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## D3.4 Synthesis report for Climate Simulations

### Part 1: Global

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## 1. Science questions

The main goal of this study is to develop a coupled model system to predict ecosystem response to climate change, from plankton to fish, at a global scale. This provided future scenarios to be compared and synthesized with region-based simulations.

## 2. Models

### *2.1. Lower Trophic Level Model: PISCES*

PISCES (Pelagic Interaction Scheme for Carbon and Ecosystem Studies) is described in Aumont and Bopp (2006). Here, only a brief summary of its entire description is given.

“PISCES is constructed on the assumption that phytoplankton growth is directly limited by the external availability in nutrients (Monod, 1942). This choice was mostly dictated by the computing cost as PISCES has been designed to suit a wide range of temporal and spatial scales, including quasi steady state simulations on the global scale.

The model has 24 compartments. Phytoplankton growth can be limited by five different nutrients: nitrate, ammonium, phosphate, silicate and iron. Four living pools are represented: two phytoplankton size classes/groups (nanophytoplankton and diatoms) and two zooplankton size classes (microzooplankton and mesozooplankton). Diatoms differ from nanophytoplankton by their need in Si, by higher requirements in Fe (Sunda and Huntsman, 1995) and by higher half-saturation constants because of their larger mean size. For all living compartments, the ratios between C, N and P are kept constant to the values proposed by Takahashi et al. (1985). On the other hand, the internal contents in Fe of both phytoplankton groups and in Si of diatoms are prognostically simulated as a function of the external concentrations in nutrients and of the light level. The Chl/C ratio is modeled using a modified version of the photoadaptation model by Geider et al. (1998). All the elemental ratios of zooplankton are kept constant. There are three nonliving compartments: semilabile dissolved organic matter (with timescales of several weeks to several years), small and big sinking particles. The two particle size classes differ by their sinking speeds (3 m/d for the small size class and 50 to 200 m/d for the large size class). As for the living compartments, constant Redfield ratios are imposed for C/N/P. However, the iron, silicon and calcite pools of the particles are fully simulated. As a consequence, their ratios relative to organic carbon are allowed to vary. The impact of ballast minerals on particles sinking speeds is not accounted for in the model (e.g., Armstrong et al., 2002).

Nutrients are supplied to the ocean from three different sources: atmospheric dust deposition, rivers and sediment mobilization. These sources are explicitly modeled and are extensively described in the supplementary material. Thus, only the main aspects are presented here. Iron deposition from the atmosphere has been estimated from the climatological monthly maps of dust deposition simulated by the model of Tegen and Fung (1995) assuming constant values for the iron content and the solubility (e.g., Jickells and Spokes, 2001; Moore et al., 2004). River discharge of carbon is taken from the Global

Erosion Model (GEM) of Ludwig et al. (1996). Fe, N, P and Si supplies are derived from the same model output by considering globally constant Fe/P/N/Si/C ratios in the rivers. Reductive mobilization of iron from marine sediments has been recognized as a significant source to the ocean (e.g., Johnson et al., 1999; de Baar and de Jong, 2001) and is parameterized in a way similar to Moore et al. (2004). PISCES has been used, at the global scale, to study past climates (Bopp et al. 2003), to understand the mechanisms that explain interannual variability in marine productivity (Aumont et al. 2008) or ocean-atmosphere carbon fluxes (Rodgers et al. 2008), to assess the impact of climate change or ocean acidification on marine ecosystems and air-sea carbon fluxes (Bopp et al. 2001, Orr et al. 2005), to evaluate geo-engineering strategies to mitigate climate change (Aumont and Bopp, 2006, Dutreuil et al., 2009).

## **2.2. Higher Trophic Level Model : APECOSM**

APECOSM (Apex Predators ECOSystem Model) is detailed in Maury et al. (2007a,b). It has been coupled recently to the PISCES model (Aumont et al. in prep). PISCES-APECOSM has been used in the frame of the French ANR-MACROES project (PI : O. Aumont, O. Maury, L. Bopp) to project the potential impact of climate change on marine upper trophic levels at the global scale. To do so, output of a climate simulation performed with the IPSL-CM5 (Dufresne et al. in rev) model have been used, but the scenario and the climate model are different from the ones used in the frame of MEECE (RCP85 vs SRES-A1B, and IPSL-CM5A vs IPSL-CM4-v2).

