMIP6 ensemble projections of mean annual 2-m temperature. All RCM ensemble members were run with 4-km grid spacing. In each case, the future 30-year period is compared with the past period, 1981–2010. The results were obtained from analysing 10 SSP126, 10 SSP245,10 SSP370 and 10 SSP585 RCM simulations. The numbers included on each plot are the minimum and maximum projected changes, displayed at their locations.

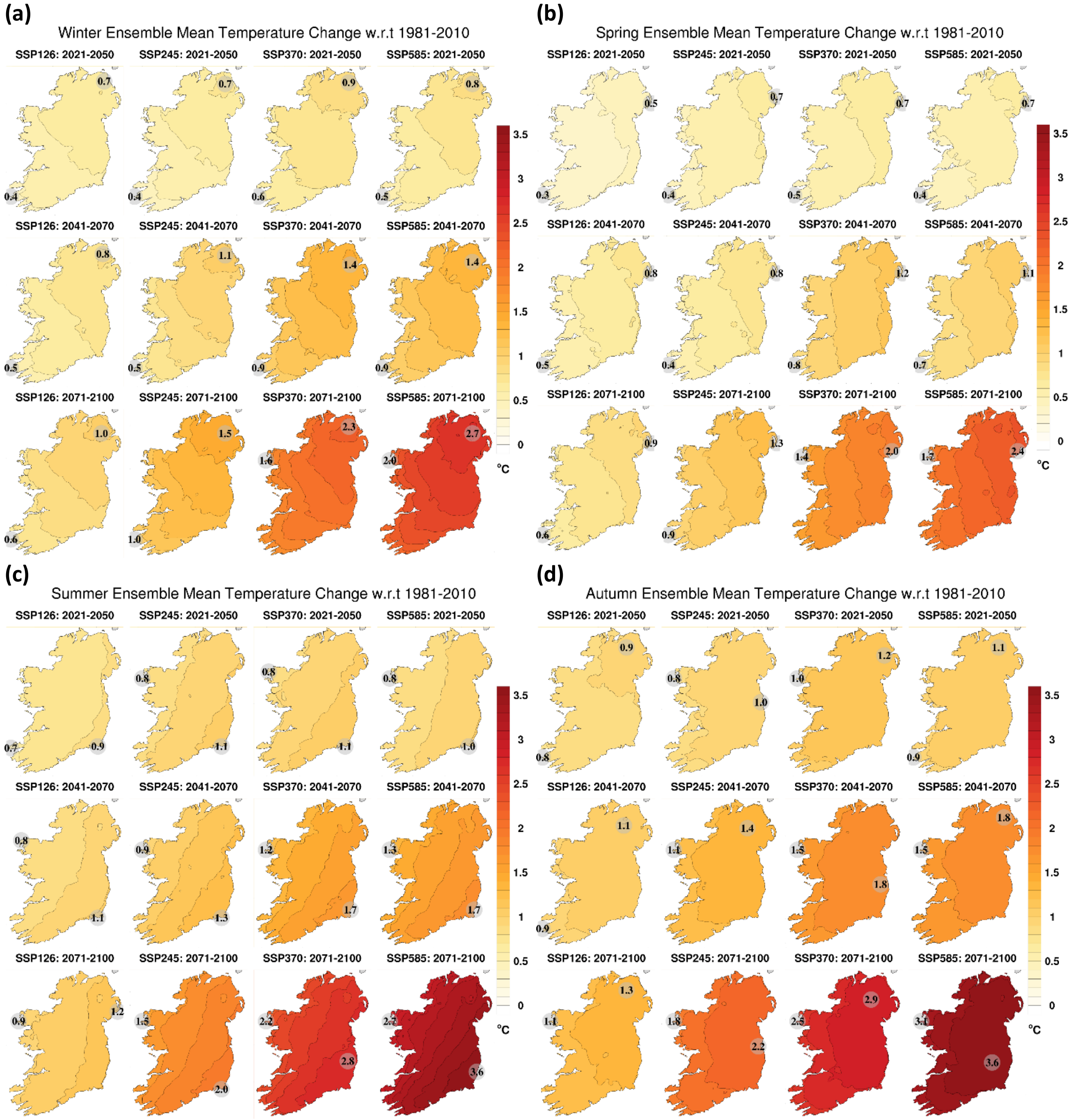

Figure 6. Seasonal RCM ensemble projections of mean 2-m temperature; **(a)** winter, **(b)** spring, **(c)** summer and **(d)** autumn. In each case, the future 30-year period is compared with the past period, 1981–2010. The numbers included on each plot are the minimum and maximum projected changes, displayed at their locations.

Annual T2M	SSP126				SSP245				SSP370				SSP585			
	P33	P50	mean	P66	P33	P50	mean	P66	P33	P50	mean	P66	P33	P50	mean	P66
2021-2050	0.43	0.47	0.66	0.56	0.4	0.49	0.75	0.58	0.4	0.7	0.86	0.85	0.41	0.45	0.79	0.73
2041-2070	0.48	0.54	0.81	0.66	0.49	0.6	1	0.72	0.93	1.03	1.36	1.3	0.78	0.85	1.36	1.32
2071-2100	0.32	0.58	1.01	1.26	0.84	0.88	1.57	1.91	1.61	1.8	2.29	2.46	1.99	2.43	2.85	3.26

Winter T2M	SSP126				SSP245				SSP370				SSP585			
	P33	P50	mean	P66	P33	P50	mean	P66	P33	P50	mean	P66	P33	P50	mean	P66
2021-2050	0.31	0.44	0.6	0.55	0.23	0.26	0.6	0.72	0.36	0.46	0.75	0.57	0.39	0.43	0.7	0.62
2041-2070	0.41	0.5	0.68	0.64	0.34	0.47	0.88	0.63	0.89	0.99	1.24	1.11	0.7	0.88	1.2	1.12
2071-2100	0.13	0.55	0.88	1.18	0.69	0.85	1.3	1.65	1.59	1.67	2.02	1.98	1.89	2.39	2.48	2.75

Spring T2M	SSP126				SSP245				SSP370				SSP585			
	P33	P50	mean	P66	P33	P50	mean	P66	P33	P50	mean	P66	P33	P50	mean	P66
2021-2050	0.08	0.13	0.39	0.58	0.15	0.27	0.55	0.5	0.2	0.38	0.58	0.56	0.09	0.24	0.53	0.44
2041-2070	0.21	0.24	0.63	0.51	0.15	0.19	0.67	0.4	0.57	0.67	1.03	0.87	0.4	0.54	0.93	0.66
2071-2100	0.07	0.23	0.78	0.9	0.37	0.47	1.11	1.14	1.18	1.31	1.77	1.61	1.43	1.67	2.14	2.28

Summer T2M	SSP126				SSP245				SSP370				SSP585			
	P33	P50	mean	P66	P33	P50	mean	P66	P33	P50	mean	P66	P33	P50	mean	P66
2021-2050	0.47	0.56	0.76	0.8	0.49	0.59	0.93	0.98	0.54	0.91	0.97	1.15	0.51	0.6	0.9	0.9
2041-2070	0.51	0.56	0.9	0.71	0.57	0.67	1.13	0.99	0.98	1.23	1.48	1.62	1.04	1.12	1.57	1.67
2071-2100	0.39	0.67	1.07	1.5	0.95	1.03	1.79	2.35	1.78	2.13	2.59	3.1	2.22	2.82	3.27	4.13

Autumn T2M	SSP126				SSP245				SSP370				SSP585			
	P33	P50	mean	P66	P33	P50	mean	P66	P33	P50	mean	P66	P33	P50	mean	P66
2021-2050	0.64	0.66	0.88	0.79	0.54	0.57	0.91	0.69	0.53	0.95	1.13	1.23	0.63	0.71	1.04	1.1
2041-2070	0.69	0.76	1.04	0.92	0.86	0.88	1.31	1.05	1.08	1.3	1.71	1.95	0.96	1.04	1.72	1.98
2071-2100	0.69	0.89	1.3	1.54	1.3	1.4	2.1	2.62	1.82	2.17	2.79	3.32	2.43	2.84	3.5	4.07

