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Context of deliverable within Work Package

The deliverable is a part of Task 2.7 in WP2 that focus on climate change effects on marine ecosystems in the Arctic. The Arctic Ocean (AO) will likely become ice-free in summer within the next two decades. This will change light conditions for primary production. Parts of the AO where primary production is presently light limited will in the future depend more on nutrient supply. It is therefore of interest to study horizontal and vertical transports of nutrients in the AO and to assess the relative importance of the different nutrient sources. We have developed a routine in SINMOD that keep track of nutrient fluxes. In the report we present results from SINMOD for the present climatic regime. This will be a basis for further sensitive studies to address uncertainty in future predictions of primary production.

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Report

Nutrient fluxes in the Arctic in the present climate regime

Subtitle

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Abstract
The Arctic Ocean (AO) will likely become ice-free in summer within the next two decades. This will change light conditions for primary production. Parts of the AO where primary production is presently light limited will be controlled also by nutrient availability in the future. It is therefore of interest to study horizontal and vertical transports of nutrients in the AO and to assess the relative importance of the different nutrient sources. In the present study we have used the coupled system SINMOD to quantify nutrient transport and mixing in the AO. The import and export of nutrients have been calculated and compared with similar results based on analysis of observational data. Vertical transport and mixing of nutrients in different parts of the Arctic are also quantified and the relative importance of the different processes are assessed.

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1 Introduction

The sea ice in the Arctic has been decreasing both in extent and in thickness over the last 10-20 years. The air temperature increase at high latitudes is greater than the global average. As the global temperature continues to increase, it is likely to expect a summer free of ice in the Arctic within a decade or two (e.g. (Stroeve et al. 2012) In the ice covered Arctic annual new primary production is limited by light but will become more controlled by nutrient availability as summer ice disappears (Vancoppenolle et al. 2013, Slagstad, Ellingsen and Wassmann 2011, Babin et al. Submitted, Roderfeld et al. 2008). Results from 3D coupled biophysical models have shown an increase in primary production over the last decades because ice becomes thinner and more light becomes available., In addition the momentum transfer from the atmosphere to the ocean become more efficient when the ice become thinner (Zhang et al. 2010) and more nutrient rich water is mixed towards the surface. However, other studies have shown that nutrient limitation will become a key factor and will limit future increase of new primary production in the Arctic Ocean (AO) (Vancoppenolle et al. 2013, Slagstad et al. 2011, Ellingsen et al. 2008). In the deep parts of the AO, the water column is highly stratified and turbulence levels are consequently low. Some upward mixing of nutrient rich water may, however, result from internal wave activity and double diffusive mixing. Along the shelf break upwelling of nutrient rich deeper water is important (Williams and Carmack 2008). Nutrients are mineralized from the bottom during autumn and winter. Popova (2013) estimated from model simulations that the continental shelf pump contributed to about 20% of the total primary production in the AO. They also estimated that nutrients from the inflow of Atlantic and Pacific water were available for production within 15-20 years. In the present study we have used the coupled system SINMOD to further analyze transport and mixing of nutrients in the Arctic Ocean. The import and export of nutrients have been calculated and compared to similar results based on analysis of observational data (Macdonald 2010, Torres-Valdes et al. 2013). Vertical transport of nutrients in different parts of the Arctic are also presented.

2 Model Configuration

The model domain used to calculate fluxes in and out of the Arctic is showed in Figure 2. In this configuration we use a horizontal resolution of 20 km and a varying vertical resolution with high resolution near the surface and lower resolution near the bottom (total of 25 layers). Bottom topography is interpolated from the IBCAO database. For Arctic Rivers, data are obtained from R-ArcticNet available through http://www.r-arcticnet.sr.unh.edu/v4.0/index.html (Vörösmarty, Fekete and Tucker 1996, Vörösmarty, Fekete and Tucker 1998). Tidal forcing is included by specifying elevation and tidal currents for 8 components along the open boundary based data from TPXO 6.2 model of global ocean tides (http://www.coas.oregonstate.edu/research/po/research/tide/global.html). Initial conditions are interpolated to the model grid from World Ocean Circulation Experiment Global Data Resource Version 3.0 (http://www.nodc.noaa.gov). In and outflow along the open boundary is set according to published data and more details may be found in (Slagstad and McClimans 2005). ERA-Interim data are used to define atmospheric forcing (10 m wind, humidity, clouds, sea surface temperature and surface air pressure). The model has been run over a period of 20 years.