We give here a brief and very general description of APECOSM as presented in Maury et al. (2010). APECOSM is a spatially explicit size-based model of open-ocean ecosystems developed in the framework of the GLOBEC-CLIoTOP synthesis and modelling Working Group. APECOSM uses a size-based approach as a practical way to obtain a realistic representation of both the non target organisms (components called OOPC for Open Ocean Pelagic Communities) and the focus species while keeping the functional complexity limited. In this way, the concept constitutes a concrete implementation of the rhomboid approach to model marine ecosystems as described by deYoung et al. (2004).

APECOSM integrates various physiological, behavioural and ecological processes acting on a variety of scales. It represents the basin wide spatial dynamics of open ocean pelagic ecosystems from phytoplankton production up to fishing, with a special emphasis on predators. APECOSM is mass conservative. It adopts a process based approach where parameterizations are derived mechanistically and where parameters are biological, physiological or behavioural meaningful constants. Physical forcings (temperature and current), biogeochemical forcings (primary and secondary production, light and oxygen fields) as well as the effects of fishing are explicitly taken into account and constrain the dynamics at various levels.

### **3. Scenarios: model validation and projections**

No hindcast simulations have been performed specifically for MEECE. However, several hindcast simulations have been carried out with the PISCES model and have been used to validate / evaluate the model (e.g. Aumont et al. 2008, Rodgers et al; 2008).

To perform the biogeochemical (PISCES only) and biogeochemical / ecosystem (PISCES-APECOSM) projections, we used an offline approach, i.e. the biogeochemical / ecosystem model is forced with monthly outputs of the climate model.

- Physical / Dynamical variables used to force the “offline” model are: 3-D ocean temperature and salinity, 3-D ocean currents (U,V,W), 3-D vertical diffusion coefficients, surface winds, net short wave radiation, freshwater flux, mixed layer depth.
- Simulations start from a pre-industrial spin-up run of 3000-yr long, using a climatological pre-industrial year from the climate model.
- Simulations are run transiently from 1860 to 2100 using an historical climate simulation followed by a future scenario (SRES-A1B, RCP85).
- Only years 1980-to-2000 and years 2080-to-2099 are kept for the subsequent analysis.

No downscaling method has been applied.

### **4. Metrics considered**

- Temperature (SST (°C)) (absolute difference)
- Acidification: pH (surface) (fractional change)
- Nutrients (fractional change)
- Phytoplankton (small and large, Biomass Depth integrated (mg/m<sup>2</sup>) (fractional change)
- Net Primary Production Depth integrated (mg/m<sup>2</sup>/d) (fractional change)
- Zooplankton (small and large, Biomass Depth integrated, mg/m<sup>2</sup>) (fractional change)
- HTL (total biomass (t) of all fish species considered in the region) (fractional change)

## **5. Results and Discussion**

### ***5.1 Hindcast validation***

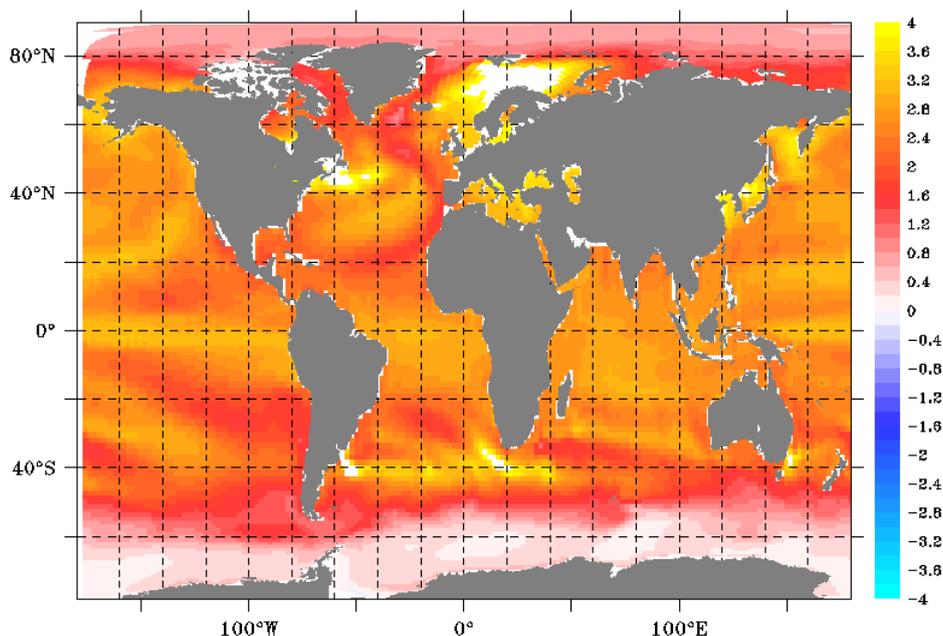
No specific hindcast simulations have been performed in the framework of the MEECE project. Several hindcast simulations, however, have been performed with the same model version of PISCES and presented / published elsewhere (e.g. Aumont et al. 2008, Rodgers et al. 2008).

