North Pacific Ocean circulation and biogeochemistry in warming climate since the Last Glacial Maximum

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Application for HLRN computing time for project hbk00060, Q3 – Q4, Year 2018 and Q1 – Q2, Year 2019

(Duration of the entire project is from August 2017 to July 2020)

Abstract

Instrumental observations have discovered significant change in the North Pacific biogeochemical environment and the marine ecosystem along with on-going global warming and atmospheric CO_2 rise. On the other hand, both paleoceanographic and paleoclimate modelling studies have argued strong correlation between the North Pacific overturning and the North Pacific biogeochemical processes throughout cold to warm climate conditions of the past. In this project, we aim to understand the physical control of the North Pacific circulation onto the biogeochemical system, by doing modelling simulations for four representative climates, including the Present Day (PD), Mid Holocene (MH, 6ka B.P. warmer than PD), Earth Holocene (EH, 9ka B.P. warmer than PD) and the Last Glacial Maximum (LGM, 21ka B.P. colder than PD). In this project, we will utilize the FESOM standalone and coupled FESOM-REcoM models in sequence, using unstructured global triangular surface mesh with a regional focus (up to 6km resolution) in the Pacific subarctic oceans. Compared to previous modeling approaches, our FESOM-REcoM experiments present the advantages of (1) a sufficient horizontal and vertical resolutions to describe the complicated bathymetry structure of the Northwest Pacific and adjacent marginal seas, (2) to receive the variation of regional nutrient supplies with respect to changes in global oceans at the same time. This thus allows us go beyond an only regional limited study to global regime. Here, the proposed modelling work is on basis of the BMBF project: *"WTZ China–NOPAWAC-North Pacific Ocean in Warming Climates During the Quaternary"* (01.08.2017 - 31.07.2020). In addition, our work in this proposal is a continuation of the current project hbk00060. Besides in-house support for model development, our modelling work is aligned with the on-going paleoceanographic proxy studies for the NW North Pacific Ocean by the Marine Geology Group at AWI.

1. Introduction

Under current tendency of global warming, North Pacific nutrient utilization and oxygenation has been a topic of major societal relevance and scientific interest. Measurements have recorded the North Pacific Ocean oxygen concentration declines and a shoaling of hypoxia depths, although there is an increase of the total nutrient budgets into the ocean (e.g. Whitney et al., 2007; Schmittner et al., 2008; Shaffer et al., 2009; Stramma et al., 2010; Keeling et al., 2010). Compared to the modern climates, severe anoxia in the Pacific also occurred over the geological past, e.g. the most recent one being a prominent mid-depth Indo-Pacific de-oxygenation during the last glacial termination, ~21-11 ka B.P. (Jaccard and Galbraith, 2012; Moffitt et al., 2015). Previous modeling studies and proxy reconstructions have shown that the North Pacific biogeochemical processes underwent drastic changes along with past ocean circulation at various global climate stages

(Jaccard et al., 2005; Schmittner et al., 2007 and 2008; Okazaki et al., 2010; Menviel et al., 2008, 2014; Rae et al., 2014; Xu et al., 2015).

Specifically, studies have been addressed on the impact of the North Pacific overturning on the biogeochemical setting in the North Pacific Ocean (Mecking et al., 2008; Deutsch et al., 2006, 2011), for instance an increase the ocean acidification (Feely et al., 2004; Orr et al., 2005) and also substantially reorganize the ocean ecosystems (Hazen et al., 2012; Di Lorenzo et al., 2013). More specifically, the high-nitrate and low-chlorophyll (HNLC) feature of the North Pacific Ocean (Kienast et al., 2004; Takeda, 2011; Kohfeld et al., 2005) is dominantly controlled by salinity-driven stratification thus strongly correlated to the North Pacific Intermediate water (NPIW) formation. In the modern ocean, the permanent halocline modulates the North Pacific productivity by controlling the supply of nutrient-rich deep water into the euphotic zone. Via the coupled physical-biogeochemical system, the North Pacific upper ocean stratification acts as a barrier for atmosphere-oceanic gas exchange. Especially in summer, the North Pacific Ocean is characterized by its high carbon export efficiency (Honda et al., 2002), known as the largest net sink of atmospheric CO_2 (Takahashi et al., 2009; Takahashi et al., 2002). Previous moderately-resolved coupled ocean-sea ice-biogeochemical models have suggested that the history of the North Pacific productivity and CO_2 budget is in line with global ocean circulation state and regional hydrographic features (e.g. Schmittner et al., 2005; e.g. Menviel et al., 2008, 2014). However, previous modelling studies were not able to reveal spatial complexities of the subarctic North Pacific (Rae et al., 2014), thus causing bias in simulating the North Pacific surface stratifications, intermediate water formations, and accompanied biogeochemical process.

