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Project Deliverable Report
Ensemble Data Set of Key Model Variables

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Project Milestone(s) achieved:
MS15 - First version of harmonised ensemble data available to project partners

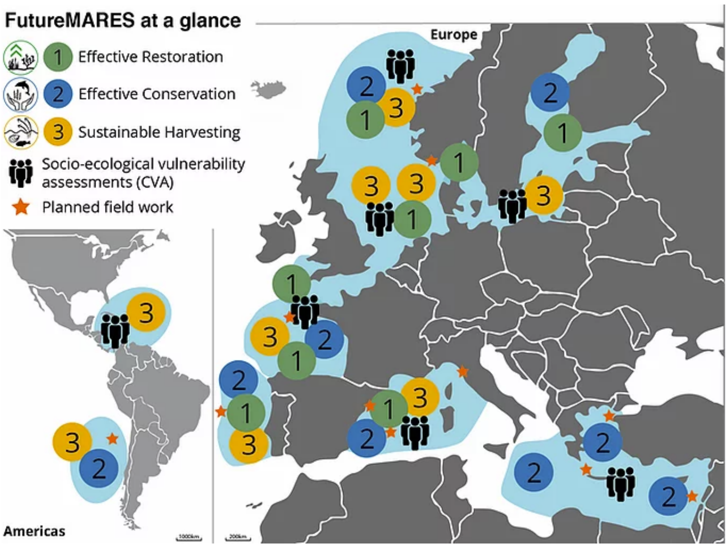
FutureMARES Project

FutureMARES - Climate Change and Future Marine Ecosystem Services and Biodiversity is an EU-funded research project examining the relations between climate change, marine biodiversity, and ecosystem services. Our activities are designed around three Nature-based Solutions (NBS):

Effective Restoration (NBS1)

Effective Conservation (NBS2)

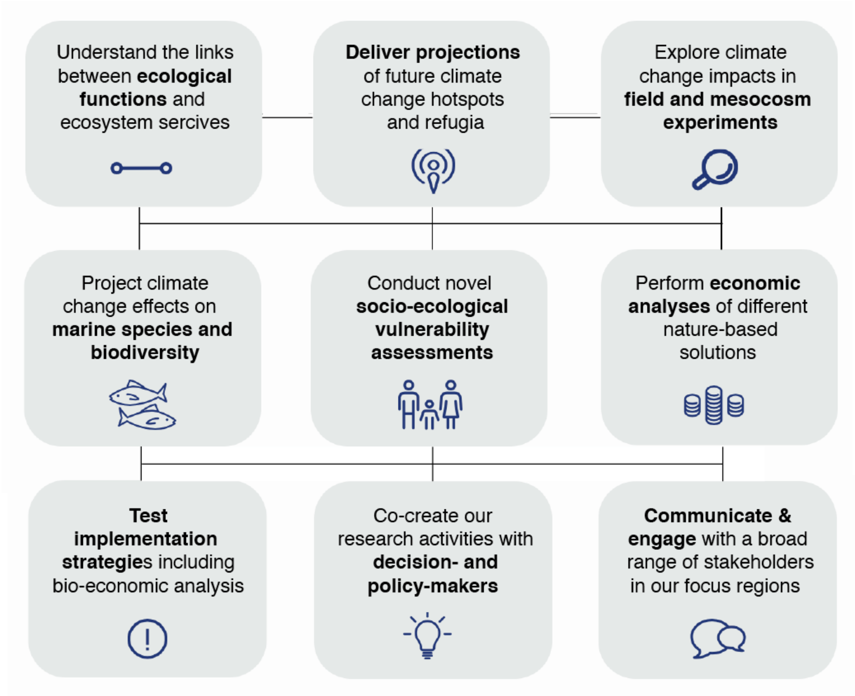
Sustainable Harvesting of Marine Resources (NBS3)



We are conducting our research and cooperating with marine organisations and the public in Case Study Regions across Europe and Central and South America. Our goal is to provide science-based policy advice on how best to use NBS to protect future biodiversity and ecosystem services in a future climate.

FutureMARES provides socially and economically viable actions and strategies in support of nature-based solutions for climate change adaptation and mitigation. We develop these solutions to safeguard future biodiversity and ecosystem functions to maximise natural capital and its delivery of services from marine and transitional ecosystems.

To achieve this, the objectives of FutureMARES defined following goals:


Understand the links between **ecological functions** and ecosystem sercives
Deliver projections of future climate change hotspots and refugia
Explore climate change impacts in **field and mesocosm experiments**
Project climate change effects on **marine species and biodiversity**
Conduct novel **socio-ecological vulnerability assessments**
Perform **economic analyses** of different nature-based solutions
Test implementation strategies including bio-economic analysis
Co-create our research activities with **decision- and policy-makers**
Communicate & engage with a broad range of stakeholders in our focus regions

Deliverable data	
Work Package(s) / Task(s):	WP2 – Changing Habitats, Task 2.1 – Ensemble hindcasts & projection
Lead beneficiary:	Norwegian Institute for Water Research (NIVA)
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Date of delivery:	01-06-2022
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Date of internal approval (for the submission to EC)	31-05-2022

Involved partners

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Document history

Version	Date	Description
01	30.04.2022	V1.0 – Initial version, by Trond Kristiansen and Momme Butenschön
02	10.05.2022	V1.1 – Myron Peck
03	31-05-2022	V1.2 – Final version, by Trond Kristiansen

Suggested citation for this report: Kristiansen, *Trond, & Butenschön, Momme (2022).* An ensemble of trend preserving statistically downscaled projections for key marine variables under three different future scenarios for the Baltic Sea, the North Sea, the Bay of Biscay, the Mediterranean, and the Yucatàn Peninsula. *FutureMARES Project Deliverable report D2.1*

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List of symbols, abbreviations, and a glossary

CC Climate change

Tn.x Task – a sub-component of a work package where “n” is a number of the work package and “x” is a number of the task within this work package

WP Work Package

Introduction

This report summarizes the work performed to fulfill T2.1 of WP2 of the EU funded FutureMares project. The task description as part of the proposal was: "The goal of this task is to collect, reformat (interpolate to a common grid and store as standardized NetCDF), and organize (make data available through a cloud server) an ensemble based on available regional hindcasts, reanalysis, and projections. The best available information is compiled from international efforts (CMEMS, C3S, FishMIP, CORDEX, CMIP), previous projects (CERES, CRESECNDO), and project partners. These datasets will provide the background for analysis of the physics and biogeochemistry of the marine realm at regional levels supporting all Storylines in the project and covering the European Atlantic, all European regional seas, the Mediterranean basin, the western Caribbean, and the SE Pacific This will be achieved by creating an ensemble of products of selected variables for the past based on available hindcasts and reanalysis products (e,g, CMEMS), and for the future based on available datasets regionally downscaled from CMIP5/6 projections for scenarios RCP4.5 and 8.5 (e.g. from C3S and the CERES project). A targeted validation and analysis of the ensemble products will be used to explore the relationship between modes of natural climate variability (e.g. NAO, ENSO, AMO), physical and biogeochemical indicators defining habitat suitability (e.g. temperature, oxygen, pH, nutrient levels), and regional features of interest to identify if the model products are correctly representing in-situ and remote sensing observations (from T1.1 and collected from public data services such as CMEMS or EModNet), in terms of the past and present state, inter-annual variability and trends (e.g. using emergent constraints). Finally, estimates of model spread and bias in key indicators of the ensembles will be calculated with particular focus on the regional character of the downscaled simulations via comparison with observations and/or reanalysis products."