Calculation of vertical and horizontal fluxes

Nitrate and ammonia concentration varies according to the equation:

$$\frac{\partial A}{\partial t} = -\frac{\partial}{\partial x}(uA) - \frac{\partial}{\partial y}(vA) + \nabla(K_H \nabla A) - \frac{\partial}{\partial z}(wA) + \frac{\partial}{\partial z}\left(K_H \frac{\partial A}{\partial z}\right) - Uptake + Remin.$$

where A denotes a model state. Horizontal fluxes (both advective and diffusive fluxes) are represented by the first three terms on the right hand side. The two following terms describe vertical advection and vertical mixing that contribute to vertical fluxes. In this report our main focus is on nitrogen and fluxes are calculated of both NH4 and NO3 to produce total N fluxes.

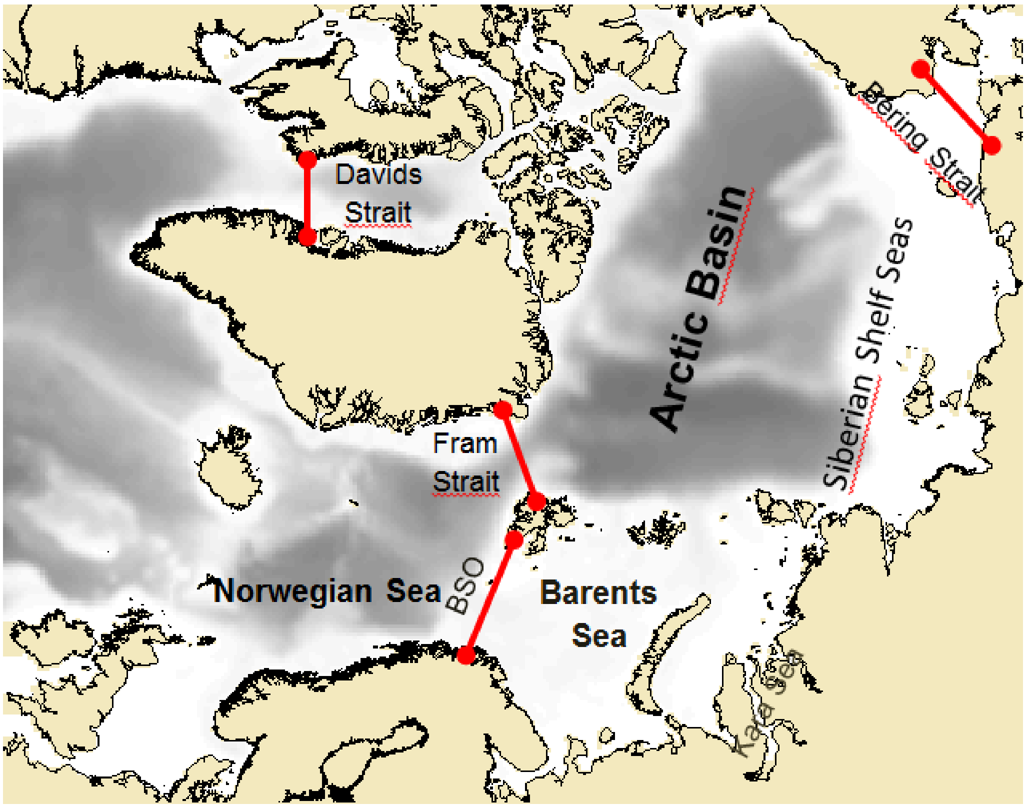

Figure 1 SINMOD model domain with 20 km resolution.