Table 3. This table corresponds to the above Annual T2M projections figures (5&6) and shows the 33rd, 50th percentile, mean & 66th percentile average over the island of Ireland (land points). A small spread (& same sign of projection) corresponds to higher certainty in the projections. Conversely, large spread corresponds to higher uncertainty. *A similar table is prepared for each projection (not shown here)*

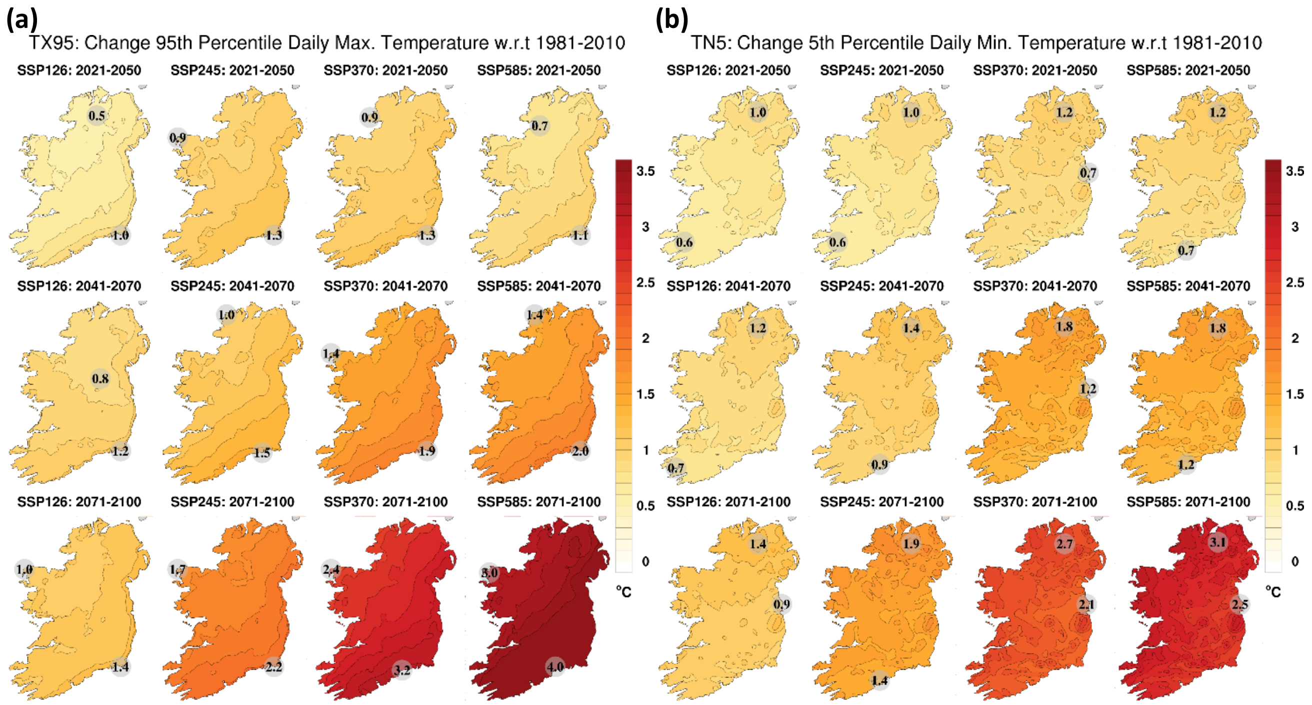

Figure 7. Projected changes in extreme 2-m temperature: **(a)** top 5% of daily maximum temperatures (warm summer days) and **(b)** bottom 5% of daily minimum temperatures (cold winter nights). In each case, the future 30-year period is compared with the past period, 1981–2010. The numbers included on each plot are the minimum and maximum projected changes, displayed at their locations.

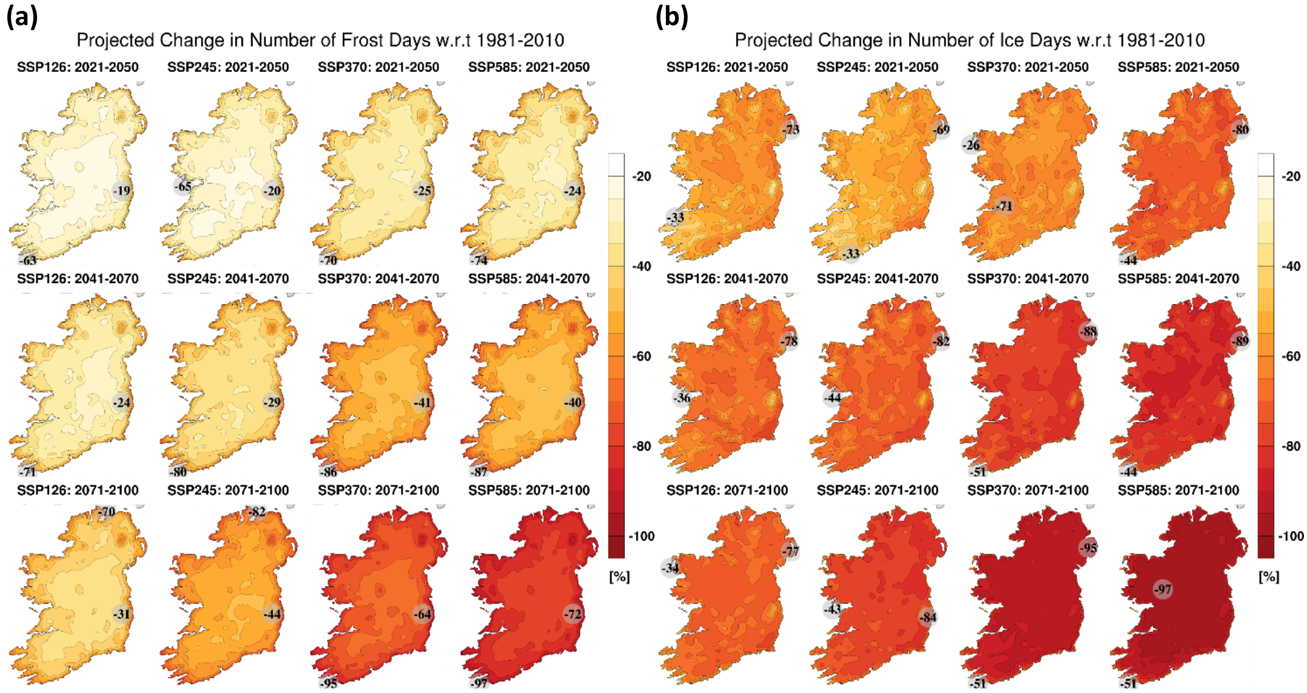

Figure 8. Projected changes in the number of: **(a)** frost days and **(b)** ice days. In each case, the future period is compared with the past period, 1981–2010. The numbers included on each plot are the minimum and maximum projected changes, displayed at their locations.

