Tipping points in the ecosystem of the ‘new Arctic’ Ocean

Phytoplankton’s response to rapid changing light and nutrient conditions

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1. Introduction

Net Primary production (NPP) in the Arctic Ocean by phytoplankton forms the basis of a unique ecosystem and is controlled by a complex interplay of light and nutrients. For the last three decades, NPP has been continuously increasing (Arrigo and van Dijken, 2015) stimulated by the loss of sea-ice which allows longer growing seasons (Arrigo et al. 2008) and therefore more light to penetrate into the water column (Nicolaus et al. 2012). The approximately 50% reduction of sea-ice volume in the last three decades (Kwok 2018, Stroeve and Notz, 2018; Serreze and Meiers, 2019) is one of the most striking illustrations of Climate Change globally. In the Arctic Ocean, it is accompanied by an atmospheric warming more than twice as fast as in temperate regions (a phenomenon referred as Arctic amplification; Serreze and Francis, 2006). Climate Change projections estimate a likely summer ice-free Arctic Ocean by the middle of the century (e.g. Sigmond et al. 2018). Therefore, we can expect the Arctic Ocean to generally move from a predominantly light-controlled (ice-covered) to a more nutrient-controlled (open water) system (Babin 2020, see **Fig. 1**).

Larger open water areas will favour wind-driven turbulent mixing (Randelhoff et al. 2018) and upwelling (Arrigo et al. 2012, Spall et al. 2014) which could replenish the photic layer with ‘new’ nutrients. This phenomenon has been already evidenced in the sub-arctic regions (Lewis et al. 2020; Crawford et al., 2020) which are subject to an increasing influence of temperate waters expanding poleward (referred as “borealization”; e.g. Polyakov et al. 2020). Some studies observed the “Atlantification” of the Arctic Ocean both in terms of water masses (Oziel et al. 2016; Barton et al. 2018; Polyakov et al. 2017) and phytoplankton species (Neukermans et al. 2018; Orkney et al. 2020; Oziel et al. 2020) over the last 4 decades. In this context, the appearance of a productive ‘Arctic green belt’ along continental shelves is hypothesized in a near future (Ardyna and Arrigo, 2020). In the central Arctic however, freshwater tended to accumulate in the last decades (Rabe et al., 2011, 2014) due to a blocking in the anticyclonic atmospheric circulation (Timmermans and Marshall, 2020). The subsequent increase in stratification inhibits replenishment of nutrients in the surface layer. The resulting impoverishment already reshaped the planktonic assemblage from large cells like diatoms toward smaller pico-phytoplankton (Li et al. 2009) which may alter the strength of the biological carbon pump (Wiedmann et al. 2020). It is rather uncertain if the trend over the last decades in freshwater accumulation will continue. There is generally a consensus that the future levels of productivity (i.e. nutrient levels) will be heavily impacted by the balance between mixing and buoyancy fluxes. When this balance is extensively studied at present time, the contribution of terrigenous nutrient and carbon inputs is completely overlooked. However, recent findings evidenced that nutrient-rich terrigenous inputs can contribute up to 30% of the Annual NPP (Terhaar et al. 2020) updating previous lower estimations (Le Fouest et al. 2013). Those issues need to be urgently tackled in a context of increasing river discharge, soil erosion and permafrost thaw (e.g. McClelland et al. 2006; Fritz et al. 2017) and greater potential for remineralization of organic matter in a warmer Arctic Ocean.

Biogeochemical modelling is the tool of choice to disentangle today's multiple environmental alterations and their uncertain outcomes for ecosystems but also for biogeochemical cycles and climate. Ocean biogeochemical models already demonstrated to be particularly relevant to identify key climate-change-mediated environmental changes that can act as multiple drivers (Bopp et al., 2013; Boyd et al., 2015; Kwiatkoski et al. 2020). In this project, we will use the Regulated Ecosystem Model, version 2.1 (REcoM2.1, Gürses et al. 2022) which uses flexible stoichiometry. Flexible stoichiometry provides undeniable advances (i.e. variable Chla:C or Si:N ratios) that are exploited for example in the investigation of physiological processes which in turn also impact biogeochemistry (e.g. through photoinhibition, Álvarez et al. 2018). In our case, it will allow us to go well beyond actual limitations (avoid instantaneous remineralization of organic matter along Redfield ratios, consider denitrification, aeolian deposition, …) of the most recent modelling advances (Terhaar et al. 2020). Here, we propose to assess possible tipping points in the Arctic NPP and their environmental drivers by running hindcast and forecast biogeochemical simulations with the highest resolution (4.5 km) in the Arctic Ocean at present time dynamically forced by the most 'up-to-date' in situ nutrient and carbon database from Arctic river and coastal erosion (spatially and monthly resolved).

