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Riverine impact on future projections of marine primary production and carbon uptake

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Abstract. Riverine transport of nutrients and carbon from inland waters to the coastal and finally the open ocean alters marine primary production (PP) and carbon (C) uptake, not only regionally but also globally. So far, this contribution is represented in the state-of-the-art Earth system models with limited effort. Here we assess changes in marine PP and C uptake projected under the Representative Concentration Pathway 4.5 climate scenario using the Norwegian Earth system model, with four riverine configurations: deactivated, fixed at a contemporary level, coupled to simulated freshwater runoff, and following four plausible future scenarios. The inclusion of riverine nutrients and carbon improves the modelled contemporary spatial distribution relative to observations, especially on the continental margins (5.4% reduction in root mean square error [RMSE] for PP) and in the North Atlantic region (7.4% reduction in RMSE for C uptake). Riverine nutrient inputs alleviate nutrient limitation, especially under future warmer conditions as stratification increases, and thus lessen the projected future decline in PP by up to 0.6 PgC yr^{-1} (27.3%) globally depending on the riverine configuration. The projected C uptake is enhanced along continental margins where increased PP, due to riverine nutrient inputs, dominates over the CO_2 outgassing owing to riverine organic matter inputs. Conversely, where the riverine organic matter inputs dominate over the nutrient inputs, the projected C uptake is reduced. The large range of the riverine input across our four riverine configurations does not transfer to a large uncertainty of the projected global PP and ocean C uptake, suggesting that transient riverine inputs are more important for high-resolution regional studies such as in the North Atlantic and along the continental margins.

1 Introduction

At global scale, the major sources of both dissolved and particulate materials to the oceans are river runoff, atmospheric deposition and hydrothermal inputs. Of these three, river runoffs play an essential role in transporting nutrients which stimulate biological primary production in the ocean (Meybeck, 1982; Smith et al., 2003; Chester, 2012). For some substances such as total phosphorus (TP) and total silicon, riverine input even acts as the absolutely dominant source. River transport of carbon influences the air-sea carbon (C) exchange, local oxygen balance and acidification level, thus further affecting marine ecosystem health. Although riverine carbon only plays a minor role in the global carbon cycle, it is very sensitive to regional and global changes (Meybeck and

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Vörösmarty, 1999). With an increasing world population and a perturbed hydrological cycle under climate change, riverine transport of nutrients and carbon from land to oceans has a potentially growing impact on the marine biogeochemistry and ecosystem. The impacts of anthropogenic activity, particularly agriculture, wastewater discharges and extensive damming, have greatly perturbed the riverine transport of nitrogen (N), phosphorus (P) and silicon (Si) to the oceans. Seitzinger et al. (2010) estimate that there is an increase in global riverine fluxes of dissolved inorganic nitrogen (DIN) and phosphorus (DIP) by 35% and 29%, respectively, between 1970 and 2000, and a further possible change of -2% to +29% in DIN and +37% to +57% in DIP between 2000 and 2050, depending on the future scenarios used in their study. The riverine carbon input is highly influenced by the magnitude of continental runoff, permafrost melting and leaching of post-glacial peat deposits, all of which are sensitive to climate change. In addition, anthropogenic change, such as land-use and land-cover changes, lake and reservoir eutrophication and sewage emissions of organic material into rivers may become an important factor in the future (Meybeck and Vörösmarty, 1999).

However, the contributions of riverine substances and associated processes are not well represented in the state-of-the-art Earth system models (ESMs). Previous modelling studies have either focused on a single riverine species, e.g., C or Si (Aumont et al., 2001; Bernard et al., 2011), or on a confined time period with constant riverine fluxes, e.g. pre-industrial or present-day (Lacroix et al., 2020; Cotrim da Cunha et al., 2007; Bourgeois et al., 2016). Although the riverine transports of nutrients and carbon have been considered in the latest ESMs (e.g., Tjiputra et al., 2020), their impacts on future projections of marine biogeochemistry have not been sufficiently addressed and warrant further investigation. Taking the advantage of the latest improvement of global river nutrient/carbon export datasets and responding to the demand of development of ESMs with increasing model resolution, the assessment of the impact of riverine nutrients and carbon on future projections of marine biogeochemistry becomes feasible and desired, especially for impact studies along continental margins.

In this study, we aim to assess the impact of riverine nutrients and carbon on the projected changes in regional and global marine primary production (PP) and air-sea CO_2 exchange by addressing the following questions:

1) How does the presence of riverine fluxes of nutrient and carbon affect the contemporary representation of marine biogeochemistry in our model?
2) How does the presence of riverine fluxes of nutrient and carbon affect the future projections of marine biogeochemistry?
3) How important is the consideration of transient changes in riverine fluxes of nutrient and carbon on the future projections?

We explore these questions by performing a series of transient historical and 21st century climate simulations under the RCP 4.5 scenario with the fully coupled Norwegian Earth system model (NorESM) under four different riverine input configurations.

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2 Methods

2.1 Model description

All simulations in this study have been performed with the Norwegian Earth System Model version 1 (NorESM1-ME, hereafter NorESM) (Bentsen et al., 2013), a state-of-the-art climate model that provided input to the Fifth Coupled Model Intercomparison Project (CMIP5) (Taylor et al., 2011). The model is based on the Community Earth System Model version 1 (CESM1) (Hurrell et al., 2013). The atmospheric, land and sea ice components are the Community Atmosphere Model (CAM4) (Neale et al., 2013), the Community Land Model (CLM4) (Oleson et al., 2010; Lawrence et al., 2011) and the Los Alamos National Laboratory sea ice model (CICE4) (Holland et al., 2011), respectively. An interactive aerosol-cloud-chemistry module has been added to the atmospheric component (Kirkevåg et al., 2013). The physical ocean component—the Bergen Layered Ocean Model (BLOM, formerly called NorESM-O) (Bentsen et al., 2013)—is an updated version of the Miami Isopycnic Coordinate Ocean Model (MICOM) (Bleck and Smith, 1990; Bleck et al., 1992) and features a stack of 51 isopycnic layers (potential densities ranging from 1028.2 to 1037.8 kg m^{-3} referenced to 2000 dbar) with a two-layer bulk mixed layer on top. The depth of the bulk mixed layer varies in time and the thickness of the topmost layer is limited to 10 m in order to allow for a faster air-sea flux exchange. The ocean and sea ice components are configured on a dipolar curvilinear horizontal grid with a 1° nominal resolution that is enhanced at the Equator and towards the poles, and its northern grid pole singularity is rotated over Greenland. The atmosphere and land components are configured on a regular 1.9° x 2.5° horizontal grid.

The ocean biogeochemistry component of NorESM is base on the Hamburg Ocean Carbon Cycle Model (HAMOCC5) (Maier-Reimer et al., 2005). The component has been tightly coupled to NorESM-O such that both components share the same horizontal grid as well as vertical layers and that all tracers are transported by the physical component at model time step (Assmann et al., 2010). Tuning choices and further improvements to the biogeochemistry component are detailed in Tjiputra et al. (2013). Here we only summarise features of particular importance to this study. The partial pressure of CO_2 (pCO_2) in seawater is calculated as a function of surface temperature, salinity, pressure, dissolved inorganic carbon (DIC) and total alkalinity. Dissolved iron is released to the surface ocean with a constant fraction (3.5%) of the climatology monthly aerial dust deposition (Mahowald et al., 2005), but only 1% of this is assumed to be bio-available. Nitrogen fixation by cyanobacteria occurs when nitrate in the surface water is depleted relative to phosphate according to the Redfield ratio (Redfield et al., 1934). Phytoplankton growth in the model depends on temperature, availability of light and on the most limiting nutrient among phosphate, nitrate and iron. Constant stoichiometric ratios for the biological fixation of C, N, P and ΔO_2 (122 : 16 : 1 : -172) are prescribed in HAMOCC, and are extended by fixed Si : P (25 : 1) and Fe : P (3.66×10^{-4} : 1) stoichiometric ratios. HAMOCC prognostically simulates export production of particulate organic carbon (POC). It is assumed that a fraction of POC production is associated with diatom silica production, and the remaining fraction is associated with calcium carbonate production by coccolithophorides. The fraction of diatom-associated production is calculated from silicate availability, effectively assuming that diatoms are able to out-compete other phytoplankton growth under favorable (high surface silicate concentration) growth conditions. Particles, including POC, biogenic silica, calcium carbonate and dust are advected by ocean circulation in the model. Those particles sink through the water column with constant sinking speeds and are remineralized at constant rates. HAMOCC includes an interactive sediment module with 12 biogeochemically active vertical layers. Permanent burial of particles out of the deepest sediment layer represents a net loss of POC, calcium carbonate and silica from the ocean/sediment system and is compensated by atmospheric and riverine inputs on a time scale of several thousand model-years. The overall performance of the physical and biogeochemistry ocean components has been evaluated elsewhere (Bentsen et al., 2013; Tjiputra et al., 2013). More detailed model description and parameters are documented in the same publications.