A number of relevant datasets that describe the past marine physical and biological conditions of the FutureMares regions are already available through the Copernicus Marine Service (https://marine.copernicus.eu/). However, a common problem is access to datasets that describes the future conditions of the marine realm, which often requires the users to be able to handle complex datasets if they are available at all. As part of the delivery for T2.1 we, therefore, created a detailed climate dataset representative across the FutureMares regions at high resolution. This dataset consists of 4 European regions; the Mediterranean, the North Sea, the Baltic Sea, and the Bay of Biscay, as well as one region in the Gulf of Mexico, the Yucátan Peninsula. The dataset was created by bias adjusting and statistically downscaling a subset of recently published CMIP6 model data.

Defining the Challenge

Climate models are used as a primary means to understand how climate has changed in the past and is expected to change in the future for a range of greenhouse gas scenarios. Climate models are complex tools that can simultaneously model the physics, chemistry, and biology of land, ocean, atmosphere, and cryosphere allowing researchers to explore their intricate relationships and dependence. For these models, expected global greenhouse gas concentrations (emerging from the Representative Concentration Pathways - RCPs) under different shared socioeconomic pathways (SSPs) up to the year 2100 (O'Neill et al. 2016) are used as input. For the 6th Intergovernmental Panel on Climate Change (IPCC) report, five narratives provide alternative socio-economic developments for the world including sustainable development (SSP1), regional rivalry (SSP3), and inequality (SSP3, SSP4), fossil-fueled development (SSP5), and middle-of-the-road development (SSP2). While in principle the two development streams of climate scenarios and socio-economic scenarios are independent, not all combinations are feasible. This dataset in particular focuses on the combinations SSP1-RCP2.6, SSP2-RCP4.5, and SSP5-RCP8.5.

An important part of the IPCC report is the analysis of output from the Coupled Model Intercomparison Project (CMIP) which simulates future climate using the described SSP narratives of future emission scenarios. The CMIP models are global in scope and cover the atmosphere, land, and ocean, which provides a wealth of invaluable broad information on a large scale. However, the relatively coarse-scale resolution of these models (1x1-degree longitude-latitude in the ocean) does not adequately resolve details of the marine regional and coastal domain, which is increasingly required for the strategic planning and management of marine resources and ecosystem services as well as for the development of climate change adaptation and mitigation policies. To provide climate projections at a more regional level we apply a statistical bias-correction (BA) and downscaling (SD) of the global CMIP6 projections. The BA corrects systematic errors in the climate data to minimize the errors between observed and modeled values for a specific control period, while the SD allows us to establish an empirical relationship between historical and large-scale climate variables and to apply these statistics to project future climate at local scales. The output is higher-resolution climate projections for a regional domain such as the European shelf seas.

Approach

To overcome the problem with coarse resolution when analyzing regional to coastal domains various downscaling approaches have been applied. While individual dynamical downscaling products exist for regional ocean domains, they lack the conceptual and standardized approach of the CMIP experiments or the CORDEX experiments available for regional atmospheric domains. This strongly inhibits the comparability of results between different systems and lacks adequate quantification of the uncertainties involved in the projections. To overcome these shortcomings, we performed a trend-preserving quantile-mapping bias adjustment and statistical downscaling. This approach produces a high-resolution climate dataset containing both the historical (1993-2021) and future projections (2022-2100). The dataset was produced using a range of CMIP6 models and ensemble members (realizations) as input to make sure we capture the uncertainty across models. The solution space for climate projections was covered by downscaling three different scenarios ranging from the green road of SSP1-2.6 to the middle of the road solution with ssp2-4.5 to the fossil-fueled development of talking the highway of SSP5-8.5 and averaging across a number of CMIP6 models (Table 1). The final high-resolution outputs produce

- Ensemble average (4-6 CMIP6 models/ensemble ids) variable statistics including the mean, min, max, and standard deviations across CMIP6 models.
- Ensemble average (4-6 CMIP6 models/ensemble ids) variable percentiles including the 2.5, 50 (median), 97.5, across CMIP6 models.

Contribution to the project

The resulting dataset of T2.1, the statistical downscaling of CMIP6 climate projections, allows FutureMares researchers access to bias-adjusted, statistically downscaled, high-resolution climate ensemble projections for the entire European coastline in addition to additional research regions such as the Yucátan Peninsula. The data available from this task provides the physical and biogeochemical habitat conditions across the project for all of its storylines. The consistency of using the same methodology in the different domains allows scientific comparisons across all regions. The dataset will contribute to a number of tasks and WPs across FutureMares, in particular WP4, WP5, and WP6.

Dissemination and Exploitation

The provided regional datasets will provide input to key analysis within FutureMares such as input to the ecosystem modeling of WP4, climate risk assessments (CRA) of WP5, and nature-based solution analysis within WP6.

The datasets are made available on Zenodo for non-commercial applications and can be utilized by researchers across the European domain. The approach used to create this dataset, i.e., the bias adjustment enables a direct comparison between climate projections for the historical period with observations, as well as a continuous timeseries for the future. The statistical downscaling enables coastal projections at the local scale to be analyzed and to identify specific regions where CC may have particularly strong impacts on the future or identify bright spots where changes will provide refugia.