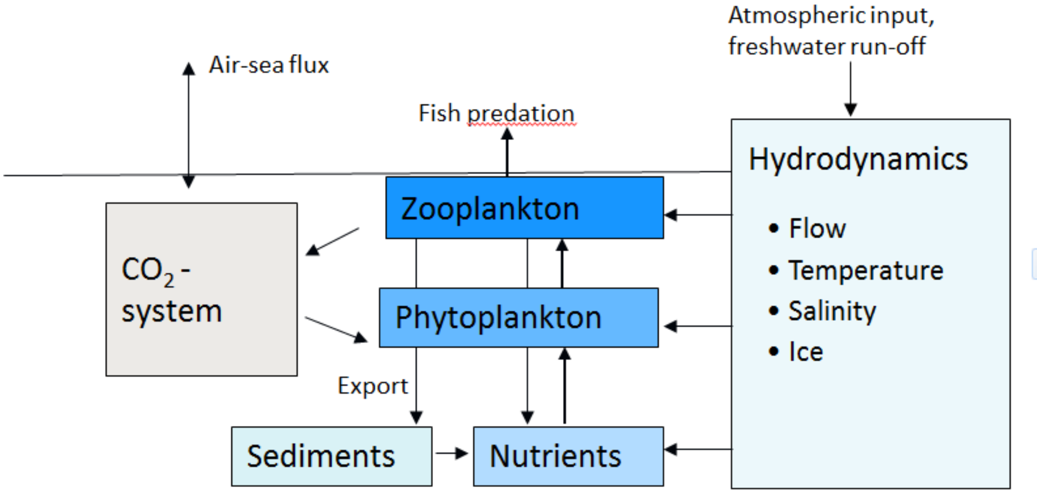

Figure 2 Overview of the SINMOD model system. See text for description

3 Results

Horizontal fluxes

We have calculated horizontal transport of Nitrogen (N) across 4 gateways to the Arctic Ocean which are the same as those used in Torres-Valdes et al. (2013) (Table 1). In SINMOD the main export occurs across the Fram Strait with a mean of 21 Tg N yr^{-1}. A major part of this export occurs in deeper water (export of -48 Tg N yr^{-1} below 1000 m). The largest import of N is through the Barents Sea Opening (25 Tg N yr^{-1} b). A little more than half of this leaves the Barents Sea and continues into the Arctic Basin and along the Siberian Shelves (13 Tg N yr^{-1}). Simulated import of N from the Pacific is 4 Tg N yr^{-1} and export through the Davis Strait is twice as much, about 8 Tg N yr^{-1}. In total, SINMOD gives a balanced import and export of N to the Arctic Ocean. There is a strong seasonal variability in the export and import and with the highest transports occurs during winter months (Figure 3).

Table 1 Horizontal fluxes of N (Tg N yr^{-1}) across the main Arctic gateways. Values from SINMOD are 10 years mean, and are shown with standard deviations.

	SINMOD 10 year mean	**st. d.**	**Torrès-Valdes et al. 2013**	**MacDonald et al. 2010**
Fram Strait	-22	3.1	-4.5	
Barents Sea Opening	25	1.0	14.8	
Bering Strait	4	0.7	4.0	
Davis Strait	-8	0.8	-13.8	
Total	-1	2.4	0.5	18.8

Vertical fluxes

Vertical transport of nutrients occurs through vertical mixing and vertical advection processes. High fluxes by vertical advection are simulated at the shelf breaks and also in the areas along the inflow path of Atlantic Water. SINMOD gives both positive and negative transports in these areas with one exception, at the Canadian side where a coherent band of follows the steep slope in the bathymetry. In the deeper basins vertical advection also plays a role, in particular near topographic features. In the deeper parts of the AO, results from SINMOD show no contribution from vertical mixing. Simulated vertical fluxes in these parts are thus only advective. In total, there is a downward flux out of 2.2 Tg N yr^{-1} at 100 m depth (Table 2). The simulations show elevated levels of mixing along the shelf break outside the Siberian Shelf and the tidally mixed parts of the Barents Sea. Vertical mixing contributes to an upward N transport in the Greenland, Iceland, Norwegian and the Barents Seas (Figure 4). There is also a significant upward transport of N along the shallow Siberian shelf Seas (Table 2).

