Modelling the combined impacts of climate change and direct anthropogenic drivers on the ecosystem of the northwest European continental shelf

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Highlights

1. Climate change could potentially drive substantial ecosystem changes by 2098
2. Direct anthropogenic divers impacts locally dominate over climate change effects
3. Direct drivers may mitigate climate change impacts on the European shelf ecosystem

Abstract

The potential response of the marine ecosystem of the northwest European continental shelf to climate change under a medium emissions scenario (SRES A1B) is investigated using the coupled hydrodynamics-ecosystem model POLCOMS-ERSEM. Changes in the near future (2030-2040) and the far future (2082-2099) are compared to the recent past (1983-2000). The sensitivity of the ecosystem to potential changes in multiple anthropogenic drivers (river nutrient loads and benthic trawling) in the near future is compared to the impact of changes in climate. With the exception of the biomass of benthic organisms, the influence of the anthropogenic drivers only exceeds the impact of climate change in coastal regions. Increasing river nitrogen loads has a limited impact on the ecosystem whilst reducing river nitrogen and phosphate concentrations affects net primary production (netPP) and phytoplankton and zooplankton biomass. Direct anthropogenic forcing is seen to mitigate/amplify the effects of climate change. Increasing river nitrogen has the potential to amplify the effects of climate change at the coast by

increasing netPP. Reducing river nitrogen and phosphate mitigates the effects of climate change for netPP and the biomass of small phytoplankton and large zooplankton species but amplifies changes in the biomass of large phytoplankton and small zooplankton.

1. Introduction

Marine ecosystems are in continual adjustment responding to changes in the climate, both from natural variability and long term anthropogenic climate change. Global climate change may impact on ecosystems through large scale changes in temperature, stratification and circulation [e.g. *Bopp et al.*, 2001; *Chust et al.*, 2014; *Holt et al.*, 2012; *Sarmiento et al.*, 2004]. Additionally, there is a direct impact from human activities, such as fishing, waste water discharge, dredging, leisure, fossil fuel extraction and off-shore energy generation [e.g. *UKMMAS*, 2010; *Ducrotoy and Elliott*, 2008; *Halpern et al.*, 2008]. These direct effects tend to be largest in coastal and shelf seas, where changes in the ecosystem are also likely to impact most directly on humans.

The physical climate influences the ecosystem through temperature, which affects chemical and physiological rates [*Boyd et al.*, 2013], and by controlling the availability of nutrients [*Holt et al.*, 2012] through horizontal transport and vertical mixing (which is inhibited by stratification). The nutrient supply, and particularly its vertical distribution, combines with the light climate (light diminishes with depth and the presence of organic and non-organic matter) to control the productivity of the lower trophic level (LTL) marine ecosystem. Carbon is taken up through photosynthesis by phytoplankton, which are grazed by zooplankton; the plankton are transported by physical processes and also sink under gravity through the water column; bacteria act to decompose dead plankton and nutrients are released through remineralisation. The LTL ecosystem has a direct effect on the environment (e.g. through the development of harmful algal blooms [*Anderson et al.*, 2002]) and supplies food for higher trophic levels (e.g. fish) used for human consumption or industry.

The northwest European continental shelf is part of the northeast Atlantic and exposed to changes in the global atmospheric and oceanic climates. It also experiences direct anthropogenic pressure from close proximity to the highly populated industrial regions of northern Europe. Fishing activity (demersal trawling) and riverine nutrient input to the ocean are two such direct anthropogenic processes that combine with changes in the climate to impact on the shelf sea ecosystem. Demersal trawling acts to disturb the seabed and induces mortality in benthic fauna, leading to disruptions of food webs and biogeochemical cycles in the vicinity of the disturbance

[*Kaiser et al.*, 2006]. Changes to nutrient loads impact the primary production and community composition, particularly in hydrodynamic regimes directly connected to the riverine sources. In particular high nutrient loads or imbalance in the ratio of nutrients may lead to deleterious eutrophication impacts such as high biomass [*Cadée and Hegeman*, 2002], toxic algal blooms [*Anderson et al.*, 2002] and near bed hypoxia [*Dethlefsen and Von Westernhagen*, 1983].

The policy driver behind this work is the Marine Strategy Framework Directive (MSFD: Directive 2008/56/EC[1]) of the European Commission, which requires member states to develop strategies to achieve a healthy marine environment and make ecosystems more resilient to climate change in all European marine waters by 2020 at the latest. The MSFD identifies 11 high level descriptors, 5 of which are considered here (D1 Biodiversity, D4 Foodwebs, D5 Eutrophication, D6 Sea floor integrity and D7 Hydrography). Each descriptor comprises a set of indicators which characterise marine ecosystems and requires an understanding of the possible pressures and impacts on them. For instance, Good Environmental Status (GES) is achieved when biodiversity is maintained (D1); the food web ensures long-term abundance of species (D4); eutrophication is minimised (D5); benthic ecosystems are not adversely affected by changes in the sea floor (D6) and the ecosystem is not adversely affected by changes in hydrographical conditions (D7). Numerical models such as applied here provide a valuable tool to improve the knowledge base on marine ecosystems and input to the development of innovative tools for understanding and assessing GES in marine waters in European regional seas to inform the implementation of the MSFD. For examples, see decision support tools developed from numerical model simulations during the Marine Ecosystem Evolution in a Changing Environment (MEECE) project[2].

Here we investigate the relative and combined effects of climate change and changes in the direct anthropogenic drivers of benthic fishing and river nutrients, and study the impacts on the LTL ecosystem over the northwest European shelf. A key question is the relative balance between climate change and direct drivers, whether they act synergistically or antagonistically,

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[1] http://ec.europa.eu/environment/marine/eu-coast-and-marine-policy/marine-strategy-framework-directive/index_en.htm

[2] http://meece.eu/

and whether management measures leading to changes in direct drivers can mitigate the effects of climate change.

A major driver of primary production is the availability of nutrients, particularly nitrogen and phosphate. Origins of these nutrients include natural (e.g. the open ocean) as well as anthropogenic sources such as the release from industry, urban waste water treatment and agriculture, through rivers and groundwater, to the ocean. For the European shelf as a whole, the largest source of nutrients is the open ocean, although regionally, such as in the English Channel and Irish Sea, river sources are significant [*Huthnance*, 2010]. For the North Sea, *Thomas et al.* [2010] estimated ~80% of nitrogen input comes through the northern boundary, ~4% from the Baltic outflow, ~9% from rivers and ~6% from the atmosphere. In coastal regions of the North Sea for a contemporary period (2000 onwards), *Artioli et al*. [2008] calculated the contribution of nitrogen from rivers to be 16%, with 26% coming from horizontal transport, 5% from atmospheric deposition and 53% from sediments (mainly through resuspension). Elevated nutrient concentrations imply that some coastal areas of the North Sea are at risk of eutrophication, giving rise to increases in biomass and the potential for detrimental effects such as oxygen depletion near the sea bed. During ~1950–1990, coastal waters of the North Sea experienced increases in nutrient loads of ~62% for nitrogen and ~45% for phosphate [*Vermaat et al.*, 2008]. Management action to reduce riverine nutrient sources to the North Sea started in the 1980s. The OSPAR Convention for the protection of the marine environment in the North-East Atlantic (http://www.ospar.org) is supported by 15 European governments and came into force in 1998; one of its aims is to tackle all sources of pollution affecting the maritime area, including the release of nutrients leading to eutrophication in the North Sea. The Paris Commission (PARCOM) made recommendations in 1988, 1989 and 1992 on reducing nutrient inputs to the North Sea [*OSPAR*, 1988; 1989; 1992].

The European shelf is also an important fishing region used by major international fishing fleets, with reported catches in the range 2.5–3.1 million tonnes/year for 2006–2012 [*ICES*, 2014]. For 1993–1996, *Rijnsdorp et al*. [1998] estimated that, in the most heavily fished regions in the southern North Sea, the Dutch beam trawler fleet covered 47–71% of the surface area up to five times per year. There is significant effort in regulating fishing effort through the Common Fisheries Policy (CFP) [*European Commission*, 2011], regulations for managing European fishing fleets and for conserving fish stocks, first introduced in the 1970s. Recent regulations [*European Commission*, 2014] are aimed at reducing the wasteful practice of discarding catch in the North Sea.