Model name	***id***	***O_2 SSP1-2.6,SSP2-4.5, SSP5-8.5***			***Temperature SSP1-2.6,SSP2-4.5, SSP5-8.5***			***Chlorophyll SSP1-2.6,SSP2-4.5,SSP5-8.5***			***pH. SSP1-2.6,SSP2-4.5, SSP5-8.5***			***Salinity SSP1-2.6,SSP2-4.5, SSP5-8.5***		
IPSL-CM6A-LR *(Boucher et al. 2020)*	*r1i1p1f1*	*x*	*x*	*x*	*x*	*x*	*x*				*x*	*x*	*x*	*x*	*x*	*x*
MPI-ESM1-2-LR *(Mauritsen et al. 2019)*	*r1i1p1f1* *r2i1p1f1*	*x* *x*	*x* *x*	*x* *x*	*x* *x*	*x* *x*	*x* *x*	*x* *x*	*x* *x*	*x* *x*	*x* *x*	*x* *x*	*x* *x*	*x* *x*	*x* *x*	*x* *x*
CanESM5-CanOE *(Swart et al. 2019)*	*r1i1p2f1*	*x*	*x*	*x*	*x*	*x*	*x*	*x*	*x*	*x*				*x*	*x*	*x*
UKESM1-0-LL *(Sellar et al. 2019)*	*r1i1p1f2* *r2i1p1f2*	*x*	*x*	*x*	*x*	*x*	*x*	*x*	*x*	*x*				*x*	*x*	*x*
GFDL-ESM4 *(Dunne et al. 2020)*	*r1i1p1f1*				*x*	*x*	*x*							*x*	*x*	*x*
CMCC-ESM2 *(Lovato et al. 2022)*	*r1i1p1f1*	*x*	*x*	*x*	*x*	*x*	*x*	*x*	*x*	*x*	*x*	*x*	*x*	*x*	*x*	*x*
CMCC-CM2-SR5 *(Cherchi et al. 2018)*	*r1i1p1f1*				*x*	*x*	*x*							*x*	*x*	*x*
MIROC-ES2L *(Hajima et al. 2020)*	*r1i1p1f2*	*x*	*x*	*x*	*x*	*x*	*x*	*x*	*x*	*x*				*x*	*x*	*x*

Table 1: The CMIP6 models and scenarios used for the downscaling of the various variables and scenarios.

Methodology

The methodology for performing the bias-corrected downscaling (BASD) follows a recently published protocol (ISIMIPBASD3, (Lange 2019)) that provides a robust bias adjustment of extreme values, improved accuracy in preserving trends across quantiles, and facilitates a distinct separation between bias adjustment and statistical downscaling (Lange 2019). The BASD is performed in two steps: (i) bias correction (BA) of CMIP6 data at their original resolution, and (ii) statistical downscaling (SD) of the bias-corrected data to a 1/12th degree resolution grid. The bias correction step is important as the process that corrects the climate models for systematic errors and provides a better fit with observation; i.e. the climate models are fitted to better represent realistic values for a given area. For the BASD presented here, we use the GLORYS12V1 global reanalysis (Drévillon et al. 2021) as “observations" for temperature and salinity and the Global Ocean Biogeochemistry hindcast (GOBH) for oxygen, pH, and chlorophyll. The GOBH model uses the PISCES model to represent biogeochemistry and a non-assimilative version of GLORYS for physics (Perruche et al. 2019). The GLORYS12V1 reanalysis assimilates available historical data (e.g., satellite, CTD, XBT, buoys) for the period 1993-2020, and represents state-of-the-art hydrodynamic and biogeochemical modeling. The hydrodynamic GLORYS model (e.g. temperature, sea-ice) provides an output at 1/12th degrees resolution while the biogeochemical GLORYS model at ¼ degrees resolution (e.g. pH, oxygen, chlorophyll). To be able to easily combine datasets we interpolated and extrapolated the pH, oxygen and chlorophyll fields to the 1/12th degree grid using the Earth System Modeling Framework (ESMF). All of the final bias-corrected downscaled climate projections for any coastal domain are on a 1/12th degree grid.

Links to datasets

Ensemble projections for three scenarios SSP1-2.6, SSP2-4.5, and SSP5-8.5 are available as 5 datasets on zenodo:

https://zenodo.org/record/6524111#.Yo1COJNBzAM

https://zenodo.org/record/6524142#.Yo1CRJNBzAM

https://zenodo.org/record/6523899#.Yo1CTpNBzAM

https://zenodo.org/record/6523926#.Yo1CaJNBzAM

https://zenodo.org/record/6524164#.Yo1CcJNBzAM

We acknowledge the World Climate Research Programme's Working Group on Coupled Modelling, which is responsible for CMIP. Generated using E.U. Copernicus Marine Service Information; https://doi.org/10.48670/moi-00021, https://doi.org/10.48670/moi-00019.

Metadata

For each variable, depth, region, and climate scenario, the dataset contains two files; one `stats` file with *min*, *max*, and *mean* values, and one `perc` file with calculated *percentiles* (2.5, 50, 97.5). Each file also contains geographic coordinates (lat, lon) and bathymetric depth. Geographic projection is EPSG:4326 (WGS 84). Fill value (missing data) is set to 1.e20. Filenames follow the convention:

{variable name}_ensemble_sd+ba_{depth level/bottom}_{perc/stats}_{scenario}.nc

Below we show an example of the metadata found in the `perc` file for bottom temperature (thetao) for the Mediterranean for the SSP5-8.5 scenario:

```
netcdf thetao_ensemble_sd+ba_bottom_perc_ssp585 {
dimensions:
	percentiles = 3 ;
	time = 1284 ;
	lat = 192 ;
	lon = 528 ;
variables:
```

```
	double percentiles(percentiles) ;
		percentiles:_FillValue = 1.e+20 ;
	int64 time(time) ;
		time:units = "days since 1993-01-01 00:00:00" ;
		time:calendar = "proleptic_gregorian" ;
	double thetao(time, lat, lon, percentiles) ;
		thetao:_FillValue = 1.e+20 ;
		thetao:coordinates = "month" ;
	double depth(lat, lon, percentiles) ;
		depth:_FillValue = 1.e+20 ;
	int64 month(time) ;
	float lon(lon) ;
		lon:_FillValue = 1.e+20f ;
		lon:standard_name = "longitude" ;
		lon:long_name = "longitude" ;
		lon:units = "degrees_east" ;
	float lat(lat) ;
		lat:_FillValue = 1.e+20f ;
		lat:standard_name = "latitude" ;
		lat:long_name = "latitude" ;
		lat:units = "degrees_north" ;
	int64 spatial_ref ;
		spatial_ref:crs_wkt = "GEOGCS[\"WGS
84\",DATUM[\"WGS_1984\",SPHEROID[\"WGS
84\",6378137,298.257223563,AUTHORITY[\"EPSG\",\"7030\"]],AUTHORITY[\"EPSG\",\"632
6\"]],PRIMEM[\"Greenwich\",0,AUTHORITY[\"EPSG\",\"8901\"]],UNIT[\"degree\",0.01745329
25199433,AUTHORITY[\"EPSG\",\"9122\"]],AXIS[\"Latitude\",NORTH],AXIS[\"Longitude\",EA
ST],AUTHORITY[\"EPSG\",\"4326\"]]" ;
		spatial_ref:semi_major_axis = 6378137. ;
		spatial_ref:semi_minor_axis = 6356752.31424518 ;
		spatial_ref:inverse_flattening = 298.257223563 ;
		spatial_ref:reference_ellipsoid_name = "WGS 84" ;
		spatial_ref:longitude_of_prime_meridian = 0. ;
		spatial_ref:prime_meridian_name = "Greenwich" ;
		spatial_ref:geographic_crs_name = "WGS 84" ;
		spatial_ref:grid_mapping_name = "latitude_longitude" ;
		spatial_ref:spatial_ref = "GEOGCS[\"WGS
84\",DATUM[\"WGS_1984\",SPHEROID[\"WGS
84\",6378137,298.257223563,AUTHORITY[\"EPSG\",\"7030\"]],AUTHORITY[\"EPSG\",\"632
6\"]],PRIMEM[\"Greenwich\",0,AUTHORITY[\"EPSG\",\"8901\"]],UNIT[\"degree\",0.01745329
25199433,AUTHORITY[\"EPSG\",\"9122\"]],AXIS[\"Latitude\",NORTH],AXIS[\"Longitude\",EA
ST],AUTHORITY[\"EPSG\",\"4326\"]]" ;
```