## 5.1 Climate forced simulations

All results discussed below are related to the SRES-A1B scenario also used also for the other regional systems. Only the HTL results come from a different scenario (RCP85) and a different model set-up (coupled PISCES-APECOSM).

### *Physical and chemical changes*

The global mean change in Sea Surface Temperature is expected to increase 2.29 °C by 2080-2099, relative to 1980-1999. Spatially, the change is always positive, but large regions show only moderate warming (e.g. along the Antarctic continent), whereas other regions show much substantial warming (e.g. in the Barents Sea, in the Gulf Stream region with warming of more than 4°C at the end of the century). These changes are very similar to other climate model projections for the same scenario (see IPCC-AR4, 2007).



*Figure 1. Change in SST (2080-2999 minus 1980-1999) (°C).*

In 2080-2099 relative to 1980-1999, the global mean change in Sea Surface pH is expected to decrease (-0.2388). Spatially, the change is always negative, and more homogeneous than for SST changes. Regions showing the largest changes in surface pH are the Arctic Ocean (down to -0.4 locally) and the North Atlantic. The Equatorial Pacific, the North Pacific, the Southern Ocean show more moderate changes (between -0.15 and -0.20). These changes are very similar to other biogeochemical model projections for the same scenario (see Orr et al. 2011).

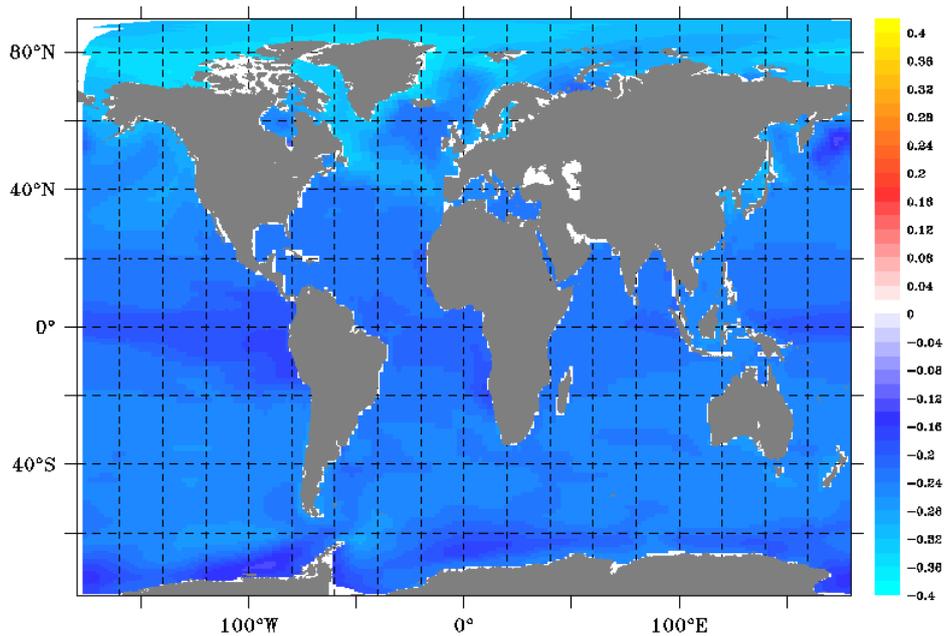


Figure 2. Change in pH (2080-2099 minus 1980-1999).

