SPECIAL PROJECT PROGRESS REPORT

All the following mandatory information needs to be provided. The length should *reflect the complexity and duration* of the project.

Reporting year	2020
Project Title:	High-Resolution EC-Earth Simulations - Ireland's Contribution to CMIP6
Computer Project Account:	spienola
Principal Investigator(s):	Dr Paul Nolan[1,2] Dr Jonathan McGovern[2]
Affiliation:	[1]Irish Centre for High-End Computing and [2]Climate Research Department, Met Éireann
Name of ECMWF scientist(s) collaborating to the project (if applicable)	N/A
Start date of the project:	01/01/2019
Expected end date:	31/12/2021

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)	23 million	23 million	20 million	12 million
Data storage capacity	(Gbytes)	50,000	50,000	70,000	10,000

Summary of project objectives (10 lines max)

The goal of the research project is to simulate the effects of climate change at the global scale using the EC-Earth model. During 2019/2020, the PI completed the following CMIP6 EC-Earth simulations:

- 5 x T255-ORCA1L75 AOGCM CMIP6 Historical Simulations, 1850-2014
- 20 x T255-ORCA1L75 CMIP6 (5 x SSP1-2.6, SSP2-4.5, SSP3-7.0 & SSP5-8.5), 2015-2100

All data were "cmor-ised" and hosted and shared on the ICHEC ESGF node.

Currently, the PI is using ECMWF resources to run EC-Earth-Veg contributions comprising of:

- 2 x T255L91-ORCA1L75 EC-Earth-Veg Historical Simulations, 1850-2014
- 8 x ScenarioMIP simulations 2015-2100; 2 x T255L91-ORCA1L75 EC-Earth-Veg for all four ScenarioMIP "tier 1" SSPs (SSP1-2.6, SSP2-4.5, SSP3-7.0 & SSP5-8.5)

These EC-Earth-Veg simulations are due to be complete in July/August 2020 and will be hosted and shared on the ESGF node.

Summary of problems encountered

The CMIP6 version EC-Earth was slow to run on cca so a careful scale testing was completed to determine the optimal configuration. Table 1 presents scaling statistics for EC-Earth GCM (3.3.0-cmip6-historical) on ECMWF cca using intel-mpi. The simulated time is one month. Three "forking" strategies are considered; no-forking (not shown), all nodes shared (ShareAll) and dedicated nodes for IFS with other components sharing nodes (not shown). rnf_numproc is set to 1 in all cases and the Elpin land removal tool was implemented for the NEMO ocean modelling component. The configuration highlighted in blue was found to be optimal. Furthermore, the LPJ-Guess interactive vegetation component of the EC-Earth-Veg configuration was found to be memory intensive so it was necessary to spread the 10 cores assigned to this executable across two nodes.

Fork	# IFS cores	# nemo cores	# Nodes	Time (mm:ss)	SBUs	SYPD	CHPSY
ShareAll	222	136	10	18:08	1795.2433	6.74	1281
ShareAll	240	118	10	19:54	1951.7020	6.14	1405
ShareAll	210	148	10	17:57	1772.6616	6.81	1268
ShareAll	209 (xios=2)	148	10	17:13	1717.8204	7.10	1216
ShareAll	208 (xios=3)	148	10	19:04	1871.0532	6.41	1346
ShareAll	207 (xios=4)	148	10	17:11	1737.1761	7.11	1213
ShareAll	200	158	10	18:37	1833.9547	6.56	1315
ShareAll	246	148	11	16:23	1777.8231	7.46	1273
ShareAll	246	148	11	16:10	1752.9833	7.56	1256
ShareAll	246	148	11	17:30	1932.1850	6.98	1359
ShareAll	**245 (xios=2)**	**148**	**11**	**15:16**	**1667.8181**	**8.01**	**1186**
ShareAll	**245 (xios=2)**	**148**	**11**	**16:52**	**1818.6314**	**7.25**	**1310**
ShareAll	**245 (xios=2)**	**148**	**11**	**16:08**	**1749.4347**	**7.58**	**1253**
ShareAll	243 (xios=4)	148	11	18:07	1996.0589	6.75	1407
ShareAll	265 (xios=2)	165	12	16:47	2074.9335	7.28	1422
ShareAll	265	165	12	16:29	1945.5017	7.41	1397
ShareAll	282	148	12	16:42	1989.7683	7.32	1415

Table 1. EC-Earth Scaling On ECMWF/cca

Summary of plans for the continuation of the project

The EC-Earth-Veg simulations (listed above) will be completed, validated, analysed, hosted and shared on the ICHEC ESGF node. The project team will commence a number of high-resolution experiments in the near future after consultation with the EC-Earth community and project partners.

List of publications/reports from the project with complete references

Paul Nolan, Alastair McKinstry (2020); EC-Earth Global Climate Simulations: Ireland's Contributions to CMIP6. Environmental Protection Agency, Research Report 310. [Read]

Summary of results

EC-Earth AOGCM Validations:

The EC-Earth ensemble members were validated by comparing the five historical ensemble members (r6i1p1f1, r9i1p1f1, r11i1p1f1, r13i1p1f1 and r15i1p1f1) with CRU observational and ECMWF ERA5 reanalysis datasets. Figure 1 presents the mean 2m temperature for the period, 1979-2014 for ERA5, CRU and each of the five EC-Earth ensemble members. The EC-Earth models exhibits a general cold bias over land and a warm bias over the Southern Ocean (Figure 2). Tables 2 & 3 present the annual & seasonal bias and MAE global average statistics for ERA5 (1979-2014) and CRU (1901-2014), respectively. The EC-Earth ensemble members exhibit a warm (cold) biased compared to ERA5 (CRU). Similarly, precipitation validations are presented in Figure 3 and Tables 4 & 5, and demonstrate that the EC-Earth model performs well.

In addition to temperature and precipitation, the PI validated EC-Earth 10m wind speed (Figures 4, 5 and 6, Table 6), mean sea level pressure, total cloud cover, snowfall, sea surface temperature (Figures 7-9, Table 7) and sea ice fraction (Figure 10).

EC-Earth AOGCM Climate Projections

Figure 11 presents the spatial distribution of annual mean 2m temperature projections for each of the four SSPs for the 30-year period 2041-2070 (relative to 1981-2010). The corresponding 2071-2100 projections are presented in Figure 12. Note that for each figure, the mean of the five ensemble members is considered. The largest increases in temperatures are noted over the land masses, in particular the northern-most regions and the Artic. Projections of temperature range from ~0.5°C over the Southern Ocean for 2041-2070 SSP1-2.6 (Figure 11a) to ~18°C over the Artic for the 2071-2100 SSP5-8.5 (Figure 12d).

Projections for DJF (not shown) follow a similar trend with the exception that increases over the northern land masses and the Artic are enhanced. The projections for JJA (not shown) follow a similar trend to the annual projections with the exception that increases over the northern land mases and the Artic are diminished whereas increases over Antarctica are enhanced.

The mean global annual temperature anomalies (relative to 1981-2010) for all five historical (1850-2014) and twenty SSPs (2015-2100) are presented in Figure 13. The bold lines represent the ensemble mean. All ensemble members show a steady increase in temperature from around 2000 with a noticeable divergence between the SSPs from around 2050. By the year 2100, the global mean temperature is projected to increase by approximately 1.5°C, 2.8°C, 4.2°C and 5.5°C for SSP1-2.6, SSP2-4.5, SSP3-7.0 and SSP5-8.5, respectively. The small spread between the individual ensemble members demonstrates a high level of agreement and adds a measure of confidence to the projections.

Figure 14 presented the spatial distribution of annual precipitation projections (%) for each of the four SSPs for the 2041-2070 period. The corresponding projections for 2071-2100 are presented in Figure 15. The general trend is for an increase in precipitation with the exception of the North Atlantic region south of Iceland and regions just north and south of the equator including North Africa and large parts of South America and South Africa. Southern Europe and the Mediterranean show a drying for the end-of-century SSP3-7.0 & SSP5-8.5 projections.

Precipitation projections for DJF (not shown) follow a similar (but enhanced) trend to the annual projections. However, Europe and the Mediterranean are projected to be wetter under all SSPs. The projections for JJA (not shown) follow a similar trend to the annual projections with a general increase in precipitation in most regions and an enhanced drying over Southern Europe, North America, South America and South Africa. For JJC, there is no drying projected in the Atlantic region south of Iceland.

The mean global annual precipitation anomalies (relative to 1981-2010) for all five historical (1850-2014) and twenty SSPs (2015-2100) are presented in Figure 16. The bold lines represent the ensemble mean. All ensemble members show a steady increase in precipitation from around 2000 with a noticeable divergence between the SSPs around 2060. By the year 2100, global mean precipitation is projected to increase by approximately 4%, 6%, 8% and 10% for SSP1-2.6, SSP2-4.5, SSP3-7.0 and SSP5-8.5, respectively.

In addition to temperature and precipitation, the PI analysed projections of EC-Earth 10m wind speed, mean sea level pressure, total cloud cover, snowfall, sea surface temperature and sea ice fraction (not shown).

Assessment of Full CMIP6 Scenario-MIP ensemble:

The full CMIP6 Scenario-MIP ensemble (as available, May 2020) was analysed to assess where our own CMIP6 EC-Earth contribution fitted within the full ensemble. For the future climate, the four tier-1 Shared Socioeconomic Pathways (SSPs; SSP1-2.6, SSP2-2.5, SSP3-7.0 and SSP5-8.5) were analysed.

Figure 17 presents the global annual 2m temperature anomaly (1900-2100) with respect to the 30-year mean 1981-2010. A total of 135 (SSP1-2.6), 170 (SSP2-2.5), 151 (SSP3-7.0) and 137 (SSP5-8.5) CMIP6 ensemble members were analysed.

Figure 18 presents the mean of the SSP annual 2m temperature anomalies.

Figure 19 presents the mean of the SSP annual anomalies alongside the EC-Earth ensemble members.