2.2 Riverine data implementation

The influx of carbon and nutrients from over 6000 rivers to the coastal oceans has been implemented in HAMOCC based on previous work of Bernard et al. (2011) but with modifications that are outlined in the following paragraphs.

The riverine influx includes carbon, nitrogen and phosphorus, each in dissolved inorganic, dissolved organic, and particulate forms, as well as alkalinity (ALK), dissolved silicon and iron (Fe). Except for DIC, ALK and Fe, all data are provided by the Global NEWS 2 (NEWS 2) model (Mayorga et al., 2010), which is a hybrid of empirical, statistical and mechanistic model components that simulate steady-state annual riverine fluxes as a function of natural processes and anthropogenic influences. The NEWS 2 data product contains historical (year 1970 and 2000) and future (year 2030 and 2050) estimates of riverine fluxes of carbon and nutrients. The future products are developed based on four Millennium Ecosystem Assessment (MEA) scenarios (Alcamo et al., 2006): Global Orchestration (GNg), Order from Strength (GNo), Technogarden (GNt) and Adapting Mosaic (GNa). These scenarios represent different focuses of future society on e.g. globalization or regionalization, reactive or proactive environmental management and their respective influences on efficiency of nutrient use in agriculture, nutrient release from sewage, total crop and livestock production along with others (Seitzinger et al., 2010).

DIC and ALK fluxes are taken from the work of Hartmann (2009). Riverine Fe flux is calculated as a proportion of a global total input of 1.45 Tg yr^{-1} (Chester et al., 1990), weighted by water runoff of each river. Only 1% of the riverine Fe is added to the oceanic dissolved Fe, under the assumption that upto 99% of the fluvial gross dissolved Fe is removed during estuarine mixing (Boyle et al., 1977; Figuères et al., 1978; Sholkovitz and Copland, 1981; Shiller and Boyle, 1991).

At the river mouths, all fluxes are interpolated to the ocean grid in the same way as the freshwater runoff, which is distributed as a function of river mouth distance with an e-folding length scale of 1000 km and cutoff of 300 km.

In HAMOCC, organic forms of carbon and nutrients are always coupled through the Redfield ratio. Therefore, the least abundant riverine organic constituent (both dissolved and particulate forms) is determined and added to the modelled dissolved organic carbon (DOC) and DET pools (detritus, particulate organic matter). Any remaining riverine organic matter is then added to its inorganic pool (see also Bernard et al., 2011).

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2.3 Experimental design

The fully coupled NorESM model is spun up for 900 years with external forcings fixed at preindustrial year-1850 levels prior to our experiments (Tjiputra et al., 2013). The atmospheric CO_2 mixing ratio is set to 284.7 ppm during the spin-up. Nutrients and oxygen concentrations in the ocean are initialised with the World Ocean Atlas dataset (Garcia et al., 2013a, b). Initial DIC and ALK fields are taken from the Global Data Analysis Project (Key et al., 2004). After 900 years, the ocean physical- and biogeochemical tracer distributions reach quasi-equilibrium states. We extended the spin-up for another 200 years with riverine input for each experiment (except for the reference run) and then performed a set of transient climate simulations for the industrial era and the 21st century (1850-2100). The simulations use external climate forcings that follow the CMIP5 protocol (Taylor et al., 2011). For the historical period (1850-2005), observed time-varying solar radiation, atmospheric greenhouse gas concentrations (including CO_2), natural and anthropogenic aerosols are prescribed. For the future period (2006-2100), the Representative Concentration Pathway (RCP) 4.5 (van Vuuren et al., 2011) is applied. Here, we assume that the middle-of-the-road scenario with some mitigations to be the most representative future scenario. The riverine input configurations employed in this study are summarized in Figure 1. The global total fluxes of each nutrient/carbon species are shown in Figure 2. The experiment configurations are described as follows:

- REF: Reference run. Riverine nutrient and carbon supply is deactivated.
- FIX and FIXnoc: Fixed at contemporary level. FIX: A constant riverine nutrient and carbon supply, representative for the year 1970 as provided by NEWS 2, is applied to the model throughout the whole experiment duration. FIXnoc: As FIX but only with nutrients supply, all carbon (DIC, DOC, POC) and alkalinity fluxes are not considered.
- RUN: Coupled to simulated freshwater runoff. Riverine nutrient and carbon supply representative for the year 1970 is linearly scaled with the on-line simulated freshwater runoff divided by the climatological mean runoff over 1960-1979 of the model. Thus, the inputs follow the seasonality and long-term trend of the simulated runoff. We assume that the nutrient and carbon concentrations in the rivers are constant at the level of 1970, but the fluxes fluctuate with freshwater runoff.
- GNS: Transient input following future projections of NEWS 2. A constant riverine nutrient and carbon supply representative for year 1970 has been applied from year 1850 to 1970. Between year 1970, 2000, 2030 and 2050 the annual riverine supply is linearly interpolated. From year 2050 to 2100 the annual riverine supply is linearly extrapolated. From year 2000, riverine supplies of the four NEWS 2 future scenarios (GNa, GNg, GNo and GNt) are applied.

By comparing FIX versus REF we assess how the presence of riverine inputs affect the contemporary marine biogeochemistry representation and also the projected changes. By comparing RUN versus FIX we assess the potential effects of riverine nutrient and carbon long-term trends associated with an intensifying global hydrological cycle on marine biogeochemistry. RUN represents a first step towards coupling riverine nutrient and carbon fluxes to the simulated hydrological cycle. By comparing the GNS configurations versus FIX we assess how plausible, realistic future evolutions in riverine nutrient and carbon fluxes may impact marine biogeochemistry projections. We span the uncertainty in future riverine nutrient and carbon fluxes by considering multiple NEWS 2 scenarios.

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An important feature of the experimental design is that the marine biogeochemistry does not feedback on the physical climate in our model setup. Consequently, the climate variability and climate trends are the same in all experiments and the interannual variability in the biogeochemical parameters—which is dominantly driven by the physical climate variability—is also virtually the same. Any uncertainty related to internal climate variability is thus effectively removed in the computation of the inter-experiment differences. In this manner, we are able to obtain statistically robust results for short time-slices without having to perform multi-member simulation ensembles for each experiment.

3 Results

3.1 Effect of including riverine inputs on contemporary marine biogeochemistry

We start with assessing how the inclusion of riverine nutrients and carbon affects the contemporary representation of the global marine biogeochemistry in our model by comparing the annual mean output over the years 2003-2012 between the REF and FIX experiments. We also compare with observational estimates to see if the inclusion of riverine nutrients and carbon improves the marine biogeochemistry representation in our model.

The annual net primary production (PP) is 40 and 43 PgC yr^{-1} in the REF and FIX experiments, respectively. The increase of PP in FIX occurs along continental margins (where seafloor is shallower than 300 m), accounting for 15% of the global total increase, and predominantly in the North Atlantic (Figure 3c). The simulated global total PP in both REF and FIX are lower than the satellite-based model estimates, including Vertically Generalized Production Model (VGPM), Eppley-VGPM and Carbon-based Production Model (CbPM) over the same time period, ranging from 55 to 61 PgC yr^{-1} (Behrenfeld and Falkowski, 1997; Westberry et al., 2008). Although the total PP in FIX is still considerably lower than the satellite-based estimates, the inclusion of riverine nutrients and carbon does slightly improve the distribution of PP especially on continental margins (Figure 3), according to our area-weighted root mean square error (RMSE) analysis. The RMSE of REF relative to mean observational estimates (mentioned above) averages 10.7 mol C m^{-2} yr^{-1} globally, while the value of FIX is 10.3 mol C m^{-2} yr^{-1}, which is reduced by 3.6%. For the continental margins, the RMSE is reduced by 5.4% from 29.0 mol C m^{-2} yr^{-1} in REF to 27.4 mol C m^{-2} yr^{-1} in FIX.

