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Increasing Arctic River Discharge and Its Role for the Phytoplankton Responses in the Present and Future Climate Simulations

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Key Points:

- Additional river discharge in the present climate increases Arctic sea ice and decreases surface phytoplankton in spring.
- The surplus nutrients due to the decrease of phytoplankton in the spring increase the surface phytoplankton in the summer.
- The present phytoplankton hotspot in the Eurasian Basin shifts to the Canadian Basin in the future climate simulation.

Abstract

Arctic amplification is known to accelerate the hydrological cycle in high-latitude landmass, which eventually leads to increased river discharge into the Arctic Ocean. However, the majority of climate models in Coupled Model Intercomparison Project 5 (CMIP5) tend to underestimate Arctic river discharge. This study elucidates the role of additional Arctic river discharge for the phytoplankton responses in the present and future climate simulations. In the present climate simulation, the additional freshwater input showed a decrease in the phytoplankton in spring due to the increasing sea ice, and in summer, it showed an increase in phytoplankton due to the surplus nitrate leftover from spring and induced vertical mixing. Similar processes occurred in future climate simulations. However, in those simulations, the major response region of phytoplankton to additional freshwater input was altered from the Eurasian Basin to the Canadian Basin and the East-Siberian Sea. This is because the current marginal ice zone in the Barents-Kara Sea, where phytoplankton mainly responds, moves toward the East-Siberian-Chukchi Sea. We suggest that Arctic river discharge is potentially an important contributing factor for Arctic ecosystems in both present and future climate that controls sea ice and nutrient distribution.

Plain Language Summary

Arctic warming is known to accelerate hydrologic cycles at high latitudes. However, most climate models still underestimate river discharges into the Arctic Ocean compared to real world. Our research studies the impact of increasing river discharge on phytoplankton in the present and future climates using the earth system model. In the present climate, increased river discharge reduces phytoplankton in spring and increases it in summer. Additional river discharge in spring increases sea ice and decreases phytoplankton. However, the limited growth of phytoplankton preserves nutrients during spring, and therefore, leads to explosive phytoplankton growth in summer. In the future climate, as in the present climate, phytoplankton in spring decreases, and phytoplankton in summer increases. However, the major response region moves from the Eurasian to the Canadian Basin. We suggest that Arctic river discharge is potentially an important contributing factor for Arctic ecosystems in both present and future climate by influencing sea ice and nutrient distribution.

1 Introduction

Arctic warming is one of the most remarkable phenomena in global surface temperature changes (Cohen et al., 2014) causing sea ice melting due to increased atmospheric carbon dioxide concentration and increased downward longwave radiation (Comiso, 2003; Serreze et al., 2007; Maslanik et al., 2007), and enhancing a strong positive feedback, e.g., ice-albedo feedback (Perovich et al., 2007; Holland et al., 2010; Kashiwase et al., 2017). The more remarkable temperature rise in the Arctic region compared to the other regions, often called Arctic amplification (AA), has influenced not only Arctic climate itself such as Arctic moistening (Min et al., 2008) and marine acidification (Terhaar et al., 2020), but imposes a remote impact via modulating and atmospheric circulation patterns onto the region with high human populations in the tropics and mid-latitudes (Kim et al., 2014; Kug et al., 2015; Coumou et al., 2018; Kennel & Yulaeva, 2020) . As AAs are projected to become stronger in the future scenarios established by Coupled Model Intercomparison Project (CMIP) models, it is of utmost importance to understand the Arctic environment and ecosystem changes due to the current and future accelerating warming (Smith et al., 2019).

Recent studies suggested that Arctic warming can be amplified by changes in marine phytoplankton biomass (Park et al., 2015; Lim et al., 2019a, b) and human-induced nitrogen flux from river discharge and atmospheric depositions in the future climate (Lim et al., 2021). The reduction of sea ice extent and its thickness allows more penetrations of shortwave radiation into the Arctic Ocean surface (Perovich et al., 2011; Nicolaus et al., 2012; Arrigo et al., 2014) that triggers the earlier bloom timing in marine phytoplankton at the edge of sea ice (Frey et al., 2015) and sub-ice bloom (Arrigo et al., 2012, 2014; Horvat et al., 2017). The increased phytoplankton biomass leads to heat redistribution in ocean layers via modulating attenuation coefficients (Morel, 1988; Manizza & Que, 2005) that may influence the simulated AA (Park et al., 2015; Lim et al., 2019a, b; Lim et al., 2021). This new mechanism to understand the possible positive feedback highlights the role of the Arctic ecosystem in terms of air-sea-biogeochemical interactions, which may be overlooked in future Arctic projections using Earth System Models (ESMs).

Lewis et al. (2020) showed that the primary productivity of the Arctic Ocean increased by 30 % from 1998 to 2012, owing to the expansion of open water. Since then, primary productivity has exhibited an increasing trend in general because of increased phytoplankton. Future projections of the primary productivity of the Arctic Ocean simulated in CMIP5 models suggested large uncertainties, mainly depending on nitrate storage (Vancoppenolle et al., 2013). Ardyna & Arrigo (2020) suggested that the shelf-break, serving as a “green belt,” can effectively supply inorganic and organic materials to increase marine productivities in the stratified Arctic Ocean.

Arctic Ocean warming alters hydrologic and oceanic circulations, such as sea ice melting, intensified precipitation (Min et al., 2008), and increased river discharge (Haine et al., 2015). In particular, while the Arctic Ocean accounts for 1 % of the global volume of the ocean, it receives more than 10 % of the global river discharge (McClelland et al., 2012). Notably, long-term changes in river discharge have been steadily increasing. In particular, Eurasian river discharge in 2018 was 12 % greater than the average for 1980−1989 (Peterson et al., 2002; Holmes et al., 2018). In addition, river discharge under the future climate conditions is projected to increase by more than 50 % compared to the present, mainly in Alaska and Siberia (Bring et al., 2017). However, in the CMIP5 models, the surface salinity around the river is overestimated because of the underestimation of river discharge with large uncertainties (Shu et al., 2018).

Several recent observational studies have reported that Arctic river discharge modulates Arctic biogeochemistry by delivering dissolved organic matter that enhances phytoplankton response (Holmes et al., 2012; Fichot et al., 2013; Tremblay et al., 2014; Ardyna et al., 2017). However, it is difficult to independently analyze the impact of additional river discharge on the marine ecosystems of the Arctic Ocean in observational studies, and studies on ESMs to clarify if these are insufficient. In addition, it is challenging to predict future Arctic ecosystems because of the uncertainty of the primary productivity simulated by models (Vancoppenolle et al., 2013; Ardyna & Arrigo, 2020).

