CE2COAST Deliverable 2.2

Report on ESMs performance and ranking at regions of interest for downscaling purposes

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Note: The section on natural thresholds and uncertainty in key indicators originally envisaged for this deliverable was moved to D1.3 and M2.2 in line with the timeline of the corresponding task T2.4.

1. Identification of key oceanic variables and suitable datasets

A set of key oceanic state variables was first identified to represent as much of the ocean pressures considered by CE2COAST (Table 2 in DoW Section 9) and to enable the evaluation of CMIP6 Earth System Models data against observations. The latter is a relevant step to fulfill the main objective of this deliverable, which is to investigate and evaluate the ESMs representations of physical and biogeochemical variables at the surface and in the interior of the oceans.

Two dedicated meetings were held with the project's partners and WP3 regional modellers in mid 2021 to collaboratively identify shared needs and discuss performance indicator metrics that could facilitate objective ESMs ranking and eventual selection for regional downscaling over the Atlantic (10.06.2021) and Pacific (14.05.2021) marine regions.

A common set of oceanic variables (Table 1) was defined that includes air-sea CO_2 fluxes (fgco2), vertically integrated primary productivity (intpp), seawater temperature (thetao), seawater salinity (so), nitrate (no3), dissolved oxygen (o2), dissolved inorganic carbon (dissic), total alkalinity (talk), and pH (ph).

Observational datasets were selected accordingly to provide an extensive spatiotemporal coverage over the recent decades for the evaluation of available CMIP6 historical simulations. The following gridded global datasets were considered in the model-to-data analyses (Table 1 reports the linkage between observations and oceanic variables and their availability in the selected Earth system models):

- WOA2018: the World Ocean Atlas 2018 (Boyer et al., 2018) is composed by climatological gridded datasets at 1°x1° of horizontal resolution obtained from the objectively analyzed, quality controlled physical and biogeochemical variables of profile data from the World Ocean Database (WOD)
- GLODAPv2: climatological gridded dataset of the marine carbonate system state variables at 1°x1° of resolution (Lauvset et al., 2016) obtained using the Data-Interpolating Variational Analysis of quality controlled observations.
- Eppley-VGPM: ocean net primary production (NPP) gridded dataset at 1/6° of horizontal resolution derived from the application of the VGPM algorithm (Behrenfeld and Falkowski, 1997) to satellite observations of chlorophyll over the period 2002-2014.

- ESACCI-SST: gridded data based on remote sensing records of sea surface temperature over the period 1981-2014 (Merchant et al., 2019) produced in the framework of the European Space Agency (ESA) Climate Change Initiative (CCI).
- Landschuetzer2016: global surface ocean gridded data of CO_2 air-sea exchanges and partial pressure reconstructed from observations contained in the Surface Ocean CO2 Atlas Version 2 (Landschuetzer et al., 2016) over the period 1982-2015 .

Based on the available CMIP6 datasets publicly distributed through the ESGF platform (https://esgf.llnl.gov/), a total of 16 Earth System Models were included in the multi-model ensemble of historical simulations for this task (see Table 1). These models were selected by taking into account only concentration driven historical experiments. If more than one simulation member was available for each model, the choice of a specific one was made by considering i) the largest availability of previously identified oceanic variables and ii) the presence of coordinated future scenarios (at least two). The latter criteria will enable for a seamless integration with the following benchmark of ESMs future projections within Task 2.3.

Table 1. Overview of the oceanic state variables included in the evaluation of 16 CMIP6 Earth System Models (first column) historical simulations against observational datasets (bottom row). Acronyms in the top row refer to air-sea CO2 fluxes (fgco2), vertically integrated primary productivity (intpp), seawater temperature (thetao), seawater salinity (so), nitrate (no3), dissolved oxygen (o2), dissolved inorganic carbon (dissic), total alkalinity (talk), and pH (ph). The "x" mark denotes the availability of monthly mean simulated data and empty cells represent missing data, while "Oyr" indicate that yearly data were used instead. The historical member (variant) used for the analysis is reported in the second column.

model	variant	fgco2	intpp	thetao	so	no3	o2	dissic	talk	ph
ACCESS-ESM1-5	r1i1p1f1	x	x	x	x	x	x	x	x	
CanESM5	r1i1p2f1	x	x	x	x	x	x	x	x	x
CanESM5-CanOE	r1i1p2f1	x	x	x	x	x	x	x	x	x
CESM2	r4i1p1f1	x	x	x	x	x		x	x	x
CESM2-WACCM	r1i1p1f1	x	x	x	x	x		x	x	x
CMCC-ESM2	r1i1p1f1	x	x	x	x	x	x	x	x	x
CNRM-ESM2-1	r1i1p1f2	x	x	x	x	x	x	x	x	x
EC-Earth3-CC	r1i1p1f1	x	x	x	x	x (Oyr)	x (Oyr)	x (Oyr)	x (Oyr)	x (Oyr)
GFDL-CM4	r1i1p1f1	x	x	x	x		x	x	x	x
GFDL-ESM4	r1i1p1f1	x	x	x	x	x	x	x (Oyr)	x (Oyr)	x
IPSL-CM6A-LR	r1i1p1f1	x	x	x	x	x	x	x	x	x
MPI-ESM1-2-HR	r1i1p1f1	x	x	x	x	x	x	x	x	x
MPI-ESM1-2-LR	r1i1p1f1	x	x	x	x	x	x	x	x	x
MRI-ESM2-0	r1i2p1f1	x	x	x	x	x (Oyr)	x (Oyr)	x	x	x
NorESM2-LM	r1i1p1f1	x	x	x	x	x	x	x	x	x
NorESM2-MM	r1i1p1f1	x	x	x	x	x	x	x	x	x
UKESM1-0-LL	r1i1p1f2	x	x	x	x	x	x	x	x	x
OBS		**Landschuetzer 2016**	**Eppley-VGPM**	**WOA18 & ESACCI-SST**	**WOA18**	**WOA18**	**WOA18**	**GLODAPv2**	**GLODAPv2**	**GLODAPv2**

2. Evaluation of ESMs performances in CE2COAST regions

The evaluation of CMIP6 ESMs was performed over four large marine regions (Fig.1) which allows to include all the key areas of CE2COAST regional downscaling applications and to ensure an adequate data coverage using coarse global scale data (mainly at 1 degree of horizontal resolution). ESMs data were systematically evaluated against observational datasets using the ESMValTool community diagnostic framework, as described in deliverable 2.1 of the project.

In the following sections, each marine region is addressed by considering the comparison of the available ESMs historical data with gridded observational datasets for the set of physical and biogeochemical variables.

The reference period for the derivation of climatological fields from either model or observations-derived datasets is 2000-2014. Analyses are carried out including the sea surface and a set of vertical levels for three-dimensional variables, namely 100, 250, 500, 1000 meters for the Atlantic sub-regions and 100, 200, 300, 800, 1000 for the Pacific one.

The evaluation of the simulated spatial patterns was carried out considering the Pearson's correlation coefficient and the Root-Mean-Squared-Differences normalized using the minimum-maximum data range of observations from the considered layer. A subset of model-data spatial evaluation examples for the sea-surface temperature are provided in the supplementary materials. Additional figures for other variables analysed in this report are available upon request.

Finally, time-series of sea surface temperature, surface primary production, and CO_2 fluxes over the last four decades are also provided as a supplement to illustrate the long-term trends of these variables as simulated by the different ESMs. These trends are plotted against long-term observational data, such as the satellite-based estimates for sea surface temperature and observation-based air-sea CO_2 exchanges.

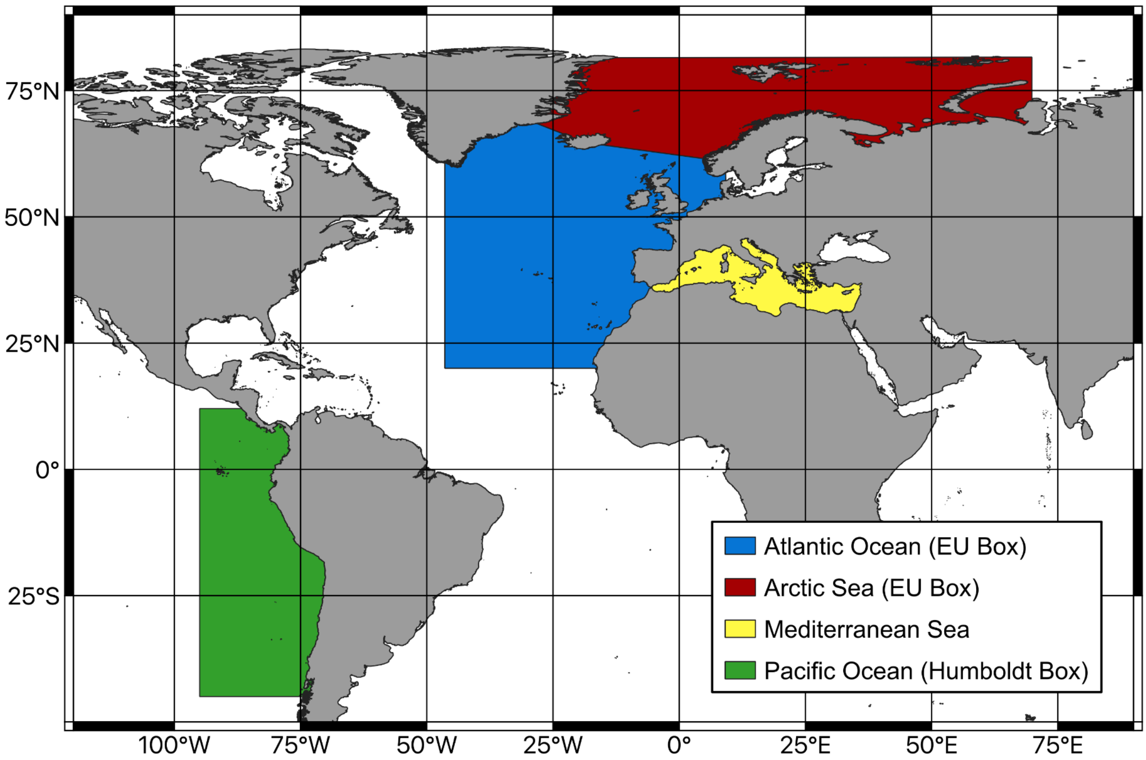

Figure 1. CE2COAST marine regions considered in the evaluation of CMIP6 ESMs historical simulations.

2.1 Atlantic Ocean (EU box)

Spatial analysis of CMIP6 ESMs physical and biochemical climatological fields for the period 2000-2014 against available observations. Pearson correlation (Tab. 2) and Root Mean Squared Deviation normalized using the min-max spatial range of observation at each layer (Tab. 3).

Table 2 shows that for the Atlantic Ocean, most ESMs are able to capture the spatial variability of temperature and salinity quite well, with spatial correlation coefficient of >0.65. The correlation is generally high at the surface and noticeably low at 1000m depth. While the oxygen spatial distribution is well simulated, this is not the case for the other biogeochemical tracers such as nitrate, pH, dissolved inorganic carbon, and to some extent alkalinity. In terms of spatial bias, most models generally simulate low bias in their temperature and oxygen fields. Biases in the alkalinity and dissolved inorganic carbon indicate that the buffer capacity may not be simulated correctly in these models, which could have implications on the long-term carbon uptakes. For surface primary production, the average relative bias is relatively low in nearly all models (Tab. 3) but the spatial correlation is weak. This illustrates the ESMs' weakness in simulating the high productive coastal regions, while in the open ocean, the observed high productivity regions are well reproduced. For surface CO_2 fluxes the spatial correlation and bias are relatively low and high, respectively.

Table 2. Spatial correlation between CMIP6 ESMs and observational datasets in the Atlantic marine region (see Fig.1) for the key oceanic state variables. Note that three-dimensional fields are reported for different depth levels below the surface.

Atlantic Ocean (EU box) - Spatial Correlation

	ACCESS-ESM1-5	CESM2	CESM2-WACCM	CMCC-ESM2	CNRM-ESM2-1	CanESM5	CanESM5-CanOE	EC-Earth3-CC	GFDL-CM4	GFDL-ESM4	IPSL-CM6A-LR	MPI-ESM1-2-HR	MPI-ESM1-2-LR	MRI-ESM2-0	NorESM2-LM	NorESM2-MM	UKESM1-0-LL
thetao 0m	0.98	0.98	0.98	0.97	0.97	0.98	0.98	0.98	0.99	0.98	0.97	0.96	0.95	0.97	0.97	0.98	0.97
thetao 100m	0.96	0.94	0.95	0.96	0.94	0.97	0.97	0.96	0.98	0.94	0.95	0.94	0.92	0.95	0.94	0.95	0.95
thetao 250m	0.95	0.89	0.9	0.94	0.9	0.95	0.95	0.95	0.97	0.91	0.93	0.9	0.87	0.91	0.89	0.91	0.92
thetao 500m	0.9	0.84	0.85	0.95	0.88	0.96	0.96	0.95	0.96	0.89	0.94	0.9	0.89	0.85	0.87	0.88	0.94
thetao 1000m	0.92	0.86	0.85	0.94	0.92	0.93	0.93	0.9	0.91	0.84	0.9	0.81	0.83	0.9	0.86	0.85	0.91
so 0m	0.91	0.93	0.92	0.88	0.88	0.9	0.9	0.85	0.93	0.92	0.79	0.8	0.79	0.91	0.91	0.91	0.83
so 100m	0.93	0.92	0.93	0.92	0.92	0.94	0.94	0.95	0.95	0.91	0.88	0.89	0.87	0.93	0.91	0.93	0.94
so 250m	0.94	0.89	0.89	0.93	0.91	0.93	0.93	0.95	0.92	0.86	0.92	0.89	0.83	0.9	0.82	0.86	0.93
so 500m	0.84	0.83	0.84	0.93	0.88	0.95	0.95	0.96	0.91	0.87	0.96	0.93	0.91	0.86	0.82	0.84	0.96
so 1000m	0.82	0.76	0.75	0.84	0.84	0.86	0.86	0.78	0.86	0.72	0.8	0.68	0.66	0.83	0.74	0.72	0.79
no3 0m	0.89	0.93	0.92	0.61	0.87	0.42	0.74	0.91		0.71	0.9	0.93	0.92	0.94	0.91	0.91	0.86
no3 100m	0.88	0.88	0.87	0.45	0.88	0.39	0.61	0.86		0.63	0.86	0.79	0.67	0.9	0.93	0.94	0.81
no3 250m	0.73	0.53	0.51	0.6	0.65	0.7	0.69	0.77		0.37	0.68	0.66	0.45	0.64	0.78	0.82	0.77
no3 500m	0.12	0.04	0.04	0.62	0.12	0.87	0.85	0.28		0.68	0.51	0.73	0.66	0.6	0.34	0.29	0.77
no3 1000m	0.57	0.83	0.83	0.78	0.77	0.84	0.91	0.88		0.79	0.89	0.77	0.87	0.58	0.34	0.25	0.85
o2 0m	0.96			0.95	0.95	0.96	0.96	0.96	0.98	0.96	0.95	0.93	0.91	0.94	0.93	0.94	0.95
o2 100m	0.92			0.9	0.91	0.9	0.93	0.93	0.9	0.89	0.89	0.89	0.79	0.88	0.89	0.9	0.89
o2 250m	0.92			0.89	0.9	0.88	0.89	0.91	0.93	0.91	0.88	0.85	0.75	0.96	0.87	0.88	0.88
o2 500m	0.92			0.91	0.82	0.9	0.91	0.85	0.95	0.9	0.85	0.84	0.81	0.9	0.76	0.77	0.89
o2 1000m	0.92			0.96	0.95	0.96	0.98	0.97	0.94	0.94	0.96	0.93	0.95	0.91	0.94	0.94	0.96
intpp	-0.12	0.04	0.03	0.53	0.28	0.54	0.35	0.39	0.54	0.45	0.62	0.58	0.36	0.28	0.16	0.12	0.74
fgco2	0.56	0.78	0.78	0.67	0.57	0.65	0.68	0.8	0.84	0.79	0.75	0.73	0.75	0.75	0.78	0.72	0.77
ph 0m		0.61	0.63	0.38	0.3	0.38	0.36	0.55	0.48	0.59	0.51	0.43	0.49	0.39	0.49	0.5	0.65
ph 100m		0.8	0.8	0.4	0.75	0.33	0.66	0.78	0.73	0.64	0.57	0.6	0.45	0.6	0.44	0.53	0.7
ph 250m		0.51	0.51	0.76	0.57	0.76	0.7	0.67	0.7	0.64	0.59	0.7	0.47	0.51	0.59	0.57	0.72
ph 500m		0.51	0.51	0.84	0.51	0.84	0.81	0.6	0.9	0.8	0.73	0.85	0.78	0.72	0.5	0.48	0.81
ph 1000m		0.89	0.89	0.52	0.84	0.33	0.73	0.88	0.74	0.68	0.91	0.89	0.92	0.77	0.85	0.84	0.16
dissic 0m	0.39	0.35	0.29	0.65	0.37	0.54	0.55	0.67	0.38	0.32	0.69	0.62	0.57	0.66	0.4	0.43	0.71
dissic 100m	-0.09	0.83	0.8	0.08	0.79	-0.35	-0.27	0.84	0.73	0.6	0.69	0.3	0.26	0.37	0.79	0.81	0.44
dissic 250m	0.03	0.51	0.52	0.55	0.51	0.3	0.17	0.83	0.65	0.51	0.8	0.37	0.25	0.38	0.71	0.72	0.52
dissic 500m	0.36	0.14	0.14	0.62	0.06	0.67	0.51	0.54	0.84	0.73	0.66	0.62	0.59	0.53	0.34	0.32	0.84
dissic 1000m	0.85	0.92	0.92	0.81	0.94	0.87	0.94	0.94	0.82	0.76	0.96	0.82	0.89	0.91	0.89	0.91	0.39
talk 0m	0.87	0.87	0.85	0.88	0.9	0.92	0.92	0.9	0.88	0.85	0.82	0.78	0.77	0.89	0.9	0.9	0.88
talk 100m	0.94	0.91	0.92	0.92	0.94	0.94	0.94	0.97	0.97	0.92	0.93	0.9	0.87	0.93	0.9	0.93	0.97
talk 250m	0.92	0.87	0.87	0.91	0.89	0.93	0.93	0.94	0.89	0.82	0.93	0.87	0.81	0.88	0.75	0.81	0.93
talk 500m	0.81	0.78	0.79	0.87	0.82	0.93	0.93	0.92	0.84	0.8	0.91	0.89	0.85	0.8	0.73	0.75	0.92
talk 1000m	0.84	0.75	0.74	0.87	0.88	0.86	0.85	0.8	0.89	0.77	0.82	0.75	0.75	0.87	0.79	0.78	0.82