The ocean annual net uptake of CO_2 is 2.8 and 2.9 Pg C yr^{-1} in REF and FIX, respectively, with a FIX-REF difference of 0.09±0.01 Pg C yr^{-1} equivalent to 3.1±0.1% relative change (note that the 2σ standard errors are small because REF and FIX share the same interannual variability). In FIX the ocean carbon uptake is generally enhanced everywhere except for the upwelling regions of the Southern Ocean and in the subpolar North Atlantic between approximately 50°N-65°N and 60°W-10°W (Figure 4c). To isolate the impact of riverine nutrients input from carbon input, an additional experiment (FIXnoc) was conducted, where the nutrient fluxes are implemented the same as in FIX, while all carbon (DIC, DOC, POC) and alkalinity fluxes are eliminated. As shown in Figure 4d, the nutrients input results in more CO_2 uptake not only at large river estuaries but also in the subtropical gyres due to enhanced primary production. In the subpolar North Atlantic and in the Southern Ocean upwelling region, the addition of riverine nutrients leads to enhanced outgassing. This is a remote effect of the generally increased primary production (by 3 PgC yr^{-1}), which leads to more remineralized carbon in deeper water masses. The

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riverine carbon input, on the other hand, leads to CO_2 outgassing mainly at river estuaries (Figure 4e), but also in a band along the gulf stream extending into the North Atlantic, where it accounts for 18% of the CO_2 outgassing in the subpolar region (50°N-65°N, 60°W-10°W). Along the continental margins the nutrients input increases the CO_2 uptake, while the carbon input has an opposite effect which induces more outgassing. The net effect of both nutrient and carbon inputs shows that the uptake of CO_2 dominates over the outgassing, along the continental margins and in subtropical gyres (Figure 4c). Compared to the observational based estimates of Landschützer et al. (2017) (Figure 4a) and according to our RMSE analysis, the inclusion of riverine nutrients and carbon does not improve the simulated air-sea CO_2 fluxes globally. The RMSE of REF relative to observational estimates averages to 0.834 mol C m^{-2} yr^{-1} globally, while the value of FIX is 0.833 mol C m^{-2} yr^{-1}. However, there is a distinguishable improvement of the distribution of air-sea CO_2 fluxes in the subpolar North Atlantic (RMSE is reduced by 7.4%, from 0.74 mol C m^{-2} yr^{-1} in REF to 0.68 mol C m^{-2} yr^{-1} in FIX), with slight degradations in some other regions (Figure 4c).

3.2 Effect of including contemporary riverine inputs on future projections of marine biogeochemistry

We now address how the inclusion of riverine nutrient and carbon fluxes affects future projections of marine biogeochemistry by comparing the average output between a future period (2050-2099) and a historical period (1950-1999) of FIX versus REF.

In both experiments the future projections of global PP averaged over the years 2050-2099 are lower than their corresponding 1950-1999 averages (Figure 5a). However, when riverine input of nutrient and carbon is included, the projected decrease of global PP is mitigated from -2.24 Pg C yr^{-1} in REF to -1.93 Pg C yr^{-1} in FIX (by 13.8%). Spatially, the decrease of PP in REF occurs largely in upwelling regions such as the tropical eastern Pacific and tropical Atlantic, as well as along a latitude band around 40ºS (Figure 6a). The riverine inputs alleviate the projected PP decrease in those regions (see further discussion in Section 4.2) and reinforce the projected PP increase in high latitudes (Figure 6b, c). For instance, the future projections of PP in the Arctic Ocean show significant increases in both REF and FIX. Climate change alone (REF, without riverine inputs) almost doubles the simulated PP in the Arctic from 0.08 Pg C yr^{-1} during 1950-1999 to 0.15 Pg C yr^{-1} in 2050-2099 (Figure 5b), likely as a consequence of sea ice retreat. FIX, which includes riverine inputs, exhibits a slightly larger absolute Arctic PP increase (from 0.102 to 0.180 Pg C yr^{-1}) albeit somewhat smaller relative increase (~76%) in its future projection (Figure 5b).

For global net uptake rate of CO_2, both experiments (REF and FIX) project a significant increase under the RCP4.5 (Figure 7a). The inclusion of riverine inputs leads to a slightly higher (~3%) projected increase of 1.280 Pg C yr^{-1} in FIX compared with 1.247 Pg C yr^{-1} in REF. The increase rate of CO_2 uptake in the Arctic closely follows the global trend (Figure 7b). Spatially, there is a widespread simulated increase in ocean uptake of CO_2 under future climate change except in the subtropical gyres (Figure 8a). Riverine nutrients input slightly increases the projected carbon uptake at large river estuaries, while decreases the projected uptake in subpolar North Atlantic (Figure 8d).

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3.3 Effect of future changes in riverine inputs on marine biogeochemistry projections

Finally, we address how future changes in riverine fluxes of nutrients and carbon affect marine biogeochemistry by comparing the projected changes for the time period 2050-2099 relative to 1950-1999 among FIX, RUN and the four GNS experiments.

The future projected decrease of PP in the four GNS averages to -1.58 Pg C yr^{-1}, which is less in magnitude compared to FIX (-1.93 Pg C yr^{-1}) and RUN (-1.82 Pg C yr^{-1}) (Figure 5a). Spatial distributions of projected PP changes in GNS and their respective differences relative to FIX are shown in Figure 9. The latter occur predominantly on the continental shelf in Southeast Asia, where the future projected increase in riverine nutrient load is the largest in the world in GNS (Seitzinger et al., 2010). Interestingly, the projected increase in PP in Southeast Asia, induced by riverine nutrient inputs in GNS, is of the same order of magnitude as the projected decrease in PP due to future climate change in REF. Thus, in GNS the PP are projected to slightly increase on the continental shelf of Southeast Asia (Figure 9a-d). The riverine nutrient induced PP increase in FIX or RUN is not large enough to compensate the PP decline due to climate change, since the projected changes in riverine nutrient inputs are not taken into account in FIX or locally underestimated in RUN.

On the other hand, the future projected increase in the global uptake of CO_2 in GNS (1.132 Pg C yr^{-1} in average) is smaller compared to FIX (1.280 Pg C yr^{-1}) and RUN (1.290 Pg C yr^{-1}). Differences emerge along continental margins, especially around large river estuaries (Figure 10e-h), where the dissolved organic matter (DOM), that is projected to increase in GNS, enters the ocean and releases CO_2 to the atmosphere (Seitzinger et al., 2010).

Despite the regional differences, there is no significant difference in the projected changes in either globally integrated PP or CO_2 uptake among the four GNS in our model (Figures 5 and 7, see further discussion in Section 4.3).

4 Discussion

4.1 Projected marine biogeochemistry changes

The projection of global total PP shows less decrease, if riverine inputs are present in the model. We argue that this is mainly because the riverine nutrient inputs into the surface ocean alleviates the increasing nutrient limitation caused by stronger stratification under future climate warming.

In our model, PP is roughly linearly related to the concentrations of the most limiting nutrient (Nut), light intensity (I), temperature (T) and the available phytoplankton concentration (Phy), i.e., $PP \sim Nut \cdot I \cdot f(T) \cdot Phy$. It is shown in Figure 6a that under climate change the projected decrease in PP occurs mainly in low- and mid-latitudes. Nitrate is the limiting nutrient (in REF experiment) in almost everywhere except in the Central Indo-Pacific region, in the South Pacific subtropical gyre, in the Bering Sea and part of the Arctic, where Fe is limiting (Figure A1). Projected reduction in surface nitrate concentrations (Figure A2c), which is tightly linked to the upper-ocean warming and increased vertical stratification (Bopp et al., 2001; Behrenfeld et al. 2006; Steinacher et al., 2010; Cabré et al., 2015), contributes to the projected decrease in PP in our model. The simulated global mean PP over 2050-2099 is 38.9 Pg C yr^{-1} in REF, which is 2.24 Pg C yr^{-1} lower than the value over 1950-1999. This -5.4% projected change in PP is comparable with the multi-model mean estimate of projected change of -3.6 (±5.7) %

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in the 2090s relative to the 1990s for RCP4.5 (Bopp et al., 2013) and sits in the range of 2-13% decrease projected by four ESMs over the 21st century under the SRES A2 scenario (Steinacher et al., 2010).

When riverine nutrient fluxes are added into coastal surface waters in FIX, the PP is higher in both historical and future periods compared to REF (Figure 5a), due to alleviated nutrient limitation. Interestingly, the effect of riverine inputs on PP for the historical and future time period is not the same, suggesting a different nutrient depletion level. The projected decrease in PP is lessened from -5.4% in REF to -4.4% in FIX. We conjecture that during 1950-1999 the riverine nutrients are not depleted by primary producers, while during 2050-2099 the riverine nutrients are utilized to a greater extent due to the exacerbated nutrient limitation and potentially to higher phytoplankton growth rate in warmer climate. Figure 12 illustrates this in a schematic diagram that shows the impact of riverine nutrients on projected PP in low- and mid-latitudes. Moreover, the inclusion of constant riverine inputs (FIX) can potentially explain one tenth of the ~10% (2-13%, Steinacher et al., 2010) inter-model spread.

In contrast to the global PP, there are considerable increases in the future projected PP in the Arctic in REF (Figure 5b). In polar regions light and temperature are the primary limiting factors for phytoplankton growth, therefore PP increases when light and temperature become more favourable owing to sea-ice melting under warmer conditions (Sarmiento et al., 2004; Bopp et al., 2005; Doney, 2006; Steinacher et al., 2010). On the other hand, the fresher and warmer surface water increases stratification, which counteracts the increase in PP. Therefore, when riverine nutrients input is present in the model, it helps to sustain the projected PP increase in the Arctic, although this effect is only minor (Figure 5b).

The ocean annual net uptake of CO_2 increases significantly during 2050-2099 compared with the uptake during 1950-1999 in REF (Figure 7a), which is mainly driven by increasing difference in air-sea partial pressure of CO_2. Our experiments show that riverine nutrient inputs have a dominant role over the organic matter inputs in FIX, enhancing CO_2 uptake along continental margins via sustaining PP in both historical and future time periods.