Summary figures

The following shows the area integrated ensemble projections for the four European regions Baltic Sea, North Sea, Bay of Biscay, and the Mediterranean, and for the Yucátan peninsula in the Gulf of Mexico. The timeseries show (CMIP6 name in parentheses) monthly values annually-averaged for salinity (**so**), chlorophyll (**chl**), temperature (**thetao**), pH (**ph**), and oxygen (**o2**) for surface (5 m depth). Thick lines and shaded regions indicate the mean value and the 95th percentile across a subset of CMIP6 models: MIROC-ES2L, MPI-ESM1-2-LR, CMCC-ESM2, IPSL-CM6A-LR, CMCC-CM2-SR5, CanESM56-CanOE, UKESM1-0-LL, GFDL-ESM4 (not all variables like chlorophyll and oxygen are available for all models; see Table 1) for three future scenarios SSP1-2.6, SSP2-4.5, and SSP5-8.5. All variables were downscaled for 5 and 25m and bottom depths, except chlorophyll which was restricted to 5 and 25 m depth levels.

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Figure 7: The Yucátan Peninsula timeseries

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Table 1: Table showing the CMIP6 models and scenarios used for the downscaling

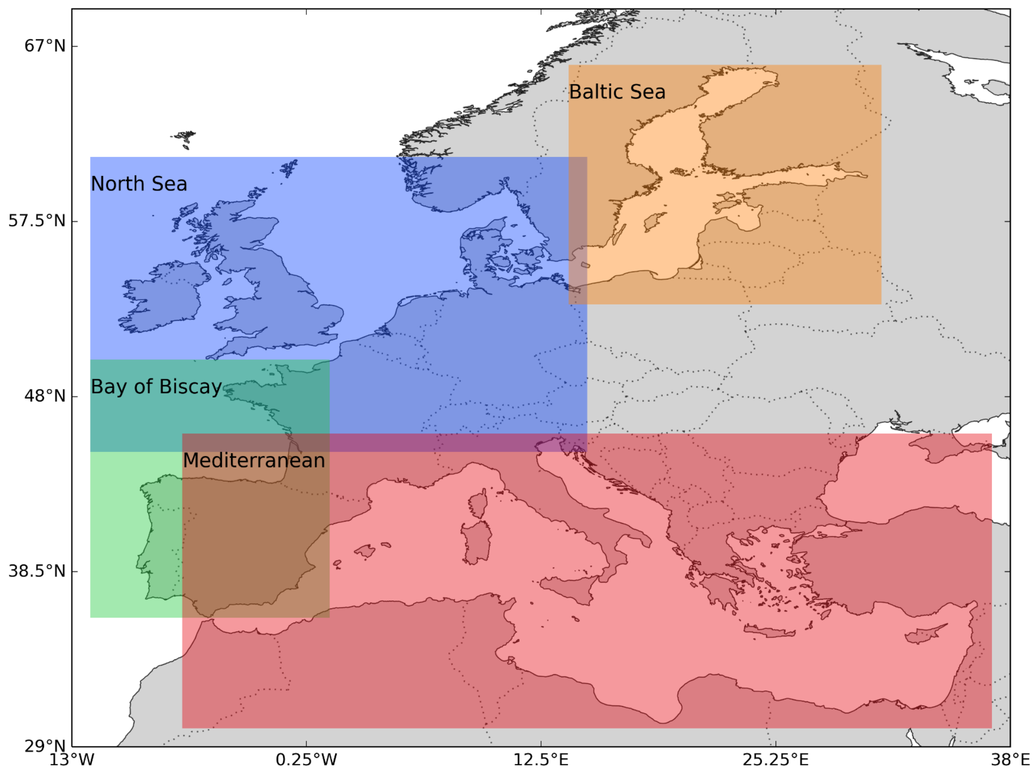

Figure 1: Map showing the 4 FutureMares European regions for statistical downscaling of CMIP6 modeled projections; the Baltic Sea (brown), the North Sea (blue), the Bay of Biscay (green), and the Mediterranean (red).