Table 3. Normalized Root-Mean Squared Differences (RMSD) between CMIP6 ESMs and observational datasets in the Atlantic marine region (see Fig.1) for the key oceanic state variables. Note that three-dimensional fields are reported for different depth levels below the surface. RMSD values were normalized using the minimum-maximum range from observations.

Atlantic Ocean (EU box) - Spatial Normalised RMSD

	ACCESS-ESM1-5	CESM2	CESM2-WACCM	CMCC-ESM2	CNRM-ESM2-1	CanESM5	CanESM5-CanOE	EC-Earth3-CC	GFDL-CM4	GFDL-ESM4	IPSL-CM6A-LR	MPI-ESM1-2-HR	MPI-ESM1-2-LR	MRI-ESM2-0	NorESM2-LM	NorESM2-MM	UKESM1-0-LL
thetao 0m	0.05	0.051	0.048	0.055	0.058	0.074	0.074	0.049	0.032	0.049	0.053	0.066	0.072	0.059	0.06	0.053	0.054
thetao 100m	0.073	0.087	0.08	0.072	0.085	0.083	0.083	0.071	0.052	0.081	0.08	0.084	0.091	0.079	0.089	0.079	0.075
thetao 250m	0.092	0.118	0.111	0.084	0.114	0.082	0.082	0.085	0.065	0.103	0.105	0.112	0.122	0.104	0.128	0.12	0.101
thetao 500m	0.115	0.135	0.129	0.075	0.113	0.086	0.086	0.087	0.058	0.123	0.105	0.115	0.103	0.115	0.141	0.133	0.098
thetao 1000m	0.082	0.087	0.088	0.084	0.06	0.071	0.071	0.069	0.085	0.101	0.071	0.115	0.105	0.077	0.174	0.189	0.066
so 0m	0.117	0.075	0.076	0.105	0.077	0.14	0.14	0.106	0.108	0.095	0.134	0.115	0.103	0.076	0.071	0.072	0.113
so 100m	0.139	0.116	0.104	0.176	0.104	0.23	0.23	0.091	0.082	0.107	0.137	0.135	0.132	0.124	0.119	0.108	0.096
so 250m	0.175	0.138	0.136	0.137	0.118	0.137	0.137	0.101	0.122	0.149	0.13	0.136	0.163	0.136	0.19	0.178	0.133
so 500m	0.306	0.216	0.208	0.19	0.165	0.224	0.224	0.159	0.112	0.189	0.169	0.168	0.12	0.154	0.277	0.249	0.179
so 1000m	0.18	0.16	0.163	0.184	0.12	0.141	0.141	0.15	0.164	0.179	0.135	0.215	0.201	0.144	0.434	0.465	0.134
no3 0m	0.143	0.108	0.113	0.24	0.175	0.277	0.21	0.18		0.313	0.189	0.167	0.131	0.102	0.226	0.239	0.187
no3 100m	0.134	0.133	0.14	0.256	0.138	0.259	0.222	0.174		0.221	0.162	0.176	0.214	0.126	0.113	0.105	0.166
no3 250m	0.128	0.155	0.157	0.166	0.14	0.133	0.132	0.133		0.189	0.135	0.139	0.204	0.14	0.134	0.124	0.117
no3 500m	0.154	0.166	0.165	0.109	0.155	0.068	0.072	0.132		0.111	0.115	0.094	0.127	0.107	0.17	0.165	0.086
no3 1000m	0.162	0.12	0.118	0.139	0.126	0.141	0.122	0.12		0.125	0.11	0.133	0.107	0.16	0.208	0.235	0.148
o2 0m	0.065			0.077	0.067	0.111	0.112	0.063	0.046	0.058	0.074	0.084	0.084	0.072	0.076	0.07	0.069
o2 100m	0.059			0.094	0.074	0.089	0.092	0.053	0.067	0.076	0.064	0.078	0.111	0.068	0.069	0.061	0.057
o2 250m	0.057			0.074	0.075	0.067	0.066	0.06	0.063	0.074	0.072	0.088	0.12	0.042	0.091	0.079	0.069
o2 500m	0.067			0.067	0.133	0.08	0.07	0.091	0.056	0.078	0.091	0.096	0.115	0.071	0.134	0.131	0.075
o2 1000m	0.115			0.1	0.089	0.141	0.107	0.08	0.091	0.084	0.087	0.086	0.092	0.106	0.081	0.092	0.125
intpp	0.075	0.071	0.071	0.06	0.071	0.059	0.065	0.064	0.128	0.062	0.055	0.056	0.076	0.066	0.07	0.071	0.046
fgco2	0.305	0.129	0.133	0.277	0.166	0.304	0.258	0.18	0.351	0.206	0.198	0.215	0.18	0.264	0.151	0.153	0.258
ph 0m		0.065	0.063	0.078	0.077	0.083	0.079	0.068	0.077	0.065	0.07	0.075	0.071	0.074	0.07	0.07	0.062
ph 100m		0.049	0.049	0.084	0.054	0.085	0.063	0.052	0.082	0.071	0.066	0.074	0.13	0.064	0.076	0.069	0.059
ph 250m		0.119	0.119	0.092	0.113	0.102	0.106	0.08	0.162	0.147	0.096	0.135	0.266	0.105	0.139	0.118	0.09
ph 500m		0.128	0.125	0.081	0.137	0.077	0.077	0.098	0.089	0.086	0.083	0.07	0.144	0.086	0.132	0.132	0.088
ph 1000m		0.07	0.068	0.135	0.123	0.144	0.115	0.09	0.13	0.114	0.088	0.072	0.088	0.107	0.084	0.082	0.149
dissic 0m	0.26	0.173	0.191	0.125	0.144	0.213	0.203	0.099	0.295	0.265	0.118	0.172	0.16	0.143	0.164	0.171	0.14
dissic 100m	0.201	0.091	0.099	0.201	0.092	0.306	0.294	0.079	0.105	0.116	0.112	0.167	0.19	0.151	0.091	0.085	0.156
dissic 250m	0.143	0.112	0.108	0.111	0.118	0.161	0.173	0.067	0.104	0.114	0.073	0.135	0.192	0.121	0.096	0.091	0.128
dissic 500m	0.123	0.169	0.163	0.099	0.185	0.095	0.119	0.105	0.085	0.099	0.096	0.113	0.171	0.106	0.135	0.134	0.078
dissic 1000m	0.153	0.107	0.109	0.157	0.123	0.174	0.113	0.128	0.163	0.172	0.12	0.15	0.153	0.154	0.139	0.143	0.248
talk 0m	0.179	0.094	0.1	0.125	0.072	0.189	0.179	0.076	0.151	0.147	0.119	0.153	0.138	0.126	0.081	0.08	0.121
talk 100m	0.142	0.093	0.086	0.154	0.08	0.236	0.222	0.058	0.072	0.101	0.08	0.125	0.119	0.137	0.099	0.085	0.067
talk 250m	0.124	0.071	0.071	0.091	0.064	0.111	0.102	0.049	0.068	0.09	0.054	0.087	0.09	0.087	0.103	0.093	0.078
talk 500m	0.419	0.246	0.236	0.336	0.177	0.397	0.368	0.155	0.171	0.298	0.201	0.281	0.201	0.215	0.31	0.265	0.27
talk 1000m	0.175	0.16	0.16	0.19	0.121	0.149	0.144	0.134	0.161	0.169	0.131	0.168	0.153	0.129	0.41	0.425	0.126

Colour scale: 0.05, 0.10, 0.15, 0.20, 0.25, 0.30, 0.35, 0.40, 0.45

2.2 Arctic Sea (EU box)

Comparison of CMIP6 ESMs physical and biochemical climatological fields for the period 2000-2014 and over different depth levels against available observations. Spatial analysis included the computation of the Pearson correlation coefficient (Tab. 4) and Root Mean Squared Deviation normalized using the minimum-maximum spatial range of observation from each layer (Tab. 5).

Except for surface temperature and surface oxygen, the spatial correlation of the evaluated variables in the Arctic Sea are at the lower end. At 1000m depth, the temperature and salinity correlation are negatives in almost all ESMs. As the surface salinity, the simulated surface alkalinity has reasonably spatial correlation across the ESMs. Nevertheless, the surface DIC correlation is relatively low, which partly explains the low surface pH correlation.

With regards to the RMSD assessment, there is also relatively large uncertainty in the simulated temperature and salinity in the deep ocean (1000m depth). For the biogeochemical tracers, GFDL-ESM4, GFDL-CM4, and MRI-ESM2-0 models have noticeably larger bias than the other ESMs. Biases in the surface primary production and CO_2 fluxes are also noticeably low across the ESMs in this region.

Table 4. Spatial correlation between CMIP6 ESMs and observational datasets in the Arctic marine region (see Fig.1) for the key oceanic state variables. Note that three-dimensional fields are reported for different depth levels below the surface.

Arctic Sea (EU box) - Spatial Correlation

	ACCESS-ESM1-5	CESM2	CESM2-WACCM	CMCC-ESM2	CNRM-ESM2-1	CanESM5	CanESM5-CanOE	EC-Earth3-CC	GFDL-CM4	GFDL-ESM4	IPSL-CM6A-LR	MPI-ESM1-2-HR	MPI-ESM1-2-LR	MRI-ESM2-0	NorESM2-LM	NorESM2-MM	UKESM1-0-LL
thetao 0m	0.92	0.96	0.95	0.92	0.96	0.95	0.95	0.95	0.94	0.94	0.93	0.97	0.92	0.97	0.97	0.95	0.93
thetao 100m	0.87	0.91	0.91	0.88	0.92	0.9	0.9	0.91	0.89	0.78	0.88	0.92	0.86	0.95	0.95	0.93	0.89
thetao 250m	0.69	0.7	0.69	0.78	0.77	0.78	0.78	0.79	0.84	0.69	0.71	0.85	0.8	0.85	0.91	0.86	0.74
thetao 500m	0.59	0.51	0.51	0.7	0.6	0.74	0.74	0.69	0.66	0.35	0.53	0.66	0.48	0.59	0.81	0.66	0.42
thetao 1000m	-0.01	-0.02	0.01	-0.51	-0.15	-0.52	-0.52	-0.25	-0.1	-0.02	-0.01	-0.27	-0.05	0.09	-0.08	0.11	-0.49
so 0m	0.66	0.76	0.77	0.76	0.64	0.78	0.78	0.81	0.82	0.88	0.82	0.89	0.89	0.84	0.89	0.9	0.82
so 100m	0.82	0.87	0.86	0.85	0.83	0.86	0.86	0.84	0.89	0.88	0.84	0.85	0.81	0.9	0.77	0.81	0.86
so 250m	0.59	0.7	0.72	0.69	0.74	0.62	0.62	0.76	0.74	0.64	0.69	0.74	0.51	0.77	0.8	0.74	0.71
so 500m	0.32	0.25	0.3	0.5	0.44	0.36	0.36	0.47	0.4	0.18	0.29	0.51	0.3	0.28	0.63	0.52	0.25
so 1000m	-0.43	-0.14	-0.28	-0.21	-0.48	-0.62	-0.62	-0.3	-0.53	-0.5	-0.28	-0.32	-0.18	-0.39	-0.59	-0.4	-0.25
no3 0m	0.41	0.7	0.68	0.3	0.46	0.62	0.6	0.4		0.63	0.26	0.36	0.32	0.67	0.13	0.14	0.49
no3 100m	0.34	0.53	0.45	0.55	0.63	0.64	0.74	0.65		0.67	0.73	0.46	0.53	0.06	0.13	0.09	0.25
no3 250m	0.33	0.71	0.67	0.6	0.75	0.49	0.71	0.74		0.54	0.8	0.46	0.58	0.32	0.3	0.22	0.34
no3 500m	-0.16	0.34	0.34	0.31	0.52	0.29	0.57	0.39		0.29	0.49	0.18	0.31	-0.16	0.36	0.23	0.1
no3 1000m	0.27	0.38	0.37	0.68	0.7	0.45	0.7	0.6		0.61	0.66	0.53	0.58	0.08	0.59	0.48	0.53
o2 0m	0.84			0.87	0.92	0.88	0.89	0.9	0.68	0.87	0.86	0.92	0.86	0.93	0.92	0.91	0.87
o2 100m	0.66			0.68	0.77	0.67	0.67	0.71	0.03	0.46	0.69	0.78	0.71	0.78	0.83	0.81	0.79
o2 250m	0.63			0.63	0.74	0.67	0.62	0.72	0.28	0.67	0.62	0.79	0.71	0.72	0.82	0.75	0.83
o2 500m	0.8			0.81	0.79	0.86	0.68	0.82	0.36	0.44	0.78	0.59	0.09	0.8	0.52	0.18	0.43
o2 1000m	0.22			0.68	0.66	0.85	0.15	0.78	0.55	0.41	0.73	-0.07	0.03	0.42	-0.21	-0.38	-0.04
intpp	-0.11	0.23	0.2	0.6	0.38	0.03	0.27	0.18	0.69	0.16	0.17	0.14	0.23	-0.02	0.24	0.3	0.2
fgco2	0.62	0.51	0.45	0.52	0.41	0.64	0.66	0.75	0.14	0.81	0.55	0.55	0.74	0.48	0.43	0.57	0.72
ph 0m		-0.13	-0.15	0.25	0.5	0.19	0.25	0.29	0.18	0.27	0.29	0.32	0.37	0.05	0.27	0.29	0.2
ph 100m		0.15	0.23	-0.42	0.4	0.45	0.58	0.49	0.18	0.19	0.59	-0.14	0.23	0.4	0.62	0.71	0.35
ph 250m		0.41	0.41	-0.33	0.67	0.54	0.54	0.72	-0.09	0.39	0.66	0.68	0.56	0.64	0.58	0.54	0.49
ph 500m		0.83	0.81	0.2	0.67	0.74	0.31	0.57	0.44	0.75	0.67	0.37	0.19	0.7	0.31	0.42	0.27
ph 1000m		-0.02	0.06	0.61	0.14	-0.02	-0.13	0.36	0.7	0.53	0.7	-0.07	0.47	0.05	0.02	0.64	0.54
dissic 0m	0.49	0.39	0.31	0.42	0.46	0.54	0.53	0.32	0.4	0.41	0.57	0.35	0.45	0.42	0.31	0.3	0.63
dissic 100m	0.49	0.5	0.5	0.49	0.28	0.53	0.51	0.35	0.33	0.53	0.49	0.57	0.57	0.36	0.47	0.42	0.55
dissic 250m	0.46	0.5	0.51	0.42	0.07	0.72	0.63	0.38	0.25	0.44	0.48	0.49	0.45	0.51	0.59	0.44	0.5
dissic 500m	0.11	0.56	0.6	0.53	0.43	0.77	0.67	0.59	0.41	0.46	0.57	0.27	0.33	0.41	0.49	0.31	0.5
dissic 1000m	0.35	0.35	0.41	0.7	0.79	0.35	0.42	0.7	0.38	0.82	0.76	0.43	0.8	0.26	0.36	0.69	0.78
talk 0m	0.63	0.8	0.77	0.48	0.62	0.65	0.65	0.85	0.57	0.71	0.79	0.78	0.84	0.76	0.75	0.75	0.82
talk 100m	0.71	0.87	0.88	0.66	0.7	0.76	0.76	0.79	0.73	0.79	0.74	0.78	0.71	0.86	0.76	0.77	0.83
talk 250m	0.39	0.45	0.48	0.56	0.61	0.57	0.56	0.56	0.76	0.56	0.53	0.59	0.39	0.63	0.76	0.73	0.62
talk 500m	0.3	0.19	0.24	0.52	0.45	0.51	0.46	0.37	0.59	0.19	0.22	0.5	0.4	0.29	0.66	0.64	0.45
talk 1000m	0.11	-0.45	-0.11	-0.32	0.03	-0.1	-0.17	-0.45	0.36	0.11	-0.38	-0.09	-0.24	0.1	0.5	0.52	-0.25