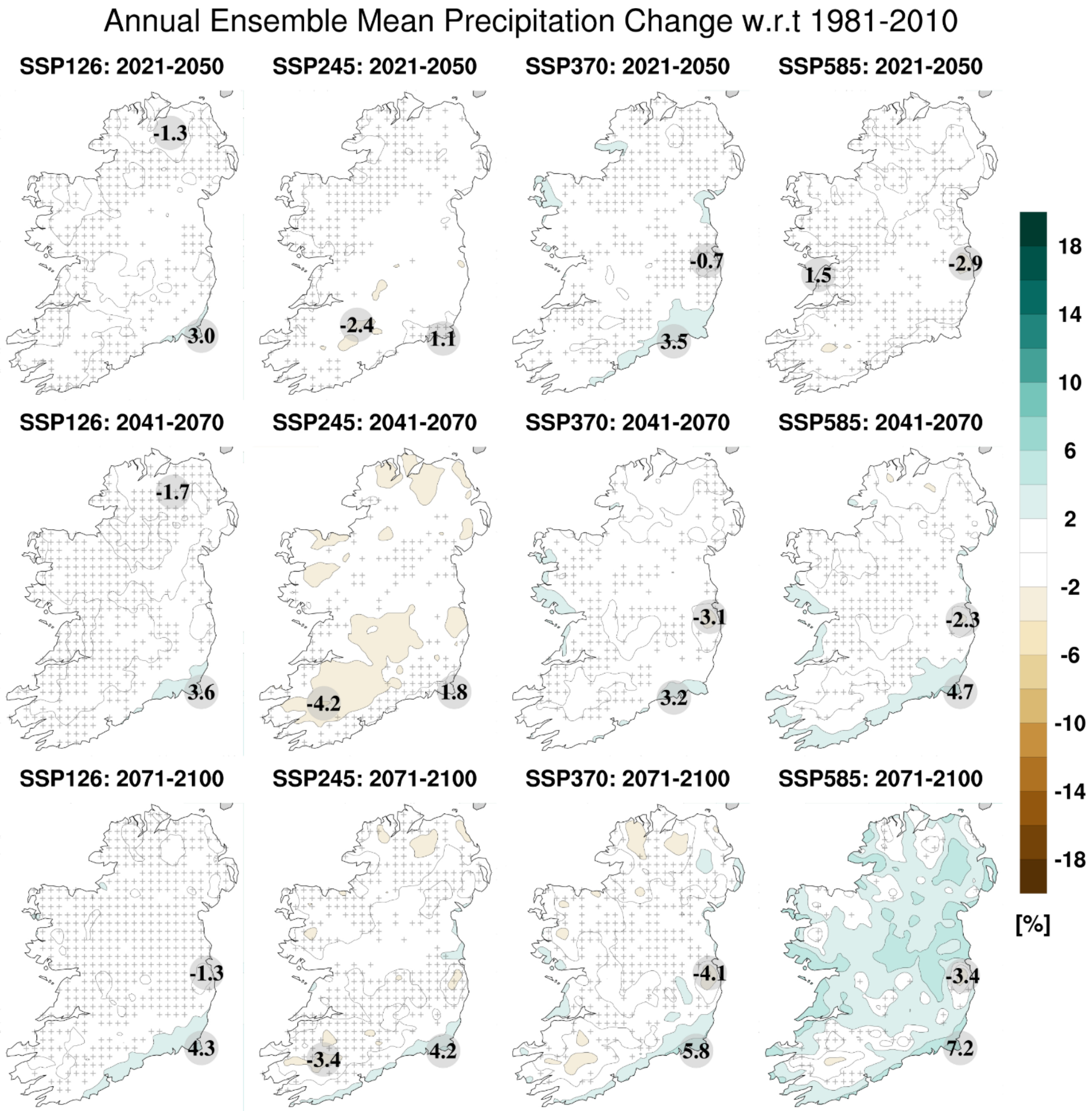

Figure 9. RCM-CMIP6 ensemble projections of mean annual precipitation (%). All RCM ensemble members were run with 4-km grid spacing. In each case, the future 30-year period is compared with the past period, 1981–2010. The results were obtained from analysing 10 SSP126, 10 SSP245,10 SSP370 and 10 SSP585 RCM simulations. The numbers included on each plot are the minimum and maximum projected changes, displayed at their locations.

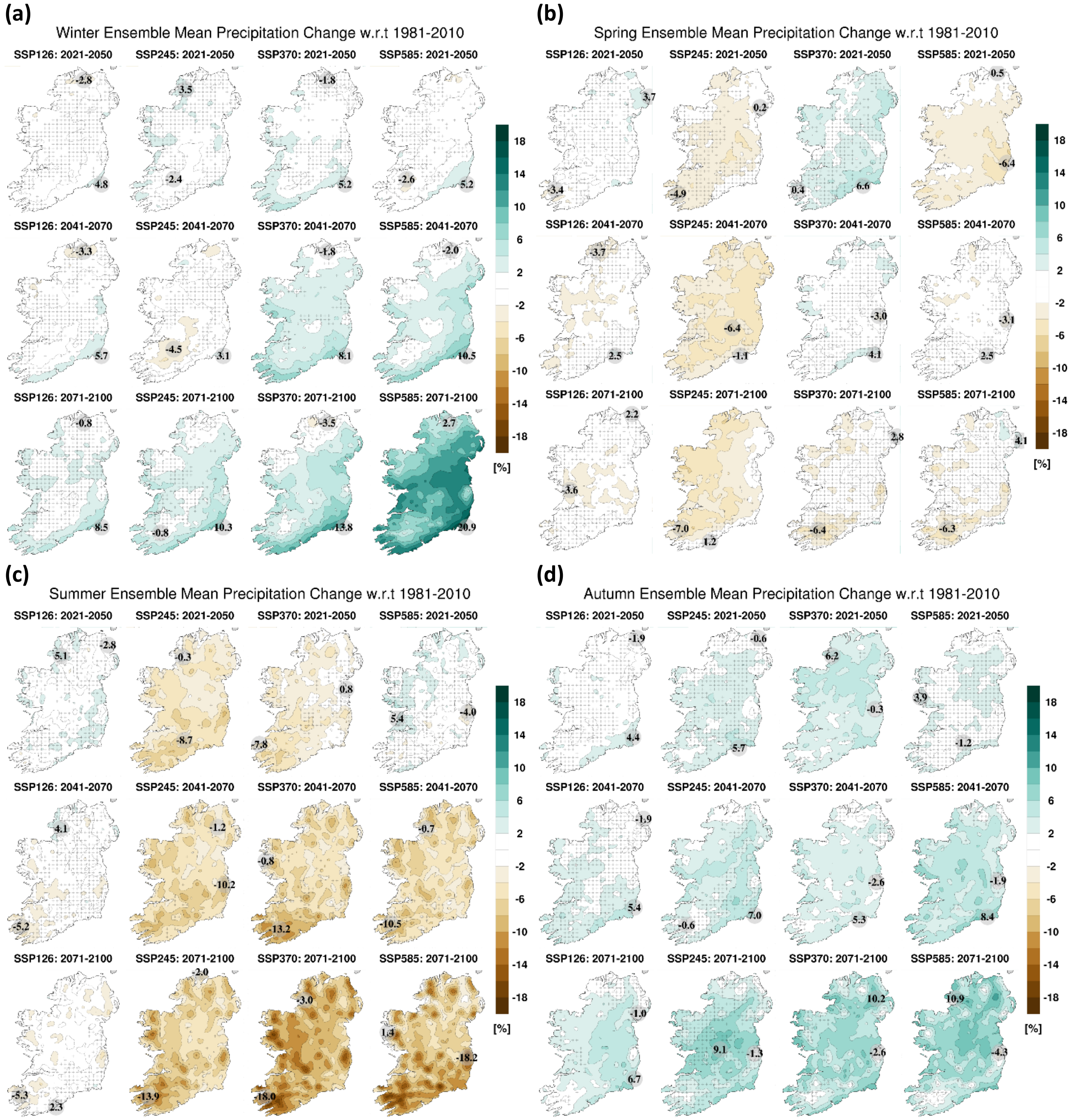

Figure 10. Seasonal RCM ensemble projections of mean precipitation (%); **(a)** winter, **(b)** spring, **(c)** summer and **(d)** autumn. In each case, the future 30-year period is compared with the past period, 1981–2010. The numbers included on each plot are the minimum and maximum projected changes, displayed at their locations.