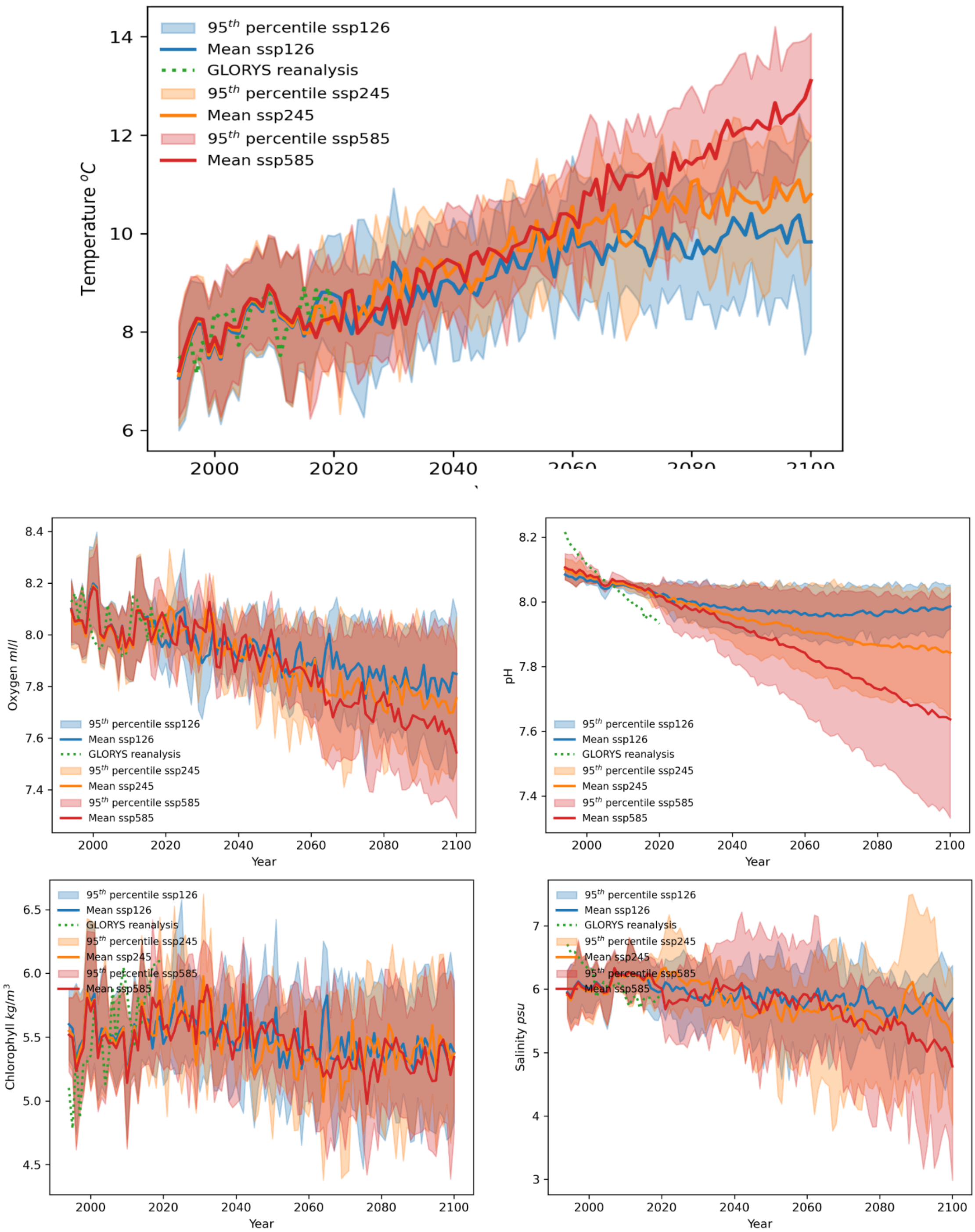

Figure 2: Temperature (°C, top), oxygen (ml/l, mid-left), pH (mid-right), chlorophyll (kg/m^3, bottom-left), and salinity (psu, bottom right) integrated across the Baltic Sea region for three scenarios SSP1-2.6, SSP2-4.5, and SSP5-8.5. The 95th percentiles are shaded around the mean values (thicker lines). Green lines indicate the GLORYS reanalysis for the historical period 1993-2019.

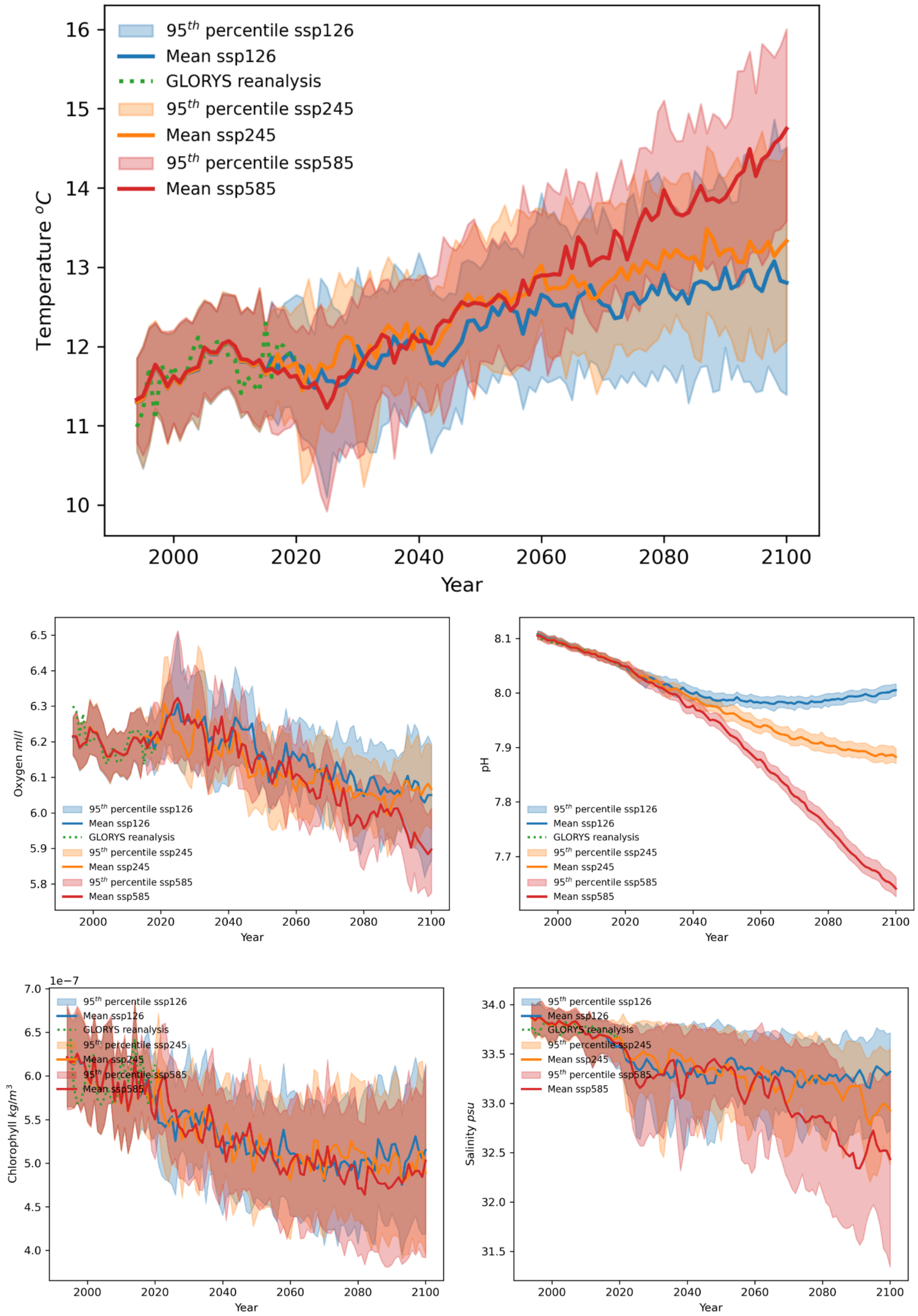

Figure 3: Temperature (°C, top), oxygen (ml/l, mid-left), pH (mid-right), chlorophyll (kg/m^3, bottom-left), and salinity (psu, bottom right) integrated across the North Sea region for three scenarios SSP1-2.6, SSP2-4.5, and SSP5-8.5. The 95th percentiles are shaded around the mean values (thicker lines). Green lines indicate the GLORYS reanalysis for the historical period 1993-2019.