Table 5. Normalized Root-Mean Squared Differences (RMSD) between CMIP6 ESMs and observational datasets in the Arctic marine region (see Fig.1) for the key oceanic state variables. Note that three-dimensional fields are reported for different depth levels below the surface. RMSD values were normalized using the minimum-maximum range from observations.

Arctic Sea (EU box) - Spatial Normalised RMSD

	ACCESS-ESM1-5	CESM2	CESM2-WACCM	CMCC-ESM2	CNRM-ESM2-1	CanESM5	CanESM5-CanOE	EC-Earth3-CC	GFDL-CM4	GFDL-ESM4	IPSL-CM6A-LR	MPI-ESM1-2-HR	MPI-ESM1-2-LR	MRI-ESM2-0	NorESM2-LM	NorESM2-MM	UKESM1-0-LL
thetao 0m	0.117	0.101	0.098	0.103	0.091	0.088	0.088	0.097	0.091	0.088	0.111	0.073	0.136	0.071	0.072	0.085	0.101
thetao 100m	0.147	0.12	0.116	0.129	0.107	0.115	0.115	0.11	0.11	0.159	0.126	0.098	0.127	0.085	0.08	0.095	0.119
thetao 250m	0.186	0.163	0.165	0.144	0.159	0.153	0.153	0.141	0.113	0.16	0.173	0.112	0.128	0.118	0.098	0.117	0.154
thetao 500m	0.251	0.213	0.211	0.173	0.227	0.177	0.177	0.201	0.156	0.244	0.244	0.165	0.197	0.22	0.148	0.165	0.244
thetao 1000m	0.76	0.311	0.315	0.511	0.463	0.827	0.827	0.475	0.396	0.448	0.537	0.594	0.411	0.41	0.393	0.515	0.642
so 0m	0.085	0.072	0.072	0.072	0.086	0.071	0.071	0.078	0.137	0.162	0.075	0.063	0.055	0.089	0.059	0.05	0.065
so 100m	0.075	0.048	0.048	0.067	0.04	0.044	0.044	0.05	0.138	0.203	0.038	0.04	0.047	0.147	0.053	0.045	0.04
so 250m	0.294	0.262	0.25	0.248	0.184	0.243	0.243	0.206	1.167	1.593	0.239	0.189	0.204	0.348	0.215	0.213	0.2
so 500m	0.477	0.454	0.427	0.338	0.339	0.357	0.357	0.407	0.353	0.411	0.522	0.317	0.269	0.527	0.294	0.306	0.413
so 1000m	1.507	0.513	0.496	0.929	0.851	1.385	1.385	1.083	0.835	0.751	1.574	1.363	1.654	0.838	1.03	1.792	1.219
no3 0m	0.244	0.182	0.186	0.248	0.268	0.214	0.204	0.234		0.217	0.262	0.236	0.243	0.193	0.289	0.311	0.227
no3 100m	0.203	0.183	0.195	0.179	0.17	0.174	0.184	0.179		0.161	0.172	0.194	0.196	0.224	0.215	0.22	0.224
no3 250m	0.127	0.099	0.103	0.146	0.091	0.121	0.11	0.101		0.135	0.095	0.121	0.12	0.127	0.129	0.131	0.135
no3 500m	0.111	0.107	0.107	0.168	0.089	0.143	0.085	0.095		0.164	0.089	0.101	0.099	0.111	0.097	0.101	0.123
no3 1000m	0.138	0.159	0.172	0.309	0.099	0.234	0.104	0.112		0.164	0.129	0.119	0.111	0.142	0.121	0.13	0.132
o2 0m	0.147			0.116	0.094	0.129	0.116	0.131	0.458	0.112	0.151	0.104	0.16	0.093	0.095	0.103	0.133
o2 100m	0.276			0.221	0.184	0.258	0.261	0.213	1.376	0.253	0.194	0.148	0.198	0.186	0.171	0.185	0.137
o2 250m	0.248			0.192	0.187	0.205	0.262	0.179	0.591	0.197	0.214	0.148	0.177	0.173	0.201	0.229	0.128
o2 500m	0.341			0.24	0.255	0.209	0.337	0.242	0.632	0.294	0.264	0.262	0.373	0.269	0.413	0.431	0.325
o2 1000m	0.257			0.274	0.175	0.146	0.254	0.154	0.512	0.415	0.169	0.267	0.257	0.209	0.316	0.475	0.368
intpp	0.073	0.071	0.071	0.066	0.068	0.073	0.071	0.071	0.072	0.072	0.071	0.072	0.07	0.073	0.071	0.07	0.071
fgco2	0.265	0.249	0.271	0.205	0.261	0.283	0.246	0.188	0.642	0.233	0.227	0.232	0.165	0.264	0.256	0.269	0.26
ph 0m		0.197	0.2	0.165	0.141	0.185	0.171	0.158	0.38	0.221	0.162	0.187	0.165	0.215	0.177	0.18	0.207
ph 100m		0.176	0.168	0.238	0.16	0.157	0.126	0.134	1.079	0.324	0.126	0.214	0.16	0.334	0.122	0.111	0.163
ph 250m		0.155	0.155	0.209	0.139	0.144	0.15	0.119	0.603	0.234	0.137	0.135	0.14	0.131	0.141	0.149	0.15
ph 500m		0.123	0.123	0.213	0.193	0.14	0.255	0.191	0.348	0.134	0.197	0.191	0.218	0.147	0.234	0.209	0.237
ph 1000m		0.214	0.204	0.148	0.187	0.23	0.276	0.174	0.134	0.158	0.134	0.235	0.167	0.214	0.227	0.146	0.158
dissic 0m	0.232	0.168	0.195	0.18	0.157	0.245	0.231	0.319	0.538	0.782	0.192	0.467	0.351	0.598	0.326	0.267	0.223
dissic 100m	0.288	0.12	0.116	0.22	0.126	0.216	0.203	0.116	0.769	0.798	0.103	0.105	0.159	0.694	0.155	0.142	0.121
dissic 250m	0.106	0.086	0.085	0.117	0.112	0.077	0.086	0.091	0.345	0.577	0.086	0.085	0.103	0.126	0.084	0.102	0.085
dissic 500m	0.178	0.133	0.129	0.146	0.143	0.103	0.12	0.134	0.237	0.16	0.13	0.154	0.164	0.146	0.138	0.166	0.137
dissic 1000m	0.201	0.192	0.183	0.143	0.14	0.225	0.239	0.138	0.204	0.12	0.146	0.238	0.195	0.202	0.239	0.188	0.147
talk 0m	0.169	0.102	0.113	0.162	0.127	0.159	0.155	0.136	0.326	0.424	0.127	0.234	0.184	0.318	0.172	0.136	0.122
talk 100m	0.411	0.186	0.167	0.378	0.142	0.263	0.255	0.116	0.599	0.889	0.133	0.186	0.247	0.825	0.199	0.16	0.157
talk 250m	0.309	0.241	0.227	0.242	0.187	0.252	0.241	0.176	0.813	1.239	0.185	0.2	0.217	0.35	0.169	0.156	0.197
talk 500m	0.378	0.33	0.309	0.237	0.267	0.276	0.267	0.264	0.242	0.348	0.299	0.259	0.229	0.419	0.191	0.192	0.293
talk 1000m	0.264	0.199	0.182	0.214	0.193	0.283	0.265	0.217	0.183	0.19	0.302	0.298	0.349	0.194	0.186	0.288	0.262

Colour scale: 0.2, 0.4, 0.6, 0.8, 1.0

2.3 Mediterranean Sea

Comparison of CMIP6 ESMs physical and biochemical climatological fields for the period 2000-2014 and over different depth levels against available observations. Spatial analysis included the computation of the Pearson correlation coefficient (Tab. 6) and Root Mean Squared Deviation normalized using the minimum-maximum spatial range of observation from each layer (Tab. 7).

The majority of ESMs satisfactorily reproduce the spatial variability of physical variables across the water column. However, the spatial correlation with observed sea surface salinity is poorly reproduced in most of the models despite the rather low RMSD values.

Among the considered biogeochemical variables, only total alkalinity is well represented in ESMs while individual model skills differ substantially for dissolved inorganic nitrogen, oxygen and the other carbonate chemistry variables. In particular, the spatial distribution of dissolved inorganic carbon simulated below 100 meters of depth is negatively correlated to observations, which is also reflected in the poor pH representation. Surface CO_2 fluxes were not included as the Landschuetzer2016 dataset does not cover the Mediterranean basin. Biases in the surface primary production are comparatively low across the ESMs in this region, whereas the spatial correlation remarkably varies across the different ESMs.

Table 6. Spatial correlation between CMIP6 ESMs and observational datasets in the Mediterranean Sea region (see Fig.1) for the key oceanic state variables. Note that three-dimensional fields are reported for different depth levels below the surface.

Mediterranean Sea - Spatial Correlation

	ACCESS-ESM1-5	CESM2	CESM2-WACCM	CMCC-ESM2	CNRM-ESM2-1	CanESM5	CanESM5-CanOE	EC-Earth3-CC	GFDL-CM4	GFDL-ESM4	IPSL-CM6A-LR	MPI-ESM1-2-HR	MPI-ESM1-2-LR	MRI-ESM2-0	NorESM2-LM	NorESM2-MM	UKESM1-0-LL
thetao 0m	0.6	0.95	0.96	0.92	0.91	0.9	0.9	0.94	0.95	0.91	0.95	0.96	0.9	0.93	0.84	0.9	0.79
thetao 100m	0.22	0.66	0.79	0.77	0.89	0.85	0.85	0.9	0.83	0.73	0.96	0.95	0.79	0.83	0.83	0.57	0.89
thetao 250m	0.22	0.16	0.36	0.86	0.93	0.93	0.93	0.97	0.97	0.87	0.95	0.96	0.85	0.91	0.92	0.64	0.94
thetao 500m	-0.15	0.03	0.54	0.95	0.89	0.91	0.91	0.97	0.94	0.9	0.9	0.83	0.75	0.84	0.92	0.91	0.92
thetao 1000m	-0.9	-0.91	0.82	0.06	0.5	0.95	0.95	0.93	0.92	0.86	0.9	0.09	0.9	0.96	0.97	0.97	0.94
so 0m	0.31	0.3	0.21	0.28	0.48	0.54	0.54	0.82	0.49	0.08	0.51	0.89	0.91	0.66	0.77	0.34	0.26
so 100m	0.64	0.5	0.41	0.64	0.82	0.82	0.82	0.91	0.87	0.68	0.86	0.94	0.93	0.8	0.82	0.53	0.86
so 250m	0.93	0.79	0.74	0.76	0.83	0.94	0.94	0.89	0.96	0.94	0.95	0.94	0.76	0.96	0.9	0.43	0.86
so 500m	0.97	0.9	0.9	0.97	0.83	0.97	0.97	0.98	0.96	0.95	0.97	0.89	0.78	0.92	0.95	0.94	0.97
so 1000m	0.98	0.95	0.96	0.92	0.92	0.96	0.96	0.97	0.94	0.95	0.95	0.97	0.91	0.98	0.99	0.97	0.99
no3 0m	0.5	-0.52	-0.52	0.28	0.32	-0.21	0.2	0.36		0.39	0.34	0.2	-0.04	0.49	-0.13	0.2	0.3
no3 100m	-0.31	-0.24	-0.16	0.62	0.75	-0.35	0.68	0.73		0.57	0.74	0.67	0.84	0.77	0.81	0.57	0.56
no3 250m	-0.62	-0.51	-0.26	-0.12	0.9	0.68	0.89	0.82		0.01	0.8	0.87	0.89	0.84	0.92	0.32	0.83
no3 500m	-0.54	-0.54	0.4	-0.58	0.72	0.72	0.79	-0.35		-0.6	-0.63	0.42	0.85	0.8	0.85	-0.47	0.82
no3 1000m	-0.34	-0.84	0.03	-0.89	-0.49	0.31	0.74	-0.91		-0.9	0.79	0.02	0.72	0.76	0.92	-0.53	0.88
o2 0m	0.61			0.72	0.62	0.68	0.68	0.64	0.67	0.59	0.73	0.81	0.73	0.76	0.7	0.73	0.73
o2 100m	-0.41			-0.21	0.65	-0.62	-0.48	0.41	-0.09	-0.19	0.44	-0.19	0.35	-0.18	-0.4	-0.25	0.04
o2 250m	-0.69			-0.44	0.64	-0.55	-0.23	0.58	0.27	-0.51	0.16	0.43	0.45	0.07	-0.33	-0.31	0.45
o2 500m	0.11			-0.05	0.57	-0.4	-0.26	-0.35	-0.18	-0.51	-0.53	0.72	0.46	0.49	-0.21	-0.06	0.48
o2 1000m	-0.02			0.56	-0.52	0.66	-0.19	0.58	0.48	0.36	0.58	0.05	0.66	-0.17	0.55	0.68	-0.63
intpp	-0.26	0.44	0.55	0.36	0.55	-0.19	0.25	-0.09	0.72	0.12	-0.05	0.17	-0.08	-0.03	0.41	0.35	0.67
ph 0m		0.3	0.32	-0.03	-0.04	0.16	0.19	-0.11	0.43	0.41	-0.29	0.6	0.73	0.57	0.15	0.22	0.25
ph 100m		0.0	0.01	0.33	0.84	-0.58	-0.51	0.81	0.2	0.29	0.86	0.04	0.69	-0.09	0.02	0.27	-0.59
ph 250m		-0.08	-0.05	-0.83	0.79	-0.94	-0.93	0.78	0.26	0.05	0.77	-0.15	0.13	-0.57	0.17	0.27	-0.73
ph 500m		0.64	0.49	-0.81	0.93	-0.77	-0.63	0.17	-0.69	-0.89	-0.47	0.26	0.1	-0.4	0.1	-0.06	0.79
ph 1000m		-0.85	-0.96	-0.89	-0.6	-0.07	0.23	0.95	-0.89	-0.93	-0.93	0.83	0.71	0.71	0.1	-0.05	0.76
dissic 0m	0.56	0.47	0.38	0.67	0.73	0.65	0.65	0.5	0.23	-0.07	0.67	0.36	0.64	0.55	0.69	0.66	0.47
dissic 100m	0.04	0.0	0.05	0.27	0.26	0.1	0.1	0.52	0.31	0.43	0.46	-0.06	0.17	0.22	0.23	0.04	0.17
dissic 250m	-0.57	-0.52	-0.5	-0.25	0.44	-0.52	-0.54	0.62	-0.37	0.03	0.58	-0.51	0.01	-0.54	-0.51	-0.6	-0.59
dissic 500m	-0.75	0.23	0.09	-0.67	0.59	-0.38	-0.33	-0.65	-0.63	-0.48	-0.66	-0.35	-0.21	-0.61	-0.65	-0.61	0.28
dissic 1000m	-0.89	-0.85	-0.89	-0.67	0.91	-0.31	-0.28	-0.91	0.86	-0.88	-0.9	0.02	0.49	0.19	-0.86	-0.8	-0.77
talk 0m	0.65	0.62	0.54	0.82	0.75	0.8	0.8	0.79	0.34	-0.08	0.87	0.46	0.68	0.58	0.73	0.71	0.59
talk 100m	0.87	0.82	0.76	0.86	0.62	0.88	0.88	0.74	0.88	0.76	0.78	0.77	0.73	0.85	0.7	0.69	0.81
talk 250m	0.9	0.77	0.73	0.82	0.55	0.89	0.89	0.56	0.89	0.78	0.8	0.89	0.66	0.77	0.88	0.75	0.81
talk 500m	0.85	0.87	0.84	0.96	-0.17	0.9	0.88	0.86	0.83	0.87	0.89	0.78	0.62	0.8	0.84	0.9	0.87
talk 1000m	0.93	0.94	0.89	0.66	-0.81	0.96	0.95	0.95	-0.87	0.9	0.92	0.94	0.84	0.95	0.94	0.97	0.95