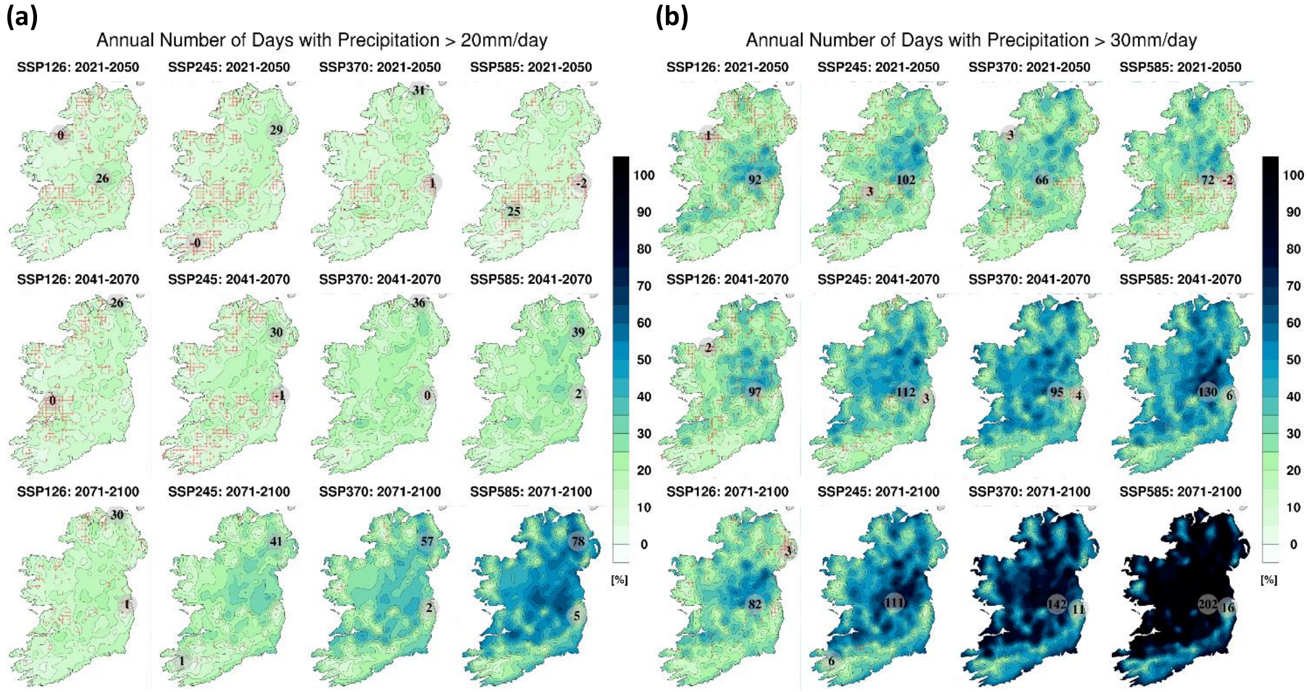

Figure 11. Projected changes (%) in the annual number of days with precipitation greater than **(a)** 20mm/day and **(b)** 30mm/day. In each case, the future 30-year period is compared with the past period, 1981–2010. The numbers included on each plot are the minimum and maximum projected changes, displayed at their locations.

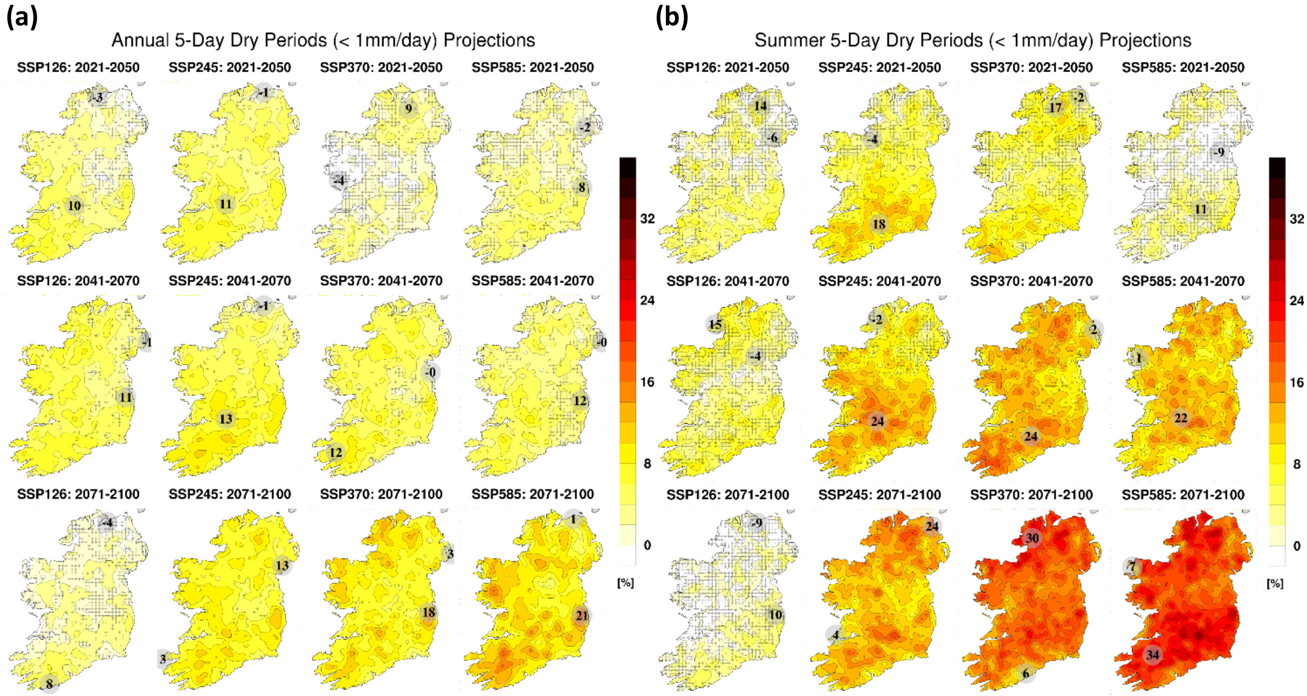

Figure 12. Projected changes (%) in the number of dry periods **(a)** annually and **(b)** in summer. In each case, the future 30-year period is compared with the past period, 1981–2010. The numbers included on each plot are the minimum and maximum projected changes, displayed at their locations.