*Lower trophic level changes: Net primary production*

In 2080-2099 and as compared to 1980-1999, the global mean change in Net Primary Production is  $-32 \text{ mgC/m}^2/\text{d}$  ( $-9.2\%$ ), from  $322.5$  to  $293 \text{ mgC/m}^2/\text{d}$  (Fig. 3). A Kruskal-Wallis test on the 20 annual-mean values returns a p-value of  $6.302\text{e-}08$ . Spatially, the changes from 1980-1999 to 2080-2099 are not homogeneous (Fig 3). Regions where the decrease in NetPP is more pronounced are the tropical oceans (Indian, Atlantic, West pacific), and the eastern North Atlantic ( $40^\circ\text{N}$ - $60^\circ\text{N}$ ). Some regions show increase of NetPP with climate change: the Southern Ocean, the Eastern Equatorial Pacific and the Arctic Ocean. Seasonally, and apart from this global mean decrease, no significant changes are simulated (Fig 4).

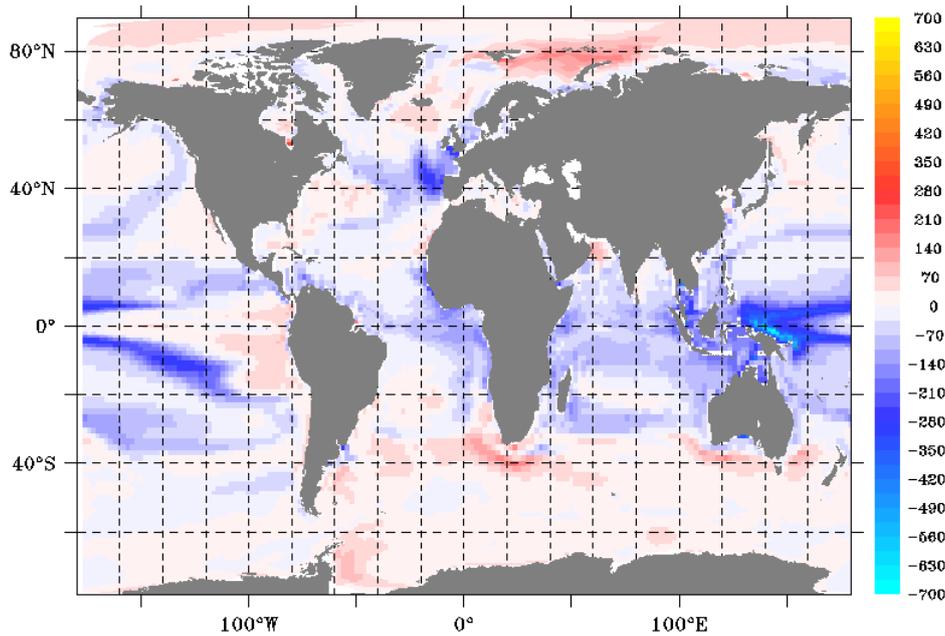


Figure 3. Change in NetPP (2080-2099 minus 1980-1999) ( $\text{mgC}/\text{m}^2/\text{d}$ ).

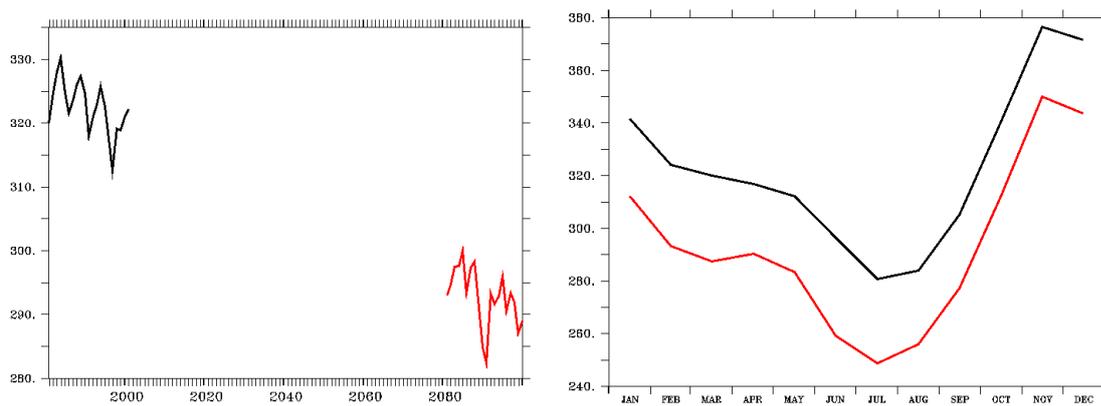


Figure 4. Time Series of Net Primary Productivity ( $\text{mgC}/\text{m}^2/\text{d}$ ) over 1980-1999 (in black) and 2080-2099 (in red). Annual-mean (left) and mean seasonal cycle (right) over the respective period.