2. Previous work with FESOM and REcoM and model set-up

The proposed project builds on a tremendous effort conducted at the Alfred Wegener Institute (AWI) for the last ~15 years to develop and maintain FESOM, a multi-resolution ocean and sea-ice model (Wang et al., 2008, 2014; Danilov et al, 2017; Scholz et al., 2019). We will use the next generation of circulation model FESOM2 (Danilov et al. 2017; Wang et al. 2020), the successor of FESOM-1.4, that has been thoroughly optimized, validated, and successfully employed for the Arctic (e.g., Wang et al., 2018, 2014; Wekerle et al., 2017). FESOM2 is computationally much more efficient than FESOM-1.4 (up to 5 times speedup, Danilov et al., 2017; Koldunov et al., 2019), thus allowing to use higher model resolution with the same available computational resources. In this project, we will use the standard 'farc' mesh (endorsed and supported by the FESOM development team, https://gitlab.awi.de/fesom/farc.git) with a horizontal resolution of the mesh of 4.5 km in the Arctic Ocean which can be considered as eddy-resolving in the central part of the Arctic basin (**Fig. 2**; see Wang et al. 2018). This mesh was initially developed for FESOM-1.4 but as been further used and endorsed with FESOM2 (Wang et al. 2020). Here, we will use 'farc' with a newly "Arctic-optimized" version of FESOM2.1 (pers. Comm. with the FESOM developing team: Dr. Nikolay Koldunov, Dr. Qiang Wang).

FESOM2 will be coupled with REcoM2, based on Schartau et al. (2007), which was developed by co-authors of the project (Hauck et al., 2013; Schourup-Kristensen et al., 2014) and successfully used globally (Hauck et al., 2020). REcoM2 was also successfully used (and validated with in situ and satellite observations) with the same 'farc' mesh (4.5 km; **Fig. 2**; Schourup-Kristensen et al. 2018). We successfully implemented FESOM2-REcoM2 with dynamically coupled rivers and erosion inputs.

The project hbk00083 was accepted in March 2021. The release of a new (FESOM2.1) 'standard' version (CORE mesh, JRA forcing) and an 'Arctic-optimized' version ('farc' mesh, JRA forcing) was initially announced for February 2021 by the FESOM development team. But the FESOM development team was able to deliver the 'standard' version in March, and the 'Arctic-optimized' version in May. The REcoM team (including myself) initiated a complete re-tuning of REcoM2 for the 'standard' version on AWI-owned HPC (FESOM2.1-

REcoM2.1, Gurses et al. 2022, in prep). In June, we faced technical issues to compile and run this new version on HLRN (as opposed to the previous FESOM2.0 which was already functioning) because of several reasons: differences in compiler versions compared to AWI-owned HPC, machine specific characteristics (e.g. number of threads that can be used a-synchronically by the model). It took us a couple months (June-July) and computing resources to fix the issue with support from the development team. Once solved, we started the ‘tuning’ of the ‘Arctic-optimized’ version on HLRN with AWI-CM forcing and the ‘farc’ mesh. The complete re-tuning was required and consumed additional computational and time resources (August-September). In total, we consumed 297 kNPL. Finally, FESOM2.1 was delivered to work with the ICEPACK sea-ice model, but not tuned for it. Re-tuning FESOM2.1 to work with ICEPACK is beyond our capacities. Given that we under-estimated the computational cost of FESOM2.1-REcoM2.1 model year in our previous proposal (see section 3), we decided not to use the advanced sea-ice model ICEPACK. This decision does not have impacts on the scientific objectives of the project whose chances of success remain very high.