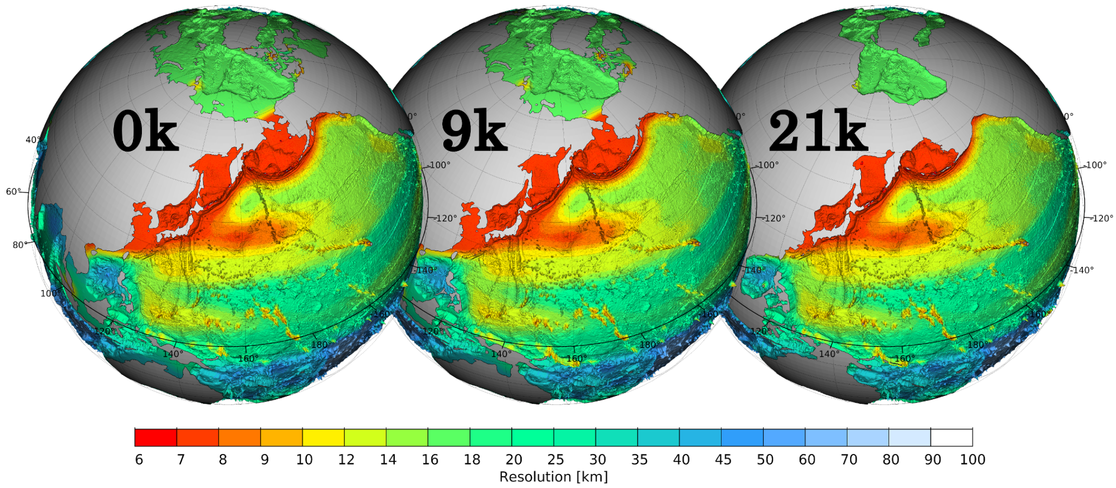

Fig. 1. Mesh resolution of the NW Pacific FESOM configuration for time-slice experiments of today's climate (0k), the early Holocene (9k), and the Last Glacial Maximum (21k). The minimum mesh resolution in the Sea of Okhotsk, in the Sea of Japan and the Bering Sea is about 6 to 8 km.

Our project proposal has been funded by the BMBF project: *"WTZ China–NOPAWAC-North Pacific Ocean in Warming Climates During the Quaternary"* (01.08.2017 - 31.07.2020). The work in this new proposal is a continuation of our current HLRN project hbk00060 (*'North Pacific Ocean circulation and biogeochemistry in warming climate since the Last Glacial Maximum', 01.07.2017 – 30.06.2018*), also the second HLRN proposal under the roof of NOPAWAC project. In this project, the conduction of FESOM stand-alone and FESOM-REcoM experiments are on basis of their good modelling performance that have been already verified by all our previous HLRN projects, including *'Climatic evolution in the marginal seas of the Northwest Pacific Ocean since the last glacial period until present day: changes in the formation of North Pacific Intermediate Water formation and their implications on the Pacific realm' (HLRN project: hbk00042)*, '*Glacial-interglacial change of the biogeochemical process in the Pacific subarctic oceans*' *(HLRN project: hbk00054) and hbk00060.* Technically, our modelling experiment develops from the HLRN project *'Exploring pathways of Atlantic Water into the Arctic Ocean: high resolution ocean-sea ice and biogeochemical simulations' (HLRN project: hbk00004)*. Moreover, our modelling work in this project is also aligned with the on-going paleoceanographic proxy-based studies focusing on the reconstruction of the deglacial Pacific subarctic climate by Marine Geology group at AWI. They will support our modelling results by providing palocenographic evidences for data-modelling intercomparisons.