The effects of climate change on the ecosystem are difficult to predict due to uncertainties in emissions scenarios, climate forcing and models. Sources of uncertainty in atmospheric climate forcing include the trajectory of greenhouse gas emissions, their conversion into atmospheric concentrations and the responses of the global climate system to this radiative forcing [*IPCC*, 2001]. In studying the impact of climate change on ecosystems the additional impact of direct anthropogenic drivers, such as those controlled by government policies, can also be considered. Foreseen and unforeseen events (e.g. changes in governments, demographics, economic recession and war) make long-term (>~50 years) projections of direct drivers highly uncertain. However, in some circumstances, the sign of change in a direct driver can be estimated: e.g., under environmental policies nutrient emissions from agriculture, waste water and industry might be restricted. The time frame considered by governments is typically ~5-6 years (e.g. duration of the European parliament). However, a time horizon of ~20-30 years is more useful for policymakers to legislate for climate change adaptation.

Models are a useful tool to study potential conditions under possible future climate, and are particularly suited to sensitivity experiments where the response of the system to changes in forcing can be assessed. There have been several recent studies downscaling global climate change projections to the ecosystem of European regional seas. *Skogen et al.* [*2014*] investigated eutrophication in the North Sea, Skagerrak, Kattegat and the Baltic Sea under a medium emissions scenario (A1B) and found little change in the North Sea eutrophication status due to changes in climate; river nutrients were kept at present day values. Also using a medium emissions scenario, *Holt et al.* [*2012*] demonstrated that the supply of nutrients from the open ocean is an important control of primary production on the northwest European shelf, particularly for the Irish shelf and the central and northern North Sea, which are exposed to exchange with the open ocean. Using a 1D water column model at three contrasting locations in the North Sea, *Van der Molen et al*. [*2013*] found that gross primary production increased and zoobenthos biomass and sea-bed oxygen decreased under climate change conditions; there was little interaction between the climate signal and the addition of demersal trawling indicating that reducing demersal trawling might mitigate the effects of climate change on benthic biomass.

Nutrient inputs from rivers and their relationship to eutrophication has substantial policy interest in this region owing to uncertainties in whether undesirable effects arise [e.g. *Gowen et al.*, 2008], costs of amelioration and the transnational nature of the problem. There have been several modelling studies on the effects of reducing concentrations of nutrients released from rivers into the North Sea under present day and recent past conditions. Using a coupled river and multi-box model of the Southern Bight of the North Sea and eastern English Channel over the last 50 years, *Lancelot et al.* [2007] showed increases in *Phaeocystis* and diatom production with increasing river nitrogen and phosphate, and decreasing production when river phosphate loads fell. *Lacroix et al.* [2007] used a 3D model of the southern North Sea and showed that reducing river nitrogen loads led to an increase in diatom biomass, whereas decreasing river phosphate reduced both diatom and *Phaeocystis* biomass; in addition, changes in open-ocean nutrient concentrations transported eastwards through the English Channel also have an impact on primary production in the Belgian Exclusive Economic Zone. *Skogen and Mathisen* [2009] studied the long term impact of river nutrient reductions on chlorophyll-a concentrations using a 3D physical-chemical-biological model of the North Sea and found that the response was largest near the coast, although oxygen levels did not react strongly to river nutrient changes. In contrast, using result from six models covering the North Sea, *Lenhart et al.* [2010] showed that areas experiencing near bed oxygen concentrations below the "oxygen depletion" threshold defined by OSPAR (i.e. 6 mg O_2/l, [*OSPAR*, 2003]) could improve their state by reducing river nutrients.

For the Baltic Sea, *Meier et al.* [2012] used a coupled physical-biogeochemical model for 1961 to 2099 to study the combined future impacts of climate change and nutrient loads from industrial and agricultural sources. Using present day nutrient loads they found that water quality deteriorates in the future and that, for moderate reductions in nutrients consistent with current legislation, the climate effect dominates the impact of nutrient changes.

In this paper we use the Proudman Oceanographic Laboratory Coastal Ocean Modelling System, POLCOMS [*Holt and James*, 2001], coupled to the European Regional Seas Ecosystem Model, ERSEM [*Baretta et al.*, 1995; *Blackford et al.*, 2004] to examine the effects of changes in climate, benthic fishing in the North Sea and river nutrient loads on the ecosystem of the European shelf. The potential ecosystem responses to climate change in the near future (2030-2040) and the far future (2082-2099) are compared to the recent past (1983-2000). For the near future time period, the relative sensitivity of the ecosystem to changes in multiple drivers (climate, river nutrient loads and benthic trawling) is also studied. Since long-term projections of direct drivers are highly uncertain and the appropriate time scale for policymakers is of the order of decades, or shorter, we concentrate on the potential impacts of direct drivers in the near future time slice. The uncertainty in the change in direct drivers is large and we focus on qualitative effects. The model setup and experiments are described in section 2. In section 3, the effects of climate and anthropogenic changes on the ecosystem are explored and regions are defined where the impact of the direct anthropogenic drivers exceeds that due to changes in the large scale oceanic and atmospheric climate. The cumulative effects of the direct drivers and climate change are also studied to investigate whether the impact of changing the direct drivers amplifies or mitigates the effects of climate change.

2. Model experiments

2.1 Model description

We use the coupled hydrodynamic-ecosystem model POLCOMS-ERSEM on the Atlantic Margin domain (Figure 1) covering the northwest European continental shelf and the adjacent deep ocean (20°W to 13°E, 40°N to 65°N). The model has horizontal resolution of ~12km and uses 42 s-coordinate levels [*Song and Haidvogel*, 1994] in the vertical. POLCOMS is a 3-dimensional finite difference model able to model shelf and deep ocean processes. ERSEM is a lower trophic level biogeochemical model which explicitly resolves carbon, nitrogen, oxygen, phosphorous and silicon cycles in a coupled pelagic-benthic system. ERSEM uses four phytoplankton types (flagellates, picoplankton, diatoms and dinoflagellates), three zooplankton types (heterotrophic nanoflagellates and micro and meso zooplankton) and bacteria. The model setup is described by *Holt et al.*, [2012] except that here we have turned off the resuspension of particulate matter from the sea bed and added an explicit representation of sea bed trawling in the North Sea (see below). Validation for the present day climate scenario simulation CNTRL (see below) showed that there is no systematic increase in errors [*Holt et al.*, 2012] compared to a hindcast using realistic atmospheric forcing from the European Centre for Medium Range Weather Forecasting (ECMWF) Reanalysis product (ERA40).

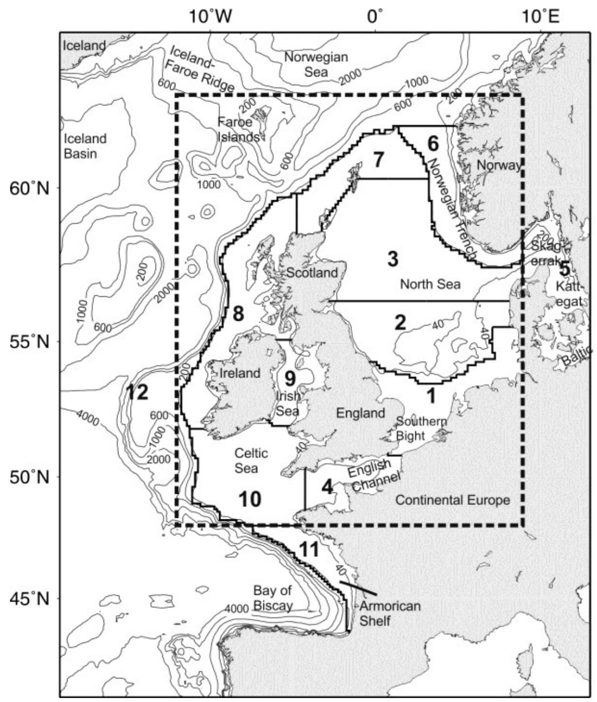


Figure 1: Location plot showing the model domain and numbered regions. The box drawn with a dashed line is the region for which results are presented.

We consider two types of trawling gear working in the North Sea, namely, beam trawls and otter trawls. Data on trawling effort consist of hours fishing per year averaged over the period 1997-2004 [*Greenstreet et al.*, 2007]. The data are converted into number of trawlers per day expected in each model grid cell. The number of trawlers, T, actively fishing in each cell is generated randomly each day from a Poisson distribution characterized by this expected value. The impact, I, of each trawler on the biomass of deposit and filter feeders (i.e. the % mortality induced by a single event) is parameterized depending on the type of sediment (mud, sand or gravel) and the type of trawler (Table 1) using data from *Allen and Clarke* [2007] and *Kaiser et al.* [2006]. The biomass of aerobic bacteria removed from the benthos is added to the biomass of pelagic bacteria in the grid cell just above the bed. Changes are scaled by a factor representing the proportion, P_r, of the total grid cell area that is actively trawled, calculated assuming that a trawler covers an area of 1.3 km^2 each day [*Dounas et al.*, 2007]. The decrease in biomass in a grid cell, relative to the original biomass is then: $(1 - 0.01\times I) \times T \times P_r$.