In this study, we used the ESM to study the sensitivity of phytoplankton to additional river discharge in the present and future climate simulation. Our model simulation outputs suggest that Arctic river discharge can control sea ice and nutrient distribution, which are factors that affect phytoplankton growth. We outlined the mechanisms by which additional river discharges under the influence of present climate conditions affect spring and summer sea ice melting and nutrient distribution. In addition, we analyzed the impact of increased river water discharge under the influence of future climate conditions on future Arctic ecosystems, thus highlighting the importance of river discharge on ecosystem changes in the future.

2 Materials and Methods

2.1 GFDL-CM2.1-TOPAZ2

In this study, we applied the ESM named GFDL CM2.1, coupled with the biogeochemical model Tracers of Ocean Phytoplankton with Allometric Zooplankton code version 2.0 (TOPAZv2; Griffies et al., 2005; Dunne et al., 2012, 2013). GFDL-CM2.1-TOPAZ consists of an atmospheric model (AM2), land model (LM2), modular ocean model (MOM5), sea ice simulator (SIS), and ocean biogeochemistry model (TOPAZv2). The AM2 and LM2 horizontal resolutions are 2° latitude × 2.5° longitude, and the vertical resolution of AM2 is 24 levels grid. MOM5 uses a tripolar grid to remove the spherical coordinate singularity of the Arctic Ocean. below the Arctic north of 65° N, and above it switches to a bipolar region with coordinate singularities over Siberia and Canada. MOM5 and SIS horizontal resolutions are 1° in the extratropics, with finer meridional grid-spacing in the tropics (~1/3°). The vertical resolution of MOM5 is 50 levels grid, with 22 evenly spaced levels over the top 220 m (Griffies et al., 2005).

TOPAZv2 considers the cycle of carbon, and nutrients such as nitrogen, phosphorus, silicon, and iron (Dunne et al., 2013). The phytoplankton is calculated by dividing it into three groups, i.e., small, large, and nitrogen-fixing diazotrophs. The phytoplankton growth rate is calculated as a function of various chlorophyll to carbon ratios and is limited by nutrients and light (Dunne et al., 2010). TOPAZv2 includes external inputs from atmospheric nitrogen deposition lithogenic dust, soluble iron, and river nitrogen. For more detailed information, see Dunne et al. (2013).

In GFDL-CM2.1-TOPAZ, river discharge is controlled in the land module. The total water storage (W) of LM2 consists of each non-glaciated cell composed of a snowpack store, a root-zone store, a groundwater store, and a glaciated cell composed of a snowpack and a glacier-ice store. Each water store has a different equation for water balance; see Milly & Shmakin (2002) for details. River discharge is the total amount of water from land to the sea. In this model, the river discharge is calculated as the sum of groundwater, melted water from glaciers and snow, and any rainfall immediately combined with melted water. To inflow additional freshwater in our study, we add a freshwater control term to this calculation.

2.2 Experiment

To analyze the changes in phytoplankton due to the additional river discharge in the present and future climates, we performed four experiments by simulating the present and future climates and controlling the river discharge in each condition. We used abbreviations to distinguish between each experiment. The freshwater addition experiments were abbreviated as "FWadd," and the standard experiments were abbreviated as "CTRL." In addition, to distinguish between the present and future climate simulations, we used parentheses after each experimental abbreviation to indicate the present and future with uppercase P and capital F, respectively [e.g., CTRL(P), FWadd(F)].

The present climate simulation was performed similarly to the 1990 level experiment, which is often used as the present experiment in previous studies using the CM2.1 model (Gnanadesikan et al., 2006; Delworth et al., 2012; Lim et al., 2019a, b). The present climate simulation is performed by prescribing greenhouse gases, such as carbon dioxide, methane, and nitrous oxide, as well as organic and inorganic nitrogen oxides prescribed for rivers and atmosphere at 1990 levels (Green et al., 2004; Hegglin et al., 2016).

The future climate simulation set twice as much carbon dioxide as the present condition to simulate the future climate. The future climate simulation (F) performed calculations for 110 years with 706 ppm carbon dioxide, increasing by 1 % from the present climate condition. Before performing the freshwater addition experiments, we performed a 1200-year spin-up to make an environment for the present climate and the future climate, respectively.

The freshwater addition experiments were based on the water-housing experiment performed in the Paleoclimate Modeling Intercomparison Project 2 (PMIP2; Stouffer et al., 2006). In existing literature that adopted water-hosing experiments, additional water was uniformly added to 50–70° N latitudes for 100 years to study vertical currents (Yin & Stouffer, 2007;Kim & An, 2019). In this study, the freshwater addition experiments were performed by simulating the addition of freshwater to the river discharge of the entire Arctic Ocean at latitude 65–90° N.

In the freshwater addition experiments, if the integration time is prolonged, the sea surface height continues to increase, which may cause water balance problems (Fig. S1). Therefore, for the integration time, a 70-year integration was performed, while considering the level that does not destroy the mass balance; only the last 30 years were analyzed considering the spin-up time of the model.

2.3 Additional river discharge forcing

We set the additional river discharge at 0.03 Sv (1 Sv = 10^6 m^3/s), the level of underestimated CMIP5 for Arctic river discharge, in the sum of all river discharge flowing into the Arctic Ocean. Shu et al. (2018) compared the CMIP5 model outputs and observation data for the hydrologic cycle. The river discharge averaged the CMIP5 model outputs of the present climate was 0.083 ± 0.036 Sv, which is underestimated by approximately 0.021 Sv, compared to the observation data of 0.102 ± 0.004 Sv. In addition, the simulated river discharge uncertainty of CMIP5 was approximately 0.036 Sv. From the above consideration, we set 0.03 Sv as an additional freshwater quantity.