2. Project targets

In this project, we aim to understand the roles of North Pacific overturning circulation in controlling the biogeochemical processes under cold and also warm climate conditions of the past. Specifically, our high-resolution grid mesh allows us to look into the coupled system of the ocean circulation and carbon cycle in the NW Pacific and its marginal seas, especially in the Bering Sea and the Sea of Okhotsk (Fig. 1). In these regions, atmospheric CO_2 sinks into the modern ocean against the on-going climate warming. By simulating the history of the North Pacific Ocean circulation and marine biogeochemistry environments, we will further develop our understanding about the climatic roles of the North Pacific Ocean in the modern climate and its evolution along with CO_2 rise. Our simulations in this project draw focus on:

- On the basis of our current project hbk00060, we will continue the modelling simulations for the present-day (PD) conditions, warmer-than-present Early Holocene (EH, 9ka B.P.), mid Holocene (MH, 6ka B.P.) and the Last Glacial Maximum (LGM, 21ka B.P.), using the FESOM standalone and coupled ocean-biogeochemistry model (FESOM-REcoM) and applying the global mesh with up-to-6 km resolution regionally.
- According to the results in the current project hbk00060, the North Pacific sea ice and vertical ocean density stratifications at the MH and LGM state are significantly different from the PD conditions. In this new project, we thus address our effort in understanding the dependence of the North Pacific biogeochemical process on halocline and sea ice.

Specifically, our simulation work in this new project will develop our knowledge correlating to the following scientific questions:

- How does the marine primary productivity and remineralization react to the shallower North Pacific Ocean ventilation during the Holocene, compared to the LGM conditions?
- How does the intermediate-depth stratification control the North Pacific carbon pool?
- How does the North Pacific Oxygen Minimum Zone (OMZ) act to the climate warming from the LGM, through the EH and MH, to PD state?

3. FESOM and FESOM-REcoM model setup

In this project, our proposed modelling work will continue using the FESOM standalone and coupled ocean-sea ice-biogeochemical FESOM-REcoM Model, developed at the Alfred Wegener Institute. It has been well used for modern biogeochemical studies with good performances in reconstructing the distribution of key biological tracers [*Schourup-Kristensen et al., 2014*]. Our model grid setup features a homogenous resolution of 17.5 km North of 50°N and 25 km South of 60°S, as well as homogeneous resolution of 30 km in an equatorial belt with a width of 15° (Fig. 1). The coastal resolution is in the order of ~0.4°, whereas the bulk resolution of the setup has a value of 1°. The marginal Seas of the Northwest Pacific (e.g. the Sea of Okhotsk, Bering Sea, Japan Sea and Yellow Sea of China) feature a homogeneous resolution of 6 km. This setup consists of ~500,000 2d surface nodes. In order to achieve a good representation of the vertical stratification and deep-water formation we decided to use 61 vertical levels which have a stepwise increasing vertical resolution from 10m to maximum of 150 m below the depth 1450 m. The entire FESOM-REcoM model setup has a size of ~ $15x10^6$ 3d node points. Thanks to the support of HLRN, the model setup has been tested with good scalability on the massive parallel computational facilities of the HLRN. Our configuration performs at a time step of 900 seconds by using 110 nodes. It takes 4 hours to simulate one model year by FESOM model and 6 hours for FESOM-REcoM coupled run.

Compared to previous modelling work, which used biogeochemical models coupled to ocean general circulation model [e.g. *Chikamoto et al., 2012; Menviel et al. 2014; Brown and Galbraith, 2015*], our established mesh grids in FESOM-REcoM Model provides a compromise between a regional focus and a global coverage by using an unstructured triangular surface mesh [*Danilov et al., 2004, 2005; Timmermann et al., 2009*], and highlights two major advantages:

- High horizontal and vertical resolutions sufficient to describe the complicated bathymetry, thus the complexity of ocean circulation in the Northwest Pacific and adjacent marginal seas [*Lohmann et al., 2013*].
- To receive the variation of regional nutrient supplies with respect to changes in global oceans at the same time [*Feely et al., 2004*].