Sediment	Deposit Feeders	Filter feeders	Meiobenthos	Aerobic bacteria
		Beam Trawlers		
sand	-23	-73	-67	-67
gravel	-67	-15	-42	-42
		Otter Trawlers		
mud	-18	-31	-29	-29
sand	-23	-4	-15	-15

Table 1: Mortality rates (%) on benthic functional types due to trawling [from *Allen and Clarke*, 2007].

Freshwater river fluxes for the present day are from a climatology of daily discharge data for 250 rivers from the Global River Discharge Data Base [*Vörösmarty et al.*, 2000] and from data prepared by the Centre for Ecology and Hydrology as used by *Young and Holt* [2007]. A mean annual cycle of nutrient concentrations is derived for each river from data used by *Lenhart et al.* [2010], including data processed by van Leeuwen (CEFAS, UK) for the UK, Northern Ireland, Ireland, France, Norway, Denmark and the Baltic and by *Pätsch and Lenhart* [2004] for Germany and the Netherlands. The river nutrient climatology is calculated using data for 1984 to 1994, covering a period of high nutrient concentrations and the start of the impact of nutrient reduction policies; it represents conditions in the recent past.

Non-biotic light absorption is simulated by using an annual cycle of SeaWiFS climatology of sediment particulate matter and coloured dissolved organic matter [*Smyth et al.*, 2006], as described by *Wakelin et al.*, [2012].

Open ocean (hydrodynamic and ecosystem) and atmospheric forcing are derived from the Institut Pierre Simon Laplace Climate model (IPSL-CM4), [*Marti et al.*, 2005] a global coupled ocean-atmosphere general circulation model (OA-GCM) run using the Special Report on Emissions

Scenarios (SRES) A1B "Business as Usual" scenario [*Nakicenovic and Swart*, 2000]. On a global scale, IPSL-CM4 exhibits results similar to other OA-GCM models used in the IPCC Fourth Assessment Report [*Meehl et al.*, 2007]. *Steinacher et al*. [2010] compared results for four OA-GCMs (IPSL, MPIM, CSM1.4 and CCSM3) under the SRES A2 emissions scenario for 1860-2100 and showed that the IPSL model results were in the middle of the range of response for global mean sea surface temperatures and primary production. In the North Atlantic, sea surface temperature increases between 1860-1869 and 2090-2099 for IPSL are approximately average compared to the other models, whereas IPSL exhibits the second strongest reduction in primary production over the same period. The IPSL model underestimates primary production in the northeast Atlantic compared to SeaWiFS climatology for 1997 to 2005, with better agreement than MPIM (which also underestimates primary production) but generally lower values than the NCAR CSM1.4 simulation [*Schneider et al.*, 2008]. Using a skill score metric to assess the skill of the four OA-GCMS to reproduce the satellite based estimates of primary production *Steinacher et al.* [2010] showed that, for the northeast Atlantic region, CSM1.4 scored best, with IPSL and CCSM3 having similar values to one another and MPIM performing worst.

Tidal boundary data for 15 constituents are provided by a tidal model of the North Atlantic [*Flather*, 1981].

We use a time-slice approach whereby mean conditions in an experiment are compared with mean conditions in a reference simulation to give a measure of the climatic/anthropogenic change, on the assumption that conditions in both time-slices are approximately stationary. Here we consider a single potential realization of the future and study the effect of substantially changing direct anthropogenic drivers.

To allow the model to adjust to its lateral boundary and surface forcing and changes in anthropogenic drivers, all simulations have a 5 year spin up period (described below) before calculating the average results presented here. Five years is ample spin-up time for the physics and pelagic biology on the Atlantic Margin domain and errors in benthic fluxes due to uncertainties in the initial conditions are significantly reduced after five years [*Wakelin et al.*, 2012].

We consider five experiments: CNTRL, A1B, BASE, WM and GC, outlined below and summarized in Table 2. The CNTRL, A1B and BASE simulations are used to investigate the impacts of large scale changes in the atmosphere and ocean under a projected near- and far-future climate in the absence of changes in direct anthropogenic drivers. For the near future period, the final two simulations (WM and GC) explore the additional impact of changes in the anthropogenic drivers of river nutrient concentrations and benthic fishing effort.

2.2 Scenario descriptions

2.2.1 Climate change scenarios: CNTRL, BASE and A1B

The CNTRL simulation is a present day simulation for the nominal period 1983-2000. A1B is a future climate scenario representative of possible conditions in 2082-2099 under the SRES A1B "business as usual" emissions scenario. The baseline simulation for the near future, BASE, is for the period 2030 to 2040 under the same emissions scenario. Physical ocean boundary and atmospheric forcing are taken directly from the OA-GCM for the relevant time slice. Open-boundary nutrient (nitrate, silicate and phosphate) and dissolved inorganic carbon (DIC) values for CNTRL are from climatologies [*Garcia et al.*, 2006; *Key et al.*, 2004]; while for the future time slices, the CNTRL values are perturbed by the fractional change in nutrients in the PISCES ecosystem model [*Aumont et al.*, 2003], included in the IPSL-CM4 model, between the time-slice and 1983-2000. IPSL-CM4 forcing data were available for the periods 1980-2000, 2030-2040 and 2080-2099; five years of spin up prior to the starts of the analysis periods (1982, 2030 and 2082, respectively) were achieved by using the first year of available forcing in each period repeatedly as necessary. For example, the CNTRL simulation comprises two initial years using forcing data for 1980 followed by data for the relevant years for the remainder of the spin-up time: 1980-1982. Initial temperature and salinity fields are interpolated from the IPSL-CM4 model for the start month of each simulation. Initial ecosystem fields for CNTRL are from a spin-up simulation where homogeneous initial values corresponding to the average bulk properties of the shelf have been spun up for five years; for BASE and A1B the nutrient fields in the CNTRL initial data are perturbed by the fractional change in nutrients in the PISCES ecosystem model.

Given the 2.5°×1.27° resolution of the IPSL-CM4 model, the precipitation at the outflow grid cell is assumed to be representative of the precipitation over each river catchment. River flows are changed in proportion to the change in precipitation at the outflow grid cell on average during each time slice compared to 1983-2000; the effect of change in precipitation on river outflow, integrated over the regions in Figure 1, varies between -7.5% and 9.7% for BASE and -22.2% and 20.7% for A1B (Table 3). River nutrient concentrations are held constant and therefore changes in river volumes impact on the total loads of nitrogen, phosphate and silicate being released to the ocean. In the absence of reliable estimates of how non-biotic light absorption might change in the future, the present day SeaWiFS climatology is used in all experiments.

For the CNTRL, A1B and BASE simulations, the direct anthropogenic drivers of fishing effort and river nutrient concentration are held at present day levels.

Name	Scenario	Description	Large scale climate	River nutrient concentrations	Fishing effort	Years
CNTRL	control run	recent past control run	recent past	climatology	climatology	1983-2000
A1B	climate	far future climate forcing	far future	climatology	climatology	2082-2099
BASE	climate	near future climate forcing	near future	climatology	climatology	2030-2040
WM	climate and anthropogenic	World Markets[a] scenario	near future	50% increase in nitrogen; climatology for phosphate	climatology	2030-2040
GC	climate and anthropogenic	Global Community[b] scenario	near future	50% decrease in nitrogen and phosphate	50% decrease in beam trawling; 75% decrease in otter trawling	2030-2040

Table 2: Summary of experiments: climatologies are averages representative of present day conditions; all % changes are relative to the relevant climatology. Large scale climate comprises atmospheric forcing, physical and ecosystem ocean boundaries and river volume outflows. Anthropogenic driver scenarios relate to [a]conditions of rapid economic growth and limited environmental policies and [b]environmental policies constraining socioeconomic growth.