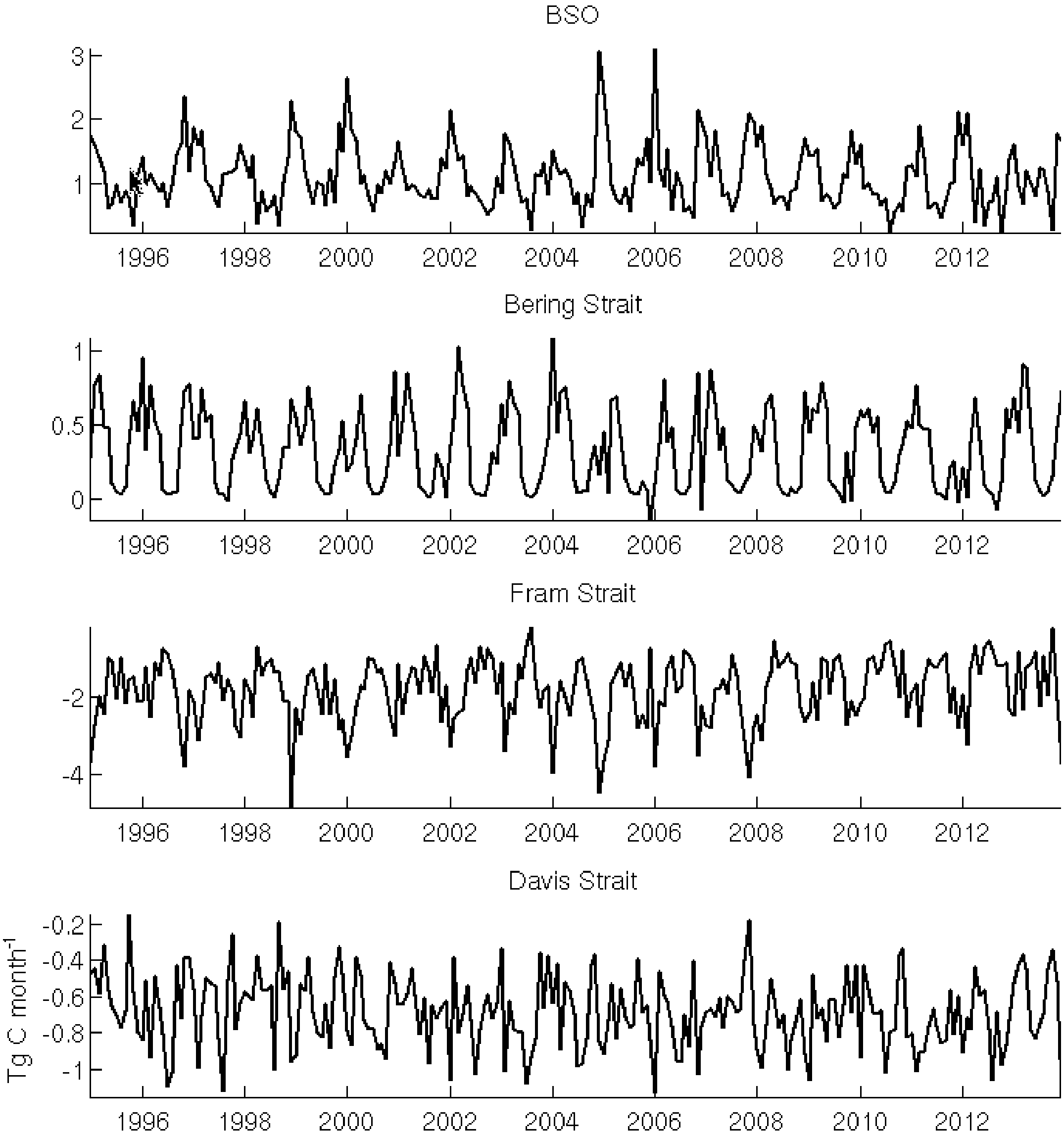

Figure 3 Monthly horizontal fluxes of nitrogen across the main gateways connecting the Arctic to the Pacific and North Atlantic Oceans (Figure 1). Positive values represent import and negative values export of N.