These changes and their drivers, as well as a comparison to other climate-marine biogeochemical simulations have been discussed in Steinacher et al. (2010) and Henson et al. (2010). In brief, the mechanisms responsible for the changes can be assigned to 2 different regimes:

- A first chain of mechanisms is dominant in the low- and mid-latitude ocean and in the North Atlantic: reduced input of macro-nutrients into the euphotic zone related to enhanced stratification, reduced mixed layer depth, and slowed circulation causes a decrease in macro-nutrient concentrations and in NetPP.

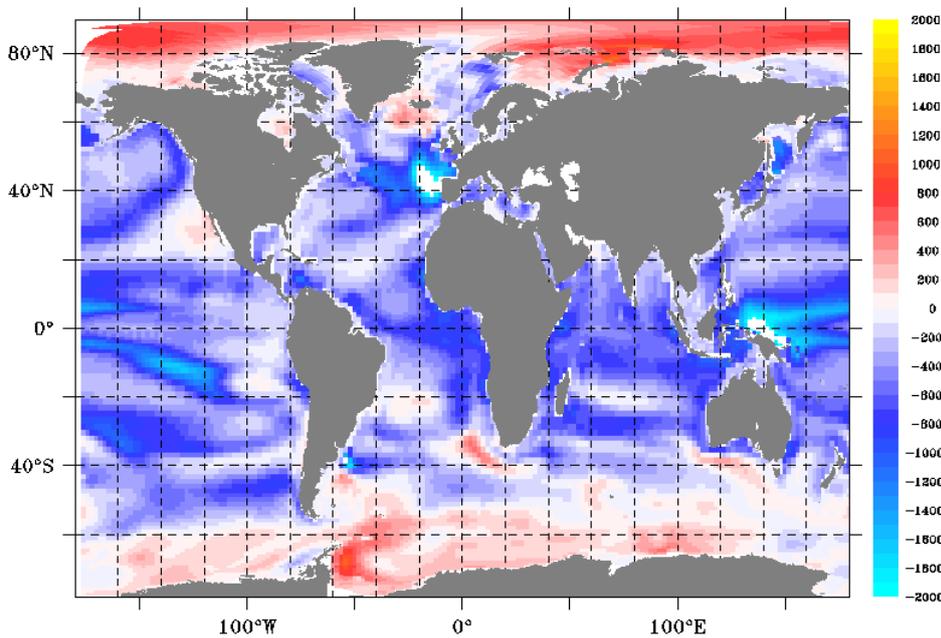
- The second regime is projected for parts of the Southern Ocean: an alleviation of light and/or temperature limitation leads to an increase in NetPP as productivity is fuelled by a sustained nutrient input.

In other regions (e.g. the Arctic Ocean, the Eastern Pacific Ocean), models disagree with projected decrease / increase of NetPP with climate change. The mechanisms and drivers explaining the disagreement are yet not clear and analysis is underway with the new CMIP5 database.

*Lower trophic level changes: Zooplankton Biomass*

In 2080-2099, relative to 1980-1999, the global mean change in zooplankton biomass is expected to decrease 10.7%, from 3354 to 2993 mgC/m<sup>2</sup>. A Kruskal-Wallis test on the 20 annual-mean values returns a p-value of 6.302e-08. Globally, the change in zooplankton biomass is of the same order of magnitude of the one simulated for NetPP.

As for Net Primary Productivity, changes in zooplankton biomass are not homogeneous with regions showing decrease (North Atlantic, tropical oceans) and regions showing increase (Southern Ocean, Arctic Ocean). Interestingly, some regions show opposite responses of NetPP and Zoo Biomass to simulated climate change (e.g. the eastern Equatorial Pacific).