4.2 Different riverine configurations

By exploring different riverine configurations (FIX, RUN, GNS) we investigate how uncertainties in future riverine fluxes translate into uncertainties in projected biogeochemistry changes. In RUN we assume constant concentrations (at 1970's level) of riverine nutrient and carbon over time and couple them to the simulated freshwater runoff. Thus, the annual global total fluxes of nutrient and carbon vary with time following the variability of runoff (Figure 2), in contrast to the constant fluxes in FIX. The global total simulated runoff, under RCP4.5 in our model, is on average higher during 2050-2099 than the runoff during 1950-1999, indicating an intensified hydrological cycle under future climate change. Hence, the global riverine fluxes of nutrient and carbon during 2050-2099 are higher than those during 1950-1999 in RUN. However, the temporal changes in global riverine fluxes in RUN are relatively small compared with the absolute flux values in FIX, which explains the slightly larger projected changes in global PP and ocean carbon uptake in RUN compared to FIX. It is noteworthy that the large inter-annual variability in the riverine fluxes of nutrient and carbon in RUN does not increase the inter-annual variability in simulated PP and ocean carbon uptake either globally or on the continental margins (Figure 11), something that warrants further investigation. The approach of RUN serves as the first step towards time-varying riverine inputs that take the hydrological variability into account. It can be utilised in future efforts

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assessing seasonal and inter-annual effects of riverine inputs on regional scale in high-resolution models with better representation of shelf processes. Although the RUN approach is more advanced compared to FIX, it employs a linear relationship between the future riverine nutrient and carbon fluxes and simulated hydrological cycle, which is a highly simplified assumption (see discussion in section 4.3).

Figure 2 shows that the inputs of DIN and DIP are considerably lower, while the dissolved silicon (DSi) and particulate organic matter (POM) are higher in the future period in RUN compared to GNS. This is because many anthropogenic processes that are important for determining the future riverine fluxes are not considered in RUN, but are considered in NEWS 2 model system, from which the GNS' future scenarios are simulated. For example, the nutrient management in agriculture, the sewage treatment and phosphorus detergent use, and the increased reservoirs from global dam construction in river system (Seitzinger et al., 2010; Beusen et al., 2009) are the key factors affecting future riverine fluxes of DIN, DIP, and DSi/POM, respectively. Therefore, it is worth exploring the merits of using GNS in future projections of marine biogeochemistry. The four future scenarios provide a range of potential outcomes resulting from different choices tending toward either globalization or regional orientation, either reactive or proactive approach to environmental threats. Surprisingly, even a large range of the riverine inputs in GNS, e.g., temporal changes in DIN fluxes across scenarios ranging 24.8-63.0% of the annual flux in FIX, do not transfer to large uncertainties in future global marine biogeochemistry projections in NorESM. However, the scenario differences might be of importance in regional projections, such as in seas surrounded by highly populated nations and near river estuaries. Simulations with high-resolution global or regional models with a good representation of shelf processes are required to accurately assess the local impact of riverine inputs.

4.3 Limitations and uncertainties

Given that the riverine nutrient and carbon inputs account for only a small proportion of the total amount of nutrients and carbon in the euphotic zone of the ocean, we acknowledge several limitations of our study, particularly related to the complexity and resolution of our ESM. Firstly, shelf processes, which are not well represented in our model, modify a large fraction of some riverine species, e.g., conversion of organic carbon to CO_2 occurs rapidly via remineralization in estuaries before they are transported to the open ocean. Secondly, coarse-resolution models tend to underestimate primary production along the coast. Such well-known model issues may offset the impact induced by riverine inputs. Moreover, we have conducted all simulations only under one IPCC representative concentration pathway scenario (the intermediate RCP 4.5), which may lead to a narrower possible range of the riverine fluxes induced impact on the projected marine biogeochemistry.

In RUN we assume constant concentrations of riverine nutrient and carbon over time and the fluxes vary with freshwater runoff. This may be applicable for some nutrients such as DIN or within a certain limit of runoff change such as for dissolved Si (Figure A3). However, this may not be appropriate for all nutrient/carbon species. Furthermore, the variability of runoff is subject to interannual to decadal climate variability, which partially masks the centennial trend. This caveat can be overcome through performing multi-realization ensemble simulations.

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5 Conclusions

In this study, we apply a fully coupled Earth system model to assess the impact of riverine nutrients and carbon delivery to the ocean on the contemporary and future marine primary production and carbon uptake. We also quantify the effects of uncertainty in future riverine fluxes on the projected changes, using several riverine input configurations.

Compared to satellite- and observation-based estimates, the inclusion of riverine nutrients and carbon improves the contemporary spatial distribution only slightly on a global scale (3.6% and 0.1% reduction in RMSE for PP and ocean carbon uptake, respectively), with larger improvements on the continental margins (5.4% reduction in RMSE for PP) and the North Atlantic region (7.4% reduction in RMSE for carbon uptake).

Concerning future projected changes, decline in nutrients supply in tropical and subtropical surface waters, due to upper ocean warming and increased vertical stratification, is projected by our model to reduce PP over the 21st century. Riverine nutrient inputs into surface coastal waters alleviate the nutrient limitation and considerably lessen the projected future decline in PP from -5.4% without riverine inputs to -4.4%, -4.1% and -3.6% in FIX, RUN and GNS (averaged over four scenarios), respectively. Different from the global value, the projected PP in the Arctic increases considerably, because light and temperature—the primary limiting factors for phytoplankton growth in polar regions—become more favourable due to sea-ice melting under warmer future conditions. When riverine nutrient inputs are presented in the model, they further enhance the projected increase in PP in the Arctic, counteracting the nutrient decline effect due to stronger stratification in the fresher and warmer surface water.

Depending on the riverine scenarios, where the riverine nutrient inputs dominate over the organic matter, the projected net uptake of CO_2 further enhances along continental margins via photosynthesis process. Conversely, where the riverine organic matter inputs are dominant over the nutrient inputs, the projected net uptake of CO_2 is reduced, especially at large river estuaries, due to higher CO_2 outgassing.

We have explored a range of riverine input configurations from temporally constant fluxes (FIX), to idealised time-varying fluxes following variations in simulated hydrological cycle (RUN), to plausible future scenarios (GNS) from a set of global assumptions. The large range of the uncertainty of the riverine input does not transfer to large uncertainty of the projected global PP and ocean carbon uptake. Our study suggests that applying transient riverine inputs in the ESMs with coarse or intermediate model resolution (~1°) does not significantly reduce the uncertainty in global marine biogeochemistry projections, but it may be of importance for regional studies such as in the North Atlantic and along the continental margins.

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Appendix A

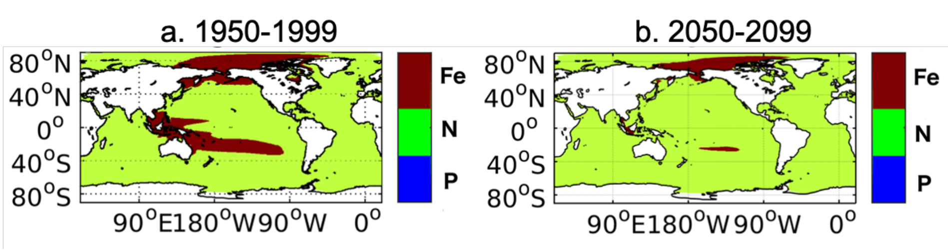

Figure A1: The limiting nutrient among iron, nitrate and phosphate in REF during (a) 1950-1999 and (b) 2050-2099.

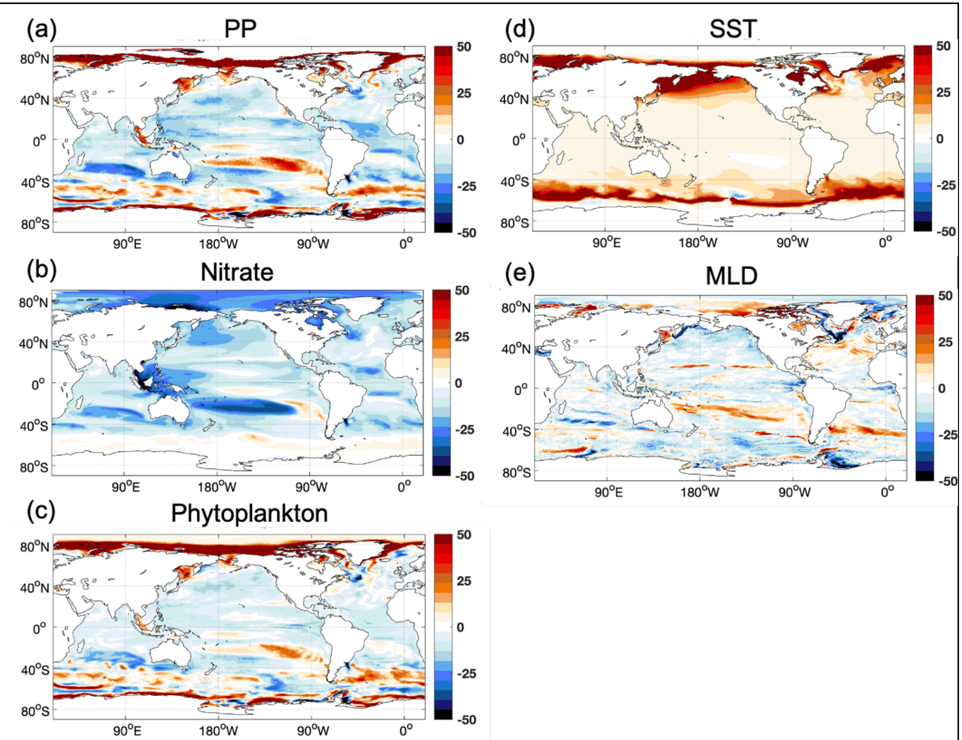

Figure A2: The relative changes in projected (2050-2099 compared to 1950-1999) (a) primary production, (b) nitrate concentration, (c) phytoplankton concentration, (d) sea surface temperature and (e) annual mean maximum mixed layer depth in REF.