We used the observational river discharge data provided by Arctic Great River Observatory (ArcticGRO) to compare the estimations from model output (Shiklomanov et al., 2021). ArcticGRO, initiated in 2002 by the Pan-Arctic River Transport of Nutrients, Organic Matter, and Suspended Sediments (PARTNERS) project, is part of a river observation project that collects and analyzes time-series water samples from six large rivers. The AricticGRO uses river discharge data from various hydrologic agencies, including near-real-time data. The LoadRunner software package is used to generate continuous daily discharge data, using calibrated regression from time series sampling observations (Booth et al., 2007). In this study, among the wide ArcticGRO river data, we compared data from five major rivers that flow into the Arctic Ocean, namely, Ob', Yenisey, Lena, Kolyma, and Mackenzie with model outputs. The analysis period of the river observation data averaged from 1981 to 2010 according to the present level.

The position of the simulated river mouth was similar to the observation point. Figure 1(a) portrays the 1000-year average river discharge for the CTRL(P). The black dots mark the river mouth simulated by the model, while the red dots are the observation points. By comparing each point, we found that the simulated river mouth position in the model did not appear to deviate significantly from the observation point. In addition, river discharge was mainly in East-Siberia and the Laptev Sea.

The amounts of river discharge in each mouth, indicated by dots in Figure 1(a), were compared to those in Figure 1(b). The gray box indicates the 1000-year average river discharge of CTRL(P), the black box indicates the river discharge added by 0.03 Sv to the 1000-year average river discharge of CTRL(P), and the red box indicates the observation data. Note that we are analyzing model data for qualitative comparison with observation data, and as most of the observation data is a regression by a statistical model, caution is required in interpretation.

Significant amount of river discharge flowed from the large rivers Lena, Yenisey, and Ob', as designed in the FWadd experiment. The model simulated river discharge was the largest in the Ob River in the Arctic, unlike the observation data. In addition, the simulated river discharge was overestimated in the Ob' and Kolyma rivers and underestimated in the Yenisey and Lena rivers. However, except for the Kolyma River, the discharge was within a relatively acceptable range.

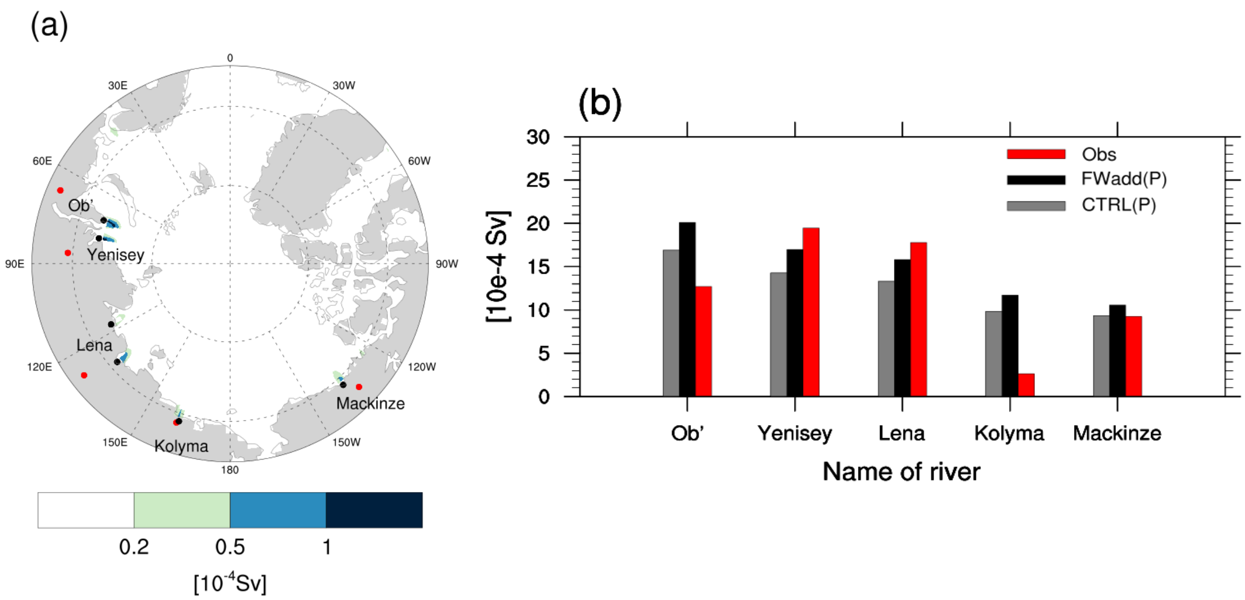

Figure 1. Comparison of annual mean river discharge of CTRL(P), FWadd(P), and observation (Obs). (a) 1000-yr annual mean river discharge of CTRL(P) (shaded). The black dots are the simulated five largest river mouths of the models. The red dots indicate the sites of observation (ArcticGRO). (b) The amount of river discharges at the mouth of each of five rivers.

3 Results

3.1 Impact of river discharge in the present climate simulation

In the present climate simulation, the overall response of phytoplankton to additional river discharge results in a decrease in the phytoplankton in spring and an increase in summer. Figure 2 shows the anomaly by averaging the upper ocean (0–20 m) chlorophyll concentrations—representing the phytoplankton—between the CTRL(P) and FWadd(P) experiments in spring (April, May) and summer (June, July). Note that chlorophyll concentration refers to the biomass of phytoplankton.