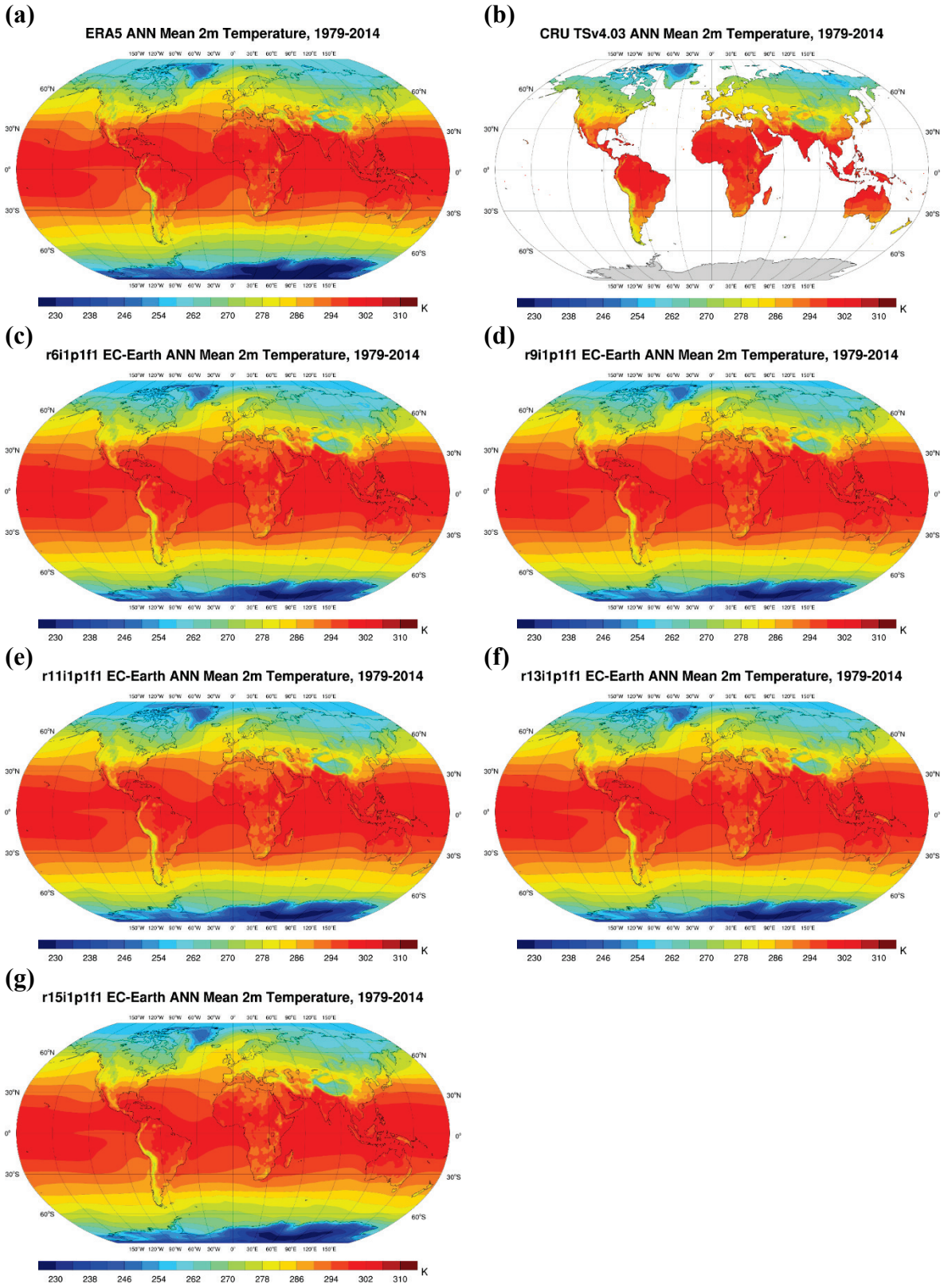


Figure 1. Annual Mean 2m Temperature 1979-2014; **(a)** ERA5 Reanalysis, **(b)** CRU ts4.03 Observations, **(c)** EC-Earth r6i1p1f1, **(d)** EC-Earth r9i1p1f1, **(e)** EC-Earth r11i1p1f1, **(f)** EC-Earth r13i1p1f1 and **(g)** EC-Earth r15i1p1f1

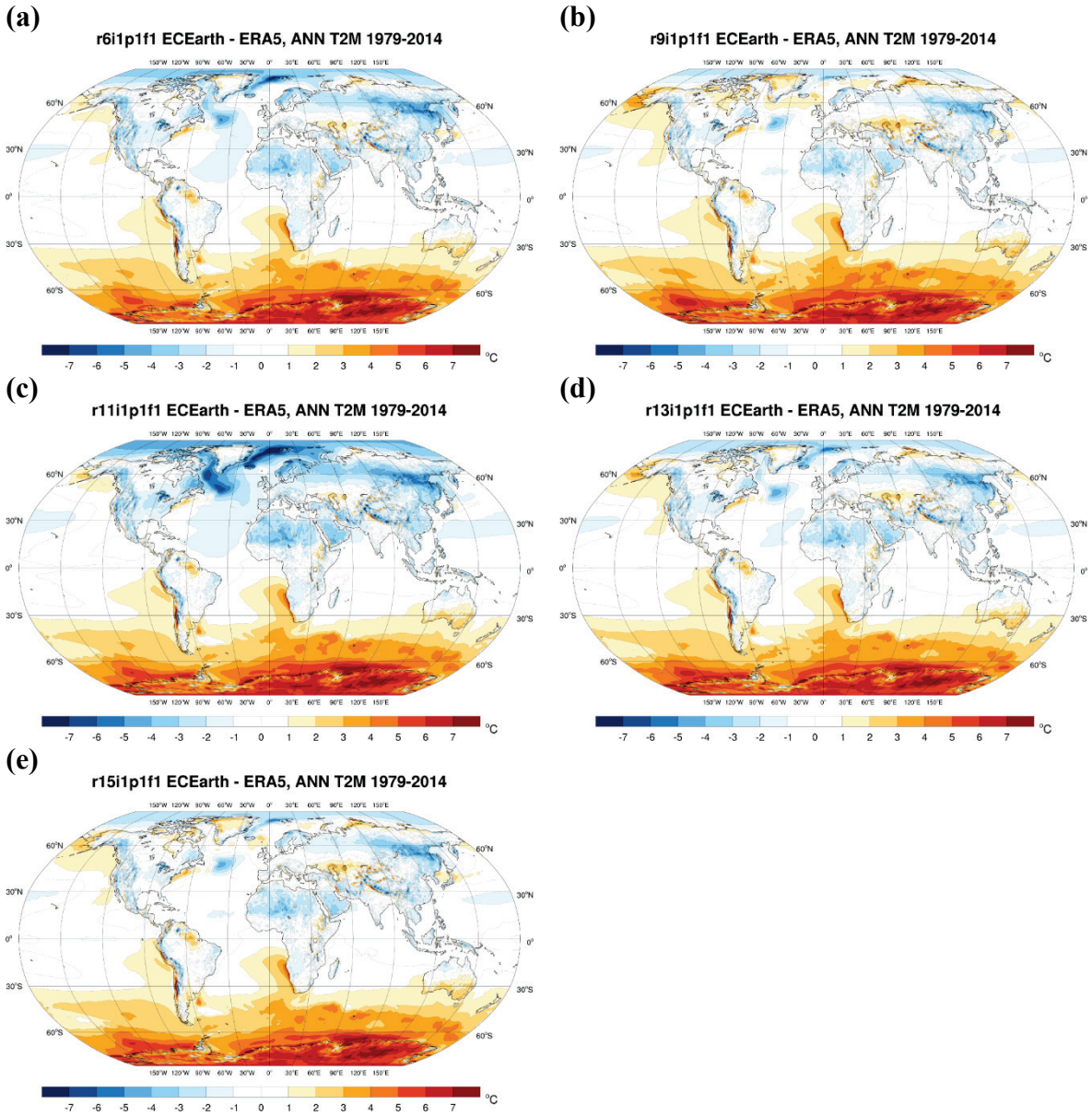


Figure 2. EC-Earth Annual 2m Temperature Bias 1979-2014 (ERA5 Reanalysis minus EC-Earth); **(a)** EC-Earth r6i1p1f1, **(b)** EC-Earth r9i1p1f1, **(c)** EC-Earth r11i1p1f1, **(d)** EC-Earth r13i1p1f1 and **(e)** EC-Earth r15i1p1f1

	r6i1p1f1		r9i1p1f1		r11i1p1f1		r13i1p1f1		r15i1p1f1	
	Bias	**MAE**	**Bias**	**MAE**	**Bias**	**MAE**	**Bias**	**MAE**	**Bias**	**MAE**
Annual	0.33	1.42	0.67	1.38	0.18	1.59	0.49	1.40	0.54	1.35
DJF	0.21	1.60	0.62	1.56	0.02	1.80	0.39	1.58	0.45	1.51
MAM	0.31	1.83	0.61	1.79	0.15	2.01	0.44	1.82	0.48	1.76
JJA	0.49	1.42	0.78	1.43	0.37	1.54	0.63	1.43	0.66	1.39
SON	0.33	1.24	0.67	1.23	0.17	1.39	0.51	1.23	0.55	1.21

Table 2. Mean global annual and seasonal 2m temperature bias & MAE (°C) for each of the five EC-Earth ensemble members. In each case the model data are compared with ERA5 reanalysis data for the period 1979-2014.

	r6i1p1f1		r9i1p1f1		r11i1p1f1		r13i1p1f1		r15i1p1f1	
	Bias	**MAE**	**Bias**	**MAE**	**Bias**	**MAE**	**Bias**	**MAE**	**Bias**	**MAE**
Annual	-1.32	1.81	-0.89	1.60	-1.11	1.71	-0.91	1.60	-0.97	1.63
DJF	-1.62	2.66	-1.07	2.48	-1.37	2.55	-1.12	2.46	-1.17	2.47
MAM	-1.70	2.36	-1.29	2.14	-1.48	2.25	-1.30	2.14	-1.38	2.18
JJA	-0.83	1.74	-0.51	1.60	-0.66	1.66	-0.54	1.61	-0.58	1.61
SON	-1.12	1.78	-0.69	1.57	-0.91	1.67	-0.66	1.55	-0.77	1.60