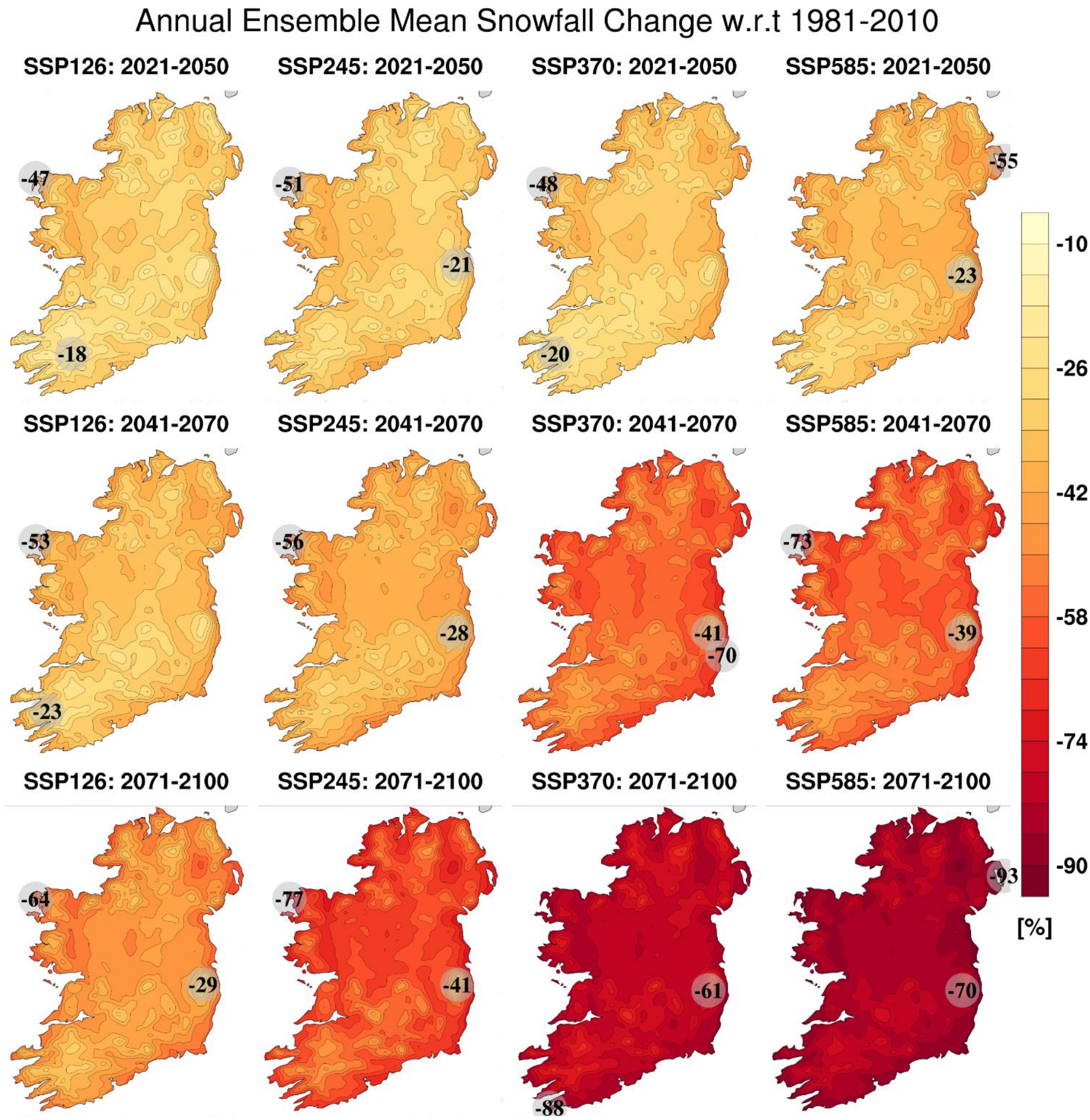

Figure 13. Annual RCM-CMIP6 ensemble mean projections of snowfall (%). All RCM ensemble members were run with 4-km grid spacing. In each case, the future 30-year period is compared with the past period, 1981–2010. The results were obtained from analysing 10 SSP126, 10 SSP245,10 SSP370 and 10 SSP585 RCM simulations. The numbers included on each plot are the minimum and maximum projected changes, displayed at their locations.

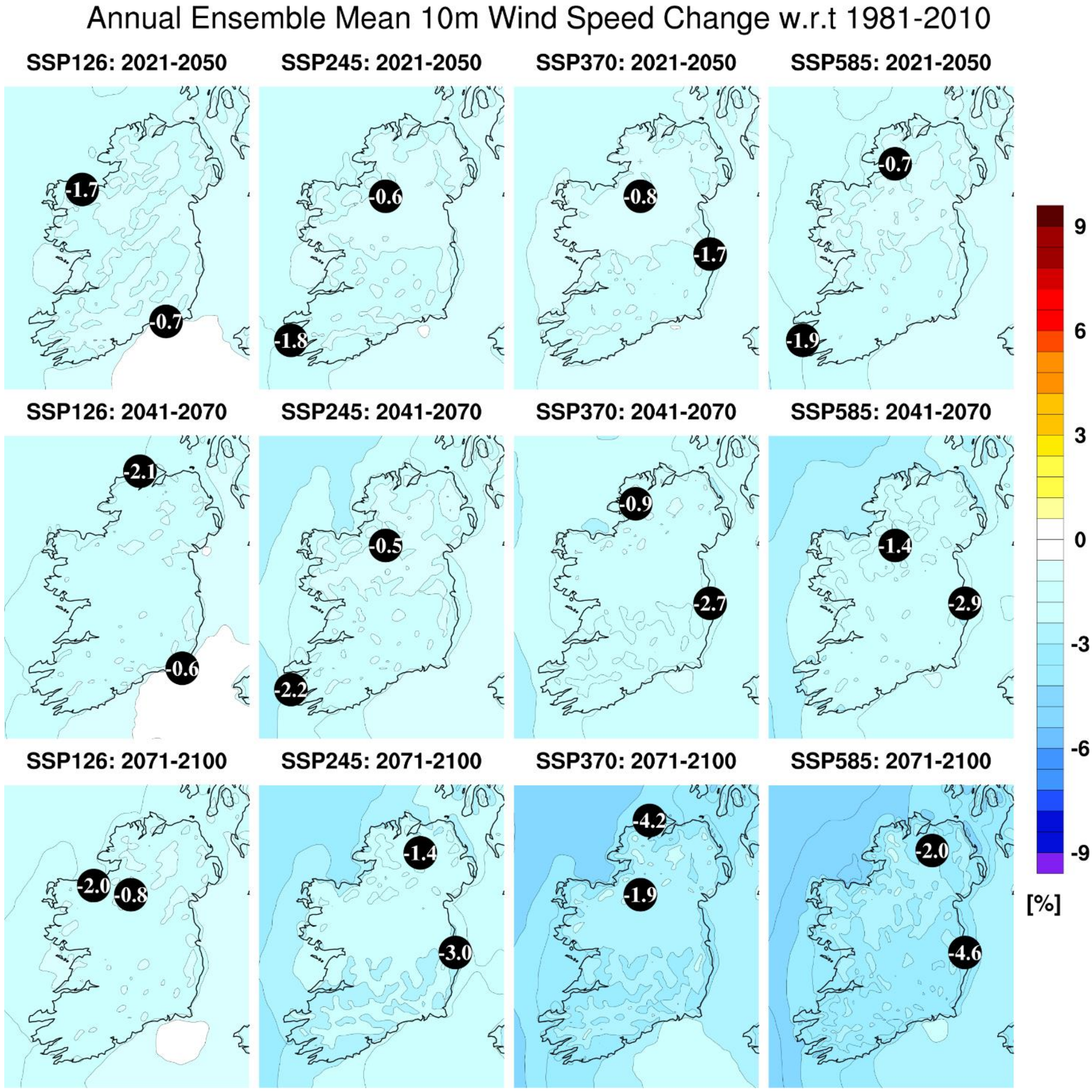

Figure 14. Annual RCM-CMIP6 ensemble projections of 10m wind speed (%). All RCM ensemble members were run with 4-km grid spacing. In each case, the future 30-year period is compared with the past period, 1981–2010. The results were obtained from analysing 10 SSP126, 10 SSP245,10 SSP370 and 10 SSP585 RCM simulations. The numbers included on each plot are the minimum and maximum projected changes, displayed at their locations.