We are now happy to announce that at the time this proposal is written, an ‘Arctic-tuned’ FESOM2.1-REcoM2.1 version (AWI-CM forcing and ‘farc’ mesh) is finally ready.

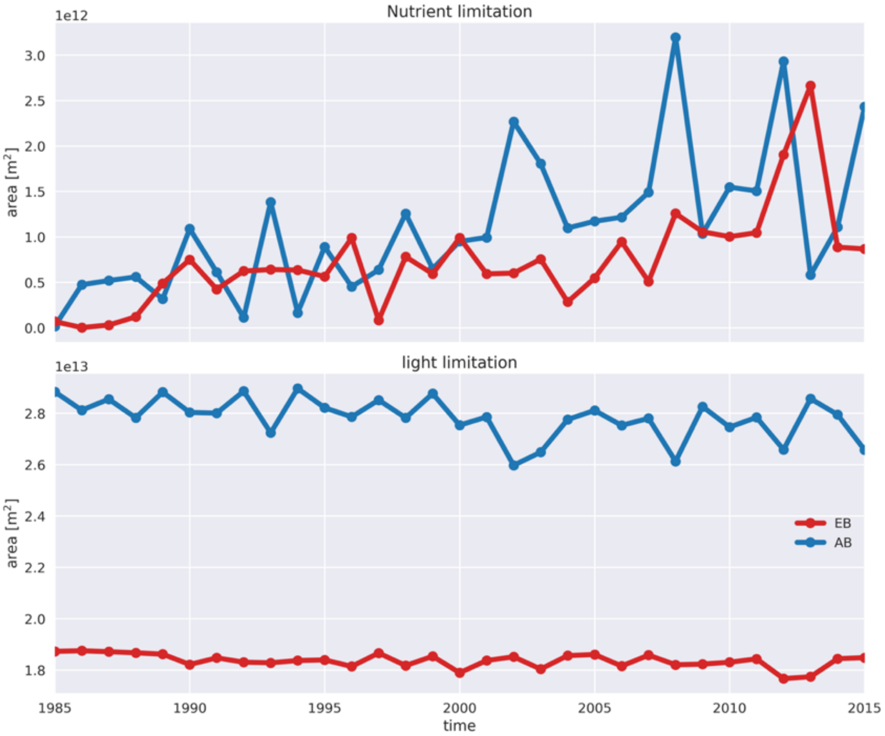

Figure 1: Cumulated area from monthly fields during the growth season between April 1st and September 30th within the two main Arctic basins (Eurasian Basin – EB - in red and Amerasian Basin – AB - in blue) which are limited either by light or nutrients. Both regions show an increasing (decreasing) area corresponding to the nutrient (light) limitation. The nutrient limitation increased from 0% of the total area in 1985 up to 14% in 2013.

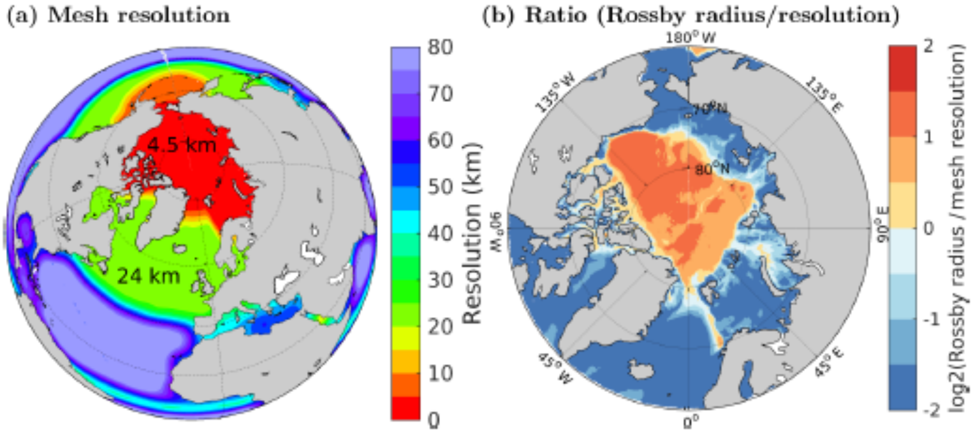

Figure 2: (a) The horizontal grid size of a mesh with 4.5 km in the Arctic Ocean (referred to as 'farc'). (b) Ratio between the first baroclinic Rossby radius and grid size shown with the log2 scale. With resolution finer than two grid cells per Rossby radius, models may start to resolve mesoscale eddies depending on numerical mixing in the model (b). Figure from Wang et al. 2018.