We will apply the CoreII reanalysis of satellite-observation data as the atmospheric forcing in our PD simulation, while the atmospheric forcing in the Early Holocene, Mid Holocene and LGM experiments are derived from our Early System Model AWI-CM. All our paleoclimate experiments will be initialized from the corresponding AWI-CM simulated ocean equilibrium states. Continuing from our current project hbk00060, we intend to our experiments of each time slice for 180 model years using FESOM standalone model in total and then 120 model years using the FESOM-REcoM coupled model. This time is estimated for the scaling of the biogeochemical tracers from the surface to intermediate depth in the Pacific subarctic oceans (in track of the renewal of NPIW) based on the existing results.

4. Modeling strategy

In our current project hbk00060, we've successfully integrate 120-yr PD, 120-yr MH, 60-yr EH and 60-yr LGM. Therefore, in this new project, we will continue our PD simulation by 60 model years, the MH run by 60 model years, the EH run by 120 model years and the LGM run by 120 model years. We are aware that this time span is not sufficient to bring the entire ocean into a quasi-equilibrium state, but it would require thousands of years of simulation, which is beyond the scope of our current project framework. Nevertheless, studies of Sidorenko et al. [2011] and Scholz et al. [2013] for the PD situation have shown that a time span of 300 years is sufficient to limit the model drift for the upper and intermediate ocean reached a sufficient quasi-equilibrium state, that was comparable with observational derived data [Scholz et al., 2014]. For our intended project targets, mostly the reliability of the upper and intermediate ocean is essential. Thus, the length of our designated simulation period should be enough, so that the upper and intermediate ocean depth layers satisfy our demand. Strategically, we conduct the 120yr FESOM-REcoM simulation on the basis of the 180yr-FESOM standalone integrations. This significantly reduce the cost of computing recourse in doing ocean spun-up.

5. **Preparatory work and the results of a current project**

In previous HLRN projects (*hbk00042*), we've spent effort to generate qualified grid meshes to reconstruct the modern North Pacific surface ocean circulation and intermediate water extension comparable with physical oceanography observations. Moreover, we've also finished a test of the high-resolution grid meshes for the LGM and EH climate bathymetry and land-sea mask in the project *hbk00054*. All our previous experience using the FESOM standalone and FESOM-REcoM coupled models allows us enough technical preparation to finish the experiments in this project.