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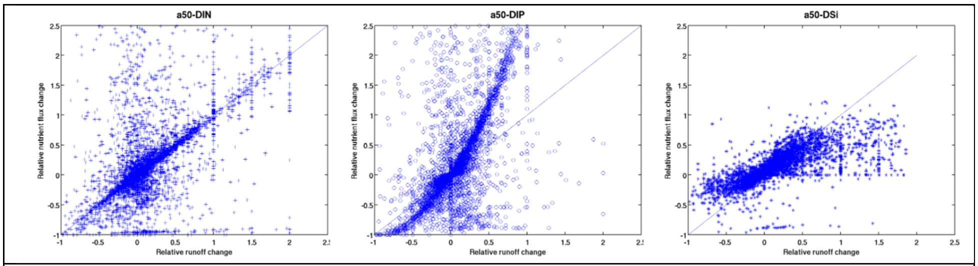

Figure A3. The relationship between relative changes in freshwater runoff and relative changes in nutrient fluxes (dissolved inorganic nitrogen, phosphorus and silicon) in 2050 according to the Adapting Mosaic future scenario in NEW2 dataset.

Code and data availability

The model code and riverine data used can be provided by the corresponding author upon request.

Author contribution

SG and IB designed the model experiments and SG developed the model code and performed the simulations with the help from IB. JS and JT contributed to the interpretation and analyzation of the results. JS, JT, IB and CH contributed to editing the manuscript. CH supervised the project work. JH and EM provided riverine data and consultation. SG prepared the manuscript with contributions from all co-authors.

Competing interests

The authors declare that they have no conflict of interest.

Disclaimer

This article reflects only the authors' view – the funding agencies as well as their executive agencies are not responsible for any use that may be made of the information that the article contains.

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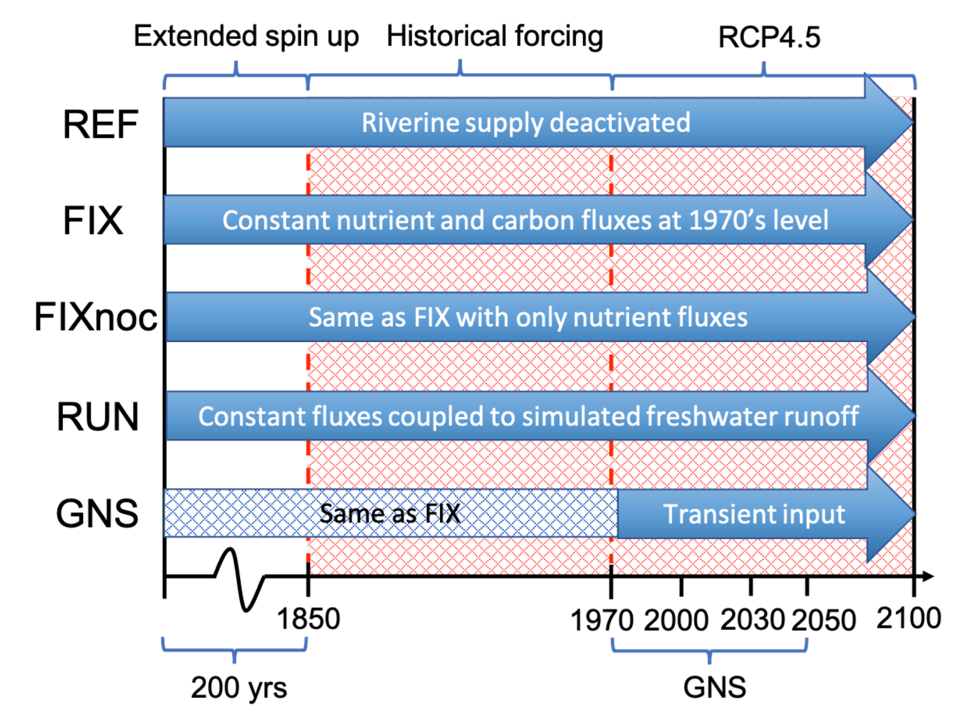

Figure 1: Schematic illustration of the spin-up and integration procedure following the experimental design described in Section 2.3.

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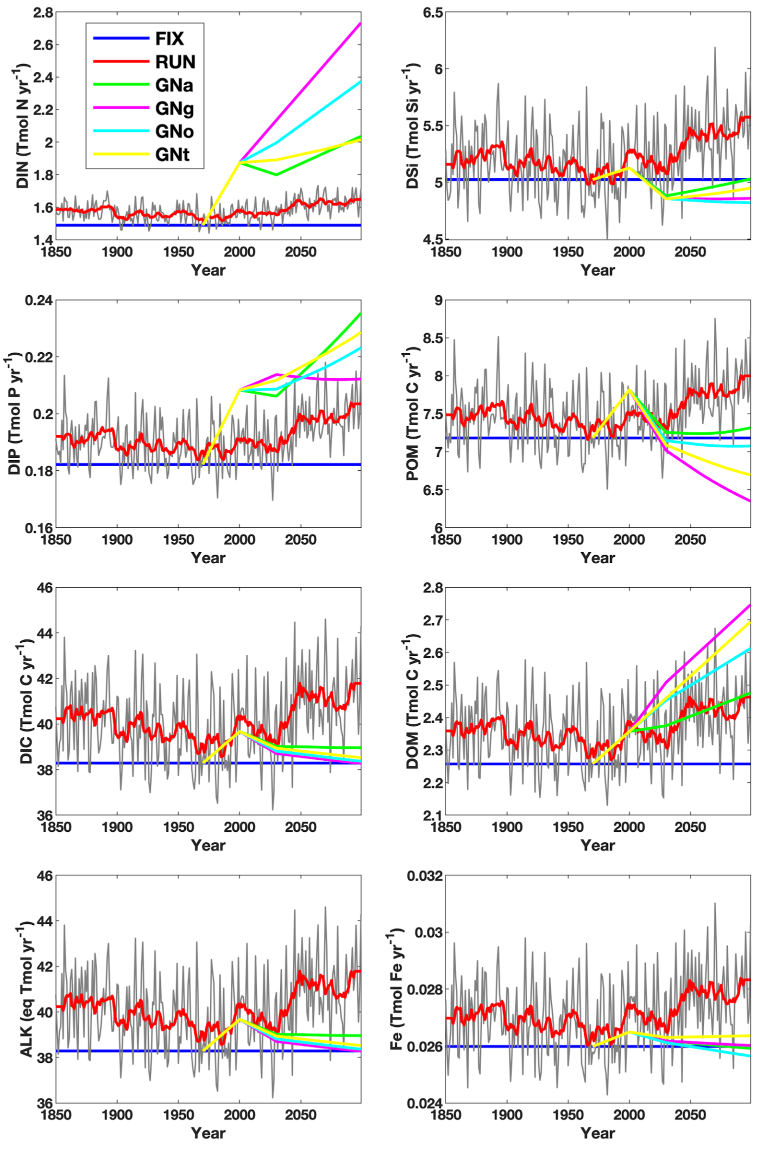

Figure 2: Time series of global riverine fluxes of nutrient and carbon to the ocean according to the configuration of six model experiments (FIX, RUN, GNa, GNg, GNo and GNt). The grey and red curves are the annual and 11-year running mean fluxes, respectively, in RUN. DIN: dissolved inorganic nitrogen; DIP: dissolved inorganic phosphorus; DIC: dissolved inorganic carbon; ALK: alkalinity; DSi: dissolved silicon; POM: particulate organic matter; DOM: dissolved organic matter; Fe: dissolved iron.