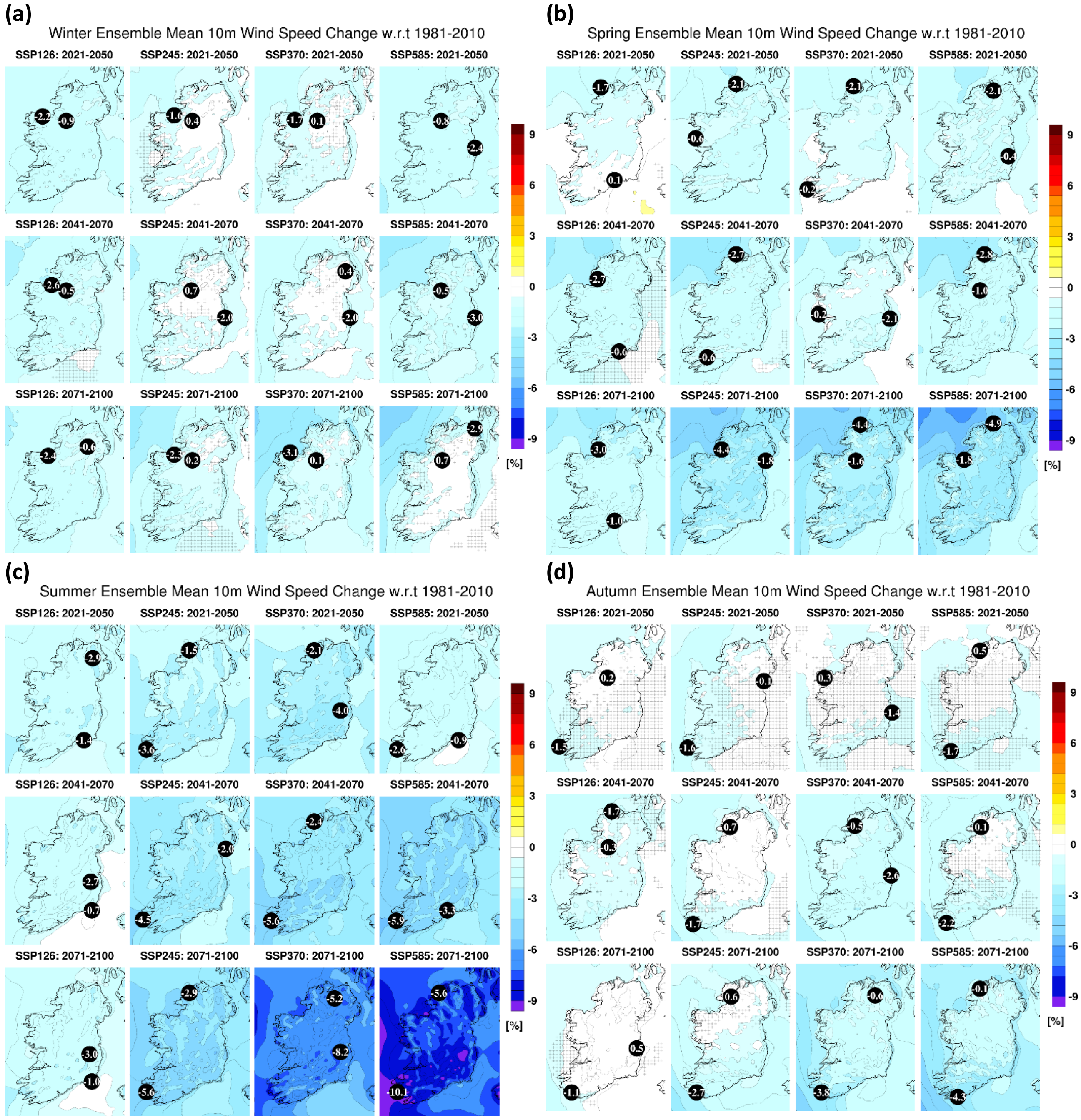

Figure 15. Seasonal RCM ensemble projections of 10m wind speed (%); **(a)** winter, **(b)** spring, **(c)** summer and **(d)** autumn. In each case, the future 30-year period is compared with the past period, 1981–2010. The numbers included on each plot are the minimum and maximum projected changes, displayed at their locations.

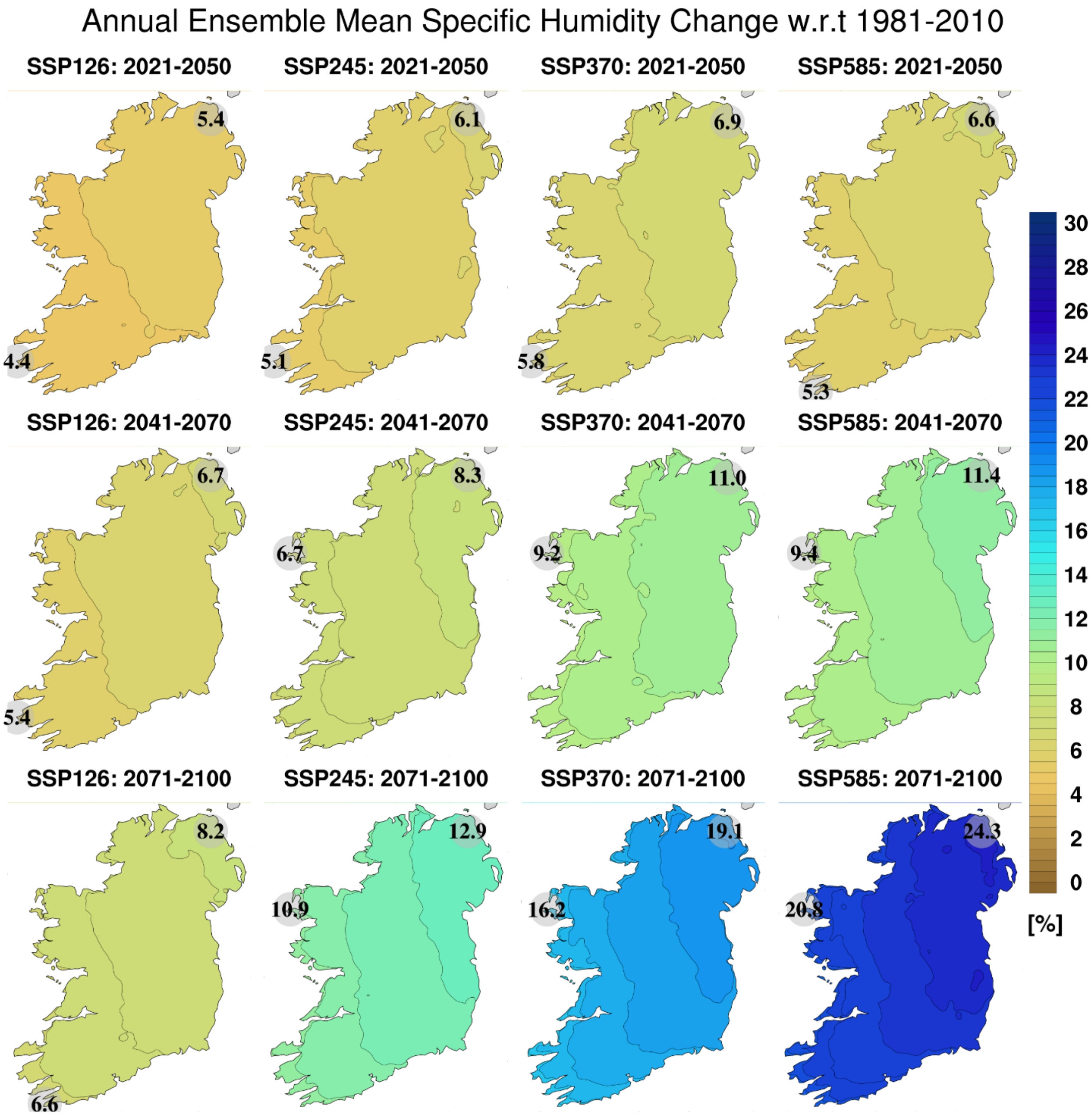

Figure 16 Annual RCM-CMIP6 ensemble projections of near-surface specific humidity (%). All RCM ensemble members were run with 4-km grid spacing. In each case, the future 30-year period is compared with the past period, 1981–2010. The results were obtained from analysing 10 SSP126, 10 SSP245,10 SSP370 and 10 SSP585 RCM simulations. The numbers included on each plot are the minimum and maximum projected changes, displayed at their locations.