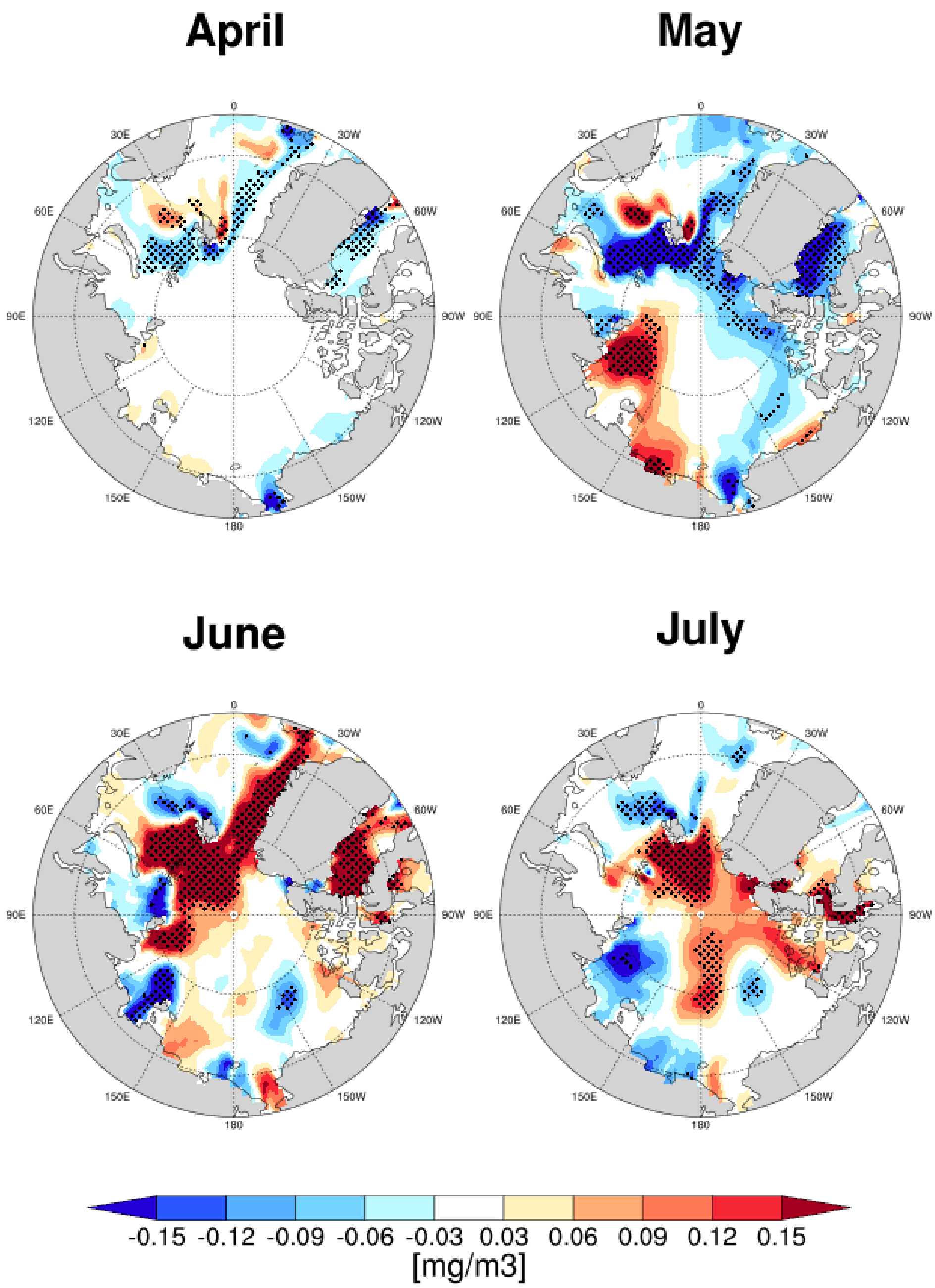

Figure 2. Impact of increased river discharge in spring (April–May) and summer (June–July) in the upper ocean (0–20 m) on chlorophyll concentration in the present climate simulation. The shaded area indicates the difference between FWadd(P) and CTRL(P) of the chlorophyll concentration. Black dots represent significant values of chlorophyll concentration at 95 % confidence level.

In the present climate simulation, we found that an increase in river discharge in spring can cause a decrease in phytoplankton, except in some areas. As for the anomaly pattern of chlorophyll concentration in April, a negative anomaly pattern appeared in the Bering Strait, Greenland Sea, and some areas of the Eurasian Basin (Fig. 2). In May, the anomaly pattern was similar to that in April, but with a more robust response. Most negative anomaly patterns in April and May appeared in the area in contact with the surrounding ocean. These results suggest that limiting factors restraining phytoplankton growth have developed near the border between the surrounding and Arctic oceans.

An increase in river discharge leads to a decrease in the surface salinity and surface temperature of the Arctic Ocean, thus, increasing the sea ice concentration in the region (Fig. S2; Fig. 3a). The decrease in surface salinity was not limited to estuaries but was also observed in the Barents Sea, where sea ice variability was relatively large. In addition, an increase in river discharge resulted in a decrease in the inflow of the surrounding ocean due to an increase in sea surface height (SSH). These results are consistent with other model experiments that examined additional river discharge in the Arctic Ocean (Nummelin et al., 2016).