*Figure 5. Change in Zooplankton Biomass (2080-2099 minus 1980-1999, z-integrated) (mgC/m<sup>2</sup>).*

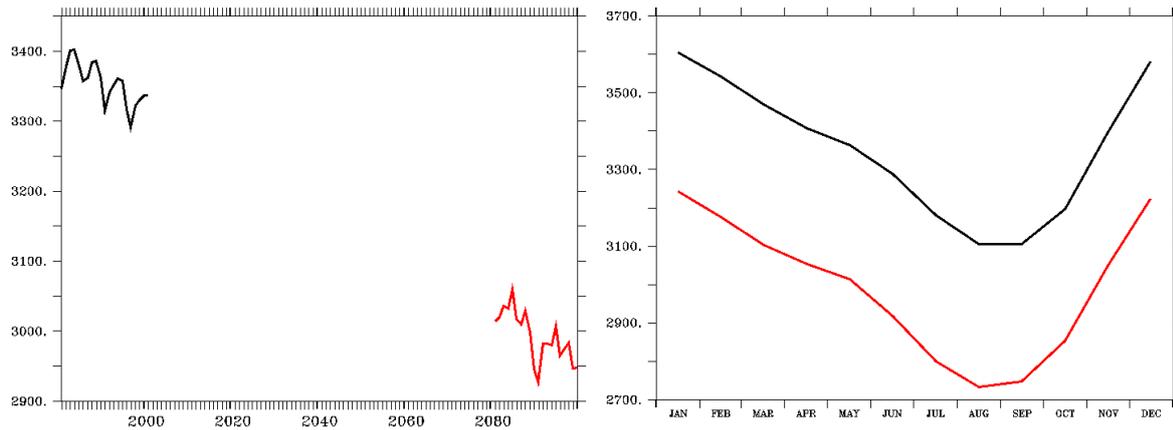


Figure 6. Time Series of zooplankton biomass (mgC/m<sup>2</sup>) over 1980-1999 (in black) and 2080-2099 (in red). Annual-mean (left) and mean seasonal cycle (right) over the respective period.

#### Higher trophic level: Integrated Fish Biomass

No HTL model has been used as part of the standard MEECE simulations performed at the global scale (as planned in the DoW). Nevertheless, we report here on early simulations using the coupled PISCES-APECOSM system, developed in the framework of another project (ANR-MACROES). These simulations have been performed forced by a more recent version of the IPSL-CM model (IPSL-CM5A, Dufresne et al. in rev, S  f  rian et al. 2012) and for another scenario (RCP85) than the MEECE-chosen A1B scenario.

In 2080-2095 and as compared to 1980-1999, the global mean change in fish biomass is -0.45 gC/m<sup>2</sup> (-17.6 %), from 2.56 to 2.10 gC/m<sup>2</sup>. A Kruskal-Wallis test on the 15-to-20 annual-mean values returns a p-value of 1.403e-08. Globally, the change in fish biomass is a slightly more pronounced than changes in phytoplankton and zooplankton biomasses for the same scenario / same simulation, suggesting some amplification of climate change-driven modifications of trophic level biomasses through a bottom-up control.

We also note very high relative sensitivity of integrated fish biomass in the North and North-East Atlantic, with decreases of down to -50% in 2080-2095 as compared to 1980-1999.

Also, different responses of the 3 Open Ocean Pelagic Communities (OOPC) are simulated: large decrease for epi-pelagic and meso-pelagic communities while the migrant communities only decreases slightly. Analysis is underway.