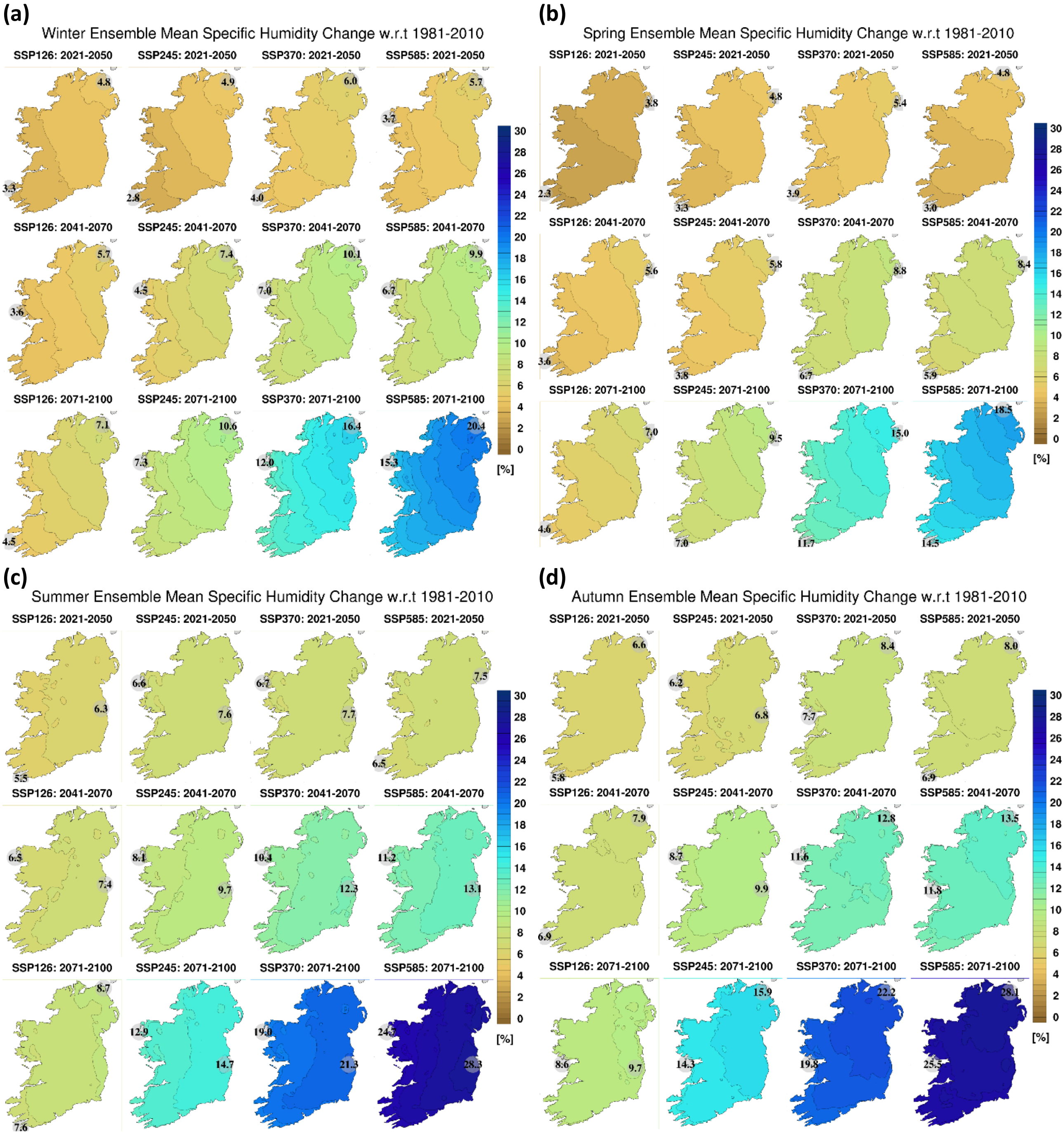

Figure 17. Seasonal RCM ensemble projections of near-surface specific humidity (%); **(a)** winter, **(b)** spring, **(c)** summer and **(d)** autumn. In each case, the future 30-year period is compared with the past period, 1981–2010. The numbers included on each plot are the minimum and maximum projected changes, displayed at their locations.

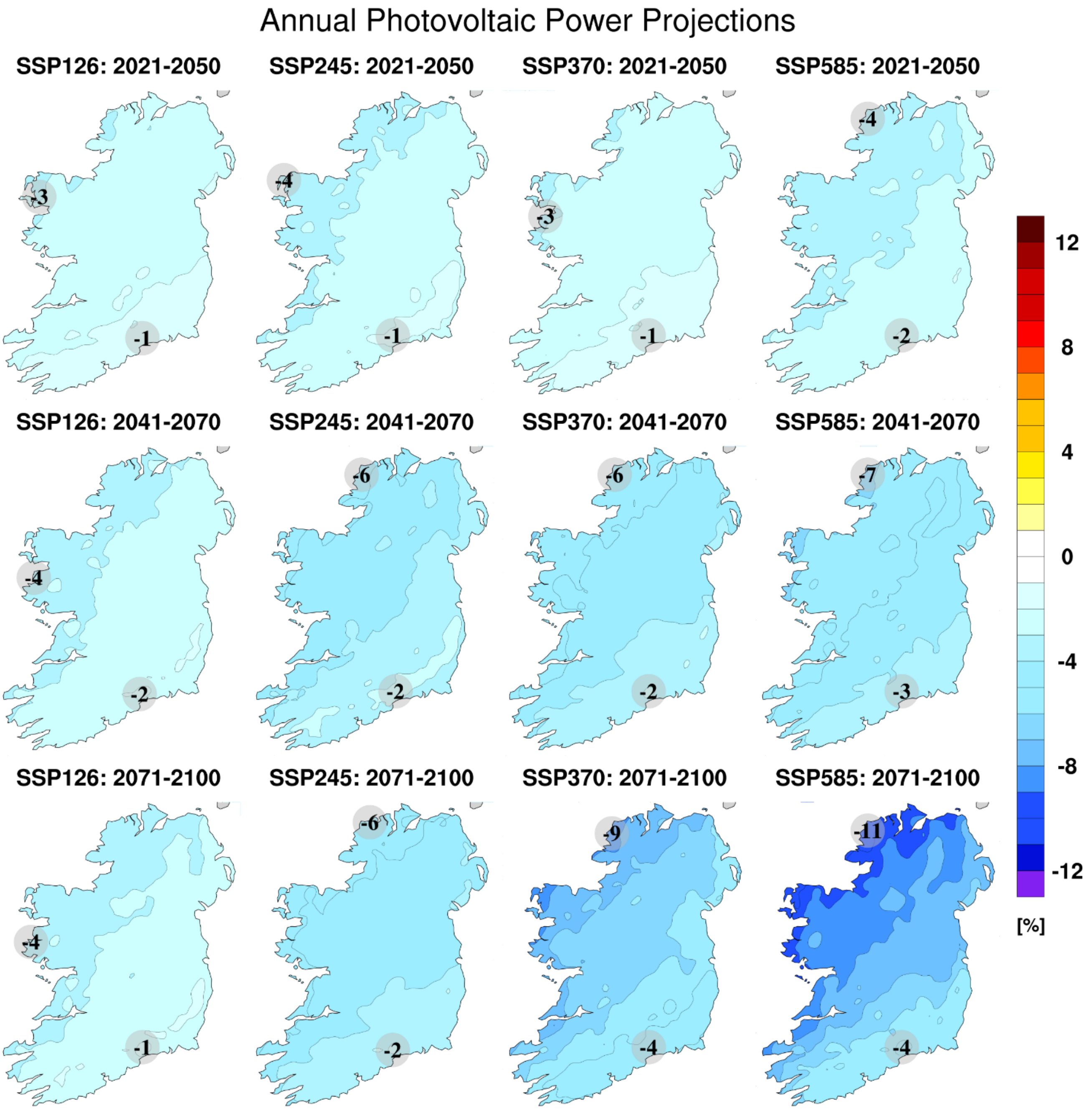

Figure 18. Annual RCM-CMIP6 ensemble mean projections of solar photovoltaic power (%). All RCM ensemble members were run with 4-km grid spacing. In each case, the future 30-year period is compared with the past period, 1981–2010. The results were obtained from analysing 10 SSP126, 10 SSP245,10 SSP370 and 10 SSP585 RCM simulations. The numbers included on each plot are the minimum and maximum projected changes, displayed at their locations.