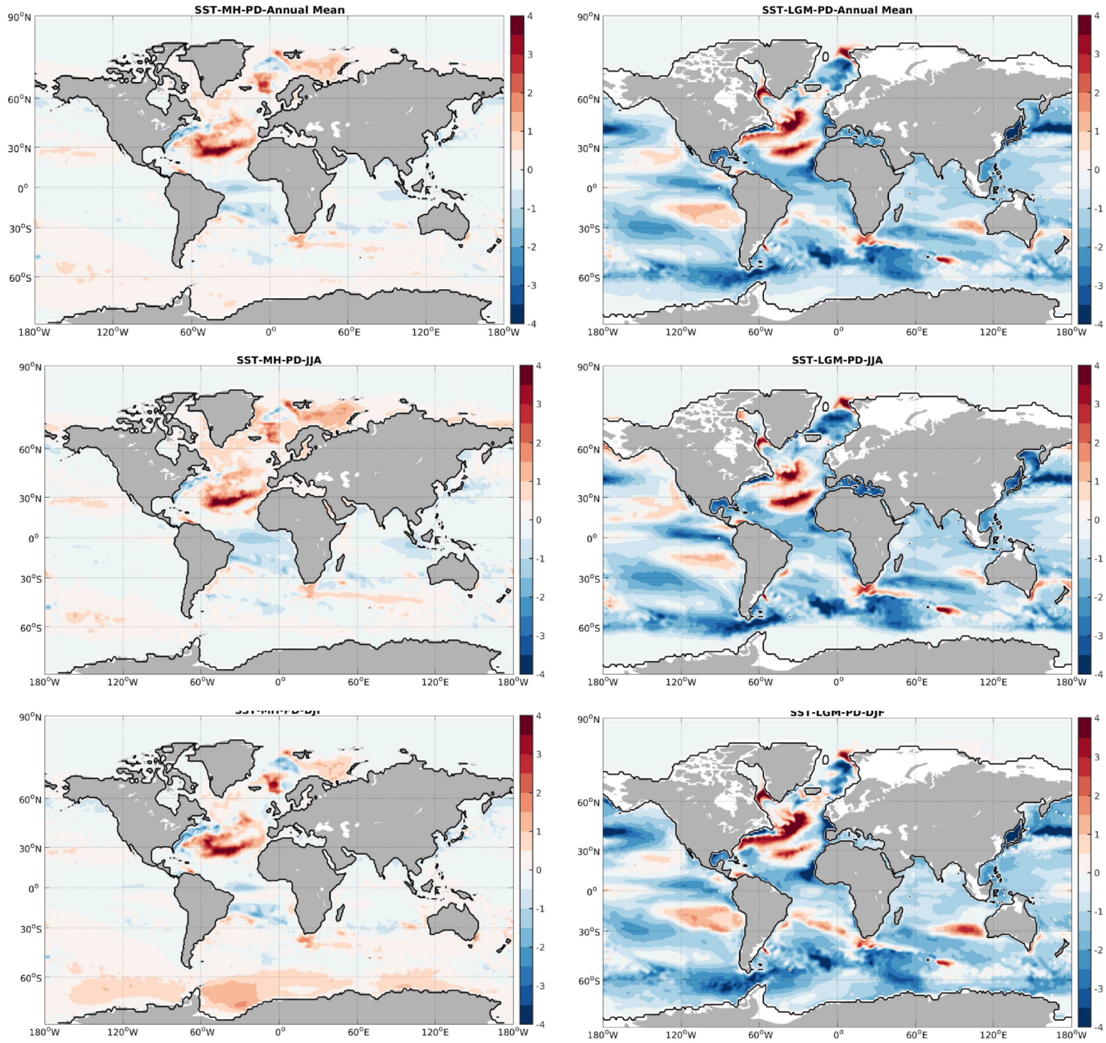

Fig. 2. Simulated sea surface temperature anomalies of the MH and LGM, compared to PD.

In the current project hbk00060, we've successfully conducted the simulations for the PD, MH, LGM climates with the EH experiment on-going, using the FESOM ocean-standalone model and on the basis of the grid mesh in Fig. 1. Specifically, our work reached the following two milestones:

- We've created a strategic way in preparing initial fields, coastal and atmospheric forcing for a paleo simulation using FESOM model.
- We've successfully start integration of the PD, MH and 21ka B.P. oceans. Our modelling results present valid surface ocean reconstructions, although deeper oceans have not spun up, which is thus proposed in this project for continuation.

As shown in Fig. 2-4, our high-resolution FESOM, MH experiment presents warmer climate compared to the Present-day conditions, while LGM experiment shows much colder surface ocean. This matches our atmospheric forcing and also paleoceanographic evidences. The simulated warmer North Atlantic of MH refers to a stronger Atlantic Meridional Overturning Circulation

(AMOC) compared to the PD, leading to a larger advection of tropical, relatively warmer water northwards (Fig. 2). In parallel, for the same physical constrain, the tropical Atlantic, more saline water is also brought into the subpolar Atlantic Ocean. In comparison, our LGM simulation reveals higher salinities of the LGM ocean globally, due to an intended addition of 1psu into the ocean concerning the 120m-lowered sea level during HS-1. Moreover, a pounced increase of sea surface salinities in the Arctic Ocean and subpolar Atlantic Ocean are controlled by the stronger AMOC of LGM, correlated to deepened winter mixed layer depths in the northern North Atlantic Ocean and Nordic Seas. Moreover, determined by the extreme cold surface atmosphere, the LGM SSTs are colder than the PD conditions in general, with pronounced lower SSTs due to polar amplification (Fig. 3). In particular, over the NW Pacific regions where we apply the up-to-6km resolutions, the regional sea ice is characterized by significant change from the PI conditions (Fig. 4). Because sea ice performs as the key factor in regulating surface halocline, we expect strong consequence of its regulation in the North Pacific Intermediate Water (NPIW) formations, and thus North Pacific oxygen minimum zone prevailing to the tropics.