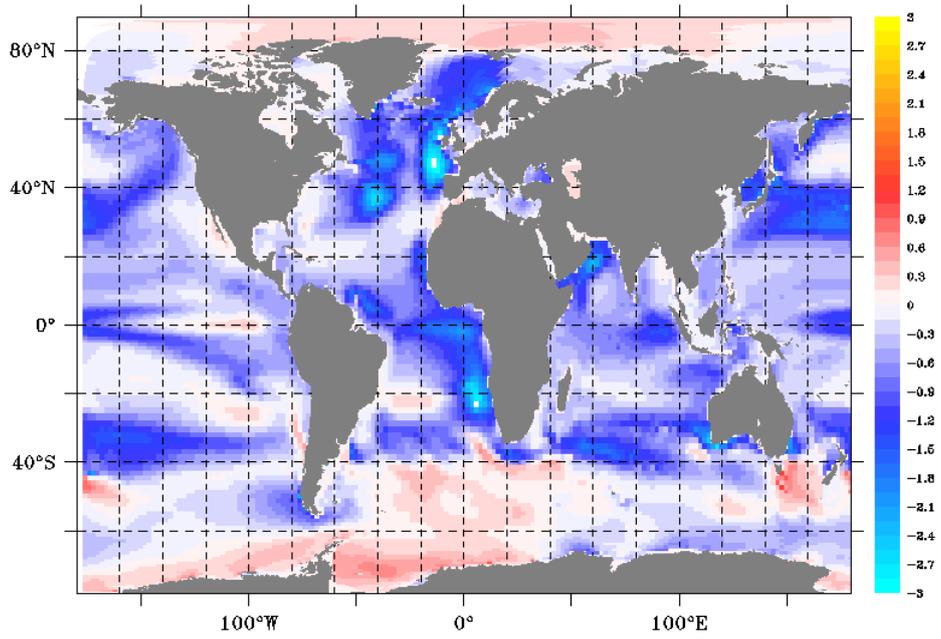


Figure 7. Change in Fish Biomass (2080-2095 minus 1980-1999, vertically integrated) (gC/m<sup>2</sup>) (note : RCP85 scenario).

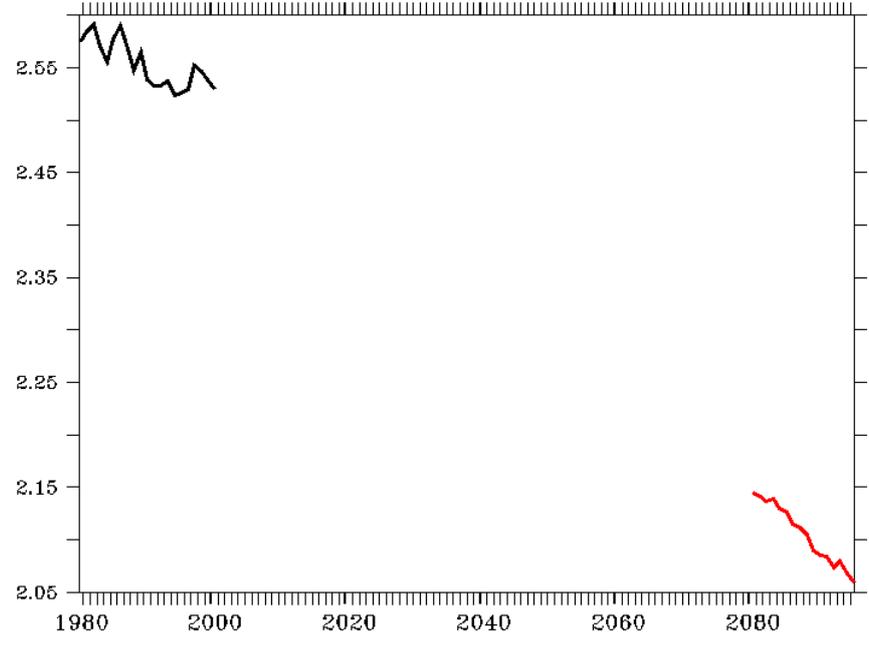


Figure 8. Time Series of annual mean fish biomass (gC/m<sup>2</sup>) over 1980-1999 (in black) and 2080-2099 (in red).