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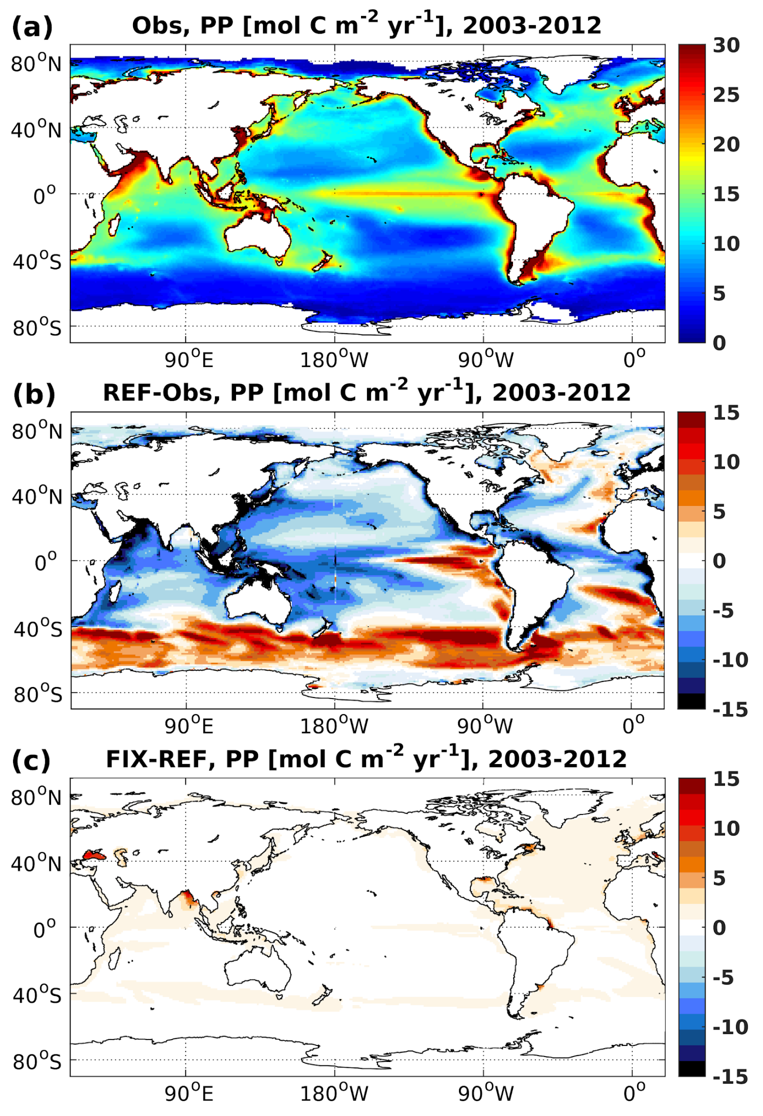

Figure 3: Vertically integrated primary production averaged over the 2003-2012 period of (a) the mean of three satellite-based climatologies derived from MODIS retrievals, (b) the difference between REF and satellite-based estimates, (c) the difference between FIX and REF.

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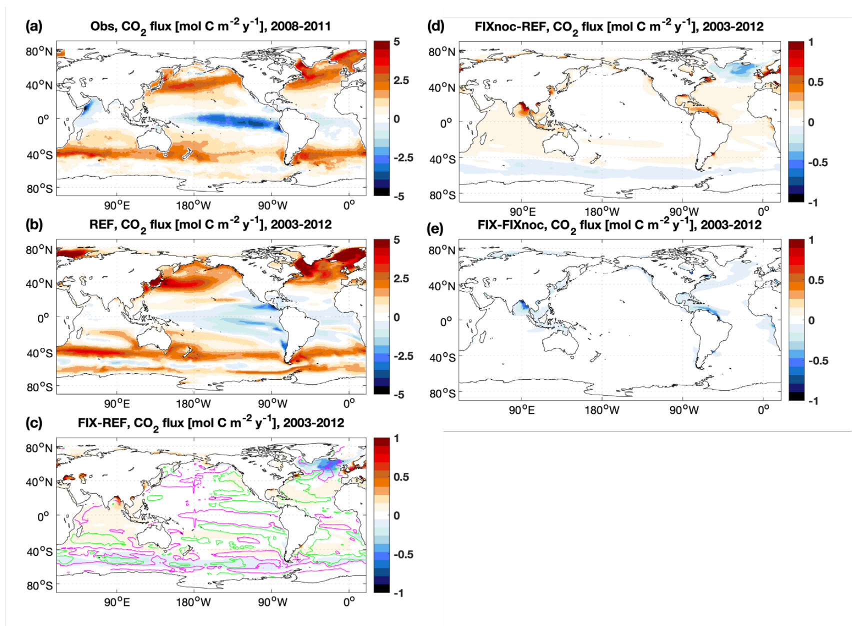

Figure 4: Annual mean air-sea CO_2 fluxes over the 2003-2012 period of (a) the observational based estimates of Landschützer et al. (2017), (b) REF, (c) the difference between FIX and REF, (d) the difference between FIXnoc and REF, and (e) the difference between FIX and FIXnoc. Contour lines in (c) are the differences between REF and Obs, purple lines (0.5 mol C m^{-2} yr^{-1}) indicate where REF overestimates C uptake compared to Obs and green lines (-0.5 mol C m^{-2} yr^{-1}) indicate the opposite.

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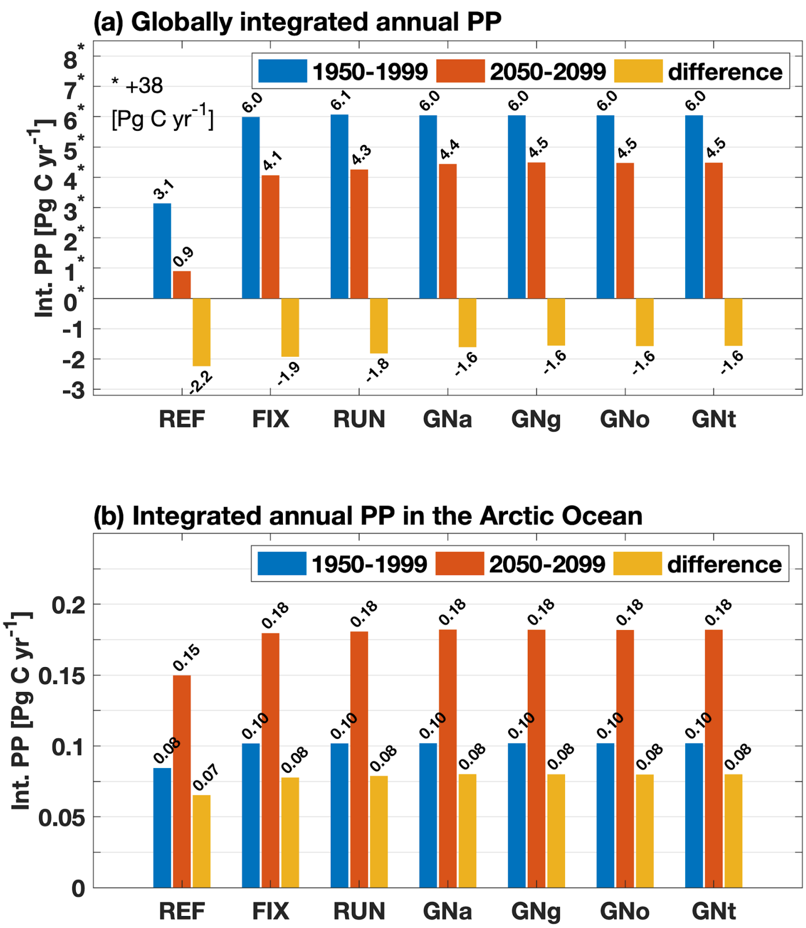

Figure 5: (a) Globally integrated annual mean primary production over 1950-1999 (blue), over 2050-2099 (red) and the differences between these two time periods (yellow) for all experiments; (b) Same as 8a) but for the Arctic Ocean (ocean area north of the Bering Strait on the Pacific side and north of 70°N on the Atlantic side) for the same time periods as in (a).