	volume			nitrogen					phosphate				silicate		
	CNTRL × 10^3 m^3s^{-1}	BASE PC %	A1B PC %	CNTRL molN s^{-1}	BASE PC %	GC PC %	WM PC %	A1B PC %	CNTRL molP s^{-1}	BASE PC %	GC PC %	A1B PC %	CNTRL molS s^{-1}	BASE PC %	A1B PC %
1. Southern North Sea	3.99	5.6	-6.1	19.88	6.6	-46.7	60.0	-5.2	1.48	6.7	-46.7	-4.4	14.18	6.3	-6.3
2. Central North Sea	0.58	-6.4	5.4	1.39	-5.1	-52.6	42.3	6.1	0.09	-4.3	-52.2	6.1	2.03	-7.2	5.2
3. Northern North Sea	0.52	-7.5	2.9	0.54	-10.9	-55.4	33.7	4.5	0.02	-8.8	-54.4	4.2	2.39	-9.5	3.8
4. English Channel	0.79	2.4	-8.8	5.15	2.4	-48.8	53.6	-9.1	0.11	6.8	-46.6	-3.1	3.07	3.1	-7.2
5. Skagerrak/ Kattegat	2.21	-6.6	3.0	0.95	-6.9	-53.4	39.7	2.5	0.05	-5.6	-52.8	3.2	4.62	-6.7	3.6
6. Norwegian Trench	0.71	0.3	3.5	0.13	0.3	-49.9	50.4	3.4	0.01	0.3	-49.8	3.4	1.56	1.1	3.7
7. Shetland Shelf	0.03	-4.2	1.6	0.01	-4.4	-52.2	43.4	1.7	0.00	-4.4	-52.2	1.7	0.06	-4.4	1.7
8. Irish Shelf	1.52	-2.8	2.8	0.85	-2.8	-51.4	45.8	4.1	0.09	-3.5	-51.7	3.2	0.74	-4.5	0.4
9. Irish Sea	0.85	-1.1	3.4	2.01	0.5	-49.7	50.8	3.7	0.14	0.4	-49.8	3.6	2.19	-0.9	3.4
10. Celtic Sea	0.88	5.5	7.0	4.02	5.7	-47.2	58.5	6.2	0.18	5.6	-47.2	5.8	2.32	7.4	7.1
11. Armorican Shelf	1.63	-5.2	-22.2	5.05	-5.3	-52.7	42.0	-22.2	0.28	-6.3	-53.2	-30.1	7.54	-5.2	-22.4
12. NE Atlantic	0.06	9.7	20.7	0.01	9.7	-45.1	64.6	20.7	0.00	9.7	-45.1	20.7	0.17	9.7	20.7
Baltic Outflow	20.83	7.2	13.4	1.18	7.2	-46.4	60.8	13.4	0.36	7.2	-46.4	13.4	8.33	7.2	13.4

Table 3: Inflows of water, nitrogen, phosphate and silicate from the Baltic Sea and from rivers into different regions (Figure 1) for the CNTRL simulation and the percentage changes for the scenario simulations defined as PC = (EXP/CNTRL – 1)×100% where EXP = BASE, GC, WM or A1B. For phosphate, the WM PC is identical to the value for BASE and, for silicate, the WM and GC PCs are both identical to BASE.

2.2.2 Anthropogenic driver scenarios: WM and GC

The final two simulations explore the impact of changes in anthropogenic drivers in addition to the climate change signal for the period 2030 to 2040. The direct driver simulations are the same as BASE but with changes in the river nutrient loads and trawling drivers consistent with the World Market and Global Community scenarios of the European Lifestyles and Marine Ecosystems (ELME) project[3]. In the ELME project, socio-economic drivers for future scenarios are used to define environmental pressures impacting on ecosystems.

In the World Markets scenario there is rapid economic growth and limited environmental policies; an increase in the use of nitrogen fertiliser in agriculture combined with no changes in urban waste water treatment (UWWT) leads to an increase in riverine nitrogen whereas river phosphate concentrations remain unchanged. Trawling effort is also unchanged from present day levels.

In the Global Community scenario economic growth is constrained by environmental objectives; reductions in the use of phosphate fertiliser together with increases in UWWT and a reduction in industrial discharge lead to a decrease in both nitrogen and phosphate released into rivers. There is also a reduction in trawling effort.

Between 1985 and 2002, the Netherlands, Germany, UK and France reduced their river nutrient outputs to the North Sea by 10-90% for ammonium and 0-70% for phosphate, with little change in levels of nitrate+nitrite from Germany, the UK and France and a reduction ~20% from the Netherlands [*Lenhart et al.*, 2010]. Given the magnitude of these changes already experienced for rivers flowing into the North Sea, we perturb all river nutrient concentrations by 50% from their climatological values as being a potentially realistic change, that also corresponds to the 1988 OSPAR recommendation to reduce nutrient loads by 50% [*OSPAR*, 1988].

To study the potential effects on the ecosystem of the changes under the World Market scenario, the WM simulation uses river concentrations of total nitrogen (nitrate and ammonium) that are 50% larger than the present day values used in the CNTRL, A1B and BASE simulations. River

[3] http://cordis.europa.eu/documents/documentlibrary/127824671EN6.pdf

phosphate loads and trawling effort are unchanged from the present day. The effect on the amount of nitrogen being discharged into different regions varies between 33.7% and 64.6% compared to CNTRL (Table 3), while the phosphate load changes vary between -6.3% and 9.7% due to changes in river volume flow.

The possible effects of the Global Community scenario are studied using the GC simulation where river concentrations of total nitrogen and phosphate are reduced by 50% compared to the present day values, resulting in area changes of between -55.4% and -45.1% for nitrogen discharge and -54.4 % and -45.1% for phosphate discharge compared to CNTRL. For the GC simulation, trawling effort is reduced by 50% for beam trawlers and 75% for otter trawlers; we assumed that the recent declining trend of fishing effort [*Greenstreet et al.*, 2007] will double its slope under the GC condition.

3. Results

The impact of the direct anthropogenic drivers is generally confined to the continental shelf and so, for clarity, we focus on the region denoted by the dashed line in Figure 1.

In order to study the integrated response of the ecosystem to changes in forcing, mean values of biomass (phytoplankton, zooplankton and benthic) and net primary production (netPP, the difference between gross primary production and respiration by phytoplankton, zooplankton and bacteria) are calculated for each simulation. By using mean values, changes in both the abundance of organisms and the timing of blooms are accounted for. The total availability of nutrients in the system is represented by using winter (December to February) means.

To study the relative magnitude and direction of change of the ecosystem variables compared to conditions in the recent past, the fractional change (FC) is used, where FC = <EXP>/<CNTRL> – 1, <EXP> represents time-averaged conditions in the BASE, GC, WM or A1B simulations and <CNTRL> the time-averaged conditions in the CNTRL simulation. FC typically lies in the range -1 to +1: FC = 0 when the future results are the same as for CNTRL; FC = -1 when the future variable is zero (e.g. nitrogen is absent); FC = +1 when future values are exactly twice those in CNTRL. In circumstances where the CNTRL values are near to zero, FC can become large even for only moderate future increases: in Figures 2-4, the FC is limited to a maximum value of 10. In Figures 2-6, regions where the change between two simulations is small compared with inter-annual variability determined by the Kruskal-Wallis test [*Kruskal and Wallis*, 1952], are masked to grey. The Kruskal-Wallis test uses one-way analysis of variance by ranks to compare the medians of two time series and determine if the samples come from the same population. We use time series of annual means at each model point and mask in grey points where the Kruskal-Wallis p-value (the probability that a chi-squared distribution is at least as extreme as the Kruskal-Wallis test statistic) exceeds 0.05.

3.1 Ecosystem changes under climate change and direct anthropogenic driver experiments

Fractional changes in near-surface winter-mean nutrients in the BASE, A1B, WM and GC experiments compared to the recent past CNTRL simulation are shown in Figure 2. In the near future (BASE) simulation there are local increases in nitrogen and phosphate on the shelf compared to CNTRL, related to increases in river nutrient input (Table 3). In particular, river volume changes due to higher precipitation in the future time slice increases nutrient outflows in the southern North Sea, English Channel, the Irish Sea and the Celtic Sea. These have a relatively large impact on the nitrogen and phosphate concentrations since nutrient outflows are already comparatively high in these regions, e.g. 19.88 mol N s^{-1} and 1.48 mol P s^{-1} for the CNTRL simulation in the southern North Sea. In the near future, silicate, recycled from detritus, increases on the shelf. In the open ocean, the surface nutrients decrease in the future simulations, with the impact increasing into the far future (A1B). This is a consequence of increased stratification in the future and also a response to reduced nutrients in the IPSL-CM4 boundary data, in turn due to increased stratification and slowed thermohaline circulation in the global model [*Steinacher et al.*, 2010]. In the same version of POLCOMS-ERSEM as used here, Holt et al. [2012] used nutrient boundary data from the present day and boundary data projected for the future to show the impact of the boundary on netPP and winter nitrogen in the far future time slice. They showed that using projected future nutrient boundary data affects the whole model domain by reducing the availability of dissolved inorganic nitrogen leading to lower netPP; the Irish and Celtic Seas and the southern Bight of the North Sea are affected less than the central and northern North Sea and the open ocean. By the far future (Figure 2), the open-ocean decrease in nutrients has spread across the shelf, although the Celtic and Irish Seas show no significant change due to larger interannual variability in these regions compared to changes from the open ocean. The increase in river nitrogen in the WM simulation causes a significant increase in nitrogen over most of the shelf compared to CNTRL, while reductions in river nitrogen and phosphate in the GC simulation lead to strong decreases at the coast.