## 6. Concluding remarks

### *Main climate projections and ecosystem responses*

- **Oceanic warming.** The global mean change in sea surface temperature is expected to increase 2.29 °C by 2080-2099, relative to 1980-1999, under climate change A1B scenario (Table 1). Warming is expected all over the oceans, although large regions show only moderate warming (e.g. surrounding Antarctic continent), whereas other regions show much substantial warming (e.g. in the Barents Sea, in the Gulf Stream region with warming of more than 4°C at the end of the century).
- **Acidification.** Global sea surface oceans are expected to suffer acidification (mean pH change of -0.239) by 2080-2099, relative to 1980-1999 (Table 1). Regions showing the largest changes in surface pH are the Arctic Ocean (down to -0.4 locally) and the North Atlantic. The Equatorial Pacific, the North Pacific, the Southern Ocean show more moderate changes between -0.15 and -0.20.
- **Lower trophic level.** Global net primary production is expected to decrease 9.2% on average by the end of the century (Table 1), with high spatial variability. Strong decrease in primary production is expected within tropical oceans (Indian, Atlantic, West pacific), and the eastern North Atlantic (40°N-60°N). Some regions show increase of net primary production with climate change: the Southern Ocean, the Eastern Equatorial Pacific and the Arctic Ocean. The mechanisms responsible for the changes can be associated to two different regimes (Steinacher et al. 2010, and Henson et al. 2010): 1) A regime dominant in the low- and mid-latitude ocean and in the North Atlantic: reduced input of macro-nutrients into the euphotic zone related to enhanced stratification, reduced mixed layer depth, and slowed circulation causes a decrease in macro- nutrient concentrations and in net primary production. 2) The second regime is projected for parts of the Southern Ocean: an alleviation of light and/or temperature limitation leads to an increase in net primary production as productivity is fuelled by a sustained nutrient input. Global mean zooplankton biomass is expected to decrease 10.7% on average by the end of the century. The future change in zooplankton biomass is of the same order of magnitude and similar spatial distribution than that expected by primary production. However, some regions show opposite responses of primary production and zooplankton biomass to simulated climate change such as the eastern Equatorial Pacific.
- **Higher trophic level.** The global mean change in fish biomass is expected to decrease 17.6%, from 2.56 to 2.10 gC/m<sup>2</sup> by the end of the century (2080-2095, relative to 1980-1999) under RCP85 scenario (Table 1). The change in fish biomass is slightly more pronounced than changes in primary production and zooplankton biomass, suggesting a potential amplification of climate change-driven modifications of trophic level biomasses through a bottom-up control. High relative sensitivity of integrated fish biomass was found in the North and North-East Atlantic, with decreases of down to -50% in 2080-2095 as compared to 1980-1999.

### *Impact to MSFD descriptors*

- **Biological diversity.** Global oceanic warming is expected to lead a decrease in the biomass of main three trophic levels (phytoplankton, zooplankton and fish). This might have consequences on biodiversity distribution patterns, species poleward shifts, and the size-structure patterns of species communities.
- **Food webs.** Global oceanic warming is expected to lead to a decrease in the mean biomass of phytoplankton and zooplankton, which in turn appears to be amplified to higher trophic levels. This change in food webs structure might have important and unpredictable consequences in top predators.
- **Hydrographical conditions.** Global oceanic warming is expected to drive two different hydrographical processes that lead to different productivity regimes : 1) A regime dominant in the low- and mid-latitude ocean and in the North Atlantic: reduced input of macro-nutrients into the euphotic zone related to enhanced stratification, reduced mixed layer depth, and slowed circulation causes a decrease in macro- nutrient concentrations and in net primary production; 2) The second regime is projected for parts of the Southern Ocean: an alleviation of light and/or temperature limitation leads to an increase in net primary production as productivity is fuelled by a sustained nutrient input.
- **Exploited fish and shellfish.** Global oceanic warming is expected to drop 17.6% of fish biomass by the end of the century. This has a direct consequence on global fish stocks and the total amount of fish catches. Since spatial distribution is highly variable, local fisherman might be severely impacted.

Table 1. Global change of main oceanic variables and ecosystem response at 2080-2100 relative to 1980-2000 (Scenario A1B, except for HTL). Legend: For model uncertainty (based on hindcast validation), Low: the model describes interannual, seasonal and spatial variability appropriately, Medium: the model describes the general observed seasonal and spatial variability, High: the model fails in describing the general pattern (seasonal and spatial). For spatial variability, Low: most of areas with same trends, High: some areas with opposite trends with respect to others. Units: SST (°C), pH (surface), netPP: Net Primary Production Depth integrated (mg C/m<sup>2</sup>/d), Zooplankton (biomass depth integrated) (mg C/m<sup>2</sup>), HTL (total biomass of all fish species considered). Range is expressed in Percentile 25 and Percentile 75. Absolute change for SST and pH. Fractional change for netPP, Zooplankton biomass and HTL.

	Change range at 2080-2100 relative to 1980-2000				
	SST	pH	netPP	Zoop biomass	HTL *
Mean	+2.293	-0.239	-0.092	-0.107	-0.177
Range	2.191; 2.404	-0.241; -0.236	-0.099; -0.085	-0.113; -0.104	-0.181; -0.173
Test kruskal-Wallis (p-value)	6.293e-08	6.284e-08	6.302e-08	6.302e-08	1.403e-06
Model Uncertainty	Low	Low	Medium	Medium	High
Spatial variability	Low	Low	High	High	High

\* Change in HTL (fish biomass) from APECOSM has been estimated with another more-severe scenario (RCP85, and not A1B), and other climate model input (from IPSL-CM5). Also, only 15 years (2080-2095) have been used.

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