Table 3. Mean global annual and seasonal 2m temperature bias & MAE (°C) for each of the five EC-Earth ensemble members. In each case the model data are compared with CRUts4.03 observational data for the period 1901-2014. The temperature data are confined to land points and exclude Antarctica.

	r6i1p1f1		r9i1p1f1		r11i1p1f1		r13i1p1f1		r15i1p1f1	
	Bias	**MAE**	**Bias**	**MAE**	**Bias**	**MAE**	**Bias**	**MAE**	**Bias**	**MAE**
Annual	-0.001	0.549	0.018	0.556	-0.012	0.567	0.004	0.540	0.008	0.537
DJF	0.051	0.666	0.071	0.685	0.037	0.677	0.054	0.655	0.061	0.666
MAM	0.027	0.859	0.042	0.857	0.017	0.879	0.029	0.845	0.033	0.840
JJA	-0.043	0.678	-0.018	0.678	-0.055	0.695	-0.032	0.667	-0.028	0.659
SON	-0.040	0.616	-0.022	0.640	-0.048	0.630	-0.032	0.622	-0.031	0.602

Table 4. Mean global annual and seasonal daily precipitation bias & MAE (mm/day) for each of the five EC-Earth ensemble members. In each case the model data are compared with ERA5 reanalysis data for the period 1979-2014.

	r6i1p1f1		r9i1p1f1		r11i1p1f1		r13i1p1f1		r15i1p1f1	
	Bias	**MAE**	**Bias**	**MAE**	**Bias**	**MAE**	**Bias**	**MAE**	**Bias**	**MAE**
Annual	0.124	0.667	0.147	0.669	0.130	0.664	0.143	0.662	0.138	0.663
DJF	0.245	0.777	0.260	0.772	0.240	0.778	0.251	0.761	0.256	0.775
MAM	0.143	0.840	0.157	0.851	0.134	0.839	0.160	0.842	0.147	0.850
JJA	-0.040	0.856	-0.011	0.861	-0.027	0.858	-0.006	0.855	-0.014	0.858
SON	0.160	0.739	0.193	0.749	0.183	0.742	0.178	0.741	0.176	0.735

Table 5. Mean global annual and seasonal daily precipitation bias & MAE (mm/day) for each of the five EC-Earth ensemble members. In each case the model data are compared with CRUts4.03 observational data for the period 1901-2014. The data are confined to land points and exclude Antarctica.

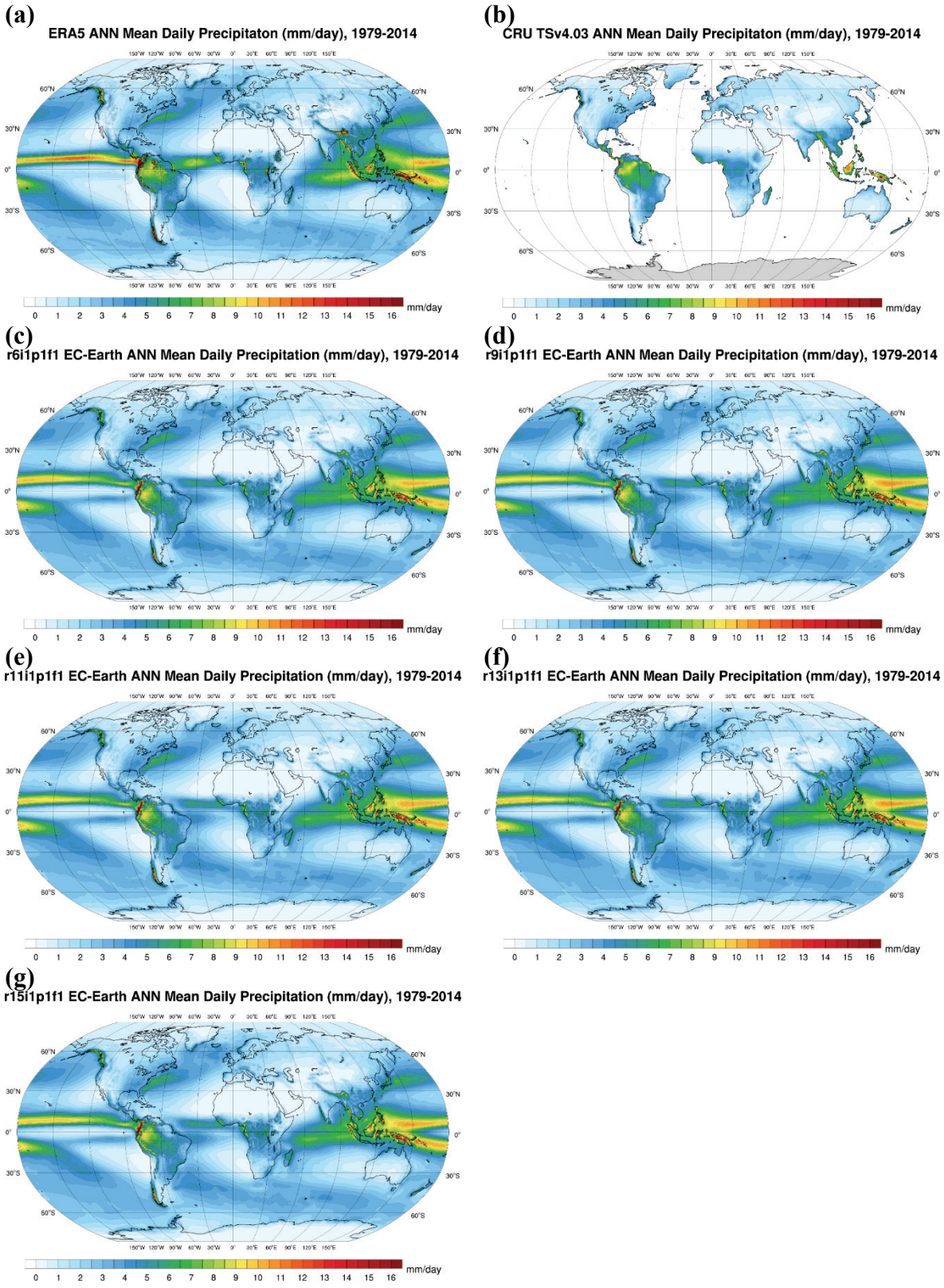


Figure 3. Annual Mean Daily Precipitation (mm/day) 1979-2014; **(a)** ERA5 Reanalysis, **(b)** CRU ts4.03 Observations, **(c)** EC-Earth r6i1p1f1, **(d)** EC-Earth r9i1p1f1, **(e)** EC-Earth r11i1p1f1, **(f)** EC-Earth r13i1p1f1 and **(g)** EC-Earth r15i1p1f1

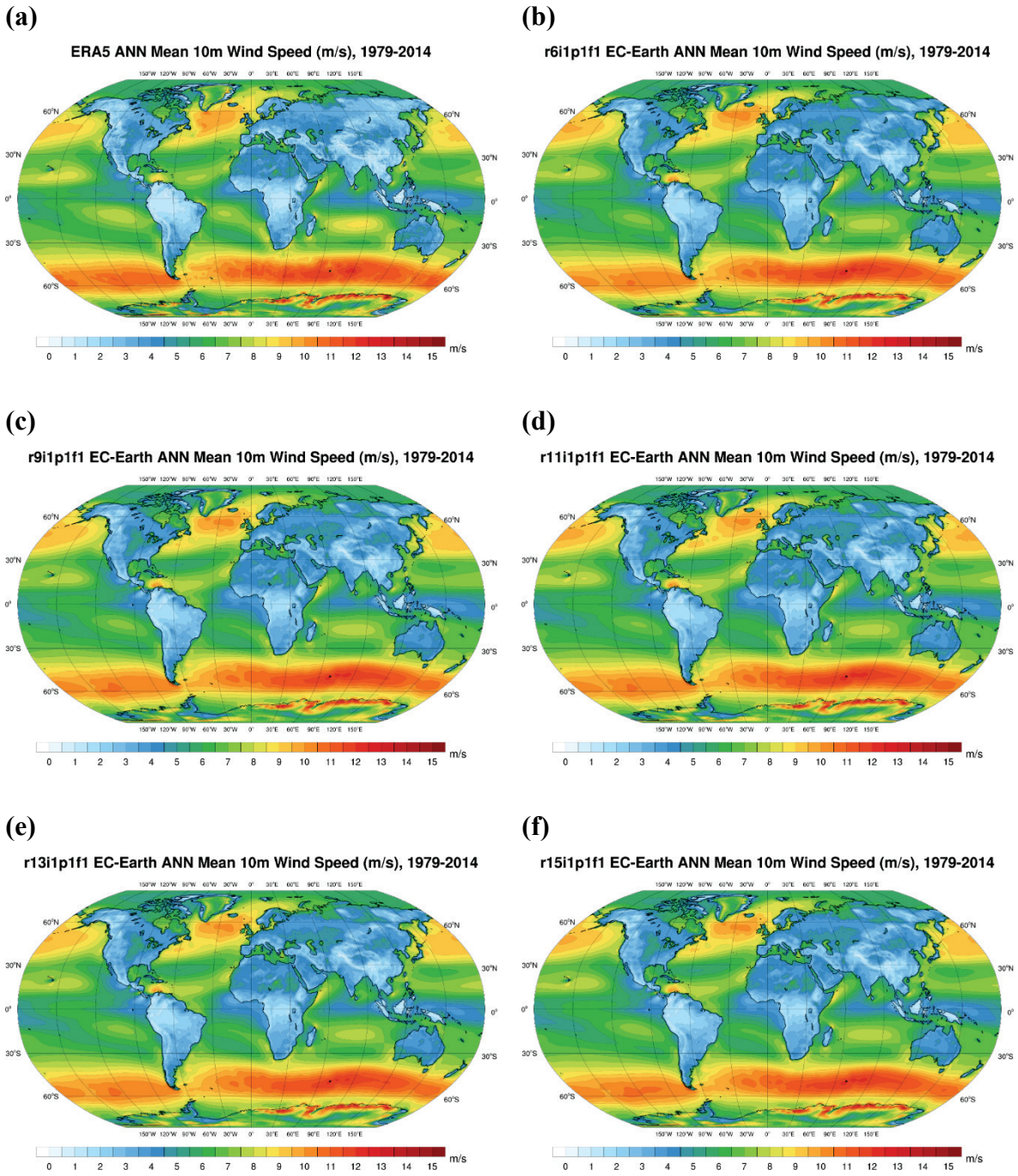


Figure 4. Annual mean 10-m wind speed, 1979–2014: (a) ERA5 reanalysis, (b) EC-Earth r6i1p1f1, (c) EC-Earth r9i1p1f1, (d) EC-Earth r11i1p1f1, (e) EC-Earth r13i1p1f1 and (f) EC-Earth r15i1p1f1.