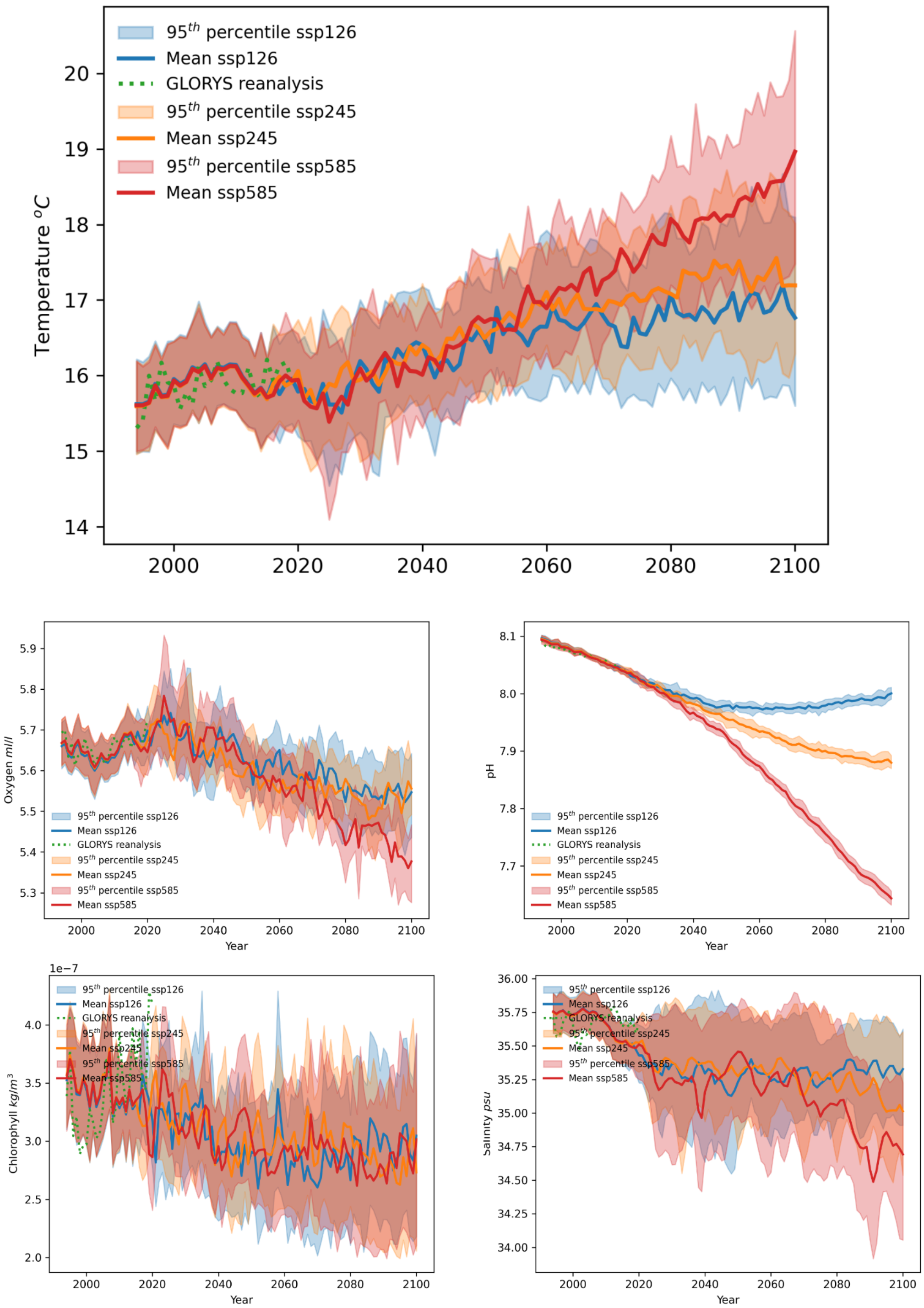

Figure 4: Temperature (°C, top), oxygen (ml/l, mid-left), pH (mid-right), chlorophyll (kg/m^3, bottom-left), and salinity (psu, bottom right) integrated across the Bay of Biscay region for three scenarios SSP1-2.6, SSP2-4.5, and SSP5-8.5. The 95th percentiles are shaded around the mean values (thicker lines). Green lines indicate the GLORYS reanalysis for the historical period 1993-2019.