Table 7. Normalized Root-Mean Squared Differences (RMSD) between CMIP6 ESMs and observational datasets in the Mediterranean Sea region (see Fig.1) for the key oceanic state variables. Note that three-dimensional fields are reported for different depth levels below the surface. RMSD values were normalized using the minimum-maximum range from observations.

Mediterranean Sea - Spatial Normalised RMSD

	ACCESS-ESM1-5	CESM2	CESM2-WACCM	CMCC-ESM2	CNRM-ESM2-1	CanESM5	CanESM5-CanOE	EC-Earth3-CC	GFDL-CM4	GFDL-ESM4	IPSL-CM6A-LR	MPI-ESM1-2-HR	MPI-ESM1-2-LR	MRI-ESM2-0	NorESM2-LM	NorESM2-MM	UKESM1-0-LL
thetao 0m	0.179	0.074	0.069	0.087	0.096	0.11	0.11	0.08	0.088	0.11	0.074	0.068	0.101	0.085	0.122	0.1	0.138
thetao 100m	0.283	0.189	0.154	0.163	0.129	0.152	0.152	0.112	0.14	0.171	0.072	0.078	0.162	0.152	0.153	0.207	0.118
thetao 250m	0.317	0.297	0.268	0.148	0.168	0.145	0.145	0.073	0.069	0.139	0.123	0.081	0.223	0.12	0.109	0.228	0.104
thetao 500m	0.29	0.254	0.23	0.08	0.199	0.145	0.145	0.065	0.093	0.181	0.152	0.162	0.531	0.165	0.259	0.109	0.106
thetao 1000m	0.573	0.332	0.298	0.323	0.305	0.111	0.111	0.123	0.214	0.388	0.573	0.307	0.215	0.083	0.44	0.079	0.114
so 0m	0.803	0.374	0.377	0.291	0.547	0.274	0.274	0.142	0.628	0.779	0.288	0.115	0.102	0.237	0.188	0.275	0.327
so 100m	0.83	0.214	0.214	0.14	0.094	0.148	0.148	0.077	0.084	0.125	0.085	0.069	0.085	0.099	0.095	0.148	0.085
so 250m	3.157	0.254	0.285	0.2	0.246	0.12	0.12	0.19	0.089	0.12	0.13	0.117	0.203	0.084	0.164	0.291	0.199
so 500m	3.623	0.166	0.161	0.146	0.219	0.071	0.071	0.09	0.1	0.102	0.077	0.148	0.269	0.114	0.29	0.104	0.138
so 1000m	4.043	0.124	0.113	0.236	0.16	0.103	0.103	0.077	0.552	0.545	0.833	0.186	0.161	0.118	0.399	0.083	0.133
no3 0m	0.176	0.612	0.716	0.295	3.001	0.198	0.197	0.331		0.729	0.314	0.194	0.471	0.179	0.409	0.331	0.197
no3 100m	0.488	0.436	0.403	0.202	0.72	0.255	0.216	0.221		0.337	0.261	0.193	0.156	0.196	0.161	0.221	0.214
no3 250m	0.563	0.632	0.515	0.381	0.49	0.256	0.197	0.177		0.402	0.184	0.182	0.12	0.189	0.165	0.258	0.188
no3 500m	0.352	0.573	0.242	0.443	0.356	0.189	0.161	0.258		0.419	0.33	0.173	0.101	0.151	0.119	0.298	0.137
no3 1000m	0.307	0.784	0.256	0.627	0.559	0.255	0.227	0.342		0.711	0.201	0.274	0.207	0.214	0.163	0.366	0.196
o2 0m	0.119			0.102	0.13	0.12	0.12	0.116	0.279	0.174	0.106	0.09	0.108	0.095	0.107	0.102	0.101
o2 100m	0.654			0.305	2.415	0.384	0.339	0.247	0.46	0.737	0.356	0.275	0.247	0.235	0.252	0.37	0.245
o2 250m	0.592			0.387	1.191	0.26	0.213	0.201	0.24	0.534	0.364	0.179	0.177	0.2	0.22	0.328	0.175
o2 500m	0.291			0.423	0.796	0.19	0.171	0.443	0.317	0.596	0.605	0.115	0.146	0.153	0.181	0.391	0.145
o2 1000m	0.207			0.425	0.206	0.115	0.137	0.385	0.325	0.845	1.062	0.186	0.102	0.142	0.117	0.26	0.174
intpp	0.12	0.107	0.104	0.112	0.099	0.115	0.114	0.137	0.198	0.12	0.136	0.113	0.121	0.116	0.109	0.11	0.105
ph 0m		0.195	0.194	0.22	0.261	0.203	0.201	0.219	0.214	0.186	0.228	0.181	0.177	0.183	0.208	0.202	0.198
ph 100m		0.266	0.261	0.223	0.895	0.327	0.306	0.137	0.248	0.261	0.12	0.247	0.177	0.251	0.265	0.228	0.31
ph 250m		0.375	0.364	0.3	0.675	0.387	0.357	0.151	0.232	0.287	0.153	0.246	0.236	0.271	0.255	0.229	0.284
ph 500m		0.382	0.359	0.466	0.781	0.463	0.425	0.325	0.405	0.63	0.403	0.318	0.329	0.367	0.385	0.4	0.25
ph 1000m		0.455	1.14	0.435	0.669	0.4	0.354	0.267	0.618	0.724	0.619	0.286	0.264	0.288	0.397	0.406	0.318
dissic 0m	0.362	0.206	0.217	0.171	0.127	0.152	0.15	0.167	0.291	0.424	0.15	0.18	0.143	0.172	0.178	0.179	0.172
dissic 100m	0.663	0.198	0.176	0.26	0.352	0.233	0.218	0.133	0.157	0.138	0.135	0.167	0.145	0.162	0.228	0.287	0.155
dissic 250m	1.612	0.522	0.492	0.317	0.627	0.346	0.304	0.205	0.299	0.308	0.222	0.256	0.21	0.298	0.438	0.489	0.253
dissic 500m	2.769	0.564	0.419	0.44	1.049	0.4	0.331	0.496	0.38	0.616	0.883	0.241	0.205	0.29	0.804	0.56	0.183
dissic 1000m	2.976	0.6	1.315	0.422	0.317	0.428	0.363	0.895	0.725	1.588	3.252	0.247	0.204	0.244	1.003	0.714	0.31
talk 0m	0.484	0.225	0.237	0.169	0.161	0.15	0.146	0.139	0.387	0.547	0.123	0.216	0.167	0.214	0.229	0.206	0.192
talk 100m	0.658	0.118	0.127	0.184	0.138	0.123	0.113	0.12	0.081	0.115	0.117	0.113	0.12	0.09	0.196	0.209	0.102
talk 250m	1.122	0.14	0.153	0.134	0.192	0.128	0.135	0.188	0.105	0.146	0.14	0.117	0.167	0.14	0.142	0.171	0.163
talk 500m	1.878	0.205	0.202	0.137	0.311	0.148	0.16	0.144	0.159	0.142	0.281	0.21	0.227	0.178	0.411	0.154	0.173
talk 1000m	2.322	0.157	0.239	0.256	0.892	0.115	0.11	0.394	1.072	0.61	1.957	0.23	0.177	0.15	0.625	0.226	0.124

2.4 Pacific Ocean (Humboldt box)

Spatial analysis of models for climatological fields obtained over the period 2000-2014. Pearson correlation and normalized RMSD (using min-max spatial range of observation from each layer).

For the Pacific domain, we have added two additional variables into the assessments: phosphate concentration and surface partial pressure of CO_2 (spco2), as requested by the regional modeling partner. The model-data spatial correlation for temperature and salinity fields are generally high in the upper ocean across the ESMs. While the correlation for phosphate is generally high, this is not the case for nitrate, which could be attributed to the bias in the simulated denitrification in this region. All models seem to simulate well the spatial distribution pattern of oxygen and DIC across the water column.

Table 8. Spatial correlation between CMIP6 ESMs and observational datasets in the Pacific Humboldt region (see Fig.1) for the key oceanic state variables. Note that three-dimensional fields are reported for different depth levels below the surface.

Pacific Ocean - Spatial Correlation

	ACCESS-ESM1-5	CESM2	CESM2-WACCM	CMCC-ESM2	CNRM-ESM2-1	CanESM5	CanESM5-CanOE	EC-Earth3-CC	GFDL-CM4	GFDL-ESM4	IPSL-CM6A-LR	MPI-ESM1-2-HR	MPI-ESM1-2-LR	MRI-ESM2-0	NorESM2-LM	NorESM2-MM	UKESM1-0-LL
thetao 0m	0.96	0.98	0.98	0.98	0.96	0.94	0.94	0.99	0.99	0.99	0.98	0.98	0.99	0.99	0.96	0.99	0.94
thetao 100m	0.87	0.91	0.93	0.93	0.84	0.85	0.85	0.98	0.96	0.93	0.94	0.93	0.96	0.97	0.87	0.95	0.88
thetao 200m	0.85	0.93	0.94	0.84	0.82	0.78	0.78	0.91	0.87	0.88	0.88	0.94	0.91	0.97	0.86	0.95	0.82
thetao 300m	0.81	0.97	0.96	0.78	0.9	0.69	0.69	0.7	0.65	0.9	0.76	0.93	0.92	0.91	0.9	0.92	0.73
thetao 800m	0.85	0.93	0.92	0.68	0.55	0.82	0.82	0.13	0.7	0.84	0.07	0.97	0.97	0.79	0.72	0.73	0.46
thetao 1000m	0.76	0.87	0.86	0.7	0.7	0.96	0.96	0.01	0.66	0.79	0.22	0.96	0.7	0.85	0.56	0.64	0.5
so 0m	0.87	0.95	0.95	0.85	0.84	0.79	0.79	0.94	0.94	0.93	0.93	0.95	0.91	0.94	0.72	0.93	0.72
so 100m	0.9	0.9	0.93	0.9	0.78	0.74	0.74	0.97	0.93	0.91	0.91	0.94	0.92	0.95	0.58	0.83	0.87
so 200m	0.86	0.95	0.97	0.88	0.86	0.78	0.78	0.86	0.84	0.84	0.9	0.96	0.88	0.84	0.74	0.83	0.87
so 300m	0.85	0.98	0.98	0.87	0.98	0.73	0.73	0.77	0.71	0.9	0.85	0.95	0.9	0.88	0.89	0.9	0.8
so 800m	0.84	0.93	0.92	0.7	0.56	0.81	0.81	0.36	0.91	0.83	0.38	0.99	0.93	0.84	0.71	0.77	0.57
so 1000m	0.87	0.91	0.91	0.77	0.6	0.9	0.9	0.39	0.93	0.91	0.49	0.97	0.89	0.9	0.72	0.77	0.66
no3 0m	0.25	0.7	0.72	-0.05	0.6	0.19	0.19			0.14	0.4	0.61	0.72		0.68	0.5	-0.07
no3 100m	0.76	0.95	0.95	0.63	0.78	0.56	0.47			0.83	0.84	0.83	0.89		0.85	0.83	0.7
no3 200m	0.75	0.91	0.9	0.06	0.43	0.62	-0.06			0.87	0.82	0.79	0.79		0.56	0.65	0.77
no3 300m	0.87	-0.05	0.05	-0.24	0.54	0.72	-0.22			0.88	0.83	0.29	0.34		-0.05	0.24	0.85
no3 800m	0.94	-0.49	-0.46	0.29	0.38	0.89	-0.28			-0.28	0.8	-0.32	-0.21		-0.64	-0.44	0.83
no3 1000m	0.93	-0.41	-0.39	0.67	0.3	0.89	-0.14			-0.42	0.69	-0.3	-0.02		-0.62	-0.51	0.75
o2 0m	0.94			0.94	0.96	0.9	0.91		0.98	0.98	0.98	0.98	0.97		0.94	0.97	0.96
o2 100m	0.92			0.94	0.9	0.88	0.94		0.92	0.91	0.96	0.93	0.95		0.95	0.95	0.94
o2 200m	0.97			0.96	0.95	0.96	0.96		0.9	0.93	0.97	0.96	0.96		0.94	0.96	0.97
o2 300m	0.98			0.97	0.98	0.98	0.98		0.78	0.91	0.96	0.95	0.95		0.97	0.97	0.99
o2 800m	0.95			0.87	0.81	0.94	0.95		0.83	0.96	0.92	0.97	0.97		0.86	0.87	0.92
o2 1000m	0.97			0.93	0.82	0.96	0.97		0.86	0.95	0.9	0.98	0.97		0.88	0.89	0.93
po4 0m	0.53		0.73	0.33					0.55	0.5	0.56		0.48		0.73	0.66	0.23
po4 100m	0.83		0.96	0.85					0.89	0.91	0.91		0.88		0.91	0.9	0.84
po4 200m	0.91		0.93	0.92					0.89	0.91	0.95		0.93		0.89	0.92	0.93
po4 300m	0.92		0.91	0.93					0.7	0.87	0.96		0.87		0.91	0.9	0.96
po4 800m	0.97		0.93	0.86					0.8	0.94	0.81		0.93		0.9	0.91	0.87
po4 1000m	0.97		0.93	0.81					0.85	0.91	0.7		0.94		0.87	0.88	0.8
fgco2	0.55	0.84	0.82	0.28	0.36	0.16	0.03	0.83	0.49	0.51	0.47	0.57	0.66	0.44	0.85	0.7	0.24
spco2	0.53	0.77	0.8		0.49	0.1	-0.0		0.6	0.57	0.33	0.58	0.56	0.51	0.86	0.8	0.29
ph 0m		0.68		0.13	0.22	-0.05	-0.04	0.56	0.46	0.31	0.35	0.58	0.39	0.45	0.43	0.33	0.16
ph 100m		0.94		0.78	0.81	0.72	0.82	0.94	0.84	0.85	0.85	0.82	0.86	0.91	0.86	0.9	0.83
ph 200m		0.91		0.69	0.81	0.86	0.89	0.86	0.89	0.94	0.87	0.92	0.89	0.94	0.89	0.89	0.91
ph 300m		0.93		0.61	0.92	0.96	0.96	0.93	0.68	0.86	0.92	0.82	0.88	0.93	0.95	0.94	0.96
ph 800m		0.94		0.71	0.63	0.93	0.94	0.92	0.81	0.94	0.88	0.91	0.94	0.96	0.77	0.81	0.92
ph 1000m		0.95		0.92	0.68	0.96	0.97	0.94	0.84	0.93	0.92	0.92	0.96	0.96	0.79	0.82	0.93
dissic 0m	0.84	0.93	0.93	0.81	0.79	0.76	0.76		0.84	0.86	0.84	0.87	0.9	0.7	0.78	0.88	0.69
dissic 100m	0.79	0.94	0.94	0.8	0.85	0.7	0.76		0.89	0.87	0.85	0.85	0.84	0.91	0.86	0.88	0.86
dissic 200m	0.86	0.92	0.9	0.89	0.81	0.83	0.85		0.92	0.93	0.91	0.93	0.89	0.93	0.87	0.89	0.91
dissic 300m	0.94	0.93	0.93	0.9	0.88	0.93	0.93		0.76	0.87	0.93	0.81	0.87	0.93	0.92	0.91	0.95
dissic 800m	0.98	0.95	0.95	0.93	0.65	0.95	0.97		0.86	0.97	0.91	0.96	0.96	0.97	0.9	0.9	0.95
dissic 1000m	0.99	0.96	0.97	0.97	0.81	0.98	0.98		0.86	0.95	0.97	0.96	0.96	0.98	0.96	0.95	0.97
talk 0m	0.86		0.91	0.86	0.85	0.86			0.88	0.88	0.87		0.92		0.71	0.89	0.74
talk 100m	0.74		0.94	0.71	0.66	0.7			0.78	0.69	0.74		0.85		0.39	0.75	0.86
talk 200m	0.55		0.9	0.51	0.58	0.59			0.55	0.43	0.74		0.65		0.47	0.57	0.78
talk 300m	0.74		0.92	0.73	0.74	0.75			0.18	0.66	0.84		0.8		0.83	0.83	0.86
talk 800m	0.98		0.98	0.91	0.77	0.98			0.91	0.97	0.96		0.97		0.95	0.94	0.94
talk 1000m	0.99		0.97	0.9	0.96	0.98			0.9	0.94	0.99		0.94		0.98	0.98	0.99