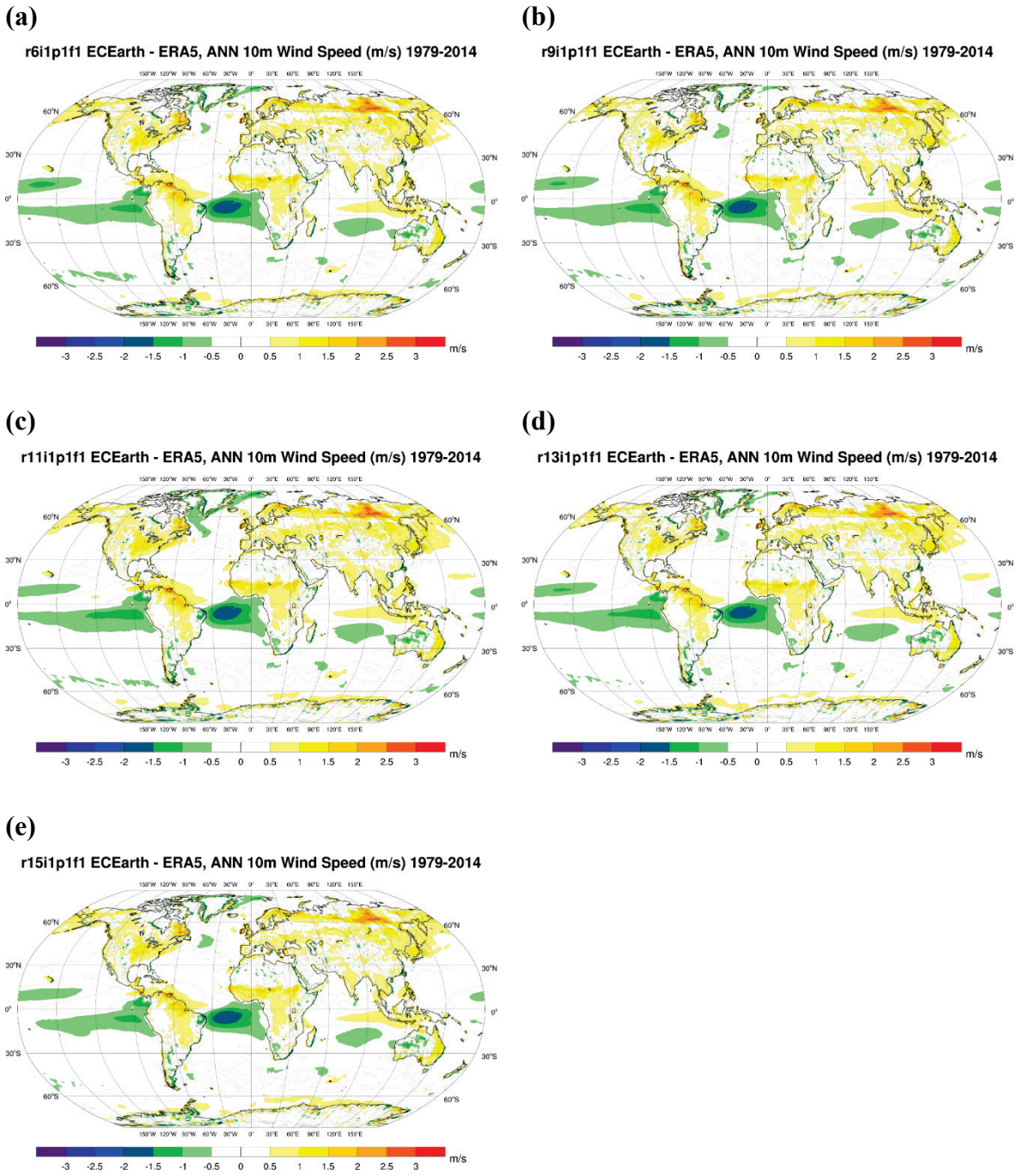
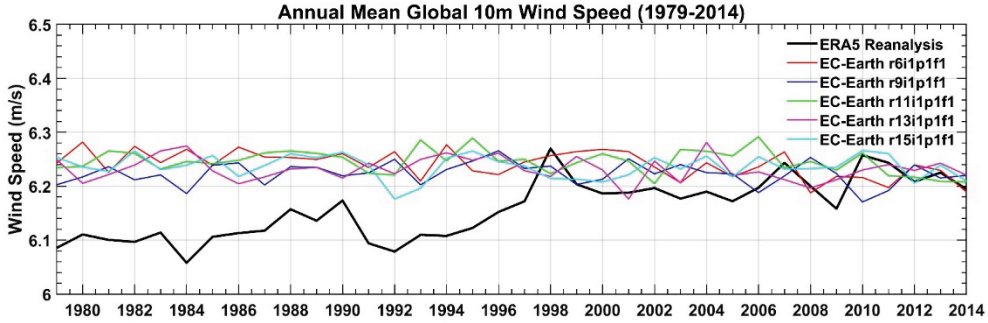


Figure 5. EC-Earth annual 10-m wind speed bias, 1979–2014 (ERA5 reanalysis minus EC-Earth): (a) EC-Earth r6i1p1f1, (b) EC-Earth r9i1p1f1, (c) EC-Earth r11i1p1f1, (d) EC-Earth r13i1p1f1 and (e) EC-Earth r15i1p1f1.

	r6i1p1f1		r9i1p1f1		r11i1p1f1		r13i1p1f1		r15i1p1f1	
	Bias	**MAE**	**Bias**	**MAE**	**Bias**	**MAE**	**Bias**	**MAE**	**Bias**	**MAE**
Annual	0.082	0.408	0.064	0.403	0.087	0.425	0.072	0.406	0.077	0.393
DJF	0.158	0.517	0.137	0.505	0.150	0.537	0.145	0.500	0.154	0.498
MAM	0.086	0.499	0.058	0.495	0.093	0.524	0.069	0.505	0.059	0.483
JJA	0.010	0.461	0.016	0.454	0.023	0.470	0.018	0.461	0.026	0.446
SON	0.073	0.456	0.046	0.460	0.081	0.460	0.057	0.451	0.069	0.443

Table 6. Mean global annual and seasonal 10-m wind speed bias and MAE (m/s) for each of the five EC-Earth ensemble members. In each case the model data are compared with ERA5 reanalysis data for the period 1979–2014.

(a)



(b)

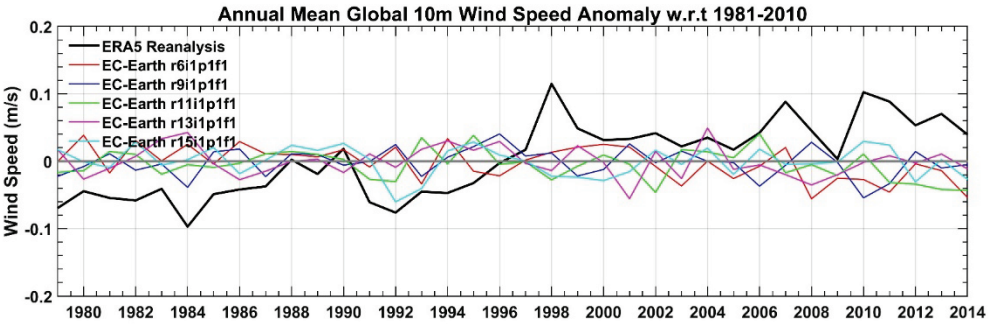


Figure 6. Comparison of EC-Earth ensemble members with ERA5 reanalysis data for the period 1979–2014: (a) 10-m wind speed and (b) 10-m wind speed anomalies with respect to the 30-year period, 1981–2010.