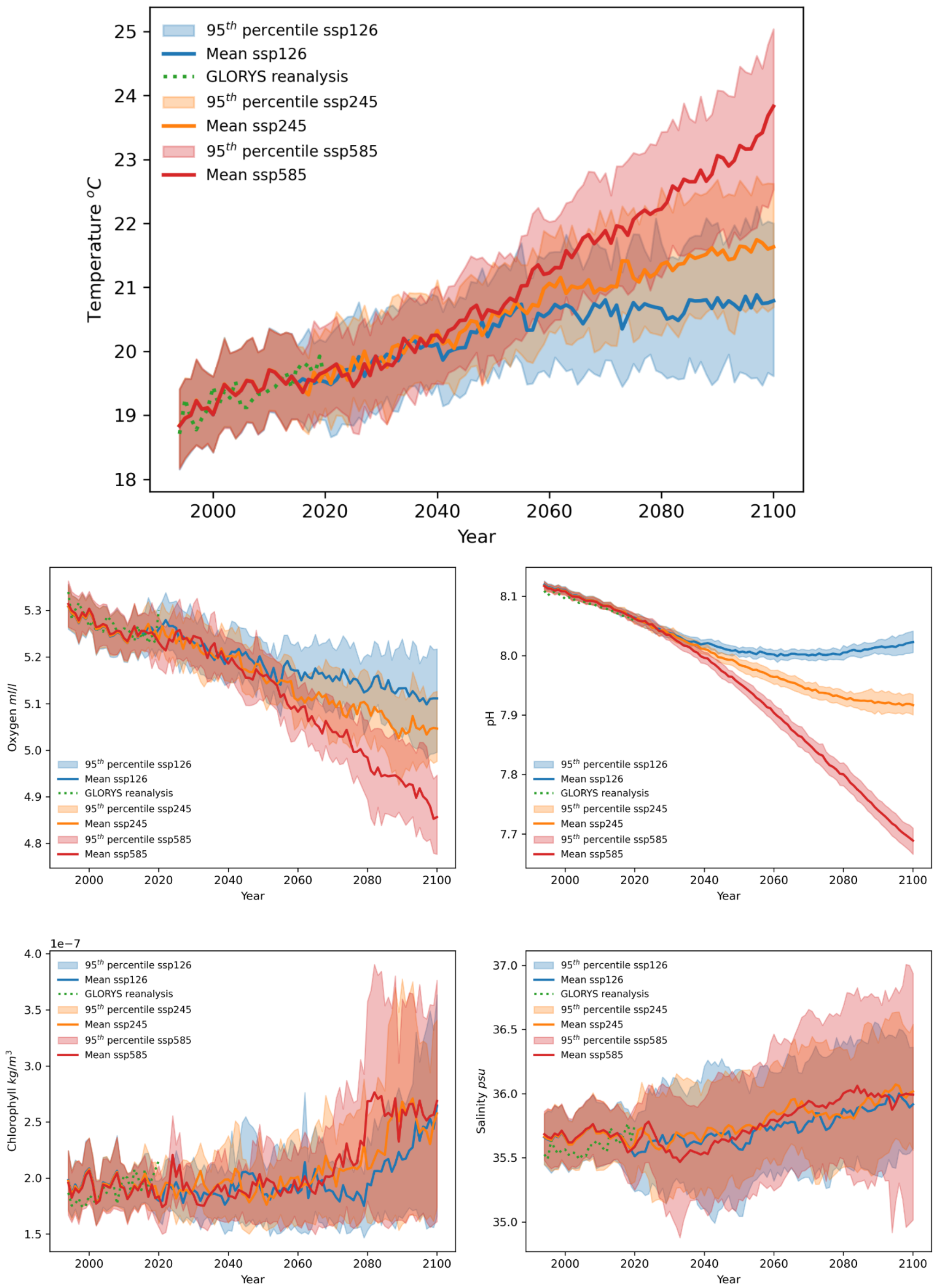

Figure 5: Temperature (ºC, top), oxygen (ml/l, mid-left), pH (mid-right), chlorophyll (kg/m^3, bottom-left), and salinity (psu, bottom right) integrated across the Mediterranean for three scenarios SSP1-2.6, SSP2-4.5, and SSP5-8.5. The 95th percentiles are shaded around the mean values (thicker lines). Green lines indicate the GLORYS reanalysis for the historical period 1993-2019.

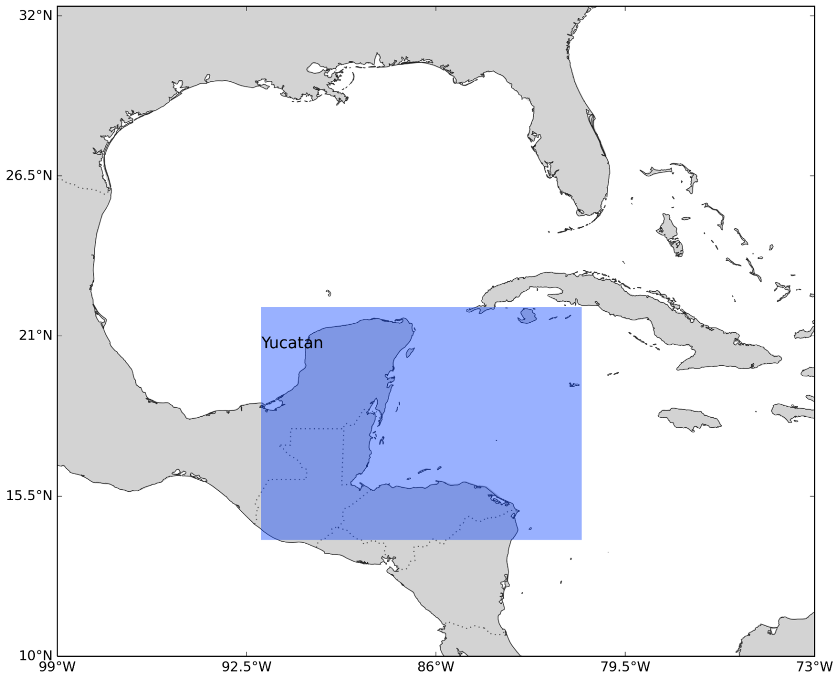

Figure 6: Map of the Yucàtan region used for statistical downscaling of CMIP6 projections. For this region, projections of pH, oxygen, and temperature are provided.