3. Planned model simulations for the Q1 2022 – Q4 2022 period

We initially planned to use a lower resolution mesh (CORE2 mesh) to spin-up the model for about 200 years and to use REcoM2 Initial fields interpolated onto the ‘farc’ mesh. This approach of interpolating biogeochemical fields to a higher resolution grid is also applied in other modelling groups to due to computational costs of running expensive biogeochemical models in high-resolution. However, we figured out that this technique triggered a ‘shock’ that required additional spin-up at full resolution anyway. We therefore need to spin up the ‘farc’ mesh anyway, which represents additional computer needs on HLRN (2 x 50 years).

To conclude, we updated the plan of the project to conduct: 2 spin-up simulations, 1 control simulation, 6 model experiments:

Simulation	forcing	scenario	CO2	Terrigenous inputs	Total years	Initial conditions
SPINUP1	AWI-CM	5x repeated historical decade 1950-1959	constant	No	50	Cold start
SPINUP2	AWI-CM	5x repeated historical decade 1950-1959	constant	Climatology	50	Cold start
CTRL	AWI-CM	Historical + ssp3-7.0	constant	No	151	SPINUP1
EXP1	AWI-CM	Historical + ssp3-7.0	Varying	No	151	SPINUP2
EXP2	AWI-CM	Historical + ssp3-7.0	Varying	Climatology	151	SPINUP2

EXP3	AWI-CM	Historical + ssp3-7.0	Varying	Varying monthly	151	SPINUP2
EXP4	AWI-CM	Historical + ssp5-8.5	Varying	Varying monthly	151	SPINUP2
EXP5	AWI-CM	Historical + ssp1-2.6	Varying	Varying monthly	151	SPINUP2
EXP6	AWI-CM	Historical + ssp2-4.5	Varying	Varying monthly	151	SPINUP2

Summary of the required resources:

We are now able to accurately quantify the HLRN resources required for one model year of FESOM2.1-REcoM2.1 on the 'farc' mesh with ~ 638.387 surface nodes: ~3h15 with 2304 cores, ~1.5 kNPL. In the previous proposal we estimated a model year of FESOM2-REcoM2-ICEPACK to require ~1.6 kNPL. The updated project plan simulations are summarized in the following **Table 1**:

Table 1:

When	**Simulation**	**# of runs**	**Model years / run**	**kNPL per model year**	**Total kNPL**
21-Q4	SPINUP1	1	50	1.5	75
21-Q4	SPINUP2	1	50	1.5	75
21-Q4	CTRL	1	151	1.5	226.5
22-Q1	EXP1	1	151	1.5	226.5
22-Q1	EXP2	1	151	1.5	226.5
22-Q2	EXP3	1	151	1.5	226.5
22-Q2	EXP4	1	151	1.5	226.5
22-Q3	EXP5	1	151	1.5	226.5
22-Q3	EXP6	1	151	1.5	226.5
22-Q4	Post-processing			30	
21-Q4 22-Q4	**TOTAL**	**7**	**855**	**1.5**	**1282.5**
22-Q1 22-Q4	**TOTAL**	**4**	**604**	**1.5**	**936 (906+30)**

At the time this extension proposal is written, the remaining resources are 414 kNPL on 2021-Q4 and 237 kNPL on 2022-Q1, with a total of 651 kNPL. The additional (+1152 kNPL) and total resources (1803 kNPL) needed for the period 2022-Q1 to 2022-Q4 are listed in the following **Table 2**:

Table 2: Resources already available or total resources are in black, additional resources needed are in red.

Quarter	**Available resources (kNPL)**	**Additional resources Needed (kNPL)**	**Total resources Needed (kNPL)**
21-Q4	414	0	414
22-Q1	237	216	453
22-Q2	0	453	453

22-Q3	0	453	453
22-Q4	0	30	30
TOTAL (22-Q1 / 22-Q4)	**237**	**1152**	**1803**

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