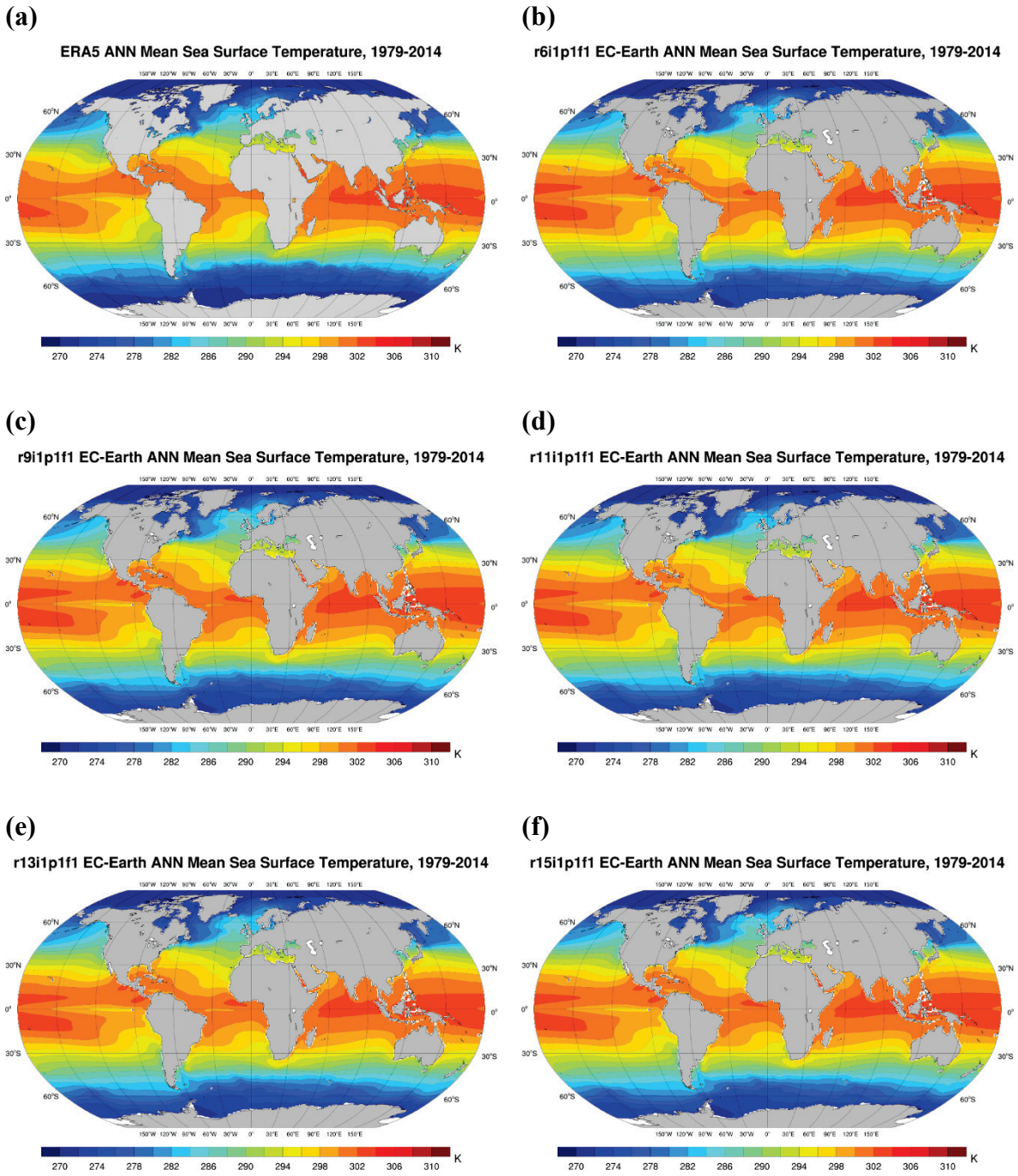


Figure 7. Annual mean SST, 1979–2014: (a) ERA5 reanalysis, (b) EC-Earth r6i1p1f1, (c) EC-Earth r9i1p1f1, (d) EC-Earth r11i1p1f1, (e) EC-Earth r13i1p1f1 and (f) EC-Earth r15i1p1f1.

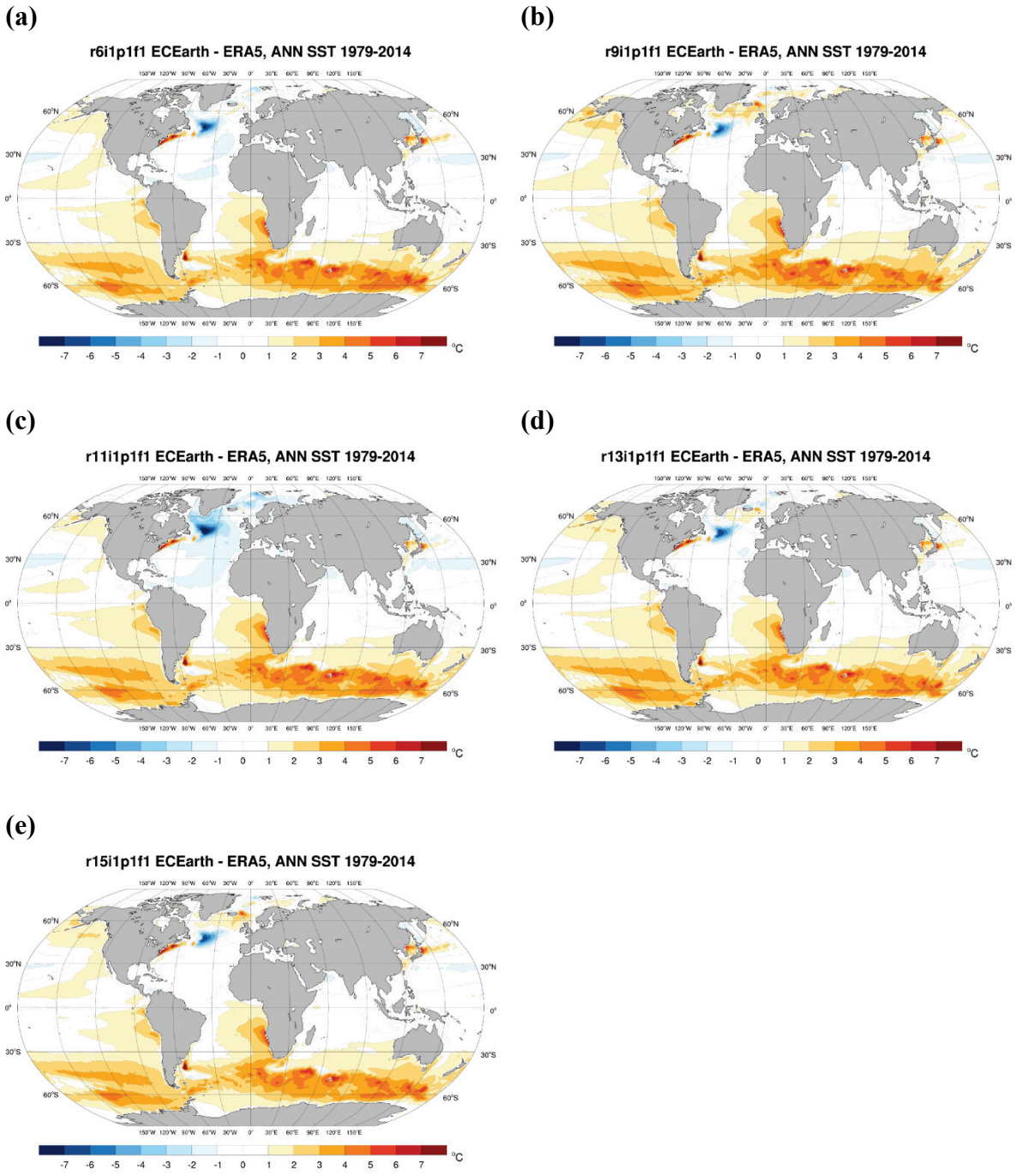


Figure 8. EC-Earth annual mean SST bias, 1979–2014 (ERA5 reanalysis minus EC-Earth): (a) EC-Earth r6i1p1f1, (b) EC-Earth r9i1p1f1, (c) EC-Earth r11i1p1f1, (d) EC-Earth r13i1p1f1 and (e) EC-Earth r15i1p1f1.

	r6i1p1f1		r9i1p1f1		r11i1p1f1		r13i1p1f1		r15i1p1f1	
	Bias	**MAE**	**Bias**	**MAE**	**Bias**	**MAE**	**Bias**	**MAE**	**Bias**	**MAE**
Annual	0.91	1.22	1.13	1.32	0.84	1.30	1.01	1.26	1.03	1.24
DJF	1.10	1.48	1.32	1.59	1.04	1.54	1.19	1.51	1.20	1.47
MAM	1.02	1.52	1.23	1.62	0.96	1.63	1.13	1.58	1.15	1.54
JJA	0.78	1.09	1.0	1.19	0.68	1.17	0.87	1.13	0.91	1.12
SON	0.75	1.03	0.96	1.13	0.67	1.08	0.85	1.07	0.88	1.06

Table 7. Mean global annual and seasonal SST bias (°C) for each of the five EC-Earth ensemble members. In each case the model data are compared with ERA5 reanalysis data for the period 1979–2014.

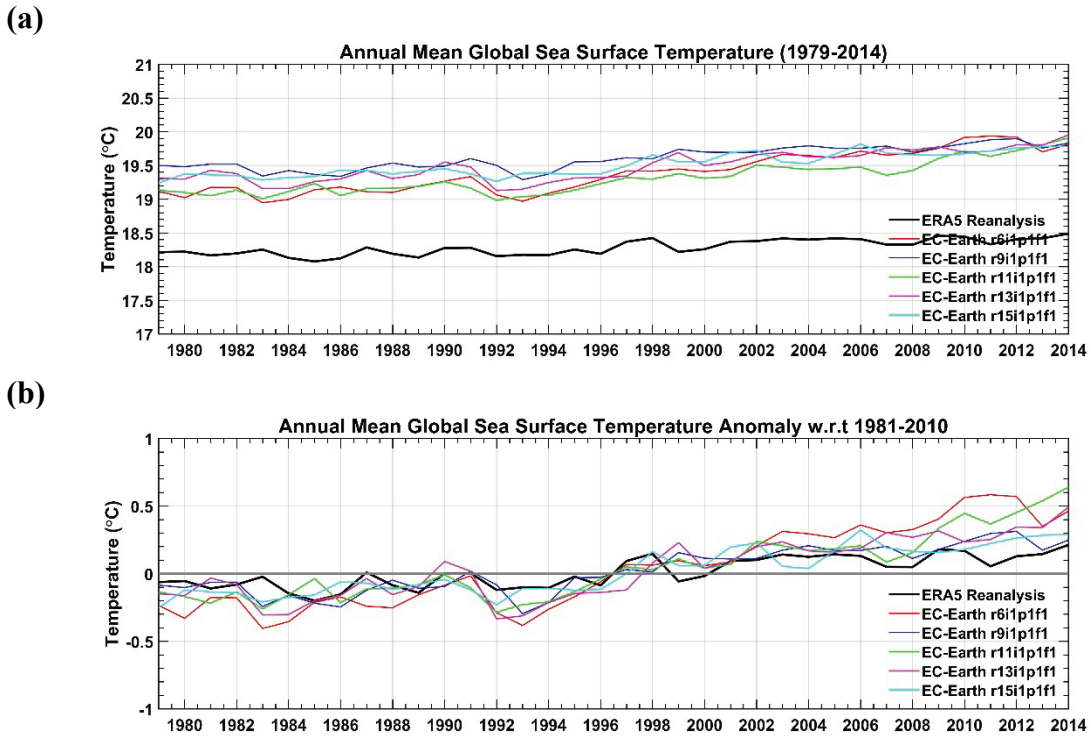


Figure 9. Comparison of EC-Earth ensemble members with ERA5 reanalysis data for the period 1979–2014: (a) SST and (b) SST anomalies with respect to the 30-year period 1981–2010.