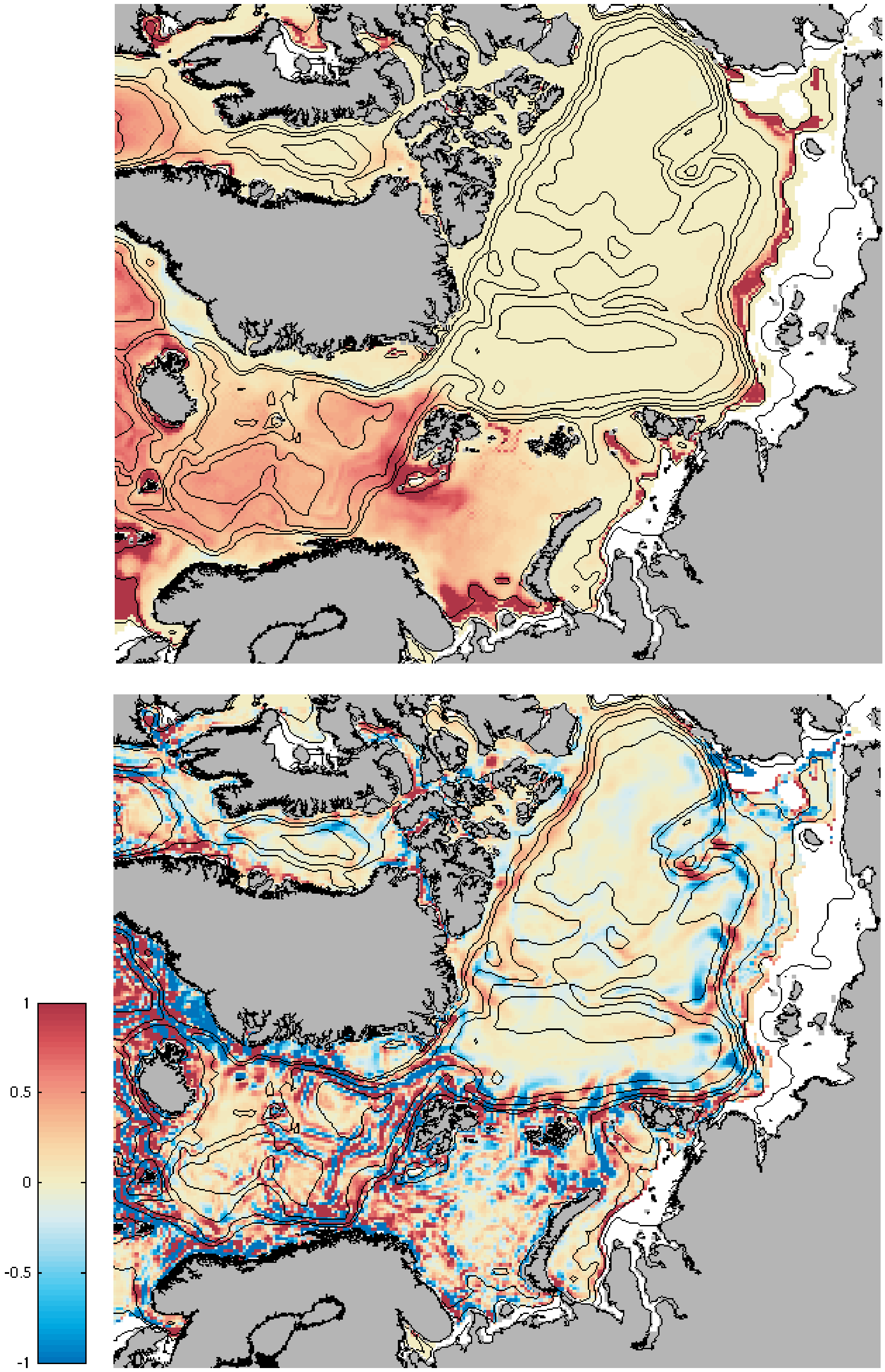

Figure 4 Annual vertical fluxes of N (t N m^{-2} yr^{-1}) to the upper 50 m by vertical mixing (upper panel) and vertical advection (lower panel). Fluxes shown are mean over the period from 1996 to 2005.

Table 2 Vertical flux of N (Tg N yr^{-1}) for different parts of the Arctic Ocean for the upper 25, 50 and 100 m layers. The forth column shows the potential of NPP (Tg C yr^{-1}) of the total transport to the upper 50 m, assuming a constant C-N ratio of 7.6. The rightmost column show the simulated total new production (NPP, Tg C yr^{-1}) for the same regions.