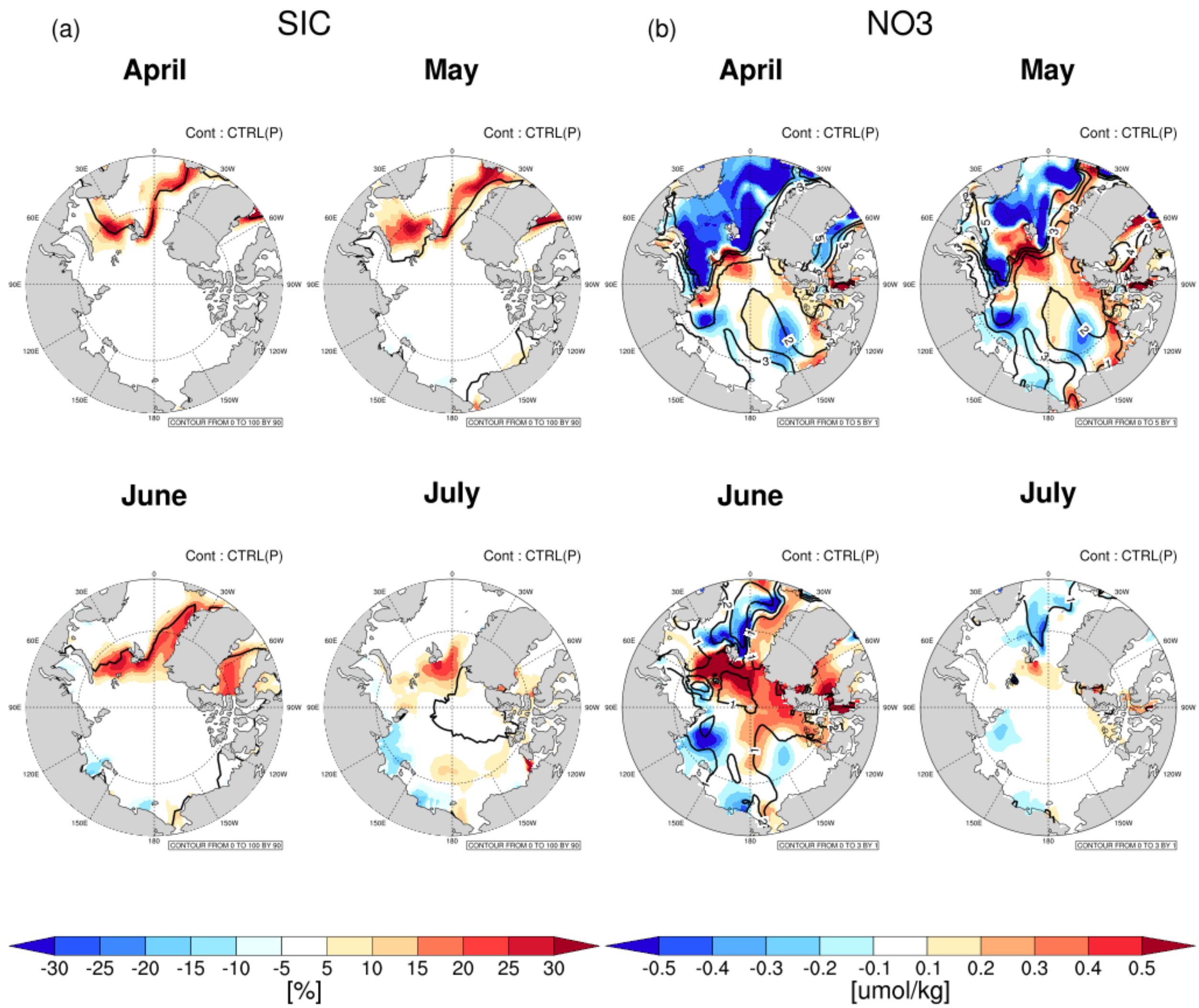

Figure 3. Changes in the limiting factors (SIC and NO_3) of phytoplankton simulated by the model in spring and summer. (a) Difference between FWadd(P) and CTRL(P) of sea ice concentration (SIC)(shaded) and the averaged sea ice extent (SIC>15%) on CTRL(P)(contour). (b) Difference between FWadd(P) and CTRL(P) of nitrate concentration (NO_3) (shaded) and the averaged NO_3 on CTRL(P)(contour).

In the present climate, an increase in summer river discharge may cause an increase in phytoplankton, particularly in the Eurasian Basin (Fig. 2). A robust positive anomaly pattern appeared in the June chlorophyll concentration anomaly pattern in the Barents Sea, Eurasian Basin, and the Baffin Bay. As for the anomaly pattern of chlorophyll concentration in July, a positive anomaly pattern appeared in the Eurasian and Makarov basins, as the pattern moved to the center of the Arctic Ocean compared with its position in June. Notably, the positive anomaly pattern in June mainly appeared in the negative anomaly pattern in May. These results suggest that the reduction in phytoplankton due to spring sea ice melting affects the growth of phytoplankton in summer.

In summer, the limiting factor for phytoplankton growth is the depletion of nitrate, the primary nutrient for phytoplankton (Kattner & Budéus, 1997). The growth of spring phytoplankton, called a “chlorophyll bloom,” consumes nitrate, leading to nitrate depletion in the summer ocean (Lim et al., 2019a). Increased freshwater increases the sea ice concentration, thereby slowing down the chlorophyll bloom and reducing nutrient depletion (Fig. S3; Fig. 3a). Figure 3b shows the April–July anomaly by averaged nitrate concentration between the CTRL(P) and FWadd(P) experiments. This indicates that the positive anomaly pattern of nitrate concentration in June and July was nearly consistent with the positive anomaly pattern of phytoplankton. These results indicate that increased nitrate levels due to the increase in summer freshwater promoted the growth of phytoplankton.

We found that the summer nitrate increase in the FWadd experiment was associated with poor spring phytoplankton growth, and the negative anomaly pattern of chlorophyll concentration in May (Fig. 2) was similar to the positive anomaly pattern of nitrate concentration in June (Fig. 3b). Consistent with this pattern, phytoplankton, which did not grow well due to increased sea ice in the FWadd experiment, had lower spring nutrient consumption. Relatively low nutrient consumption promoted the growth of summer phytoplankton. Below the upper ocean layer (0–20 m), there was a decrease in phytoplankton because as the upper layers became nutrient-rich in summer, the subsurface chlorophyll maximum depth became shallow (Fig. S3).

Another reason for the increase in nitrate could be the increased summer sea ice. Sufficient summer light and shallow sea ice do not limit the light required for phytoplankton growth. However, in the process of sea ice formation, the ocean mixed layer depth under the salty sea ice deepens, owing to the brine rejection process (Peralta-Ferriz & Woodgate, 2015). This mechanism causes vertical mixing within the deep ocean, increases the nutrient levels, and may affect phytoplankton growth.

In the FWadd experiment, brine rejection occurred in summer in the Eurasian Basin (Fig. S4). Even though brine rejection did not appear in the entire area that experienced increased sea ice, brine rejection appeared near the Eurasian Basin, which is relatively far from the estuary, indicating a positive salinity anomaly. As a result, the mixed layer depth around the Eurasian Basin increased. This mechanism may be responsible for the substantial increase in nitrate levels, especially in the Eurasian Basin.

3.2 Impact of river discharge on future

In the previous subsection, we reported on analysis of the effects and mechanisms of additional river discharge on phytoplankton in present climates. In this subsection we report on the analysis of the impact of additional river discharge on phytoplankton in the future climate simulation. In this simulation, the significant response of phytoplankton to additional river discharge showed a decrease in spring and an increase in summer, similar to that observed in the present climate simulation. However, while the changes in phytoplankton in the present climate appeared mainly in the Eurasian Basin, they extended to the Canada Basin in the future climate.

Figure 4 shows the upper ocean chlorophyll concentration anomaly between CTRL(F) and FWadd(F) in spring and summer. Notably, the future Arctic Ocean is expected to become more stratified under the future climate conditions compared to the present climate conditions by melting ice and strengthening the hydrological cycle (Haine et al., 2015). Most models project that, in the future, surface nitrate concentrations will decrease due to the stratification of the Arctic Ocean (Vancoppenolle et al., 2013). The CTRL(F) results are consistent with the above-mentioned previous studies; the simulation showed a significant decrease in surface nitrate and phytoplankton levels compared to the CTRL(P).