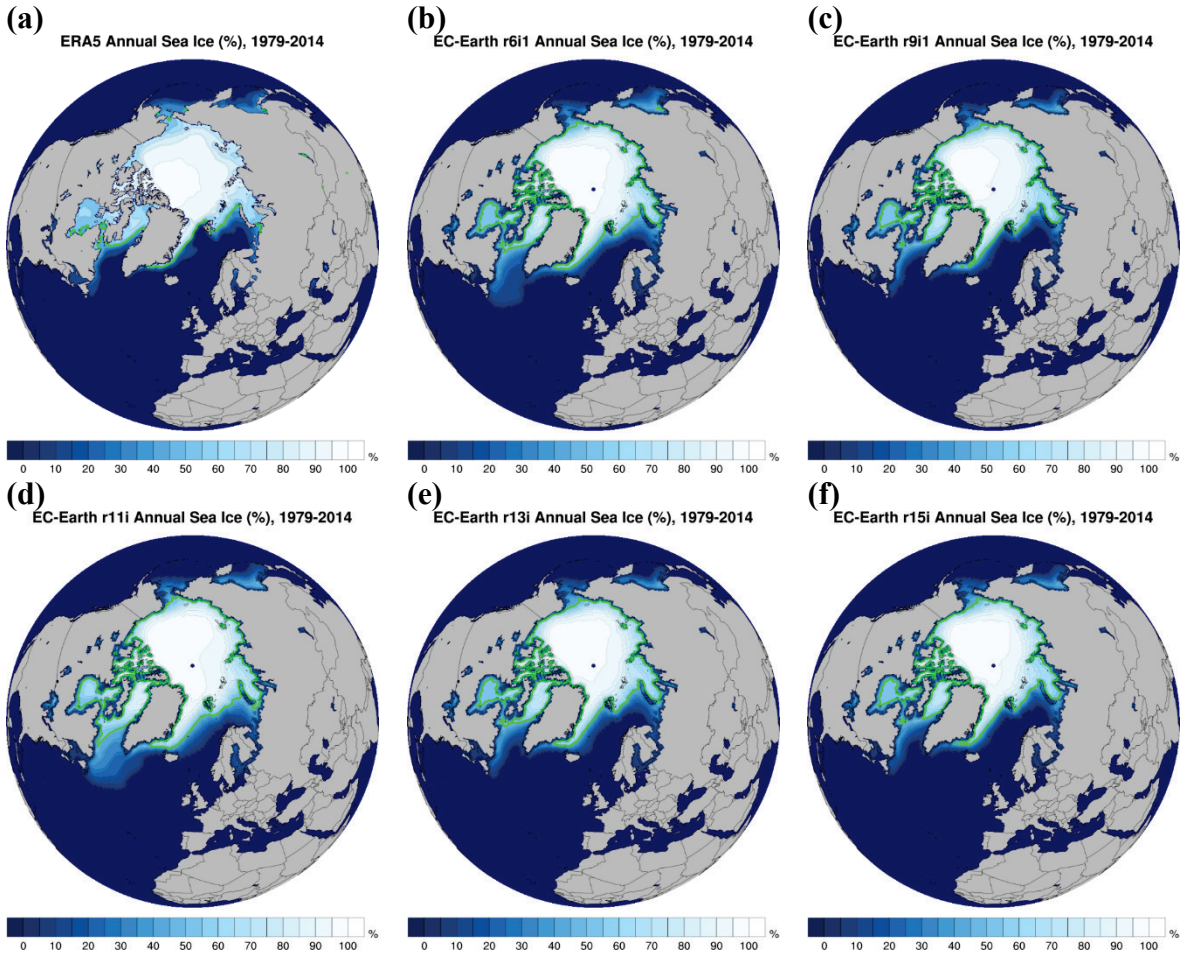


Figure 10. Northern Hemisphere annual mean sea ice fraction (%), 1979–2014: (a) ERA5 reanalysis, (b) EC-Earth r6i1p1f1, (c) EC-Earth r9i1p1f1, (d) EC-Earth r11i1p1f1, (e) EC-Earth r13i1p1f1 and (f) EC-Earth r15i1p1f1. The green line shows the 50% contour line.

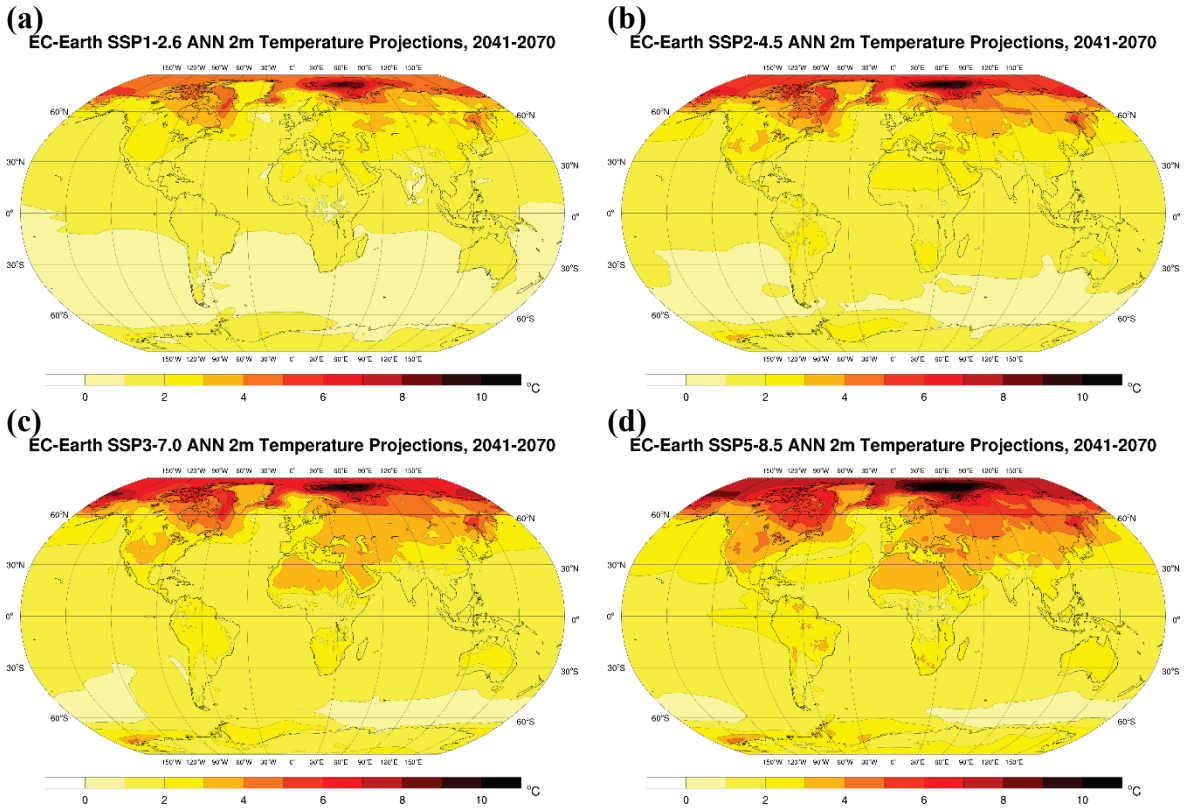


Figure 11. EC-Earth Annual 2m Temperature Projections (2041-2070 vs 1981-2010); **(a)** SSP1-2.6, **(b)** SSP2-4.5, **(c)** SSP3-7.0 and **(d)** SSP5-8.5. In each case, an average is taken of the ensemble members r6i1p1f1, r9i1p1f1, r11i1p1f1, r13i1p1f1 and r15i1p1f1.