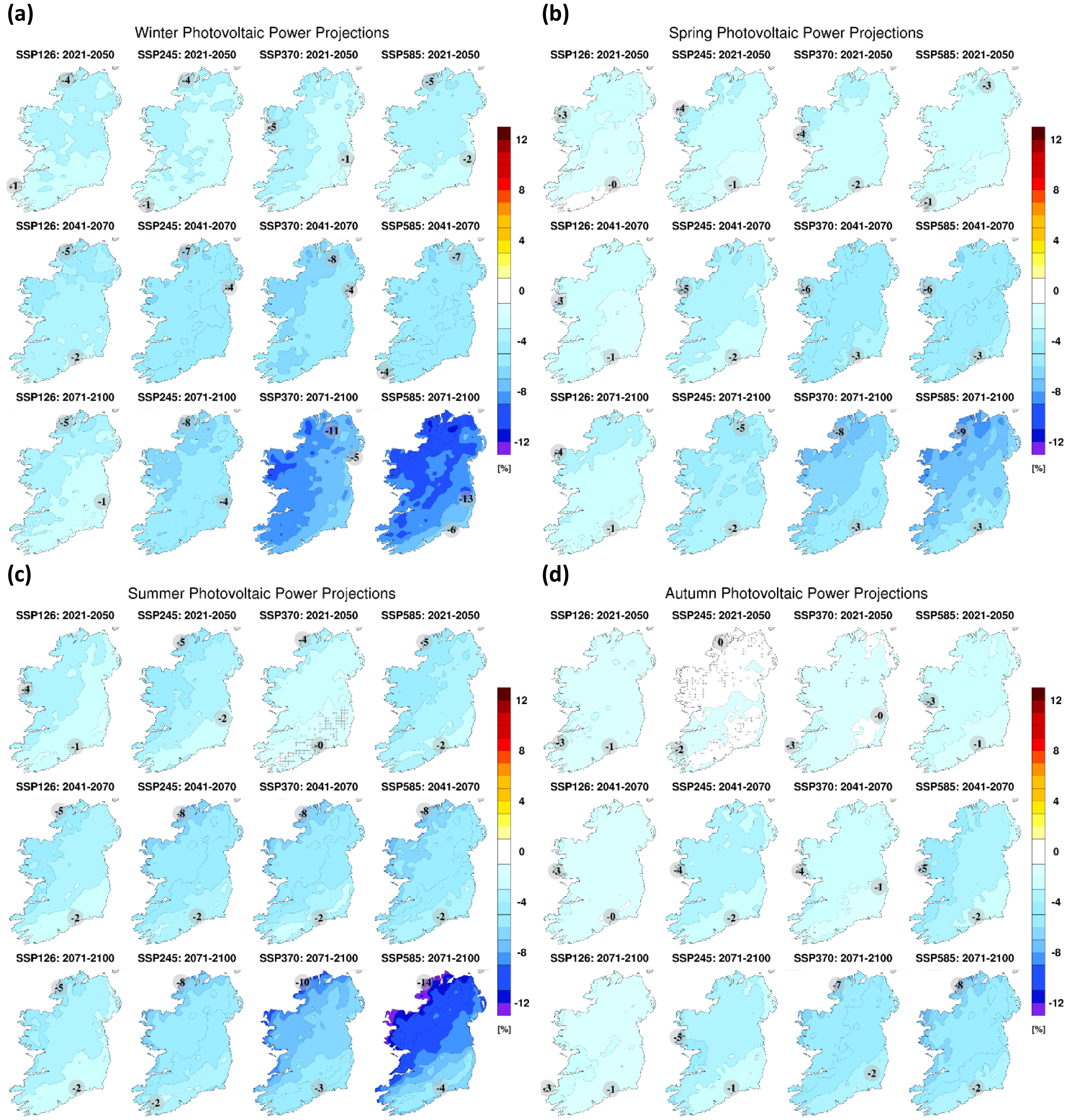

Figure 19. Seasonal RCM ensemble mean projections of solar photovoltaic power (%); **(a)** winter, **(b)** spring, **(c)** summer and **(d)** autumn. In each case, the future 30-year period is compared with the past period, 1981–2010. The numbers included on each plot are the minimum and maximum projected changes, displayed at their locations.

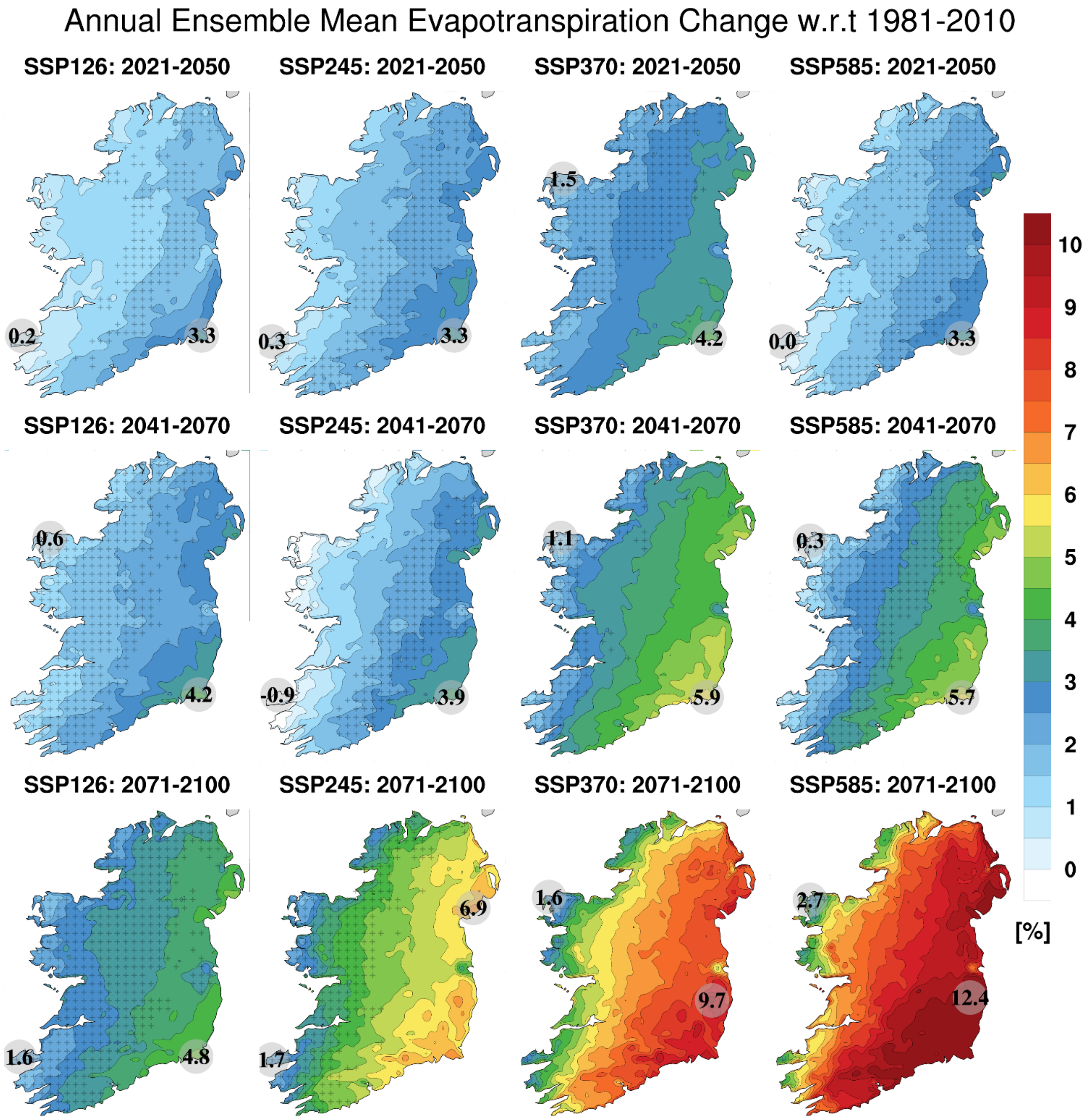

Figure 20. Annual RCM-CMIP6 evapotranspiration (%). All RCM ensemble members were run with 4-km grid spacing. In each case, the future 30-year period is compared with the past period, 1981–2010. The results were obtained from analysing 10 SSP126, 10 SSP245,10 SSP370 and 10 SSP585 RCM simulations. The numbers included on each plot are the minimum and maximum projected changes, displayed at their locations.