	25 m	50 m	100 m	Potential	NPP
Barents Sea	14.1	11.1	8.2	84	75
Arctic Shelves	41.1	18.6	1.1	24	56
Arctic Basin	3.2	-.5	-2.2		53
Norwegian Seas	13.0	7.4	5.8	53	73

4 Discussion

SINMOD simulates a nearly balanced budget of import and export of N, even though there are some interannual variability (Table 1). Taking into account denitrification in the Arctic that was estimated by Chang and Devol (2009) to be in the range between 6 to 29 Tg N yr^{-1} , the model still gives a net loss of N in the Arctic Ocean. River input of N is calculated to be around 0.1 Tg N yr^{-1} , and is not a significant contribution on pan Arctic scales (Le Fouest, Babin and Tremblay 2013). There are large gaps between simulated results and estimates based on analysis of hydrographic and hydrochemical data byTorres-Valdes et al. (2013), even though the net results are comparable. Their results indicate a higher export through the Davis Strait and less through the Fram Strait. They also obtain a lower import through BSO. The analysis of Torrès-Valdes et al. is based on data from June and August, when SINMOD simulates the lowest transports. With the 20 km resolution of SINMOD the outflow through the Canadian Archipelago are not well represented. An underestimation of the outflow here is likely to be accounted for with a higher outflow of deep water across Fram Strait. Macdonald (2010) obtained a net import of 18.8 Tg N yr^{-1}. All these results demonstrate that there are still large uncertainties in the estimates of transport. The calculated vertical transports of nutrients highlight the importance of horizontal transports. The simulated production in the Arctic Basin of 53 Tg C yr^{-1} is mainly fueled by nutrient import from the Atlantic and Pacific Oceans. The total import through the Barents Sea Opening and the upper 1000 m of the Fram Strait are of comparable size, and adds a total of 51 Tg N yr^{-1} to the Arctic Ocean (the net export through the Fram Strait results from a high outflow of deep water outflow).

We have calculated a "new production potential" by assuming that all of the nitrate mixed and transported upwards above 50 m depth would be exploited by the phytoplankton, assuming a C-N ratio of 7.6 (used in the SINMOD model) (Table 2). Comparing NPP and this number we find that the NPP in the Barents Sea is lower than this potential. This results from both light limitation but possibly also nutrient availability due to a thin upper mixed layer in the northern Barents Sea. At the shallow shelf of the Siberian Shelf Seas, production is about twice the potential. However, the transport to the upper 25 m is significantly higher. The impact of inflow of nutrient on NPP can also be read off from a map of simulated NPP in the Arctic (Figure 5). The highest production in the AO is found at the inflow shelves, and it is also here there is a potential for increase in NPP in the future.

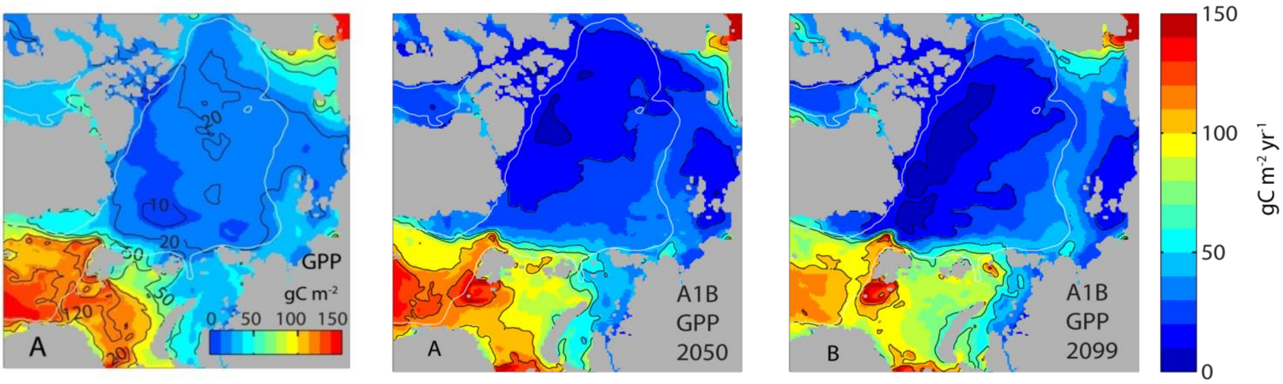

Figure 5 Primary production in Arctic Ocean for present (left) and future scenario for 2050s (middle) and 2099 (right)

5 Future work

There are uncertainties in the quality of the simulated fluxes by SINMOD. Compared with published data we have a too large export through the Fram Strait. This will be addressed in the ongoing development of SINMOD. This version will have a horizontal resolution of 12 km in addition to an improved bottom topography. Since a grid size of 20 km is too coarse to resolve mesoscale eddies and eddy induced mixing and transport, we will also look at these processes in a downscaled version run on a 4km grid.

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