The mean annual netPP for CNTRL for the period 1983 to 2000 is shown in Figure 3a. Comparison with observations [*Holt et al.*, 2012] shows that the model netPP values fall within the observed ranges. Fractional changes between mean netPP in the experiments compared to the CNTRL simulation (Figure 3b) show a range of responses. The projected climate-forced increase in the near future BASE simulation is significantly different from the CNTRL values only in the southern North Sea, the Celtic and Irish Seas, the English Channel and west of Scotland, where there in an increase in netPP; and in some isolated patches off-shelf. By the far future, the A1B simulation shows a general decline in netPP compared to the recent past CNTRL simulation; regions of increasing netPP in the southern North Sea and Celtic Sea are no longer significantly different from CNTRL as they were in the BASE simulation, although rates of netPP in coastal regions of the English Channel and the Irish and Celtic Seas are still significantly larger than in CNTRL. The decreases in netPP are caused by reductions in the available surface nutrients (Figure 2) in the future open ocean and in the northern North Sea by 2082-2099. In these regions, changes in oceanic nutrients are a first order factor in determining primary production changes [*Holt et al.*, 2012]. On-shelf increases in netPP correspond to regions with increased nutrient availability, particularly phosphate and silicate. Other processes affecting netPP under climate change, such as increased nutrient recycling in both the pelagic and benthic systems due to warmer waters, and increases in on-shelf stratification are discussed in detail by *Holt et al*. [2012].

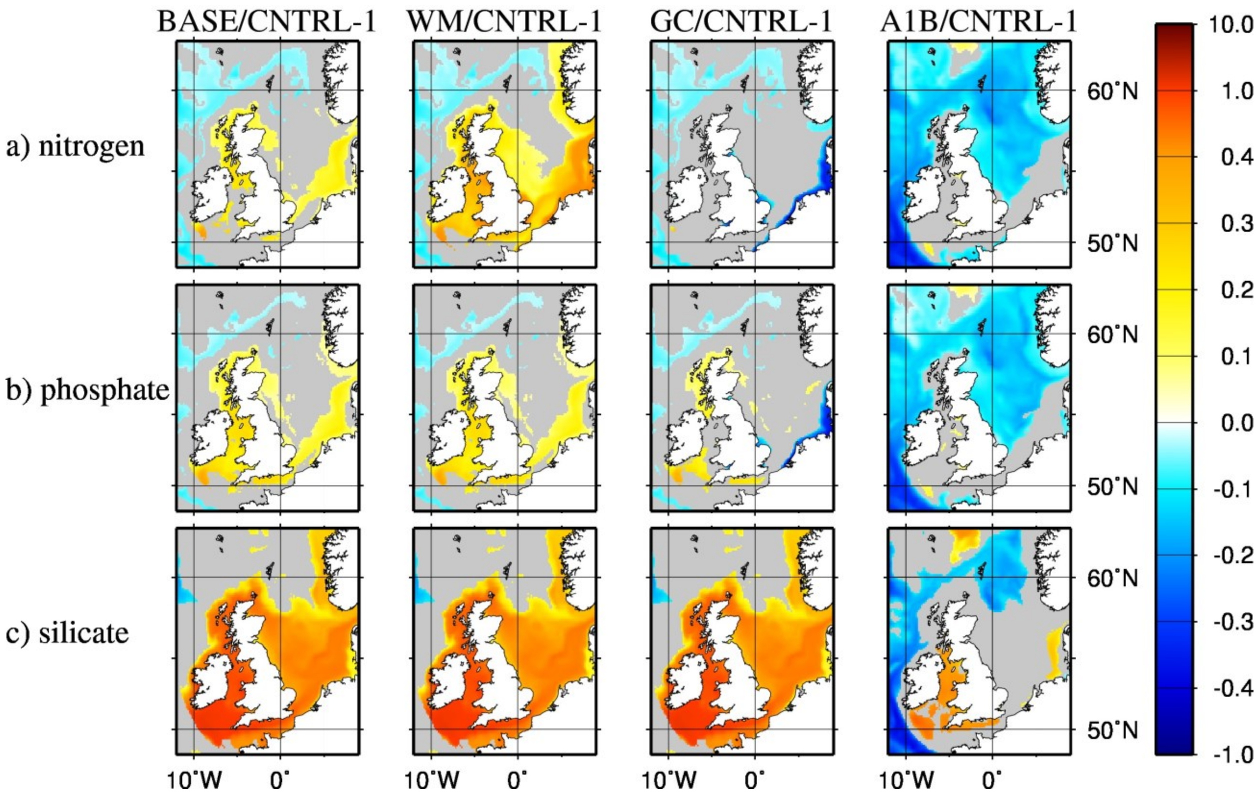


Figure 2: Fractional changes in surface winter-mean a) nitrogen, b) phosphate and c) silicate under the BASE, WM, GC and A1B climate and anthropogenic driver experiments compared to CNTRL. A colour version of this figure is available online.

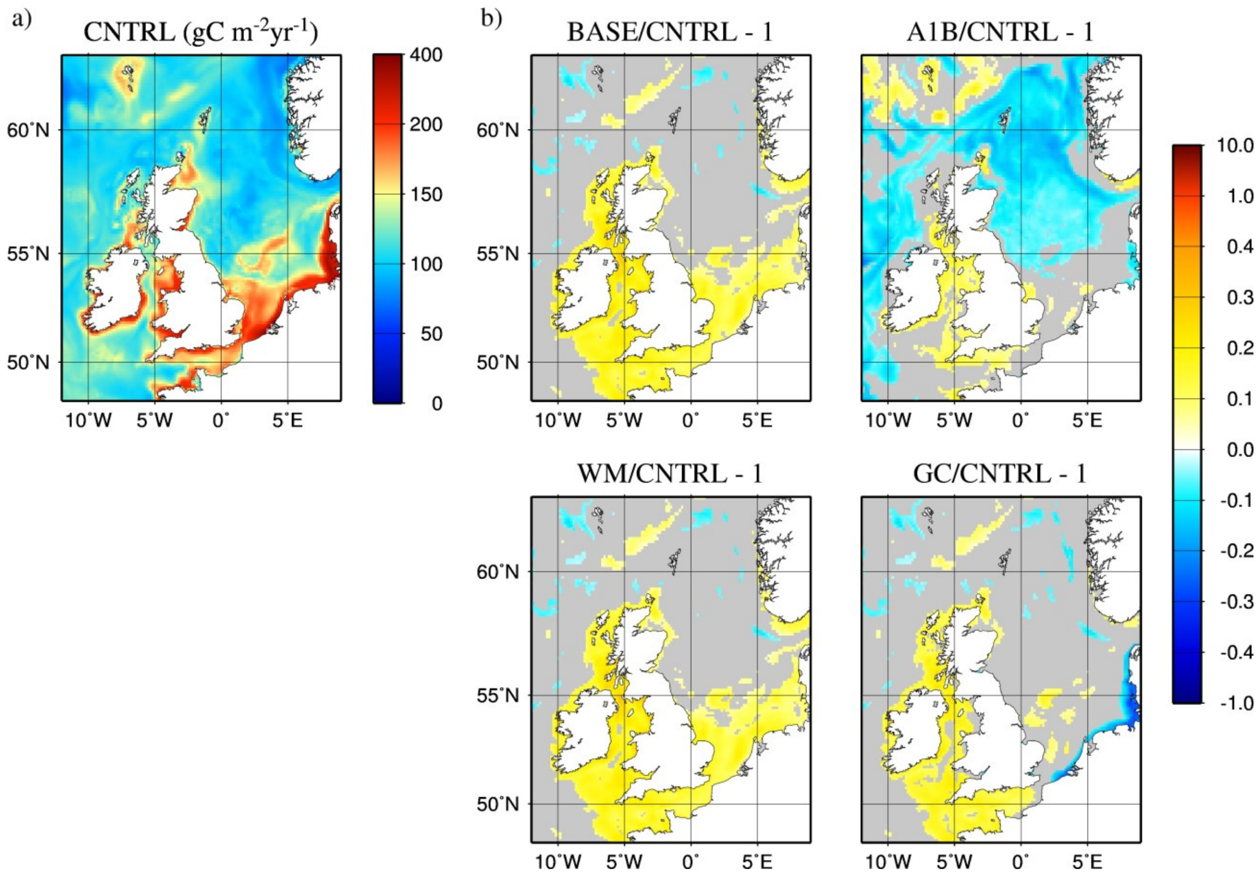


Figure 3: a) mean depth integrated net primary production for CNTRL (1983-2000) and b) the fractional change in mean net primary production for BASE, A1B, WM and GC compared to CNTRL. A colour version of this figure is available online.