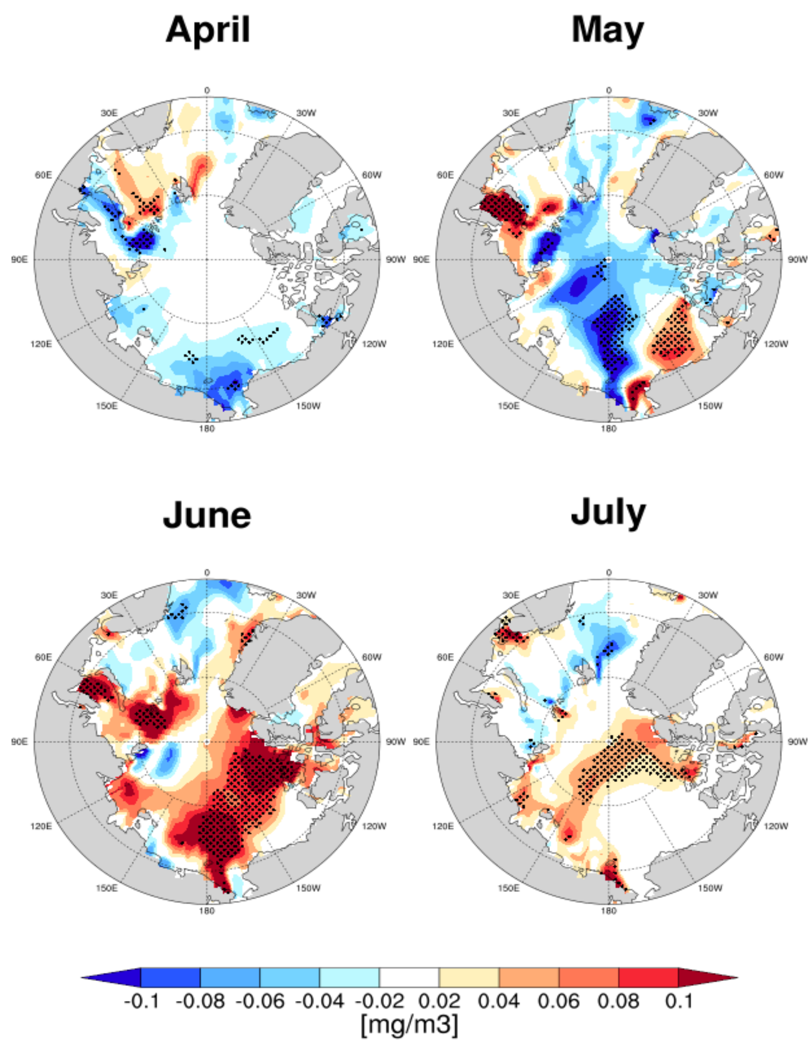

Figure 4. Impact of increased river discharge in spring (April–May) and summer (June–July) upper ocean (0–20 m) on chlorophyll concentration in the future climate simulation. The shaded area indicates the difference between FWadd(F) and CTRL(F) of chlorophyll concentration. Black dots represent significant values of chlorophyll concentration at 95 % confidence level. Note that the future climate simulation was applied by adjusting the minimum and maximum values of the shading bar used in the present climate to approximately 70 %.