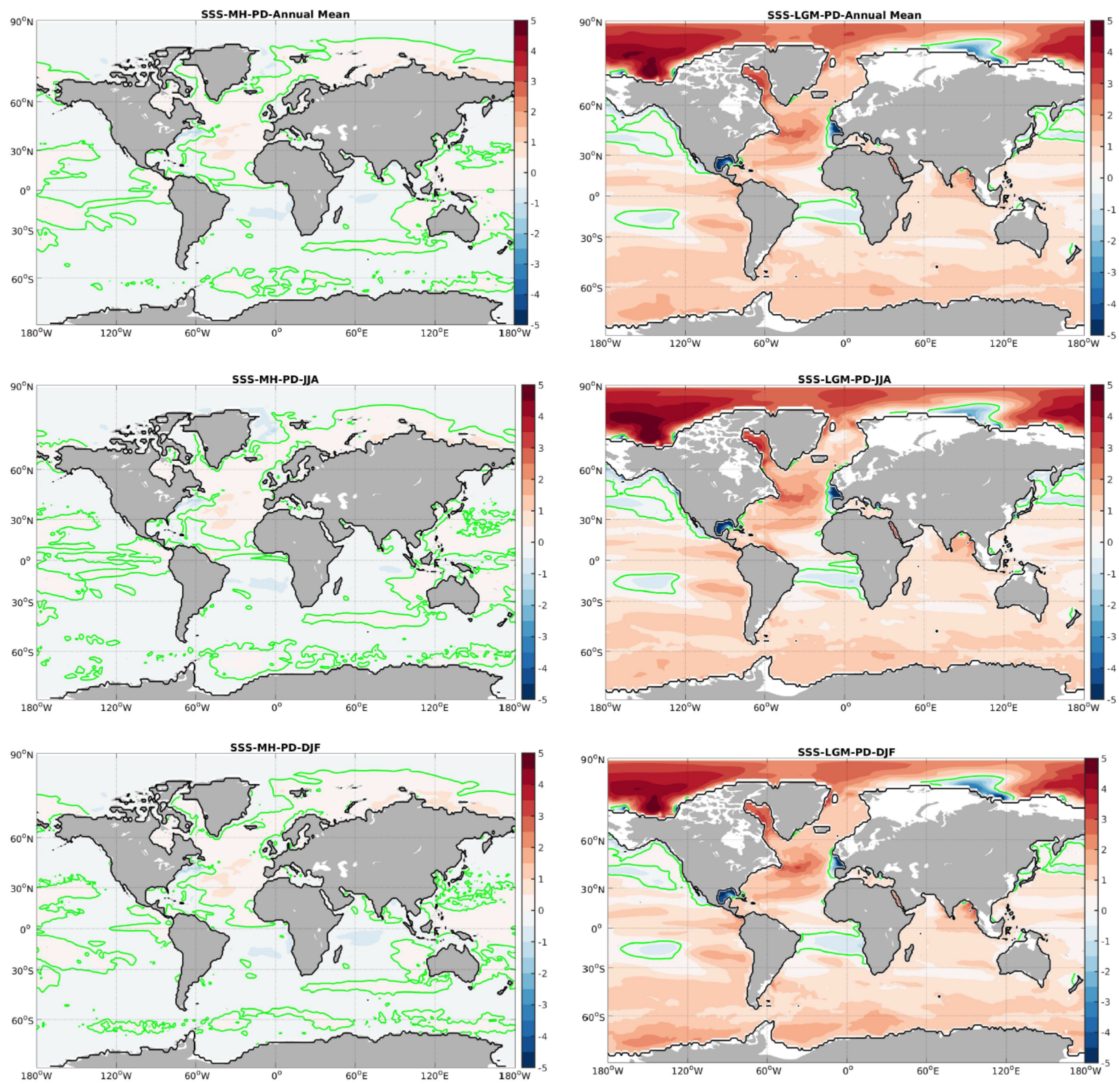

Fig. 3. Simulated sea surface salinity anomalies of the MH and LGM, compared to PD.