For the near future period, 2030-2040, the changes under the direct driver experiments (WM and GC) are compared with the changes due to climate alone from the BASE experiment. The fractional change in netPP for the WM simulation (Figure 3b) appears the same as for the BASE simulation: the increase in river nitrogen load has little impact on netPP, which must be limited by other factors, such as light, or phosphate or silicate availability that are (almost) identical in the BASE and WM simulations. In contrast, the GC simulation shows a reduction in the climate-induced increase in netPP in the southern North Sea, where increases that occur in the BASE simulation become not significant or decrease in value under the GC scenario. NetPP calculated by POLCOMS-ERSEM shows lower sensitivity to reductions in river nutrients compared to other regional models covering the southern North Sea [*Lenhart et al.*, 2010]. In coastal seas, the ratio of carbon, nitrate and phosphate in phytoplankton can vary significantly: in contrast to most models, which use a fixed carbon to nutrient (C:N) ratio, ERSEM allows the C:N ratio to vary and, through this buffering effect, is less sensitive to changes in nutrient availability [*Allen*, 1997]. The decrease in netPP in the southern North Sea for reduced concentrations of phosphate and nitrate in GC (Figure 2) suggest that phosphate and/or nitrate limit primary production in this area. Observations in the Southern Bight of the North Sea and the eastern English Channel indicate that silicate or phosphate are the main nutrients potentially limiting phytoplankton growth [*Lefebvre et al.*, 2011; *van der Zee and Chou*, 2005] under recent climatic conditions.

Fractional changes in biomass due to climate and anthropogenic driver changes are shown in Figure 4. The benthic biomass is the total of deposit feeders, filter feeders and meiobenthos; phytoplankton and zooplankton biomass are depth integrated and divided into small (flagellates and pico) and large (diatoms and dinoflagellates) phytoplankton and small (micro and heterotrophic nanoflagellates) and large (meso) zooplankton. In the near future, the benthic biomass increases in the North Sea, but then decreases across the shelf by the far future time slice. The biomass of small zooplankton and both sizes of phytoplankton tend to decrease, with the signal being stronger in the far future than the near future. However, in the Celtic Sea the biomass of large phytoplankton increases corresponding to regions where the netPP increases. For the large zooplankton in the Norwegian Sea biomass increases, with the change increasing between the near and far future. On the shelf, increases in large zooplankton biomass in the near future (due to changes in silicate) reduce in extent in the far future although still significantly exceed present day values. There is no coherent transfer of the climate change signal between trophic levels, for example, significant increases in netPP in the southern North Sea and Irish Sea in the near future (BASE) do not translate into a significant change in phytoplankton biomass in these regions, although concentrations of detritus do increase (not shown). Also, the biomass of zooplankton changes over large areas of the shelf where there is no significant change in either size class of the phytoplankton biomass. In the future, large zooplankton increase at the expense of small zooplankton, either by out-competing for phytoplankton or by consuming the small zooplankton.

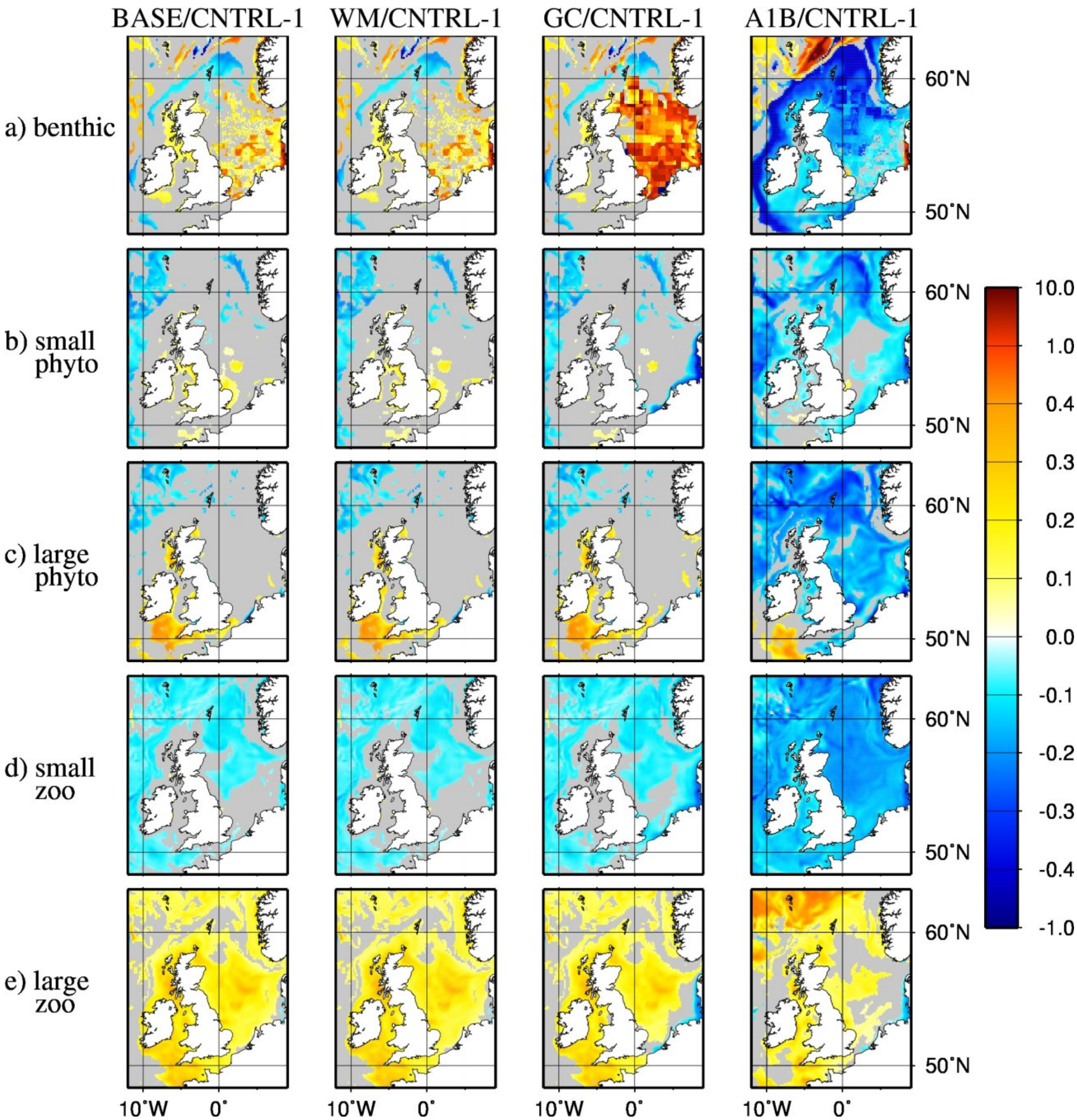


Figure 4: Fractional changes in a) benthic biomass and the depth integrated biomass of b) small phytoplankton, c) large phytoplankton, d) small zooplankton and e) large zooplankton under the BASE, WM, GC and A1B climate and anthropogenic driver experiments compared to CNTRL. A colour version of this figure is available online.

For changes in anthropogenic drivers, increases in river nitrogen concentrations in the WM simulation have no effect on biomass. The reduction in river nitrogen and phosphate in the GC simulation leads to decreases in small phytoplankton and small and large zooplankton biomass in coastal regions. The reduction in fishing effort in the North Sea in the GC simulation leads to higher benthic biomass, demonstrating the potential to mitigate the climate-forced decrease in benthic biomass projected for the far future. Comparing the anthropogenic driver simulations GC and WM with the near future climate simulation (BASE) demonstrates the sensitivity of the system to anthropogenic driver changes in the near future (not shown). Consistent with the differences between BASE/CNTRL−1 and GC/CNTRL−1 in Figure 4, reductions in fishing effort and river nutrients in GC compared to BASE lead to an increase in benthic biomass in the North Sea and decreases in zooplankton and small phytoplankton biomass near the coast, especially in the southern North Sea. There are no significant changes in the biomass for WM compared to BASE.

Given the semi-quantitative nature of these scenarios it is now appropriate to focus on the sign of the potential change.

3.2 Relative impact of climate-induced and direct anthropogenic driver effects

In the near future time period, Figure 4 suggests that the impact of the direct anthropogenic driver changes in river nutrients and benthic trawling effort compared to the impacts of changes in ocean and atmospheric forcing are small (in the case of the WM simulation) or limited to near coastal regions and the benthos (in the GC simulation). To consider this in more detail, the model simulations are used to define regions where the climate or direct driver impacts dominate: for the WM simulation, the change in the ecosystem due to climate forcing CF = <BASE> – <CNTRL> is compared to the change due to the direct drivers DD = <WM> – <BASE>. For regions with |CF| > |DD|, the effect of the climate forcing dominates, and for |CF| < |DD|, the effect of the direct drivers dominates. Where neither <BASE> nor <WM> are significantly different from <CNTRL>, measured using the Kruskal-Wallis test [*Kruskal and Wallis*, 1952], there is no significant change.