With respect to RMSD assessment, all models simulate relatively low bias for temperature, salinity, and oxygen across the water column. The RMSD for the carbon chemistry variables: DIC, alkalinity, and pH are generally low at surface but increasing with depth. For nutrients, the models simulate lower bias for phosphate than nitrate, reiterating uncertainties related to the nitrogen cycle in this domain.

Table 9. Normalized Root-Mean Squared Differences (RMSD) between CMIP6 ESMs and observational datasets in the Pacific Humboldt region (see Fig.1) for the key oceanic state variables. Note that three-dimensional fields are reported for different depth levels below the surface. RMSD values were normalized using the minimum-maximum range from observations.

Pacific Ocean - Spatial Normalised RMSD

	ACCESS-ESM1-5	CESM2	CESM2-WACCM	CMCC-ESM2	CNRM-ESM2-1	CanESM5	CanESM5-CanOE	EC-Earth3-CC	GFDL-CM4	GFDL-ESM4	IPSL-CM6A-LR	MPI-ESM1-2-HR	MPI-ESM1-2-LR	MRI-ESM2-0	NorESM2-LM	NorESM2-MM	UKESM1-0-LL
thetao 0m	0.076	0.068	0.051	0.062	0.07	0.117	0.117	0.038	0.052	0.038	0.053	0.074	0.048	0.049	0.073	0.039	0.101
thetao 100m	0.098	0.081	0.068	0.071	0.102	0.099	0.099	0.039	0.053	0.076	0.074	0.07	0.053	0.052	0.094	0.065	0.09
thetao 200m	0.118	0.073	0.069	0.107	0.114	0.121	0.121	0.082	0.095	0.099	0.1	0.067	0.081	0.05	0.103	0.073	0.111
thetao 300m	0.139	0.062	0.066	0.143	0.117	0.163	0.163	0.159	0.173	0.104	0.145	0.08	0.089	0.096	0.124	0.114	0.153
thetao 800m	0.2	0.131	0.127	0.264	0.204	0.166	0.166	0.321	0.174	0.142	0.278	0.077	0.057	0.149	0.178	0.168	0.266
thetao 1000m	0.231	0.144	0.149	0.2	0.19	0.068	0.068	0.268	0.172	0.148	0.225	0.075	0.163	0.123	0.203	0.181	0.202
so 0m	0.08	0.054	0.05	0.125	0.121	0.147	0.147	0.055	0.1	0.067	0.092	0.061	0.065	0.054	0.12	0.062	0.151
so 100m	0.08	0.083	0.071	0.08	0.119	0.141	0.141	0.046	0.068	0.076	0.085	0.073	0.074	0.059	0.175	0.105	0.086
so 200m	0.102	0.055	0.049	0.116	0.095	0.141	0.141	0.096	0.091	0.091	0.087	0.075	0.095	0.099	0.117	0.093	0.102
so 300m	0.114	0.047	0.052	0.141	0.031	0.156	0.156	0.138	0.124	0.077	0.102	0.076	0.087	0.083	0.079	0.077	0.138
so 800m	0.198	0.114	0.116	0.224	0.184	0.179	0.179	0.278	0.098	0.173	0.224	0.035	0.084	0.12	0.21	0.191	0.238
so 1000m	0.158	0.098	0.097	0.135	0.133	0.091	0.091	0.184	0.072	0.117	0.15	0.042	0.076	0.074	0.153	0.14	0.14
no3 0m	0.533	0.167	0.163	0.559	0.242	0.623	0.524			0.467	0.281	0.185	0.18		0.191	0.333	0.699
no3 100m	0.312	0.108	0.099	0.25	0.166	0.277	0.235			0.169	0.148	0.151	0.12		0.142	0.147	0.464
no3 200m	0.495	0.104	0.109	0.447	0.217	0.33	0.34			0.181	0.163	0.155	0.151		0.197	0.186	0.569
no3 300m	0.69	0.331	0.313	0.737	0.186	0.422	0.556			0.181	0.172	0.299	0.285		0.35	0.305	0.64
no3 800m	0.51	0.599	0.602	0.291	0.221	0.348	0.495			0.454	0.145	0.539	0.449		0.575	0.485	0.174
no3 1000m	0.439	0.518	0.515	0.182	0.228	0.331	0.37			0.553	0.173	0.524	0.372		0.564	0.496	0.164
o2 0m	0.075			0.088	0.066	0.124	0.12		0.292	0.047	0.049	0.064	0.059		0.08	0.055	0.063
o2 100m	0.145			0.122	0.157	0.15	0.113		0.169	0.129	0.092	0.118	0.114		0.116	0.106	0.15
o2 200m	0.122			0.124	0.111	0.117	0.113		0.179	0.123	0.089	0.1	0.105		0.118	0.113	0.098
o2 300m	0.101			0.093	0.065	0.072	0.095		0.203	0.138	0.084	0.097	0.112		0.1	0.13	0.05
o2 800m	0.108			0.174	0.239	0.122	0.108		0.186	0.098	0.176	0.077	0.098		0.185	0.189	0.151
o2 1000m	0.133			0.101	0.19	0.153	0.119		0.224	0.151	0.14	0.157	0.172		0.163	0.181	0.119
po4 0m	0.237		0.103	0.25					0.218	0.221	0.152		0.183		0.108	0.181	0.33
po4 100m	0.208		0.09	0.167					0.136	0.107	0.107		0.123		0.111	0.11	0.302
po4 200m	0.264		0.096	0.204					0.155	0.107	0.084		0.102		0.115	0.1	0.31
po4 300m	0.353		0.107	0.256					0.244	0.128	0.062		0.208		0.11	0.123	0.306
po4 800m	0.378		0.25	0.146					0.321	0.165	0.178		0.535		0.15	0.156	0.14
po4 1000m	0.318		0.253	0.164					0.318	0.195	0.205		0.506		0.146	0.145	0.17
fgco2	0.358	0.123	0.132	0.259	0.292	0.437	0.36	0.129	0.313	0.333	0.224	0.188	0.186	0.912	0.126	0.172	0.471
spco2	0.411	0.14	0.133		0.219	0.421	0.339		0.324	0.244	0.237	0.18	0.206	0.976	0.114	0.15	0.409
ph 0m		0.114		0.166	0.168	0.237	0.195	0.142	0.151	0.173	0.15	0.128	0.149	0.369	0.143	0.161	0.221
ph 100m		0.085		0.166	0.188	0.226	0.148	0.106	0.171	0.141	0.136	0.163	0.163	0.44	0.134	0.109	0.419
ph 200m		0.125		0.21	0.177	0.248	0.142	0.154	0.164	0.099	0.143	0.124	0.156	0.52	0.134	0.142	0.408
ph 300m		0.134		0.236	0.114	0.22	0.119	0.112	0.289	0.162	0.12	0.228	0.224	0.597	0.105	0.136	0.333
ph 800m		0.325		0.228	0.257	0.38	0.186	0.157	0.459	0.14	0.172	0.393	0.355	0.439	0.214	0.206	0.127
ph 1000m		0.524		0.098	0.188	0.565	0.247	0.092	0.676	0.244	0.099	0.613	0.532	0.524	0.186	0.195	0.099
dissic 0m	0.117	0.079	0.081	0.168	0.142	0.192	0.194		0.128	0.111	0.141	0.12	0.094	0.157	0.132	0.106	0.203
dissic 100m	0.215	0.083	0.086	0.151	0.176	0.212	0.17		0.136	0.121	0.129	0.136	0.146	0.297	0.127	0.119	0.326
dissic 200m	0.27	0.121	0.133	0.136	0.174	0.212	0.165		0.126	0.104	0.126	0.118	0.153	0.388	0.142	0.134	0.346
dissic 300m	0.399	0.188	0.183	0.149	0.137	0.207	0.175		0.236	0.143	0.112	0.317	0.319	0.544	0.171	0.184	0.334
dissic 800m	0.435	0.312	0.316	0.141	0.249	0.248	0.154		0.298	0.13	0.161	0.757	0.831	0.253	0.252	0.279	0.101
dissic 1000m	0.528	0.449	0.454	0.087	0.182	0.348	0.183		0.446	0.284	0.091	1.088	1.052	0.277	0.28	0.316	0.069
talk 0m	0.098		0.08	0.116	0.103	0.114			0.117	0.093	0.1		0.079		0.135	0.087	0.143
talk 100m	0.167		0.126	0.198	0.18	0.201			0.205	0.227	0.17		0.132		0.322	0.197	0.115
talk 200m	0.349		0.238	0.798	0.275	0.345			0.352	0.381	0.252		0.291		0.352	0.306	0.245
talk 300m	0.304		0.393	1.252	0.227	0.324			0.435	0.286	0.205		0.558		0.422	0.341	0.221
talk 800m	0.073		0.259	0.164	0.258	0.109			0.198	0.143	0.199		1.597		0.523	0.527	0.128
talk 1000m	0.083		0.241	0.137	0.2	0.127			0.145	0.299	0.158		1.595		0.518	0.534	0.084

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Supplementary Materials

Decadal trends within CE2COAST marine regions

Table S1. Decadal trends from area-weighted timeseries as simulated in ESMs and from long term satellite observations over the period 1982-2014. Data for sea surface temperature (tos) are from ESACCI-SST (v2.2) and for air-sea CO2 fluxes (fgco2) from Landschuetzer et al. (2016).

Trends per decade	Atlantic Ocean (EU box)		Arctic Sea (EU box)		Mediterranean Sea	Pacific Ocean (Humboldt box)	
	tos (K)	fgco2 (g m-2 yr-1)	tos (K)	fgco2 (g m-2 yr-1)	tos (K)	tos (K)	fgco2 (g m-2 yr-1)
OBS	**0.28**	**1.77**	**0.28**	**1.66**	**0.33**	**0.01**	**-0.87**
ACCESS-ESM1-5	0.38	0.64	0.38	0.84	0.48	0.27	0.43
CESM2-WACCM	0.27	1.15	0.26	1.23	0.45	0.04	0.87
CESM2	0.26	0.90	0.31	0.44	0.38	0.41	0.36
CMCC-ESM2	-0.13	-0.51	0.31	-1.31	0.19	0.13	0.59
CNRM-ESM2-1	0.28	0.39	0.24	1.45	0.38	0.12	0.41
CanESM5-CanOE	0.32	-0.23	0.79	3.66	0.47	0.18	0.81
CanESM5	0.32	-0.37	0.79	4.09	0.47	0.18	0.92
EC-Earth3-CC	0.37	0.16	0.55	1.44	0.39	0.18	0.22
GFDL-CM4	0.29	1.30	0.43	2.25	0.40	0.14	0.84
GFDL-ESM4	0.14	1.21	0.17	1.23	0.36	0.08	0.73
IPSL-CM6A-LR	0.25	0.05	0.18	1.13	0.30	0.14	0.97
MPI-ESM1-2-HR	0.03	0.26	0.41	2.07	0.23	0.08	0.57
MPI-ESM1-2-LR	0.16	0.58	0.46	1.45	0.20	0.04	0.57
MRI-ESM2-0	0.26	1.26	0.44	2.00	0.50	0.16	1.79
NorESM2-LM	0.14	1.44	0.16	0.08	0.46	0.15	0.50
NorESM2-MM	0.14	1.07	0.15	0.14	0.28	0.16	1.02
UKESM1-0-LL	0.55	-0.33	0.42	1.88	0.53	0.13	1.34
CMIP6 Mean	0.24	0.53	0.38	1.42	0.38	0.14	0.67
CMIP6 StDev	0.15	0.66	0.19	1.28	0.11	0.10	0.52

Atlantic Ocean (EU box)

Figure S1. Temporal evolution of sea surface temperature (tos) from area-weighted annual mean values simulated in selected CMIP6 ESMs and from ESACCI-SST (v2.2) observations within the marine region (see Fig.1 for location).

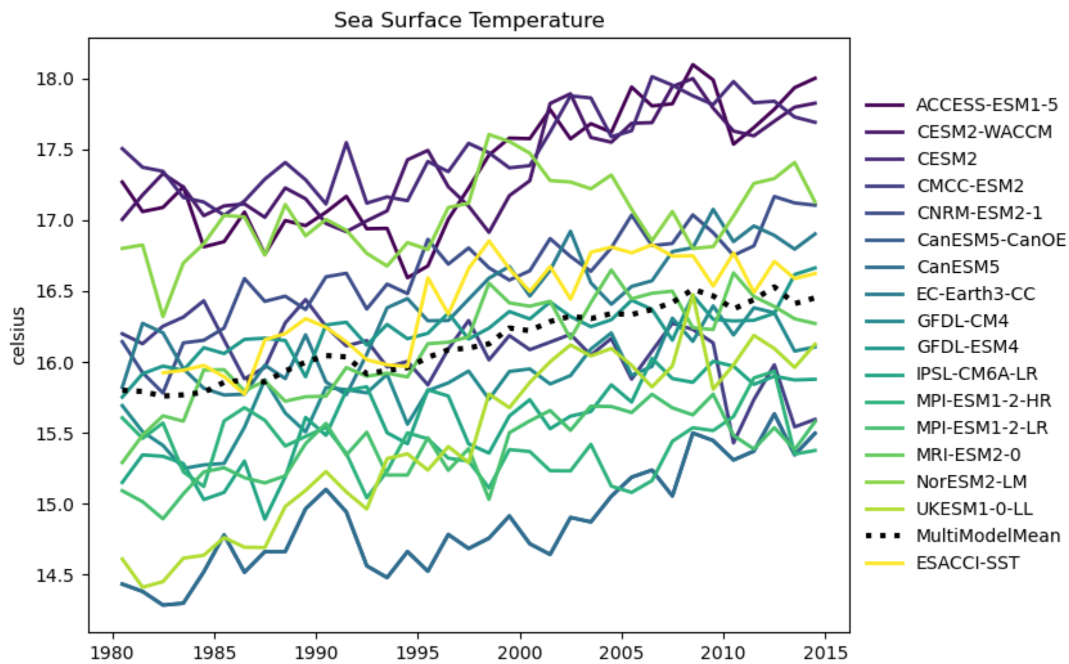


Figure S2. Temporal evolution of primary organic carbon production (intpp) from area-weighted annual mean values simulated in selected CMIP6 ESMs and from Eppley-VGPM-MODIS satellite-based estimates within the marine region (see Fig.1 for location).