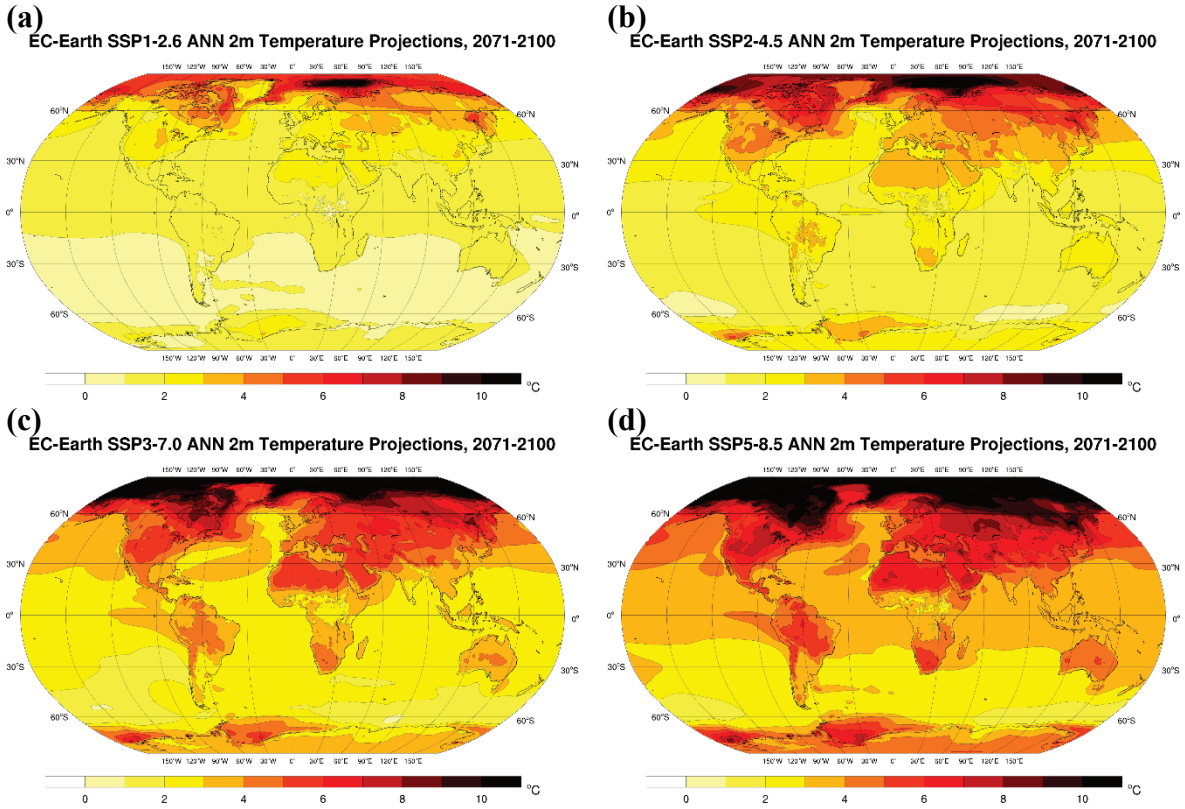


Figure 12. EC-Earth Annual 2m Temperature Projections (2071-2100 vs 1981-2010); **(a)** SSP1-2.6, **(b)** SSP2-4.5, **(c)** SSP3-7.0 and **(d)** SSP5-8.5. In each case, an average is taken of the ensemble members r6i1p1f1, r9i1p1f1, r11i1p1f1, r13i1p1f1 and r15i1p1f1.

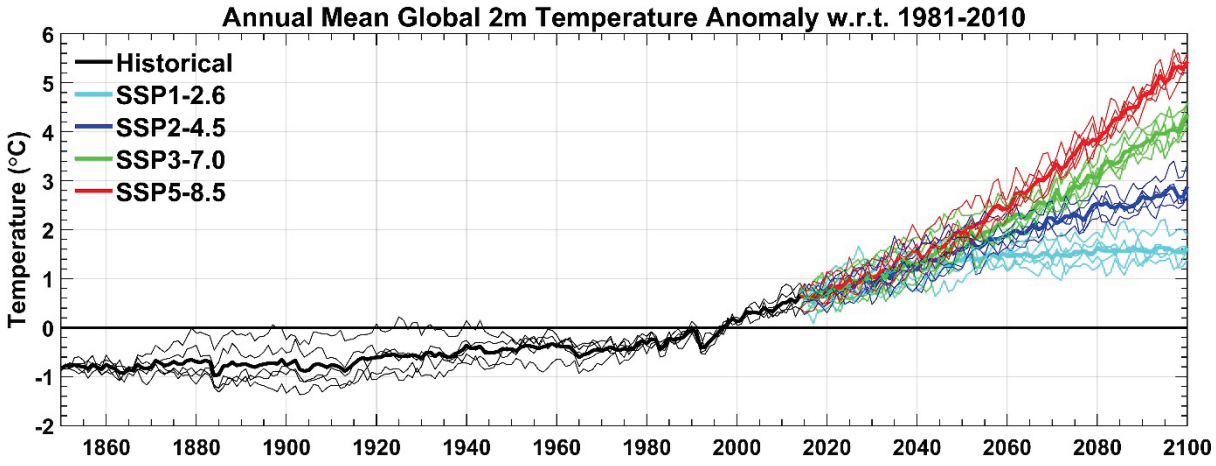


Figure 13. Global Annual 2m temperature anomaly with respect to the 30-year period 1981-2010; EC-Earth ensemble members r6i1p1f1, r9i1p1f1, r11i1p1f1, r13i1p1f1 and r15i1p1f1. The bold lines represent the ensemble mean.

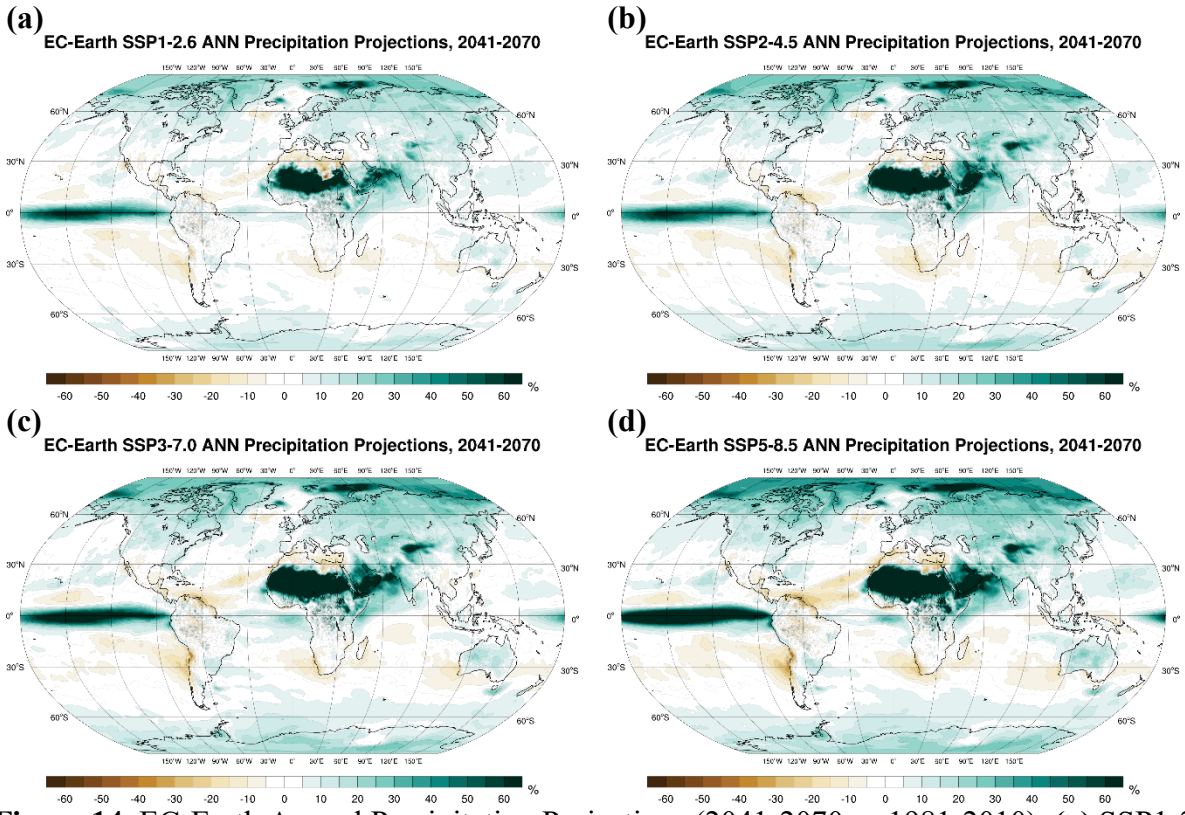


Figure 14. EC-Earth Annual Precipitation Projections (2041-2070 vs 1981-2010); **(a)** SSP1-2.6, **(b)** SSP2-4.5, **(c)** SSP3-7.0 and **(d)** SSP5-8.5. In each case, an average is taken of the ensemble members r6i1p1f1, r9i1p1f1, r11i1p1f1, r13i1p1f1 and r15i1p1f1.

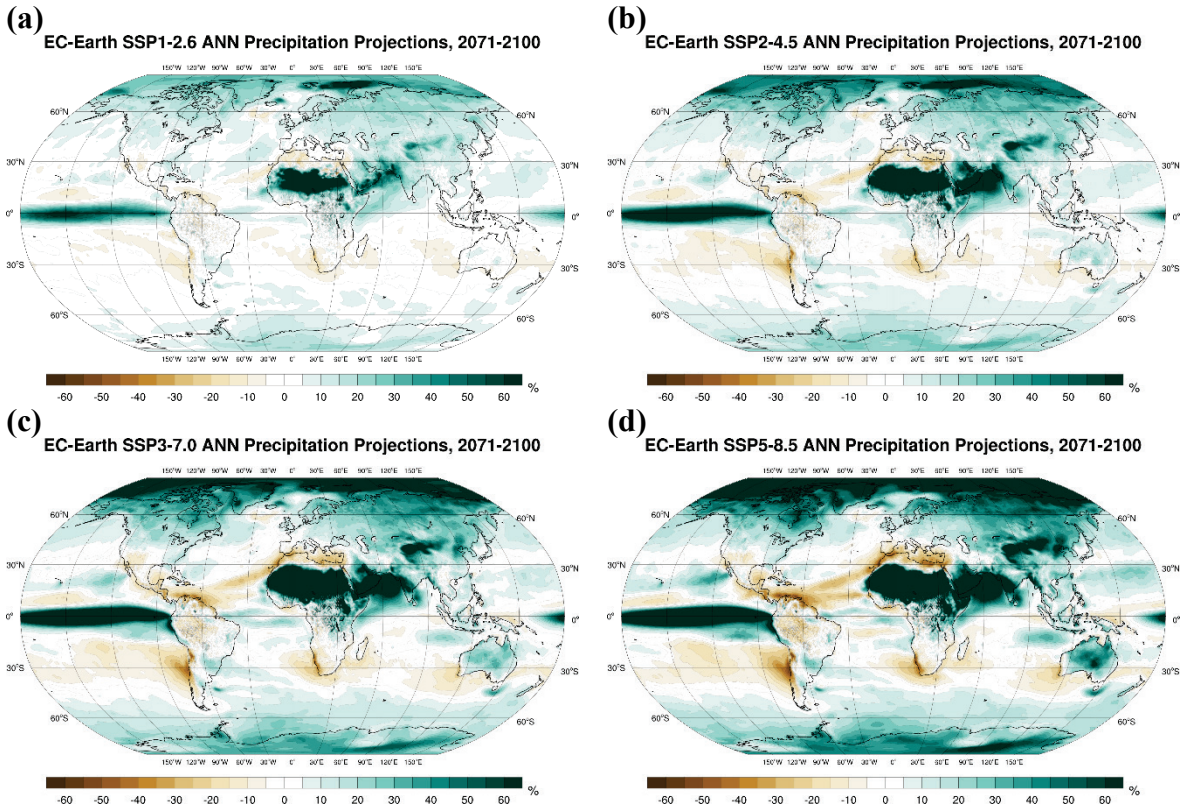


Figure 15. EC-Earth Annual Precipitation Projections (2071-2100 vs 1981-2010); **(a)** SSP1-2.6, **(b)** SSP2-4.5, **(c)** SSP3-7.0 and **(d)** SSP5-8.5. In each case, an average is taken of the ensemble members r6i1p1f1, r9i1p1f1, r11i1p1f1, r13i1p1f1 and r15i1p1f1.