For the WM simulation, the influence of the increase in river nitrogen load is evident in surface nitrogen (Figure 5a), with the direct driver dominating changes at the coast, in the southern and western North Sea and in the Norwegian Coastal Current; the climate change signal dominates in the open ocean reflecting changes in ocean boundary forcing and seasonal stratification. For the other parameters, the climate response dominates over the effect of the direct driver impact. Surface phosphate has a similar open ocean response to the climate forcing as surface nitrogen and experiences a climate dominated change in the southern North Sea as a response to increases in river sources of phosphate of 6.7% (Table 3) in that region.

A similar analysis for the GC simulation (Figure 5b) shows that reducing the river nitrogen and phosphate levels and trawling fishing effort has more of an impact relative to climate-induced changes than increasing river nitrogen levels in the WM simulation. The region of surface nitrogen significantly changed by the change in direct driver is similar to WM but does not extend as far west and north in the North Sea. The region of surface phosphate impacted is more restricted to very near coastal areas, where the netPP, the small phytoplankton biomass and the biomass of both large and small zooplankton are also dominated by changes in the direct driver. This demonstrates that the availability of phosphate in these regions is a stronger control on netPP than nitrogen availability, there being sufficient nitrogen in the water column but limited phosphate to support production. The large phytoplankton (including diatoms) are not affected by phosphate reductions as they grow early in the season when phosphate is still abundant. Except for off the west coast of Denmark, the reduction in benthic fishing effort in the North Sea has a larger impact on the benthic biomass than changes in the climate.

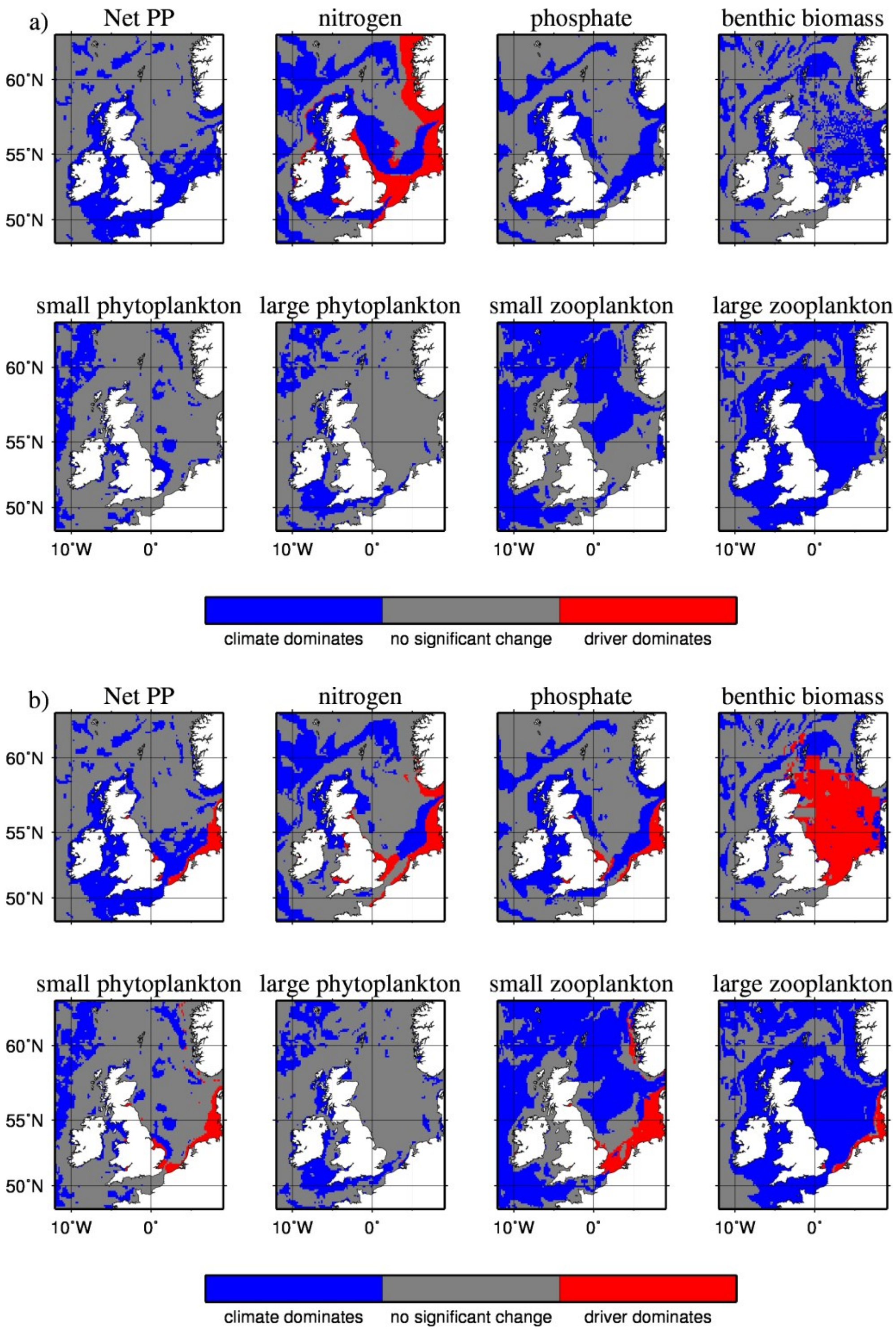
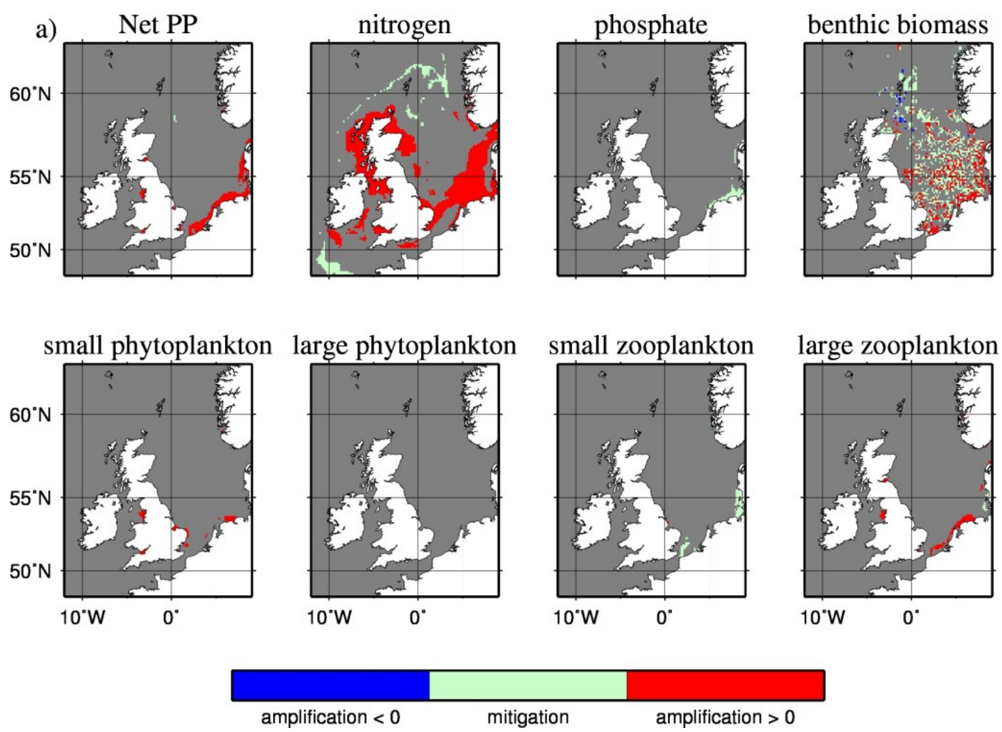


Figure 5: Regions of climate or anthropogenic driver change dominance on the ecosystem for a) World Market (WM) and b) Global Community (GC) scenarios for 2030-2040.

Although the direct anthropogenic drivers effects exceed the climate change impacts only locally (and the benthic biomass for changes in benthic fishing), the influence extends to other areas too. In Figure 6 we examine whether the direct anthropogenic drivers act to amplify or mitigate the effects of climate change on the ecosystem in the near future (2030-2040). For the WM simulation, for example, the total change TC = <WM> – <CNTRL> is compared to the change due to climate forcing alone, CF = <BASE> – <CNTRL>. If TC > CF > 0, the direct driver acts to positively amplify the climate signal and strengthens the increase in values due to climate forcing; if TC < CF < 0, the driver amplifies the climate signal but acts to strengthen the negative signal; if CF > 0 and TC < CF or CF < 0 and TC > CF, the direct driver and the climate forced change are acting to change the ecosystem in different directions and the effect of the direct driver is to mitigate the effects of changes in climate forcing. Regions where either there is no significant climate signal (<BASE> – <CNTRL>), measured using the Kruskal-Wallis test, or the change induced by the direct driver is very small (< 5% of the change due to climate) are masked in grey.