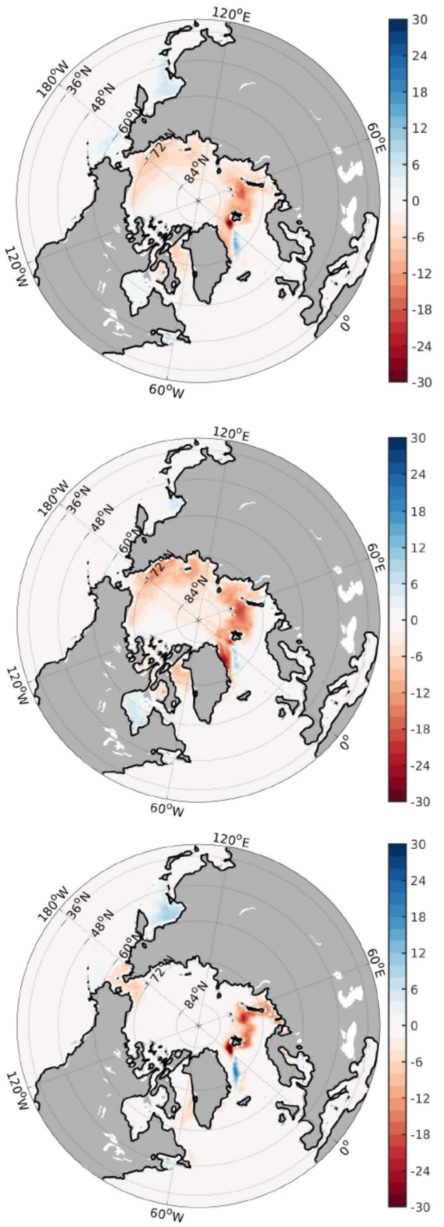

Fig. 4. Simulated sea ice concentration anomalies of the MH and LGM, compared to PD.

6. Plan for Year 2018 Q3-Q4 and Year 2019 Q1-Q2

As soon as we get the permission of computational resources from the HLRN, we will continue our simulations in the current project hbk00060. In sequence, we will start the FESOM-REcoM experiments for PD, LGM, MH and EH since the 4th quarter of Year 2018 until the 2nd quarter of Year 2019 (Table 1). In summary, 1140480 NPLs are proposed for our FESOM and FESOM-REcoM simulations in this project (see Tab. 2) and equally distributed over quarters, i.e. 285120 NPLs/quarter. In addition, the output data is 28 GB/yr in FESOM run and 40GB/yr in FESOM-REcoM coupled run. Totally, we propose 8TB in work directory and 24 TB for the tape storage, for the outdata as well as the files of model forcing, grid mesh and scripts.

Tab 1. Time plan of Year 2018 and 2019.

Year 2018, Q3			Year 2018, Q4			Year 2019, Q1			Year 2019, Q2		
Jul.	Aug.	Sep.	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	Jun.
Continuing PD FESOM			PD, FESOM-REcoM								
Continuing MH FESOM						MH, FESOM-REcoM					
Continuing EH FESOM									EH, FESOM-REcoM		
Continuing LGM FESOM					LGM, FESOM-REcoM						

Tab 2. Planned computational cost for each simulation.

FESOM simulations	Model years	NPL per model year	Total requirement (NPLs)
PD	60	1056	63360
Mid Holocene	60	1056	63360
Early Holocene	120	1056	126720
LGM	120	1056	126720
FESOM-ReCOM simulations	Model years	NPL per model year	Total requirement (NPLs)
PD	120	1584	190080
Mid Holocene	120	1584	190080
Early Holocene	120	1584	190080
LGM	120	1584	190080
Total	**840**		**1140480**

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