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Phytoplankton responses to increasing Arctic river discharge under the present and future climate simulations

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Abstract

In recent decades, the unprecedented rate of Arctic warming has accelerated the high-latitude landmass hydrological cycle, leading to increased river discharge into the Arctic Ocean. This study elucidates the role of Arctic river discharge, which was the large model uncertainty in the Coupled Model Intercomparison Project 6, for the phytoplankton responses in present-day and future climate simulations by adding fresh water into the model. In the present-day climate simulation, additional river discharge decreases the spring phytoplankton biomass. Freshening of Arctic seawater facilitates freezing, increasing sea ice concentration in spring and eventually decreasing phytoplankton due to less availability of light. On the other hand, in the summer, phytoplankton increases due to the surplus of surface nitrate and the increase in the vertical mixing induced by the reduced summer sea ice melting water. In the future climate, the plankton response to the additional freshwater input is similar to the present-day climate. Nevertheless, the major phytoplankton responses are shifted from the Eurasian Basin to the Canada Basin and the East-Siberian Sea, mainly due to the marginal sea ice zone shift from the Barents-Kara Sea to the East Siberian-Chukchi Sea in the future.

1. Introduction

The Arctic has been warming at least four times faster than the global mean temperature since 1979 (Rantanen *et al* 2022), and this phenomenon is often called the Arctic amplification (AA). In association with the AA, the Arctic climate environment is rapidly changing in both atmosphere and ocean, such as atmosphere moistening (Min *et al* 2008), ecosystem environment changes (Ardyna and Arrigo 2020), marine acidification (Terhaar *et al* 2020), and atlantification (Polyakov *et al* 2017). The AA is also suggested to drive changes in the atmospheric circulation patterns in the midlatitude high-populated regions (Cohen *et al* 2014, Kim *et al* 2014, Kug *et al* 2015, Coumou *et al* 2018). Since future AA is projected to become stronger under future climate scenarios of Coupled Model Intercomparison Projects 5 and 6 (CMIP5, CMIP6), understanding the Arctic environment and ecosystem changes due to the current and future accelerating warming remains uncertain (Smith *et al* 2019, Hu *et al* 2021).

Recent studies suggested that the interactive feedback further enhances the AA with marine phytoplankton biomass (Park *et al* 2015, Lim *et al* 2019a, 2019b) and by the human-induced nitrogen fluxes from river discharge and atmospheric depositions to the Arctic in the future climate (Lim *et al* 2021). The reduction of sea ice extent and thickness allows more penetrations of shortwave radiation into the Arctic Ocean surface (Perovich *et al* 2007, Nicolaus *et al* 2012, Arrigo *et al* 2014) that triggers the earlier blooming 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 redistributes heat in ocean layers, modulating attenuation coefficients (Morel 1988, Manizza and Le Que 2005) that lead to the simulated AA (Park *et al* 2015, Lim *et al* 2019a, 2019b, 2021). This new mechanism to understand the possible positive feedback highlights the role of the Arctic ecosystem in air-sea-biogeochemical interactions, which have been 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 generally exhibited an increasing trend because of increased phytoplankton biomass. The future Arctic primary productivity in CMIP5 is subject to large uncertainty due to the subtle balance between sea ice loss (increasing the primary productivity) and stratification-induced nutrient depletion (decreasing the primary productivity) (Vancoppenolle *et al* 2013). However, Ardyna *et al* (2017) suggested that the shelf-break, serving as a 'green belt,' can effectively supply inorganic and organic materials to increase marine productivity in the stratified Arctic Ocean.

Arctic warming impacts various hydrologic cycles, such as sea ice melting, intensified precipitation (Min *et al* 2008), melting of land-based glaciers (Hugonnet *et al* 2021), and increased river discharge (Haine *et al* 2015). The increased freshwater entering the Arctic Ocean increases ocean stratification. Although the Arctic Ocean accounts for 1% of the global ocean volume, it receives more than 10% of the global river discharge (McClelland *et al* 2012). Long-term river discharge has been steadily increasing, particularly in 2020, with the total annual discharges of the eight largest Arctic rivers at 2623 km^3 12% greater than the 1981–2010 discharge average (Peterson *et al* 2002, Holmes *et al* 2021). River discharge under future climate conditions is projected to increase by more than 50% compared to the present, mainly in Alaska and Siberia regions (Bring *et al* 2017).

Many studies highlight the importance of Arctic Ocean freshwater content not only in the Arctic hydrological cycle but also in the biogeochemical and physical processes (Haine *et al* 2015, Carmack *et al* 2016, Fu *et al* 2020, Pnyushkov *et al* 2022). Despite these efforts, the Arctic hydrologic cycle process in the CMIP6 was hardly improved over CMIP5 (Khosravi *et al* 2022, Wang *et al* 2022). In particular, CMIP models tend to overestimate the sea surface salinity near the estuary, which can be influenced by the representation of river discharge (Shu *et al* 2018, Zanowski *et al* 2021).