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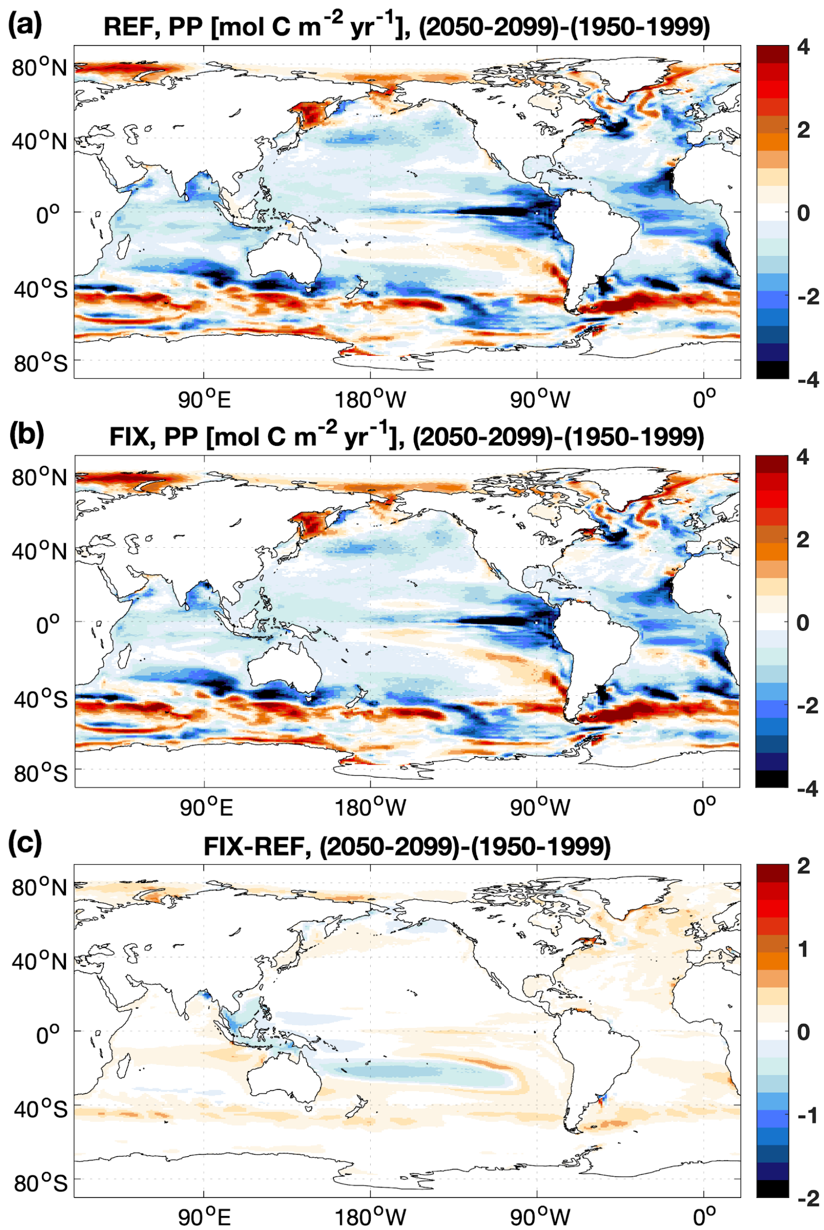

Figure 6: The difference in vertically integrated primary production between 2050-2099 and 1950-1999 time periods in (a) REF, (b) FIX, and (c) the difference between (b) and (a).

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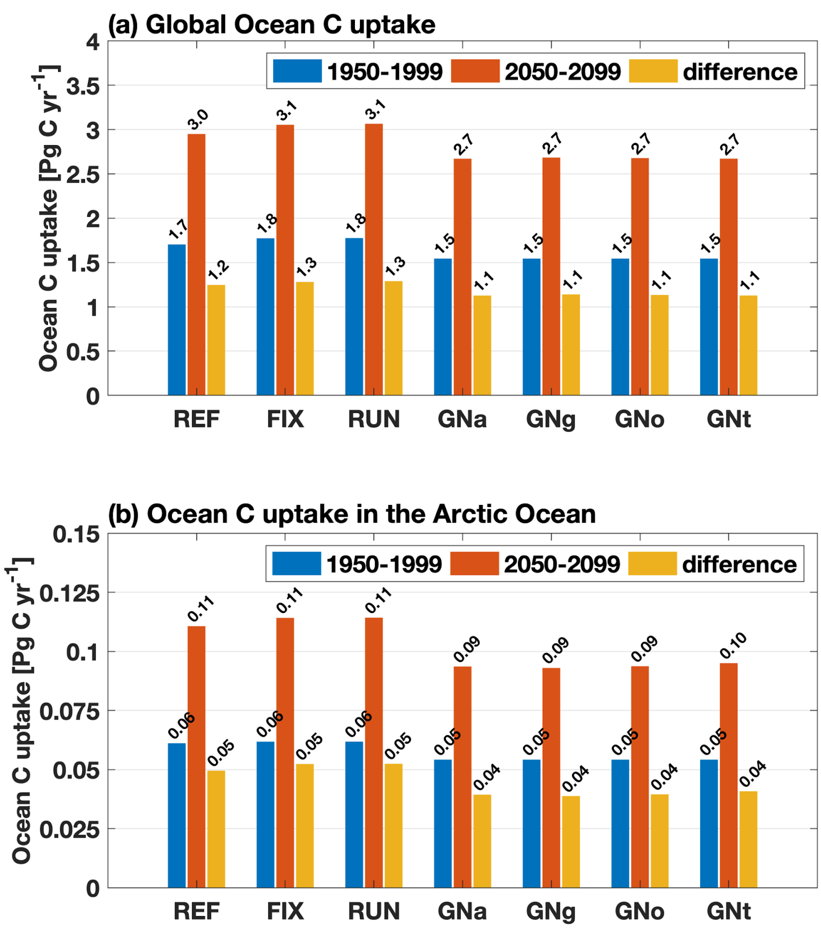

Figure 7: (a) Globally integrated annual mean ocean carbon uptake over 1950-1999 (blue), over 2050-2099 (red) and the differences between these two time periods (yellow) for all experiments; (b) Same as (a) but for the Arctic Ocean (ocean area north of the Bering Strait on the Pacific side and north of 70°N on the Atlantic side) for the same time periods as in (a).

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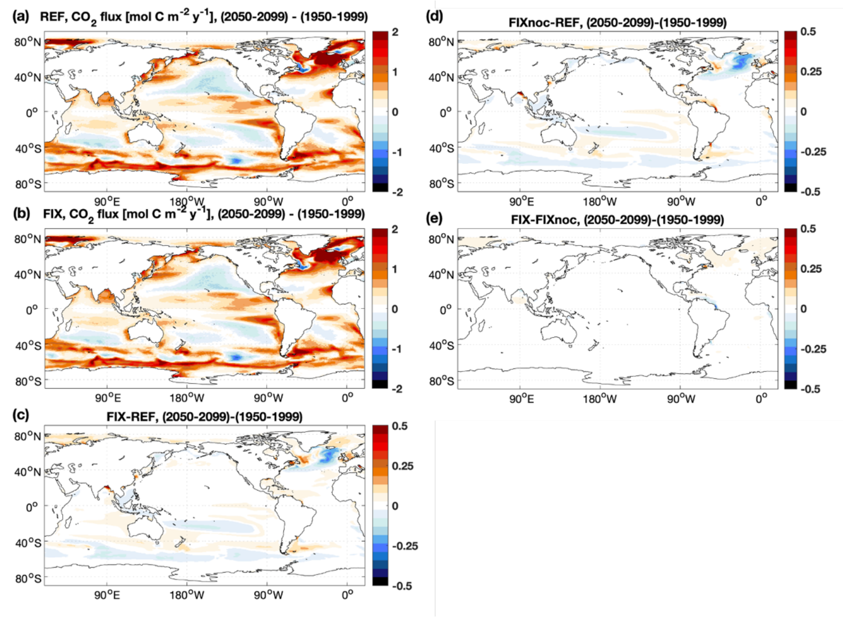

Figure 8: Differences in annual mean air-sea CO_2 fluxes (mol C m^{-2} yr^{-1}) between 2050-2099 and 1950-1999 periods in (a) REF, (b) FIX, (c) the difference between FIX and REF, (d) the difference between FIXnoc and REF, and (e) the difference between FIX and FIXnoc.

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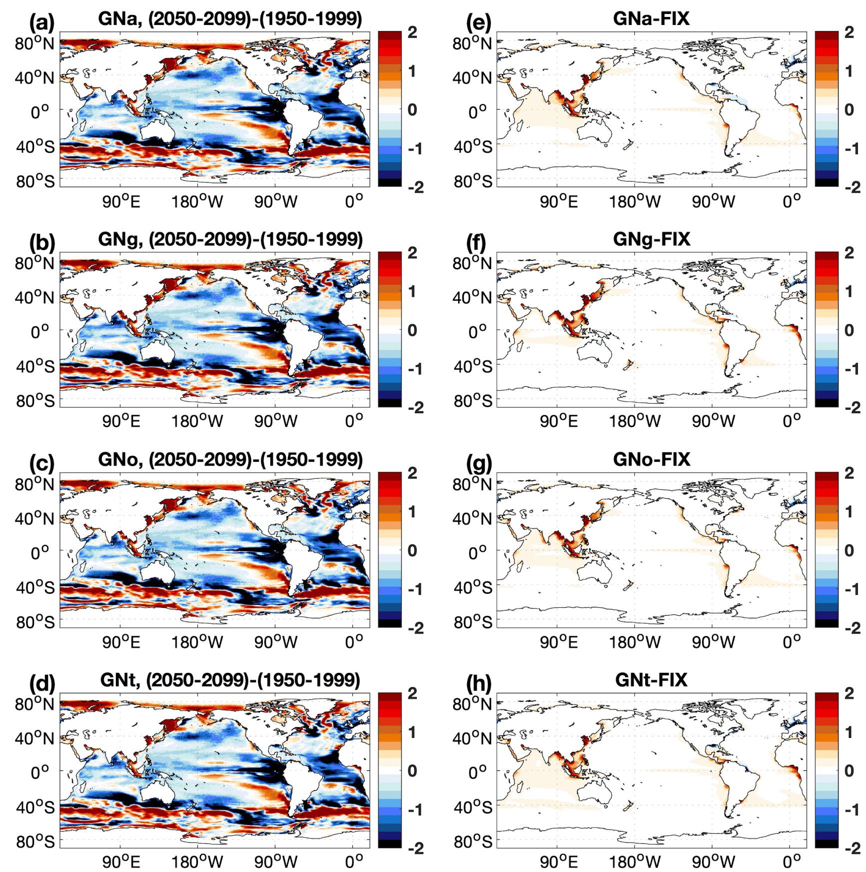

Figure 9: (a-d) Projected changes in vertically integrated primary production (mol C m^{-2} yr^{-1}) in four GNS experiments between 2050-2099 and 1950-1999 periods; (e-h) The difference in projected changes in vertically integrated primary production (mol C m^{-2} yr^{-1}) between each GNS experiment and FIX.