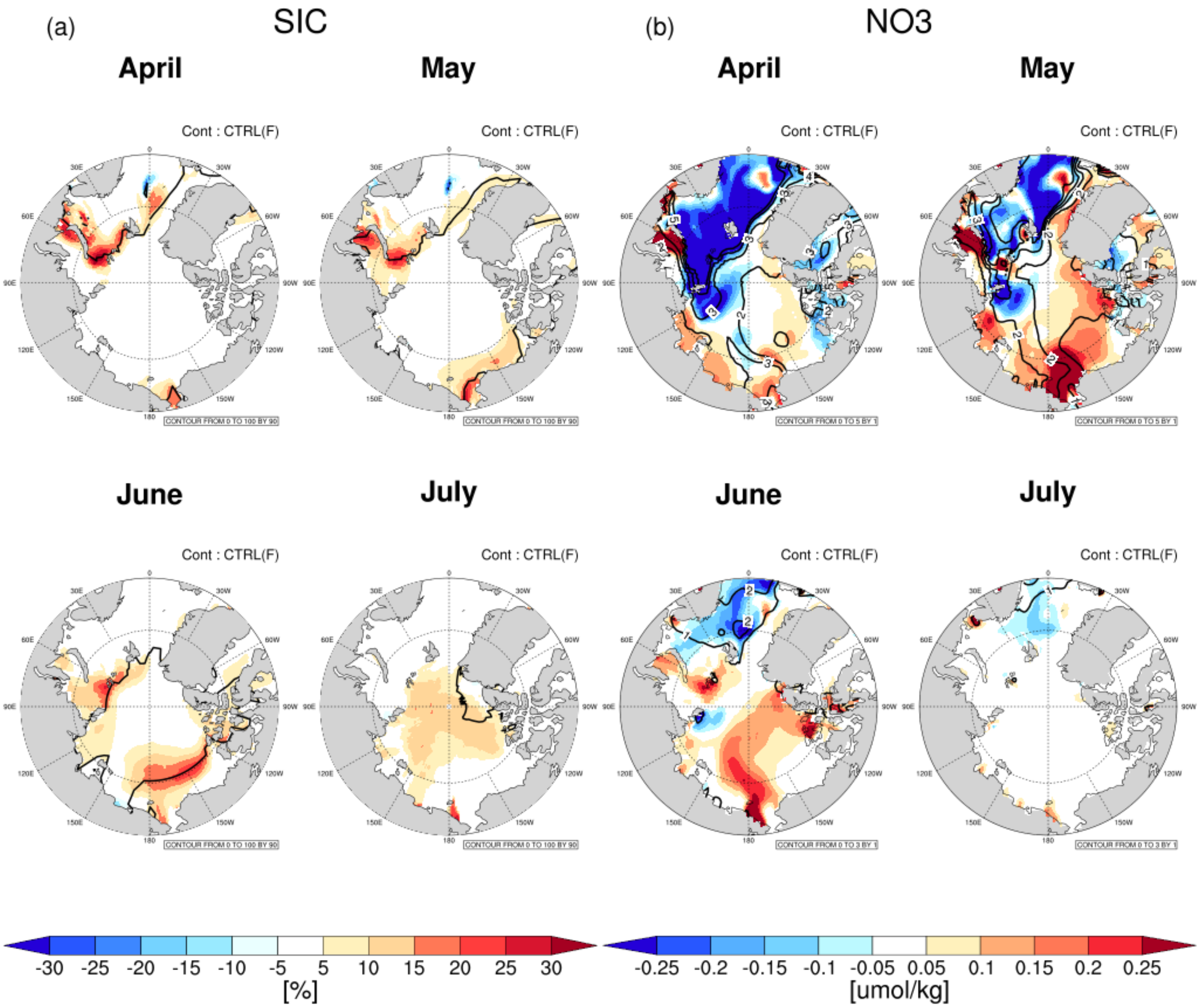

Figure 5. Changes in the limiting factors (SIC and NO_3) of phytoplankton simulated by the future in spring and summer. (a) Difference between FWadd(F) and CTRL(F) of sea ice concentration (SIC)(shaded) and the averaged sea ice extent (SIC>15%) on CTRL(F)(contour). (b) Difference between FWadd(F) and CTRL(F) of nitrate concentration (NO_3) (shaded) and the averaged NO_3 on CTRL(F)(contour). Note that the future climate simulation of nitrate concentration was applied by adjusting the minimum and maximum values of the shading bar used in the present climate to approximately 50 %.

In the future climate simulation, the increase in river discharge in spring resulted in a negative anomaly of chlorophyll concentration. In addition, similar to the mechanism in the present climate, the decrease in the phytoplankton biomass in response to sea ice increased. However, compared with the results of the present climate simulations, negative anomaly patterns appeared in the Kara and Chukchi seas, which are generally close to the interior of the Arctic Ocean.

Figure 5a shows the average sea ice concentration anomaly between CTRL(F) and FWadd(F) during April–July. The positive anomaly pattern of sea ice concentration appears similar to the negative anomaly pattern of phytoplankton. The consistency of this pattern indicates a decrease in phytoplankton due to light blocked by increased sea ice, similar to the present climate simulation. However, in the future climate simulation, the sea ice extent was significantly reduced compared to the present climate simulation, resulting in broader negative anomaly patterns of phytoplankton. The mechanism of sea ice formation by freshwater was the same as that in the present climate simulation (Fig. S2).

The seasonal evolution of the marginal ice zone from May to June is remarkably different between the present and future climates (Fig. 6). In the present climate, the difference in sea ice concentration between May and June is significant in the Eurasian Basin with the Barents-Kara Sea. In contrast, more extensive sea ice fluctuations appear in the Beaufort and East-Siberian-Chukchi Sea in the future climate. These results suggest that future sea ice distribution changes may shift summer phytoplankton hotspots.

An increase in river discharge in future climate simulation caused an increase in summer phytoplankton similar to that in the present climate simulation; a response in the Canada Basin appeared broader and larger than in Eurasian Basin (Fig. 4). In June, the main anomaly pattern of chlorophyll concentration is the positive anomaly in the Eurasian Basin, Canada Basin, and East-Siberian-Chukchi Sea. However, the positive anomaly in the Eurasian Basin was narrow, while the anomaly in the Canadian Basin was wide. In July, the anomaly intensity weakened, and the pattern shifted toward the center of the Arctic Ocean, relative to that in June.

Unlike in the present, in the future climate simulation, summer nutrient changes due to additional river discharge were only related to spring phytoplankton blooming. Figure 5b shows the differences in the nutrients between CTRL(F) and FWadd(F). The nitrate positive anomaly pattern in June was similar to that of the chlorophyll concentration negative anomaly pattern in May, which showed the same mechanism as the present climate simulation. The consistency of this anomaly pattern implies that freshwater-induced spring sea ice increases contribute to summer phytoplankton growth, even in the future climate simulation.

The mechanism of the nutrient increase caused by brine rejection is weakened in future simulations (Fig. S4). Excessive stratification of the Arctic Ocean and additional river discharge lowers the ocean salinity when the sea ice freezes, with relatively little brine left behind within the sea ice. The decrease in the salinity within the sea ice reduces the increase in salinity caused by brine rejection in the Eurasian Basin in present climates. For this reason, the vertical mixing induced by brine rejection is weakened, and ocean stratification due to the addition of river discharge becomes stronger.