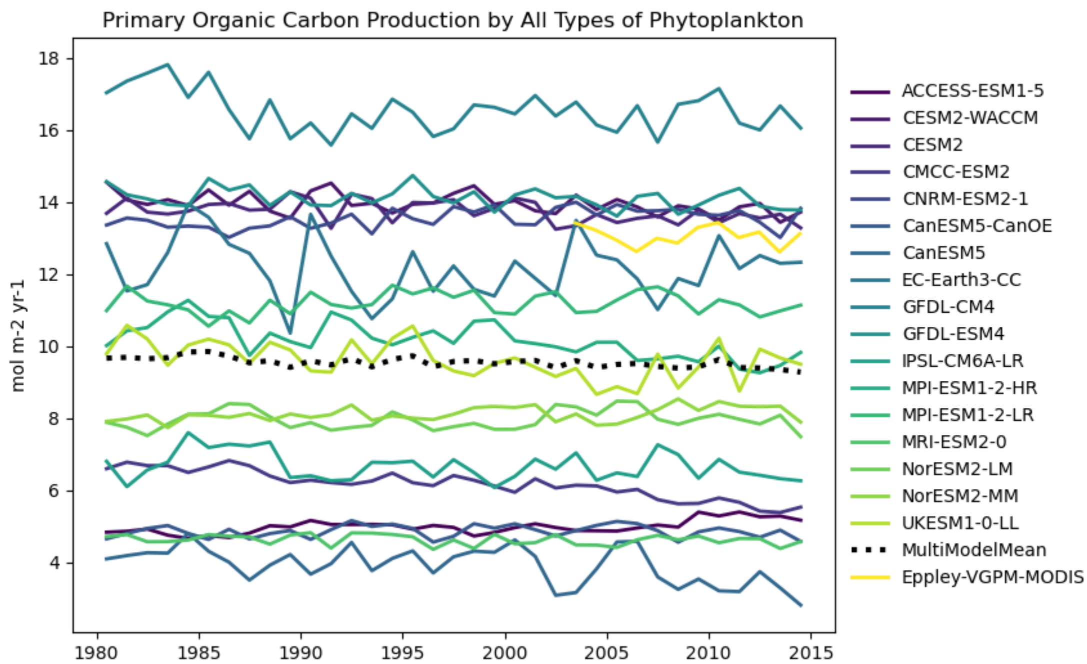


Figure S3. Temporal evolution of air-sea CO2 fluxes (fgco2) from area-weighted annual mean values simulated in selected CMIP6 ESMs and from Landschuetzer et al. (2016) observation-based reconstruction within the marine region (see Fig.1 for location).

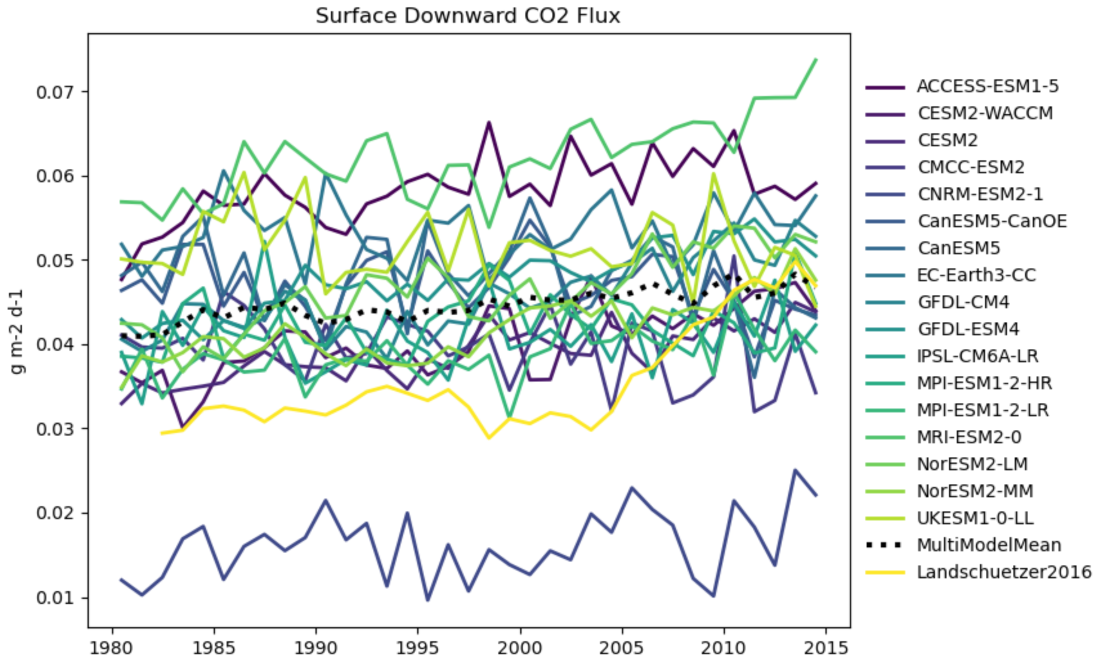


Figure S4. Spatial distribution of sea temperature (thetao) at the surface from WOA2018 observation-based reconstruction (top panel) and differences obtained from the comparison of the climatological fields computed over the period 1980-2014 for each ESM.

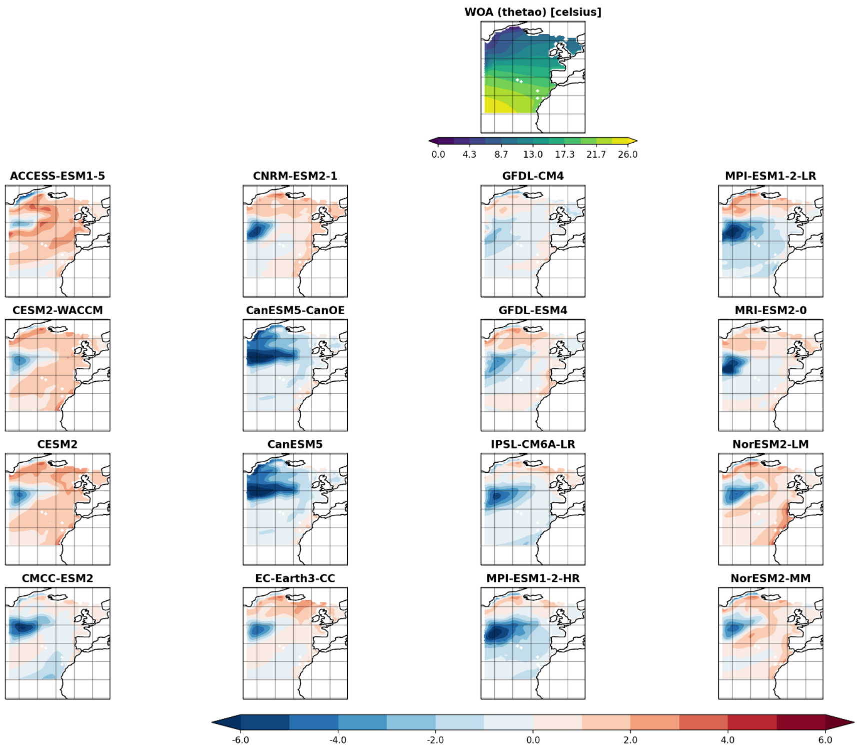
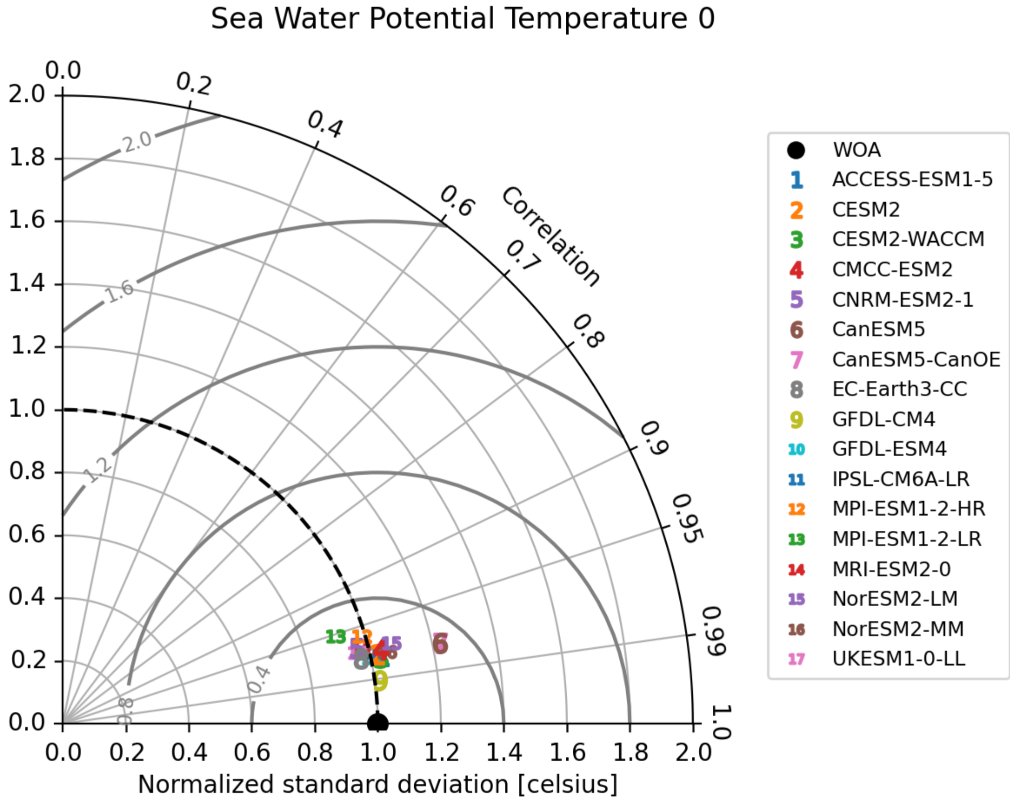


Figure S5. Taylor diagram based on the spatial statistics for sea temperature (thetao) at the surface obtained from the comparison between WOA2018 data and the climatological fields computed over the period 1980-2014 for each ESM.



Arctic Sea (EU box)

Figure S6. Temporal evolution of sea surface temperature (tos) from area-weighted annual mean values simulated in selected CMIP6 ESMs and from ESACCI-SST (v2.2) observations within the marine region (see Fig.1 for location).

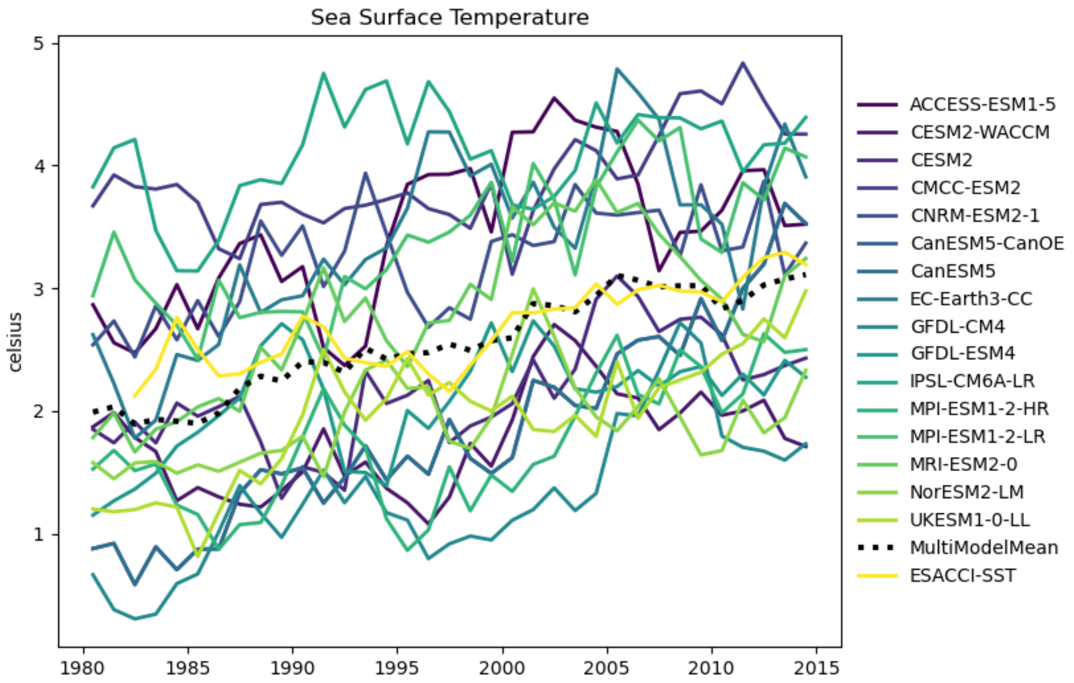


Figure S7. Temporal evolution of primary organic carbon production (intpp) from area-weighted annual mean values simulated in selected CMIP6 ESMs and from Eppley-VGPM-MODIS satellite-based estimates within the marine region (see Fig.1 for location).

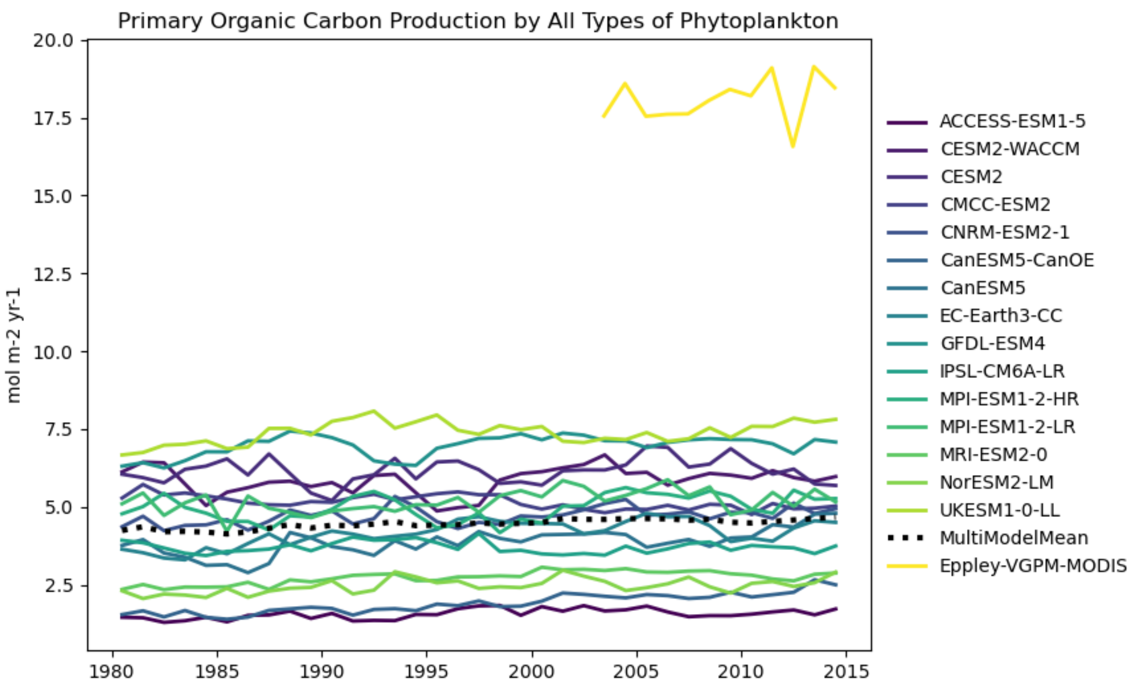


Figure S8. Temporal evolution of air-sea CO2 fluxes (fgco2) from area-weighted annual mean values simulated in selected CMIP6 ESMs and from Landschuetzer et al. (2016) observation-based reconstruction within the marine region (see Fig.1 for location).