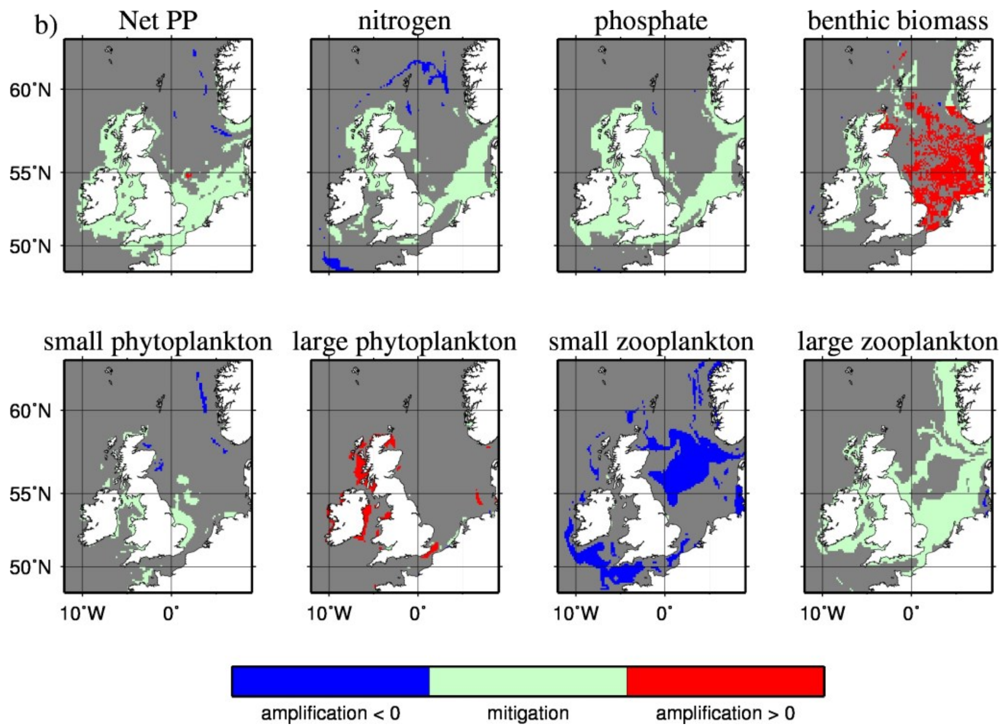


Figure 6: Regions of mitigation or amplification of the climate signal on the ecosystem by anthropogenic drivers for a) World Market (WM) and b) Global Community (GC) scenarios for 2030-2040. Grey regions are where there is no significant affect (see text). A colour version of this figure is available online.

Changes in river flow due to changes in precipitation give a small increase (6.6%, Table 3) in nitrogen from the rivers with outflows in the southern North Sea, which the WM direct driver of increasing river nitrogen acts to amplify. Elsewhere, climate-induced decreases (Figure 2) in surface nitrogen from the open ocean are offset by increases from river loads. The main impact of the WM driver is to amplify increases in netPP in the southern North Sea and the western Irish Sea, leading to amplification of the increase in small phytoplankton biomass in coastal areas. The increase in large zooplankton biomass is also amplified in the same regions. However, there is no impact on the biomass of large phytoplankton and little impact on small zooplankton.

For the GC driver, with reduced river levels of nitrogen and phosphate, the response of surface nitrogen mirrors that of the WM driver: where WM amplifies (>0) the response, GC mitigates and, where WM mitigates the response, GC amplifies (<0). River increases in phosphate from climate change are mitigated by the GC reduction leading to mitigation of the netPP increase in the southern North Sea, the Irish Sea and around UK coasts. The climate-induced increase in the large phytoplankton biomass around the UK coast is slightly amplified by the GC driver whilst the increase in small phytoplankton biomass is mitigated. Decreases in small zooplankton biomass are amplified and increases in the large zooplankton biomass are mitigated, with a potential impact on high trophic levels and fisheries. Reduced fishing effort in the North Sea amplifies the increase in benthic biomass experienced under conditions of climate change in the near future.

4. Conclusions

We studied a single realization of possible future climate conditions and investigated the effects of additional substantial changes in direct anthropogenic drivers of benthic trawling effort in the North Sea and river nutrient loads. Climate change can potentially drive major ecosystem changes in primary production and plankton biomass in both the near (2030-2040) and far (2082-2099) future. Direct driver effects dominate climate effects only locally: changes due to river nutrients are confined to coastal regions and the southern North Sea, and changes due to benthic trawling affect the benthic biomass. Direct drivers can mitigate or amplify the effects of climate change on the ecosystem of the European shelf. In a modelling study of climate change and nutrient load reductions for the Baltic Sea, *Meier et al.* [2012] showed that the relative impacts of climate and nutrient reductions depends on the magnitude of the nutrient reduction: climate change dominates changes in water quality for moderate reductions in nutrients consistent with current legislation, leading to a reduction in water quality, whereas larger nutrient reductions can improve water quality.

The ecosystem response to changes in the climate forcing is not linear, but responds to multiple processes mediating the climate change signal [*Holt et al.*, 2014]: for example, initial increases in netPP in the southern North Sea by 2030-2040 disappear by 2082-2099. However, in general, the changes in plankton and benthic biomass become larger and more widespread in the far future than in the near future. The importance of oceanic effects appears to increase with time as larger reductions in concentrations of oceanic nutrients by the end of the 21st century give rise to significant changes further on the shelf, particularly into the North Sea. This might potentially offset the more local effects due to increases in temperature on the shelf, e.g. causing a reduction in silicate concentrations in the North Sea in the far future.

By comparing changes in the average conditions due to changes in climate forcing to direct anthropogenic driver experiments, our results show the potential impacts and limits of government and environmental policies affecting river nutrient loads and benthic trawling effort. In the northeast Atlantic, away from the European continental shelf, such policy measures have little impact on the ecosystem and the climate change effects dominate. In our results, these mainly reduce netPP. On the continental shelf, the impact of climate change on netPP and plankton biomass may be mitigated to some extent by environmental policies that reduce river nutrients, particularly in near coastal regions. The mitigation of increases in netPP supports the MSFD GES indicator D5 on minimizing eutrophication. However, such environmental policies could amplify the effects of climate change on the biomass of large phytoplankton and small zooplankton, with a potential detrimental impact on the GES indicator D4 through changing food webs. Policies that allow river nitrogen loads to increase in the absence of any increase in river phosphate loads have little impact on net primary production and phytoplankton and zooplankton biomass, although they will cause a stronger imbalance in the N:P ratio with potential increase in toxicity of harmful algal bloom [*Glibert et al.*, 2014], and negative impacts on biodiversity (D1) and food webs. There is also a small amplifying effect on netPP and the biomass of small phytoplankton and large zooplankton in coastal regions. Reducing trawling effort in the North Sea leads to an increase in benthic biomass. Perturbations in the benthic fishing effort and river nutrient loads that are realistic in magnitude potentially alter the response of the ecosystem by more than 5% of the response due to changes in the climate. This has a potential impact on the GES indicator D6 by changing the benthic community structure and increasing biomass. To effectively manage the marine ecosystem under climate change requires a quantitative assessment of the combined impacts of climate and anthropogenic changes using improved models (see below) and better knowledge of anthropogenic pressures and their likely magnitudes.

An assessment of the skill of the recent past (CNTRL) simulation [*Holt et al.*, 2012] shows similar results to a simulation forced by atmospheric reanalysis data. However, it is difficult to assess the likelihood or skill of the near and far future simulations. To understand the uncertainty in climate projections needs a large number of simulations forced by different climate models spanning a range of responses. For the atmosphere, *Christensen et al.* [2009] compiled ensembles of high resolution regional climate models for Europe and concluded that the minimum number of simulations needed to sample uncertainty is two Regional Climate Models that are forced by two Global Climate Models. We assume that the IPSL-CM4 'business as usual' scenario climate forcing exhibits a possible 'middle of the road' climate response and study average conditions over 2030-2040 and 2082-2099 compared to the recent past period 1983-2000. The averaging periods of 11 and 18 years respectively are not sufficient to completely remove the effects of decadal variability from the long-term climate signal but instead give a snapshot of possible average conditions during these periods. Additionally, the ~12km resolution of this model does not accurately resolve all the regions where primary production is expected to be high, especially as many of the dominant effects of anthropogenic drivers are constrained to coastal regions. To address these issues requires a series of higher resolution, transient simulations using a range of climate models, which is the subject of a future project.

5. Acknowledgements

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