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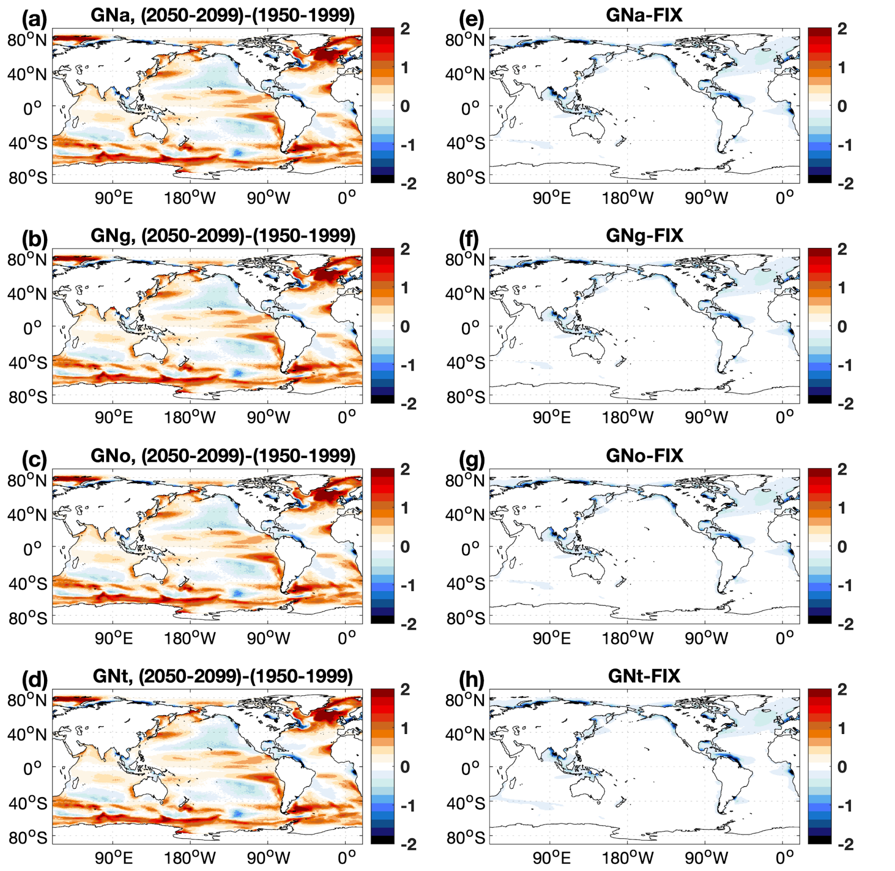

Figure 10: Projected changes in annual mean air-sea CO_2 fluxes (mol C m^{-2} yr^{-1}) in four GNS experiments between 2050-2099 and 1950-1999 periods; (e-h) The difference in projected changes in annual mean air-sea CO_2 fluxes (mol C m^{-2} yr^{-1}) between each GNS experiment and FIX.

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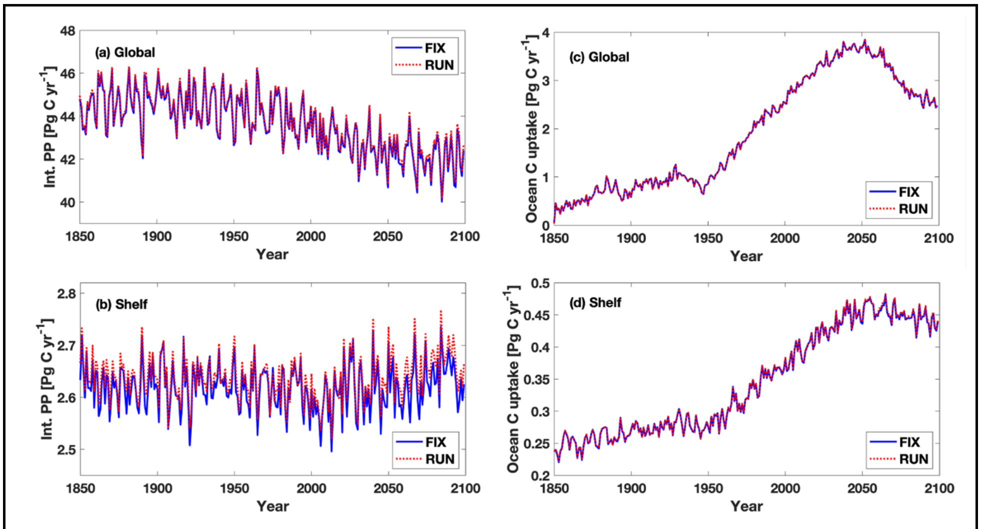

Figure 11: Time-series of integrated annual primary production and ocean carbon uptake during 1850-2099 in FIX and RUN (a, c) globally and (b, d) on continental shelves.

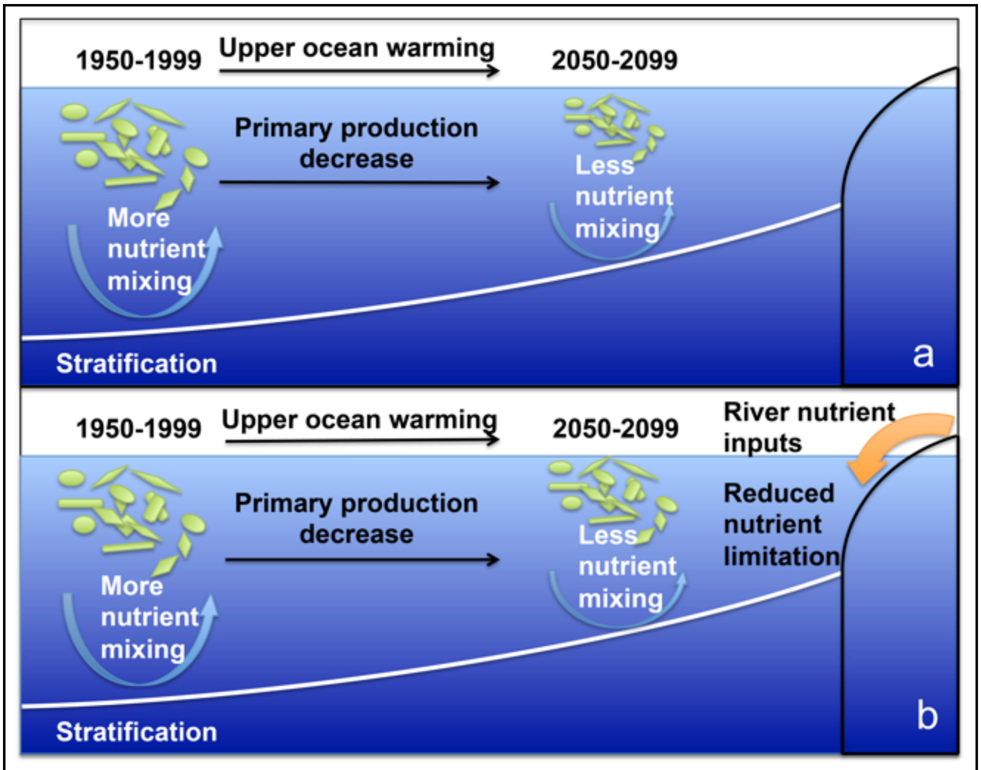

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Figure 12: Schematic drawing of impact of riverine nutrient inputs on future projections of marine primary production. Adapted from Aditi Modi (2014) (http://www.climate.rocksea.org/people/aditi-modi/). (a) Decline in nutrients supply into subtropical surface waters, due to the upper-ocean warming and increased vertical stratification, is projected by models to reduce primary production over the 21st century. (b) Riverine nutrient inputs into surface coastal waters alleviate the nutrient limitation and lessen the projected future decline in primary production.