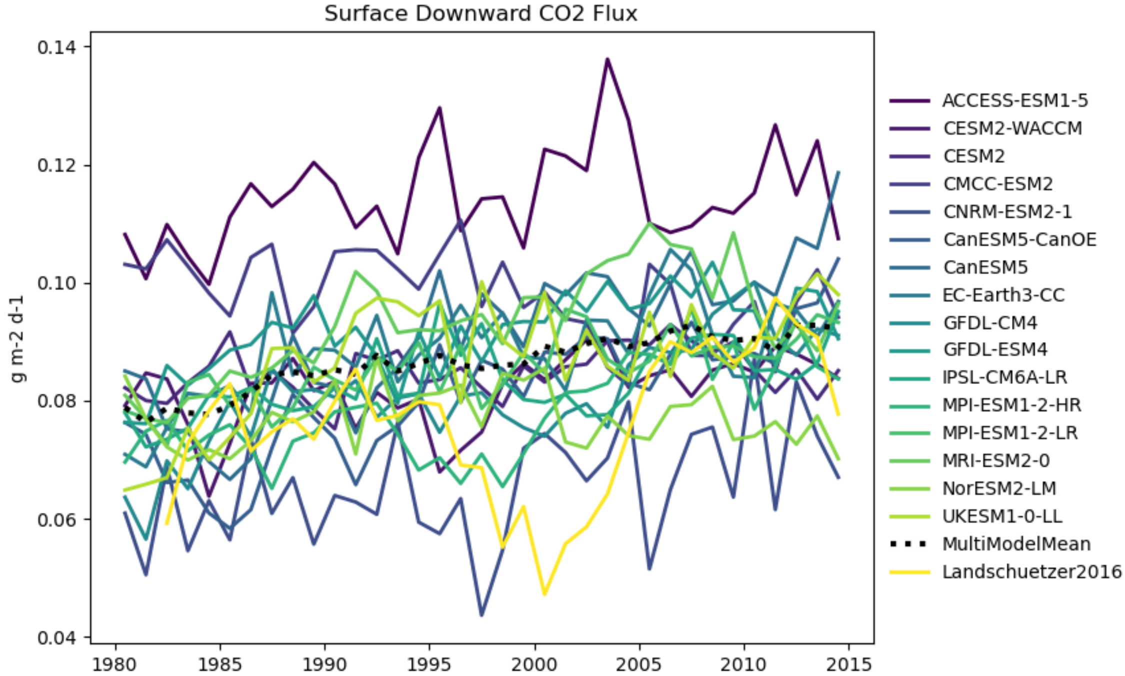


Figure S9. Spatial distribution of sea temperature (thetao) at the surface from WOA2018 observation-based reconstruction (top panel) and differences obtained from the comparison of the climatological fields computed over the period 1980-2014 for each ESM.

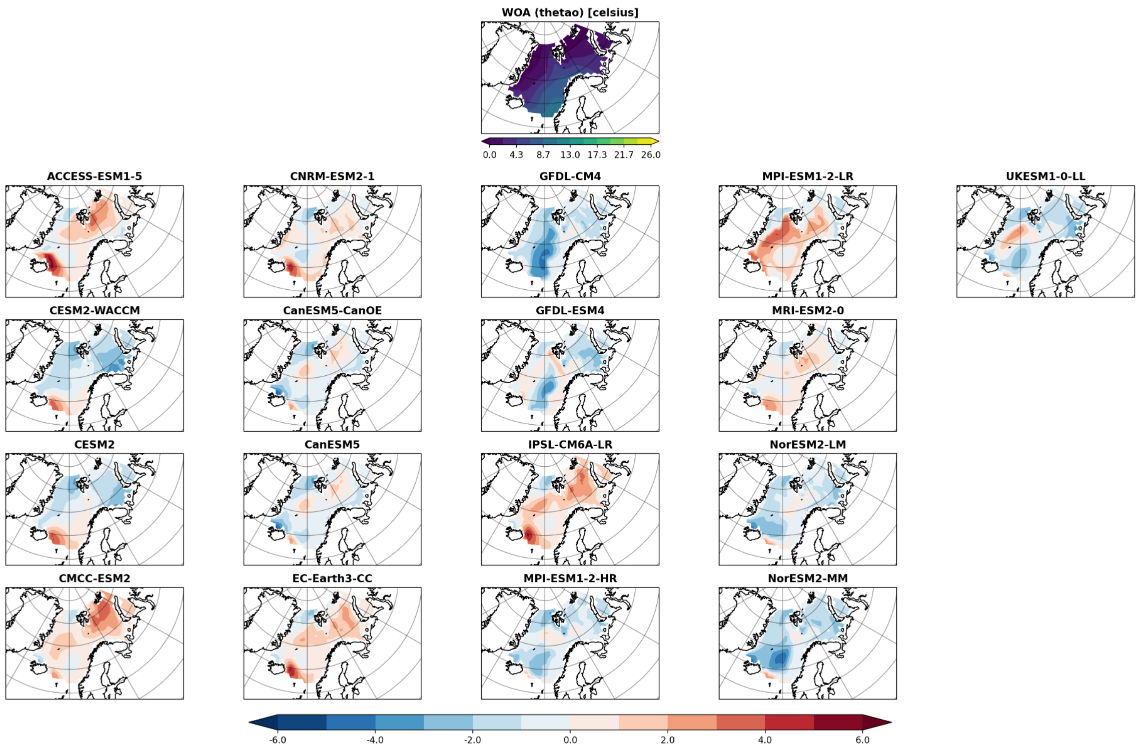
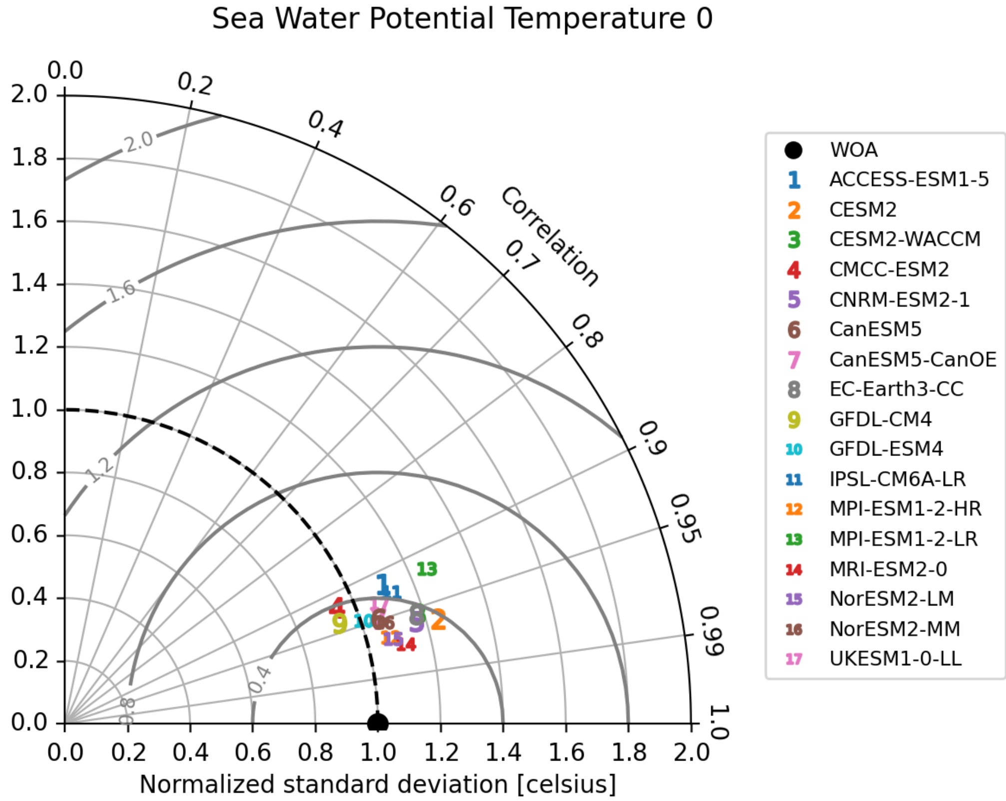


Figure S10. Taylor diagram based on the spatial statistics for sea temperature (thetao) at the surface obtained from the comparison between WOA2018 data and the climatological fields computed over the period 1980-2014 for each ESM.



Mediterranean Sea

Figure S11. Temporal evolution of sea surface temperature (tos) from area-weighted annual mean values simulated in selected CMIP6 ESMs and from ESACCI-SST (v2.2) observations within the marine region (see Fig.1 for location).

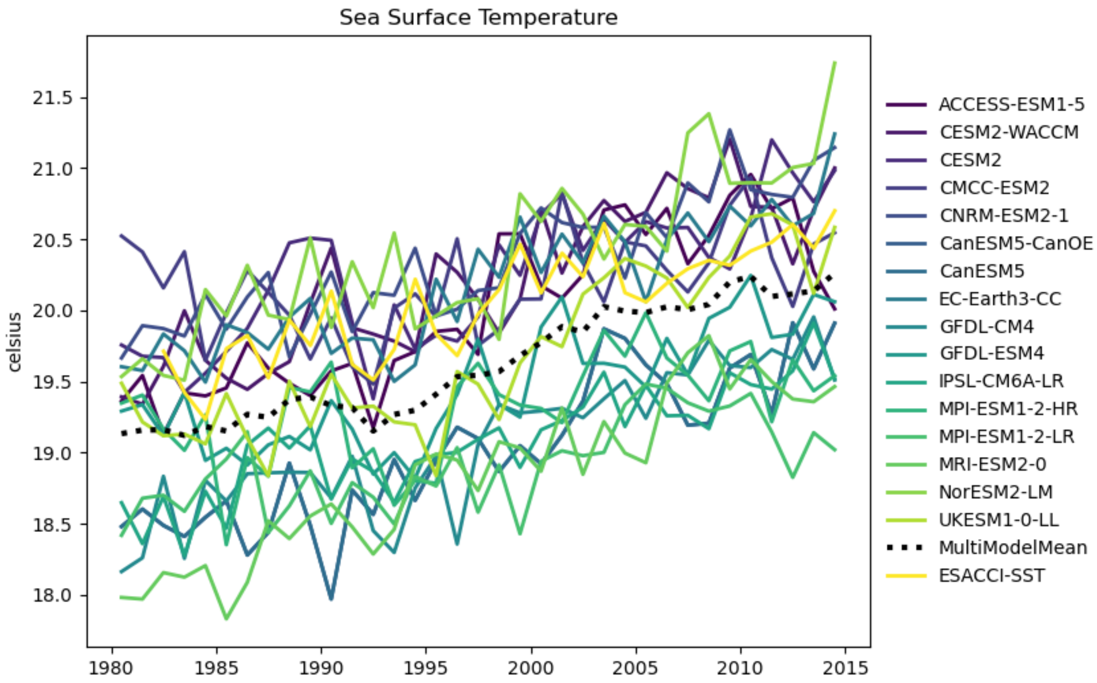


Figure S12. Temporal evolution of primary organic carbon production (intpp) from area-weighted annual mean values simulated in selected CMIP6 ESMs and from Eppley-VGPM-MODIS satellite-based estimates within the marine region (see Fig.1 for location).

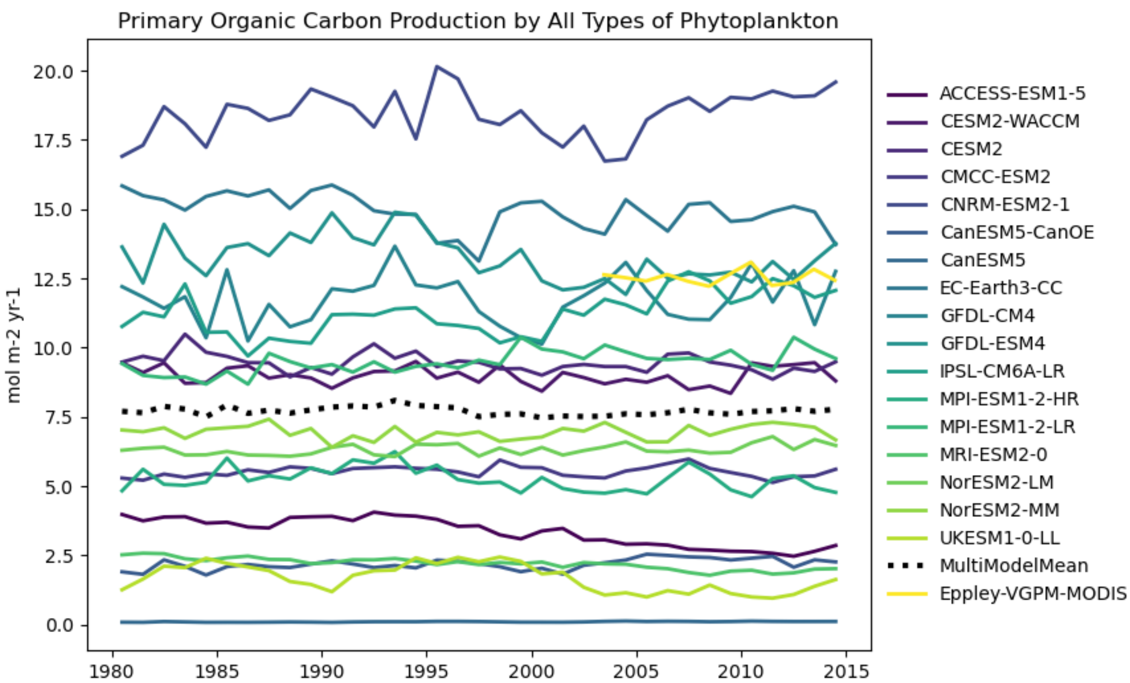


Figure S13. Spatial distribution of sea temperature (thetao) at the surface from WOA2018 observation-based reconstruction (top panel) and differences obtained from the comparison of the climatological fields computed over the period 1980-2014 for each ESM.