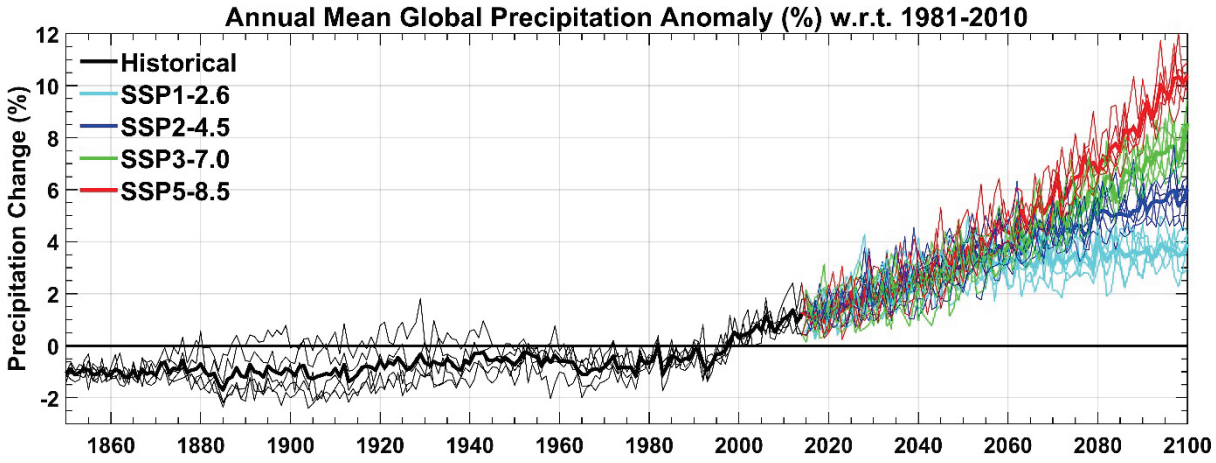


Figure 16. Global Annual Precipitation anomaly (%) with respect to the 30-year period 1981-2010; EC-Earth ensemble members r6i1p1f1, r9i1p1f1, r11i1p1f1, r13i1p1f1 and r15i1p1f1.The bold lines represent the ensemble mean.

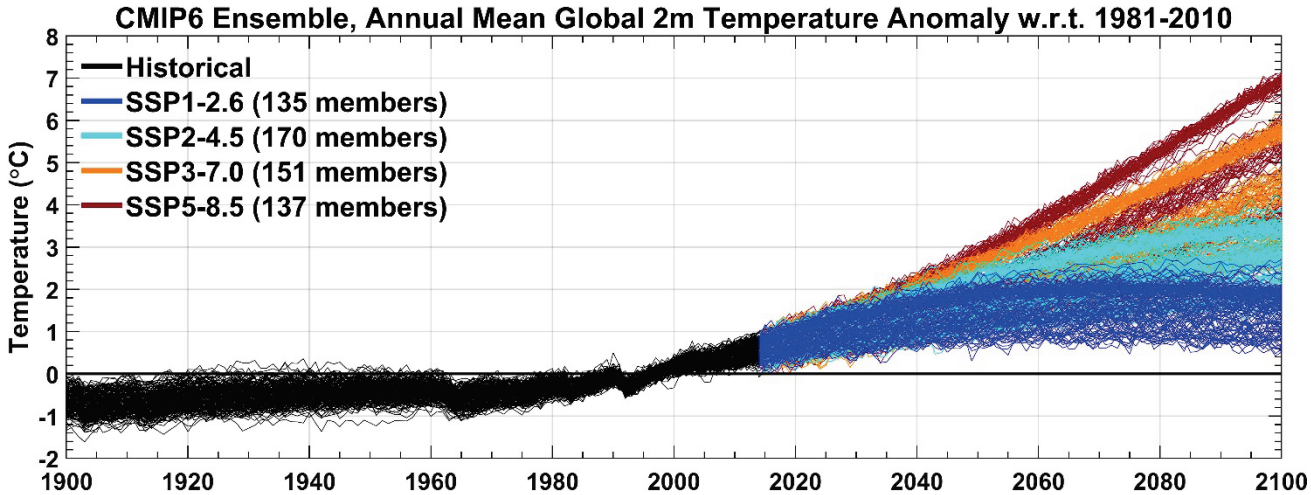


Figure 17. The global annual 2m temperature anomaly with respect to the 30-year mean 1981-2010. The future climate is analysed under the SSP1-2.6, SSP2-2.5, SSP3-7.0 and SSP5-8.5 SSPs

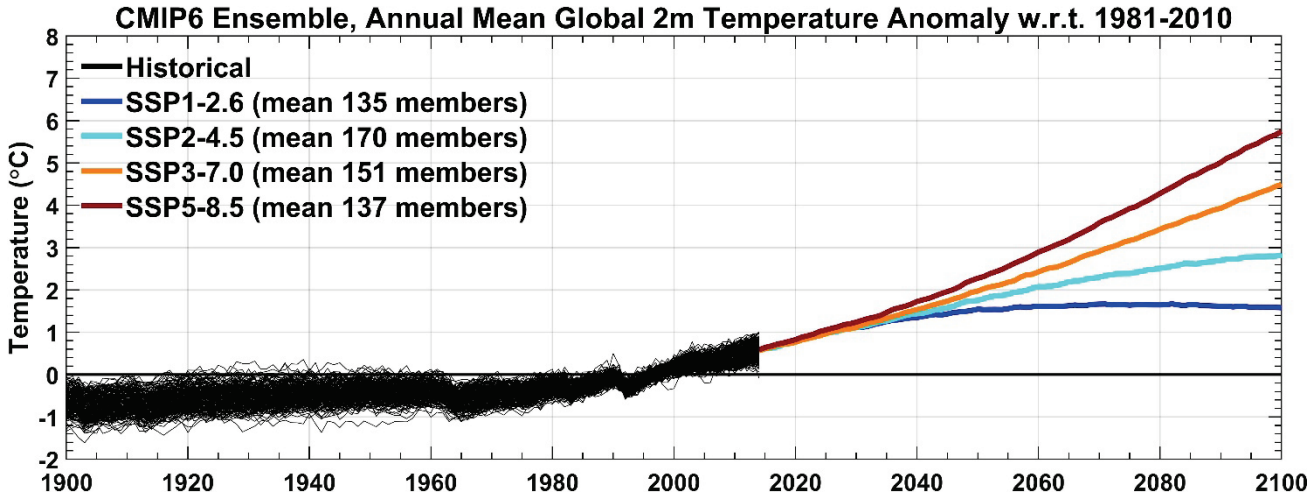


Figure 18. The global annual 2m temperature anomaly with respect to the 30-year mean 1981-2010. The mean of the SSP1-2.6, SSP2-2.5, SSP3-7.0 and SSP5-8.5 SSP ensemble members is presented.

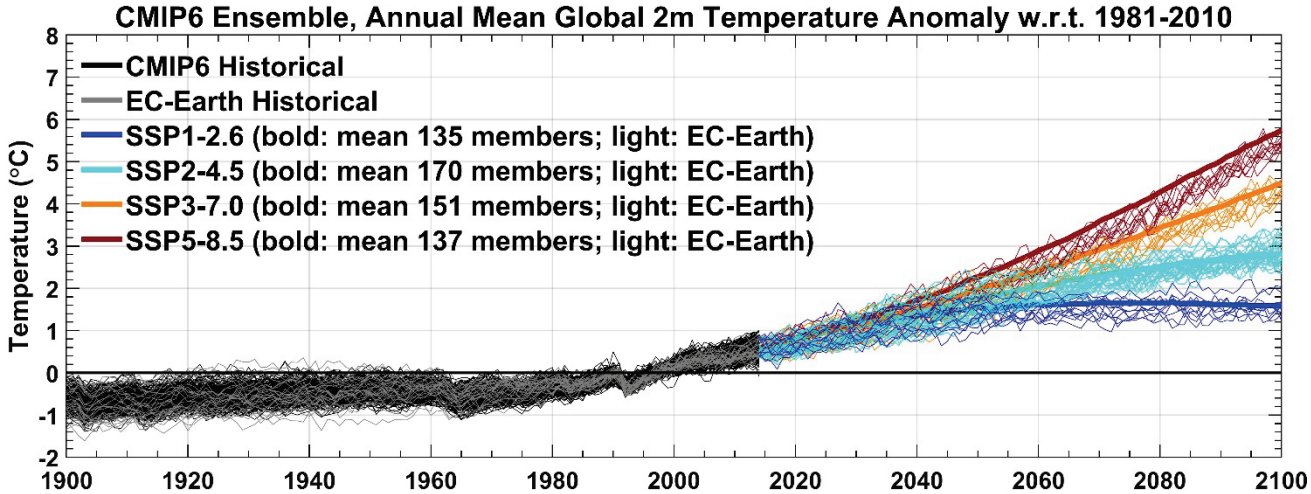


Figure 19. The global annual 2m temperature anomaly with respect to the 30-year mean 1981-2010. The EC-Earth ensemble members are presented alongside the CMIP6 mean to assess where the EC-Earth simulations fit within the full CMIP6 ensemble.