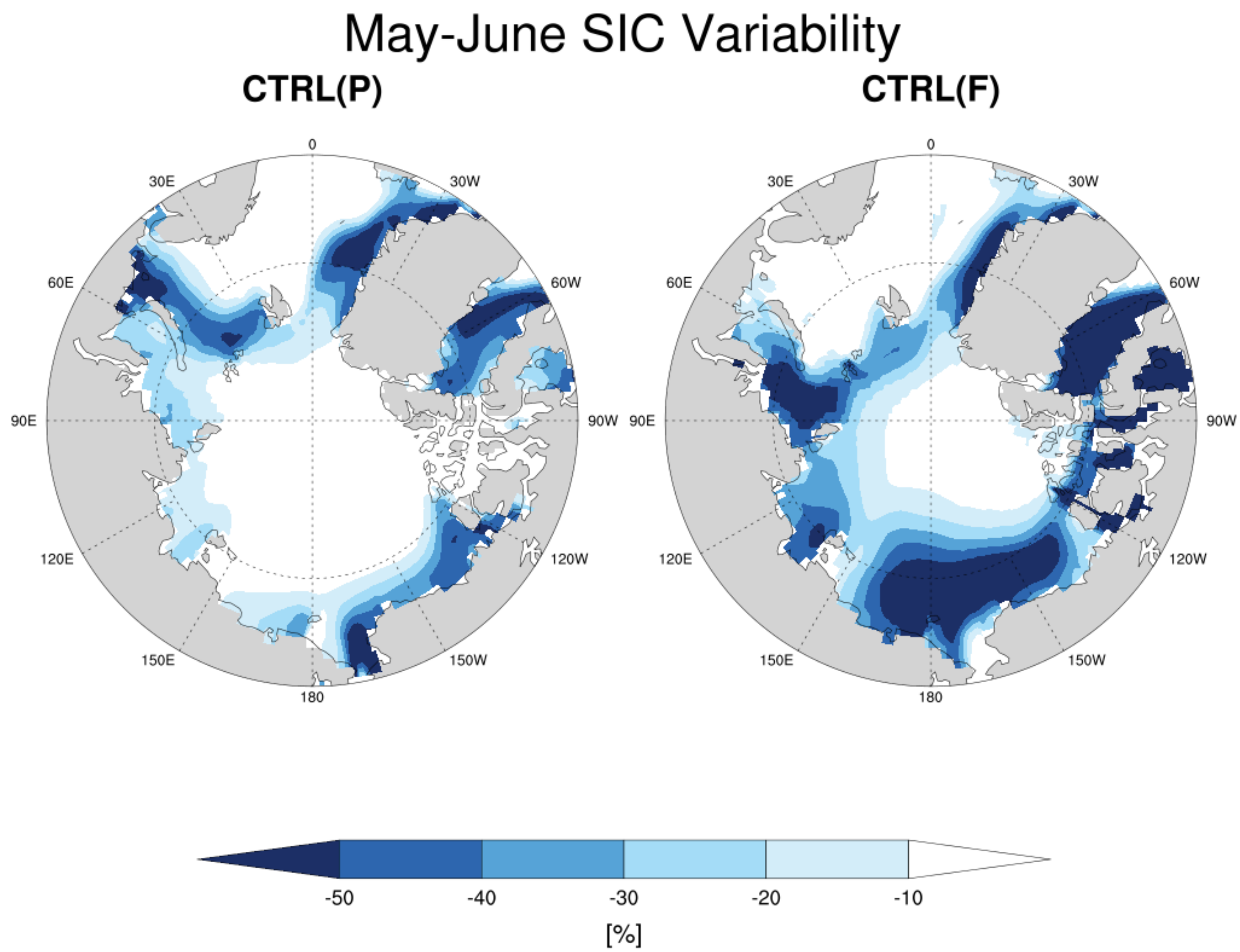

Figure 6. Changes in the May-June marginal ice zone in the present and future climate experiments. The left figure shows the difference in sea ice concentration in May and June in CTRL(P). The right figure shows the difference in sea ice concentration in May and June in CTRL(F).

4 Summary and Discussion

We studied the mechanism by which the increase in Arctic river discharge—underestimated in most models—affects spring and summer phytoplankton in the present and future climates. In the present climate simulation, additional river discharge in spring decreased the phytoplankton biomass near the Eurasian Basin due to the light blocked by increased sea ice. In summer, additional river discharge increased the phytoplankton biomass, mainly in the Eurasian Basin, as indicated by the nutrients not consumed in the spring and the vertical mixing caused by brine rejection. In the future climate simulation, similar to the present climate simulation, phytoplankton decreased in spring due to increased sea ice. In addition, although an increase in phytoplankton appeared in the summer, it strongly emerged in the Canada but not in the Eurasian Basin. We suggest that the shift of the significant response region of phytoplankton in future climates is largely controlled by future sea ice distribution.

The comparison between observational and model data performed in the Method Section is a qualitative comparison, and it is not necessary to focus on the quantitative differences between these results. Actually, direct comparison with observation might not be possible in this case. As described in the Result Section, the phytoplankton response mainly occurred over the marginal sea-ice zone far from the freshwater source region. Therefore, our interpretation would still be valid even if different spatial patterns of river discharge were simulated by the model.

Previous studies have revealed that future phytoplankton can enhance the AA (e.g., Park et al., 2015). It has been suggested that phytoplankton blooming in early spring could enhance positive feedback by ice-albedo and biogeophysical feedback (Lim et al., 2019a). However, an increase in river discharge may weaken the effect of the biogeophysical feedback owing to a decrease in phytoplankton. Therefore, when performing the quantitative evaluation of the AA using phytoplankton in the Arctic Ocean or by prospecting Arctic ecosystems, we suggest that precise forcings of the freshwater input and more realistic response of sea ice are needed for the accurate simulation of phytoplankton growth. In this respect, it should be mentioned that the model used in this study is known to underestimate summer sea ice (Griffies et al., 2011). Therefore, careful interpretation is needed because our results indicate that phytoplankton response to the river discharge strongly depends on the distribution of sea ice concentration both in the present and future. Furthermore, Li et al. (2009) showed that an increase in river discharge does not lead to a change in total phytoplankton biomass but does lead to an increase in the small size of phytoplankton. Although TOPAZv2 assumes three different size distributions of phytoplankton, it only explicitly provides the total biomass of phytoplankton.

Note that the current state-of-art EMSs do not realistically capture the complex bio-geophysical feedback between the Arctic environment and ecosystem (Vancoppenolle et al., 2013; Tangliabue et al., 2021). Multi-model ensemble mean estimates of present and future climate simulation from CMIP6 are generally known to exhibit superior results compared to those from CMIP5. However, they exhibit even greater uncertainties with respect to many variables especially for the biogeochemistry category, i.e., biomass of phytoplankton (Tagliabue et al., 2021). Therefore, our results can be useful for improving future Arctic ecosystem response simulations.

Due to the expected permafrost thawing in the future, additional nutrients input by river discharge was considered in the future simulation of the Arctic environmental and ecosystem change (Fichot et al, 2013; Turetsky et al., 2019). An increase in river discharge nutrients may cause an increase in shelf break, which can also be found in observations from previous studies (Ardyna et al., 2017). Terhaar et al. (2021) considered nutrients not only from river water but also from coastal erosion. However, Wikner & Andersson (2012) showed that an increase in river discharge leads to a decrease in the phytoplankton biomass because of increased microbial production. This is mainly due to the negative effects of freshwater and total organic carbon discharge on phytoplankton growth, despite a concomitant increase in nitrogen and phosphorus discharge. The mechanisms by which nutrients affect additional river discharge become increasingly more complex. Therefore, future modeling studies should consider positive and negative effects using more sophisticated biogeochemical models and evaluate their impact.

Importantly, we did not consider the temperature of rivers due to global warming. Recent studies demonstrated that the river temperatures have been increasing globally (Liu et al., 2020). The temperatures of arctic rivers do not appear to rise remarkably, mostly because they consume heat energy for phase change. However, Park et al. (2020) suggested that an increase in river water temperature could cause positive feedback in the Arctic climate. In future research, we plan to quantify the sensitivity to the riverine heat with respect to studying the actual future climate.

We looked at the sensitivity of freshwater inflows only by river water. However, Brown et al. (2019) pointed out that an increase in precipitation may be more effective in Arctic Ocean desalination than an increase in river discharge. In addition, the Arctic Ocean may be further desalinated by Greenland glaciers, which were not considered in this study (Arrigo et al., 2017; Kwiatkowski et al., 2019). Notably, it will be of great importance to conduct additional research by combining several desalination processes in the Arctic Ocean, in addition to our current experiment.

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