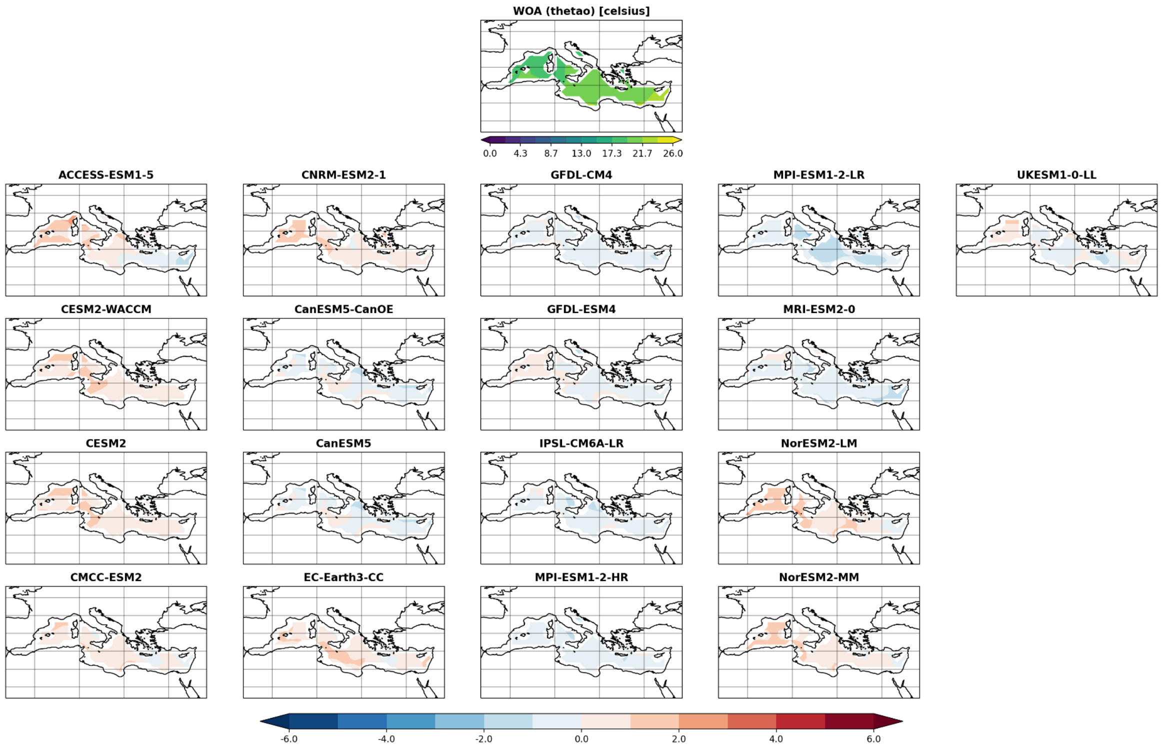
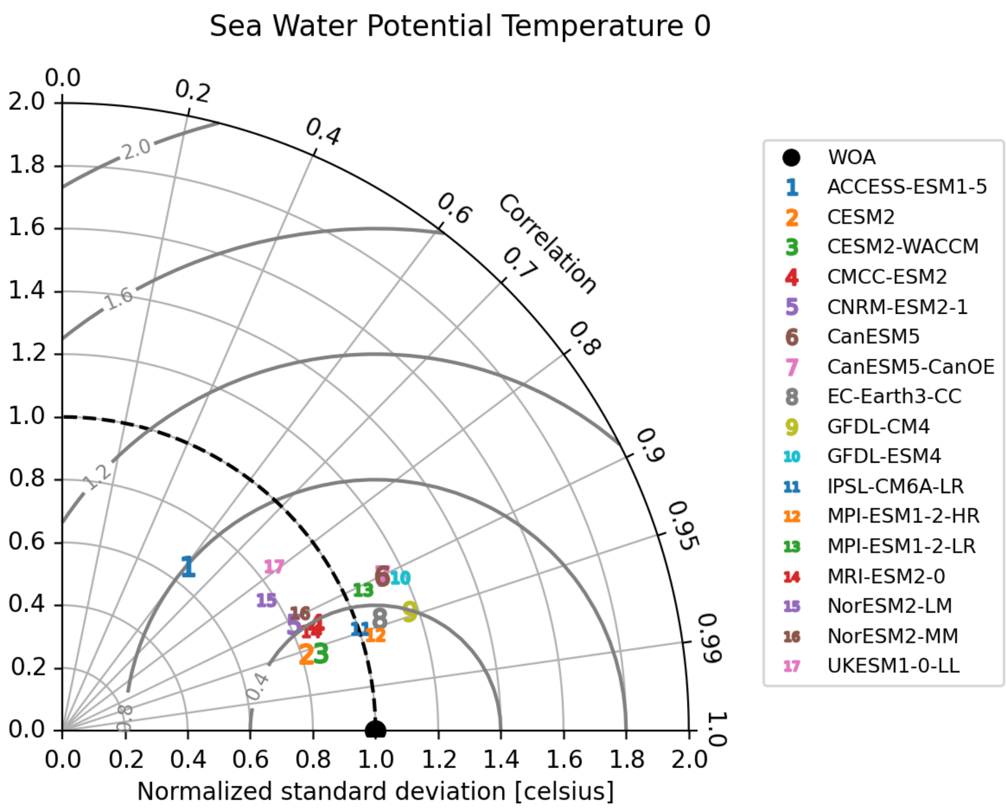


Figure S14. Taylor diagram based on the spatial statistics for sea temperature (thetao) at the surface obtained from the comparison between WOA2018 data and the climatological fields computed over the period 1980-2014 for each ESM.



Pacific Ocean (Humboldt box)

Figure S15. Temporal evolution of sea surface temperature (tos) from area-weighted annual mean values simulated in selected CMIP6 ESMs and from ESACCI-SST (v2.2) observations within the marine region (see Fig.1 for location).

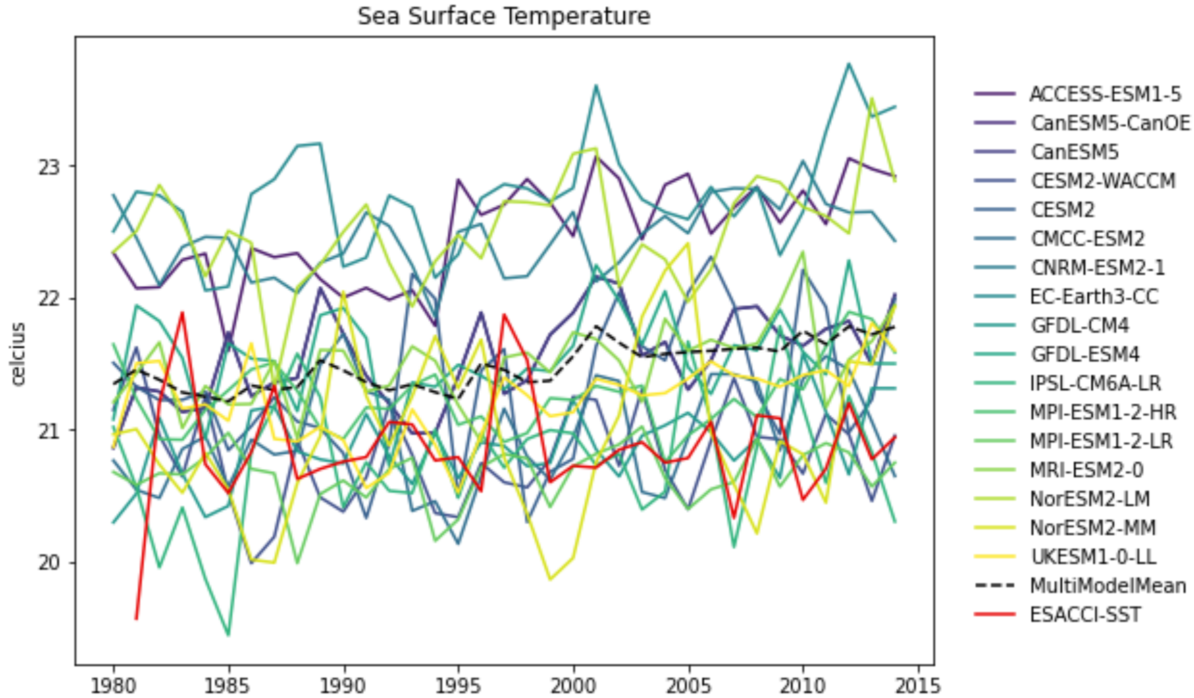


Figure S16. Temporal evolution of primary organic carbon production (intpp) from area-weighted annual mean values simulated in selected CMIP6 ESMs and from Eppley-VGPM-MODIS satellite-based estimates within the marine region (see Fig.1 for location).

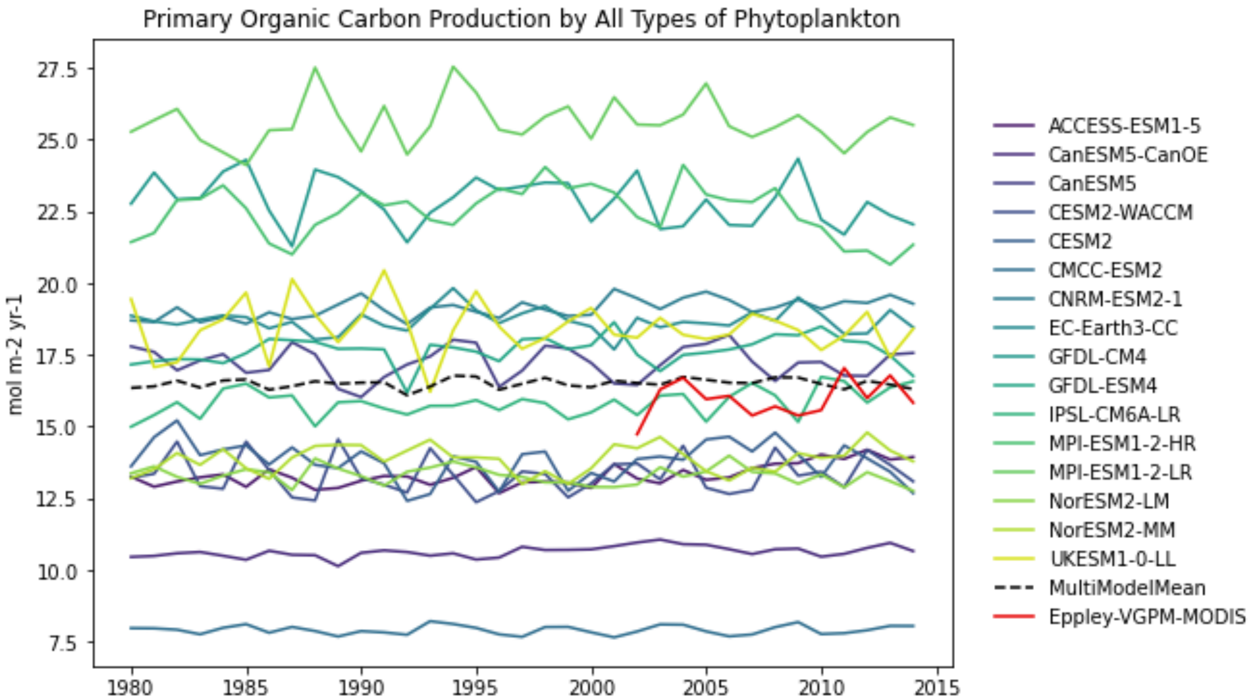


Figure S17. Temporal evolution of air-sea CO2 fluxes (fgco2) from area-weighted annual mean values simulated in selected CMIP6 ESMs and from Landschuetzer et al. (2016) observation-based reconstruction within the marine region (see Fig.1 for location).

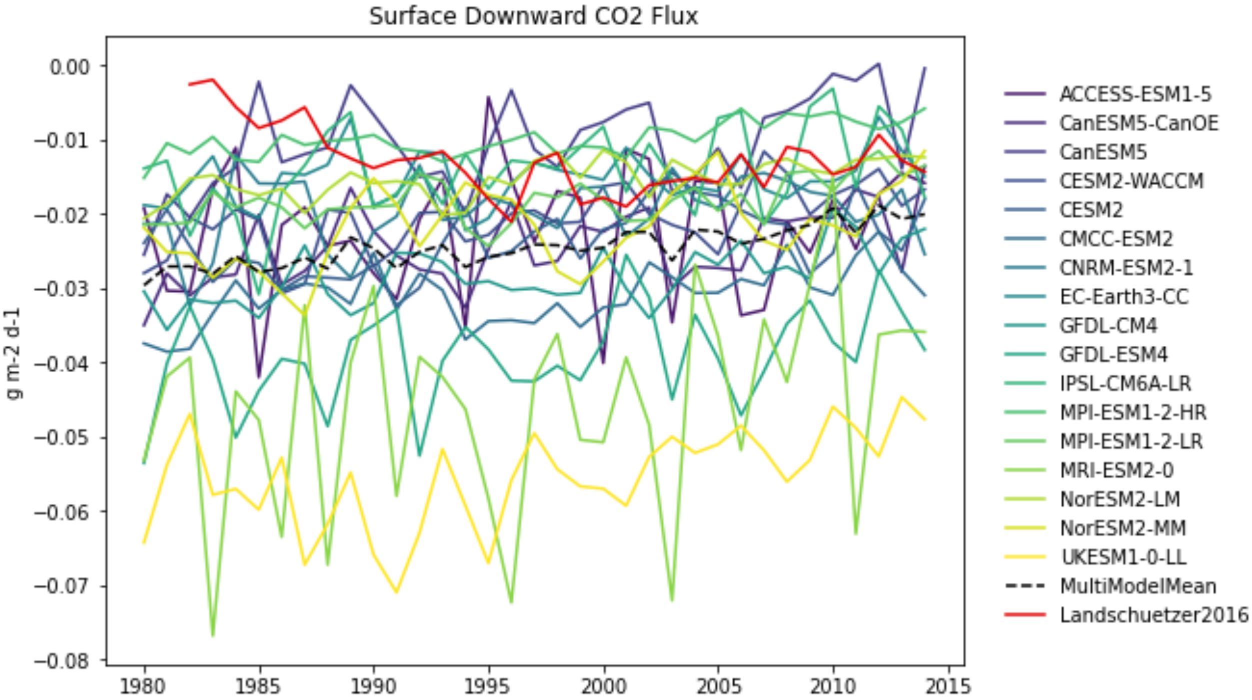


Figure S18. Spatial distribution of sea temperature (thetao) at the surface from WOA2018 observation-based reconstruction (top panel) and differences obtained from the comparison of the climatological fields computed over the period 1980-2014 for each ESM.

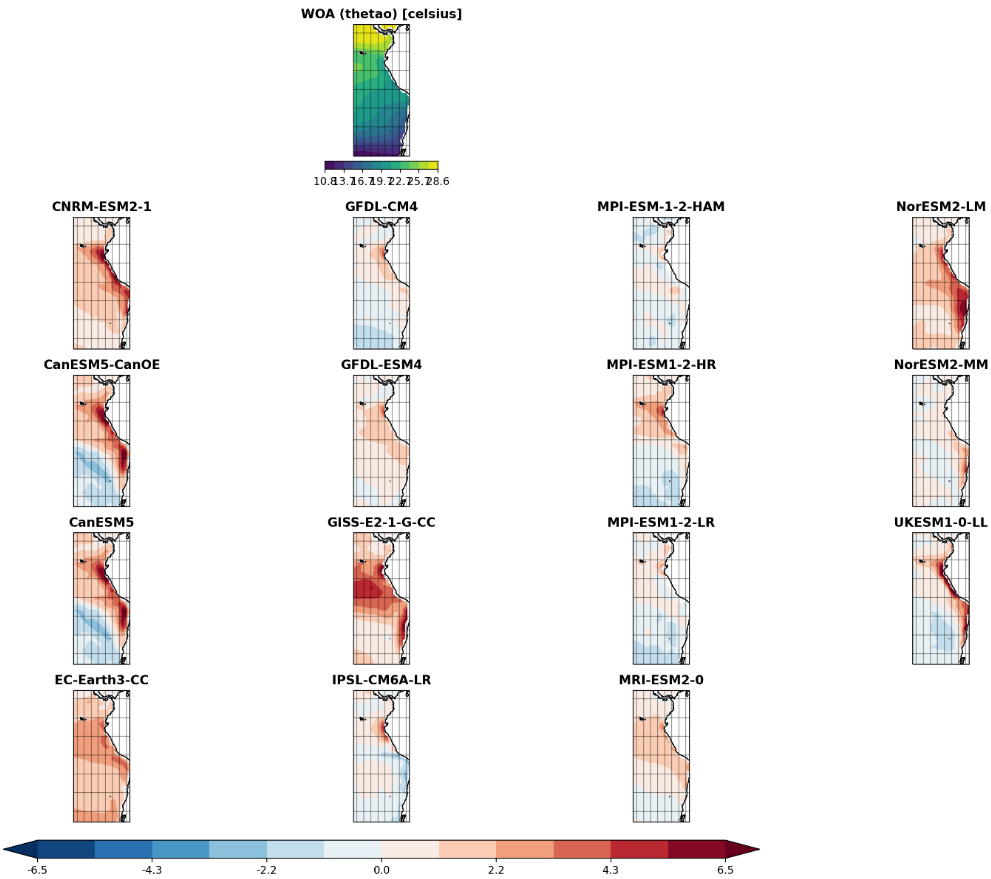


Figure S19. Taylor diagram based on the spatial statistics for sea temperature (thetao) at the surface obtained from the comparison between WOA2018 data and the climatological fields computed over the period 1980-2014 for each ESM.