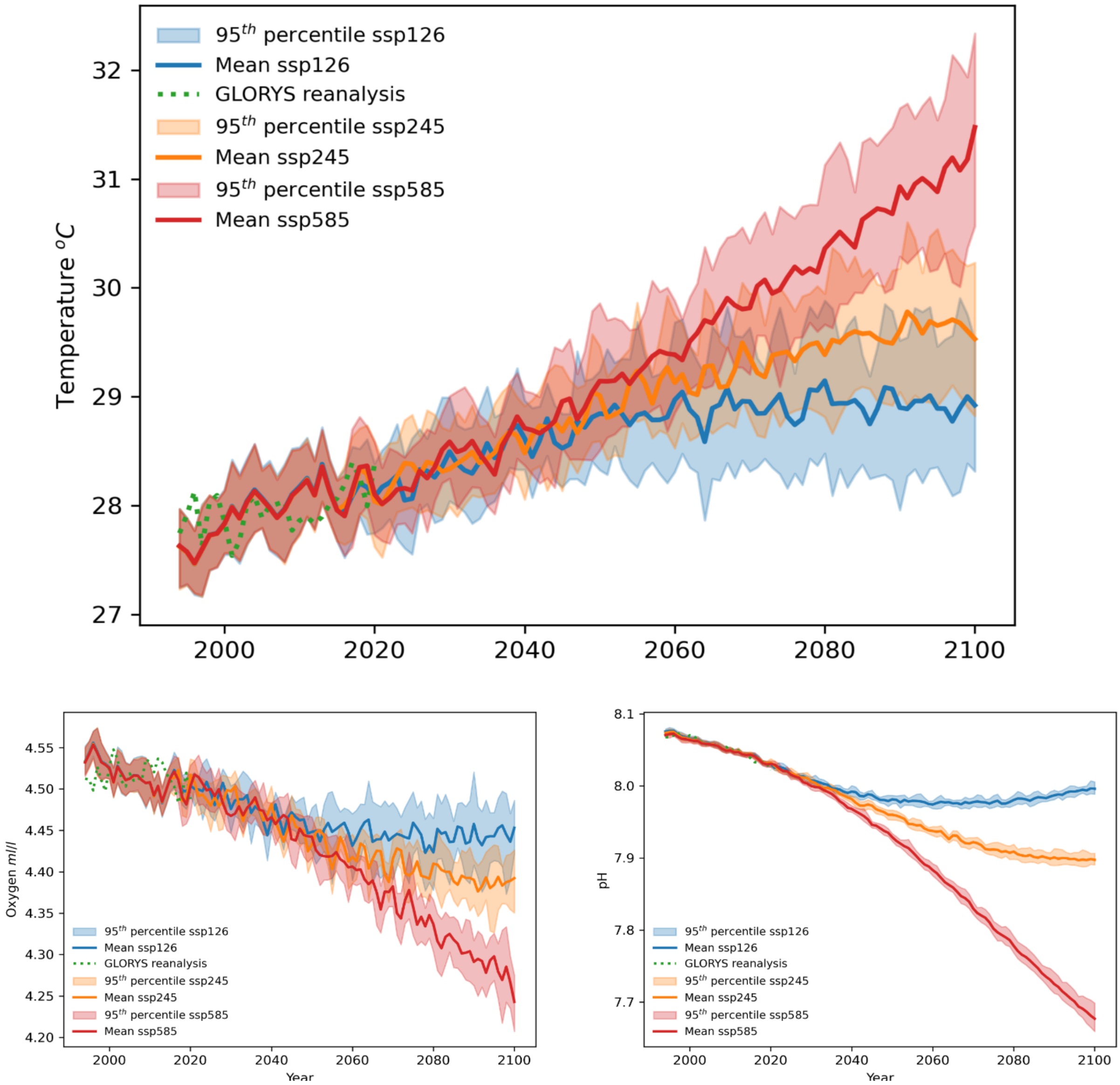

Figure 7: Temperature (ºC, top), oxygen (ml/l, left), and pH (right) integrated across the Yucatan region for three scenarios SSP1-2.6, SSP2-4.5, and SSP5-8.5. The 95th percentiles are shaded around the mean values (thicker lines). Green lines indicate the GLORYS reanalysis for the historical period 1993-2019.

References

Boucher, Olivier, Jérôme Servonnat, Anna Lea Albright, Olivier Aumont, Yves Balkanski, Vladislav Bastrikov, Slimane Bekki, et al. 2020. "Presentation and Evaluation of the IPSL-CM6A-LR Climate Model." *Journal of Advances in Modeling Earth Systems* 12 (7). https://doi.org/10.1029/2019ms002010.

Cherchi, A., P. G. Fogli, T. Lovato, D. Peano, D. Iovino, S. Gualdi, S. Masina, et al. 2018. "Global Mean Climate and Main Patterns of Variability in the CMCC-CM2 Coupled Model." *Journal of Advances in Modeling Earth Systems*, no. 2018MS001369 (December). https://doi.org/10.1029/2018ms001369.

Drévillon, M., J-M Lellouche, C. Régnier, G. Garric, C. Bricaud, O. Hernandez, and R. Bourdallé-Badie. 2021. "QUID For Global Ocean Reanalysis Products GLOBAL-REANALYSIS-PHY-001-030." *Copernicus.eu*. marine.cmems.eu. https://catalogue.marine.copernicus.eu/documents/QUID/CMEMS-GLO-QUID-001-030.pdf.

Dunne, J. P., L. W. Horowitz, A. J. Adcroft, P. Ginoux, I. M. Held, J. G. John, J. P. Krasting, et al. 2020. "The GFDL Earth System Model Version 4.1 (GFDL-ESM 4.1): Overall Coupled Model Description and Simulation Characteristics." *Journal of Advances in Modeling Earth Systems* 12 (11). https://doi.org/10.1029/2019ms002015.

Hajima, Tomohiro, Michio Watanabe, Akitomo Yamamoto, Hiroaki Tatebe, Maki A. Noguchi, Manabu Abe, Rumi Ohgaito, et al. 2020. "Development of the MIROC-ES2L Earth System Model and the Evaluation of Biogeochemical Processes and Feedbacks." *Geoscientific Model Development* 13 (5): 2197–2244.

Lange, Stefan. 2019. "Trend-Preserving Bias Adjustment and Statistical Downscaling with ISIMIP3BASD (v1.0)." *Geoscientific Model Development* 12 (7): 3055–70.

Lovato, T., D. Peano, M. Butenschön, S. Materia, D. Iovino, E. Scoccimarro, P. G. Fogli, et al. 2022. "CMIP6 Simulations with the CMCC Earth System Model (CMCC-ESM2)." *Journal of Advances in Modeling Earth Systems* 14 (3). https://doi.org/10.1029/2021ms002814.

Mauritsen, Thorsten, Jürgen Bader, Tobias Becker, Jörg Behrens, Matthias Bittner, Renate Brokopf, Victor Brovkin, et al. 2019. "Developments in the MPI-M Earth System Model Version 1.2 (MPI-ESM1.2) and Its Response to Increasing CO2." *Journal of Advances in Modeling Earth Systems* 11 (4): 998–1038.

O'Neill, Brian C., Claudia Tebaldi, Detlef P. van Vuuren, Veronika Eyring, Pierre Friedlingstein, George Hurtt, Reto Knutti, et al. 2016. "The Scenario Model Intercomparison Project (ScenarioMIP) for CMIP6." *Geoscientific Model Development* 9 (9): 3461–82.

Perruche, C., C. Szczypta, J. Paul, and M. Drévillon. 2019. "QUID for Global Ocean Biogeochemistry Hindcast." GLOBAL_REANALYSIS_BIO_001_029. marine.cmems.eu. https://resources.marine.copernicus.eu/documents/QUID/CMEMS-GLO-QUID-001-029.pdf.

Sellar, Alistair A., Colin G. Jones, Jane P. Mulcahy, Yongming Tang, Andrew Yool, Andy Wiltshire, Fiona M. O'Connor, et al. 2019. "UKESM1: Description and Evaluation of the U.k. Earth System Model." *Journal of Advances in Modeling Earth Systems* 11 (12): 4513–58.

Swart, Neil C., Jason N. S. Cole, Viatcheslav V. Kharin, Mike Lazare, John F. Scinocca, Nathan P. Gillett, James Anstey, et al. 2019. "The Canadian Earth System Model Version 5 (CanESM5.0.3)." *Geoscientific Model Development* 12 (11): 4823–73.