Several recent observational studies have reported that Arctic river discharge modulates Arctic biogeochemistry by delivering dissolved organic matter and enhancing phytoplankton response (Holmes *et al* 2012, Fichot *et al* 2013, Tremblay *et al* 2014, Ardyna *et al* 2017, Terhaar *et al* 2021). However, it is difficult to analyze the impact of additional river discharge on the marine ecosystems of the Arctic Ocean in observational studies, and so far, studies using ESMs to clarify this 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 and Arrigo 2020).

In this study, we investigate the effect of additional river discharge on phytoplankton biomass using the ESM via the present-day and future climate simulation. Our model simulations suggest that Arctic river discharge can control sea ice and nutrient distribution, affecting phytoplankton growth. In addition, we analyzed the impact of increased river 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

In this study, we applied the Geophysical Fluid Dynamics Laboratory ESM 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). TOPAZv2 considers the cycle of carbon and nutrients such as nitrogen, phosphorus, silicon, and iron (Dunne *et al* 2013). 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) and supplementary.

We performed four experiments to analyze the changes in phytoplankton due to the additional river discharge in the present-day and future climate. The freshwater addition experiments were abbreviated as 'FWadd,' and the standard experiments were abbreviated as 'CTRL.' In addition, to distinguish between the present-day and future climate simulations, we used parentheses after each experimental abbreviation with uppercase P and F, respectively [e.g. CTRL(P) for present-day control experiment,

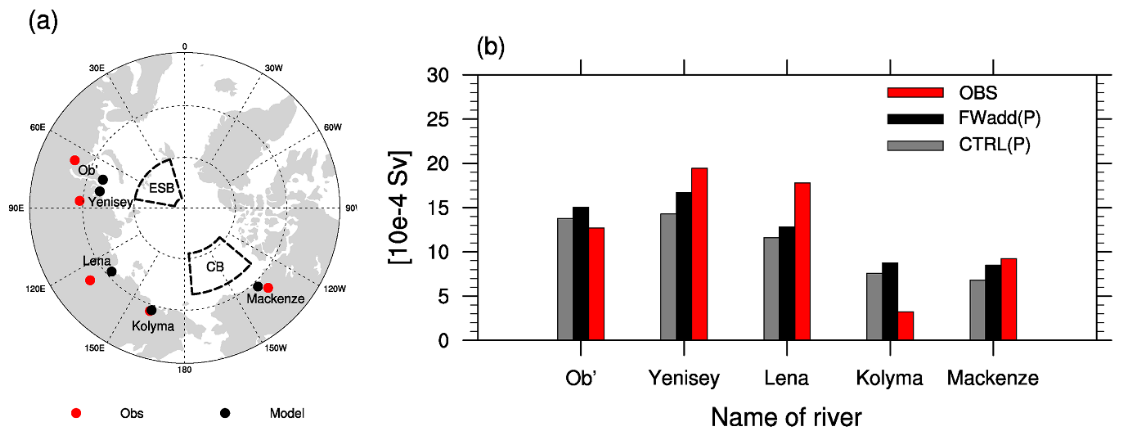

Figure 1. (a) River mouth of CTRL(P), (b) comparison of annual mean river discharge of CTRL(P), FWadd(P), and observation (Obs). In (a) the black dots are the simulated five largest river mouths of the models and the red dots are the site of observation (ArcticGRO). The dash lines are Eurasian Basin (ESB) and Canada Basin (CB), which are the major response areas for phytoplankton by additional river discharge. In (b) the model result is the sum of 9 model grids surrounding the black dots in (a).

FWadd(F) for the future freshwater addition experiment].

The present-day climate simulation was performed similarly to the 1990 level experiment, which is often used as the present-day experiment in previous studies using the CM2.1 model (Gnanadesikan *et al* 2006, Delworth *et al* 2012, Lim *et al* 2019a, 2019b). The present-day climate simulation is performed by prescribing greenhouse gases, including carbon dioxide, methane, nitrous oxide, among others, as well as organic nitrogen oxides and inorganic nitrogen oxides prescribed for rivers and the 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-day condition, similar to the CO_2 concentration level in 2100 for the middle of the road scenario in shared socioeconomic pathways (SSP2-4.5).

In FWadd experiment, we additionally supplied 0.03 Sv of total freshwater to the Arctic Ocean. The additional freshwater amount of 0.03 Sv is a value derived from the model uncertainties of CMIP5 and CMIP6 (Shu *et al* 2018, Wang *et al* 2022). As freshwater was forced into the FWadd experiment, surface salinity decreased and sea level rose, leading to a continuous increase in sea level as the experiment progressed (figure S1). Although the FWadd experiment was conducted for 100 years, the first 40 years were considered a spin-up period, and 71–100 years were excluded from the analysis due to sea level rise. Consequently, the study analyzed only the results from 41 to 70 years.

We used the observational river discharge data provided by Arctic Great River Observatory (ArcticGRO) to compare the estimations from the model output (Shiklomanov *et al* 2021). In this study, we compared data from the five major rivers, Ob′, Yenisey, Lena, Kolyma, and Mackenzie, that flow into the Arctic Ocean with model outputs. The river observation data analysis period averaged from 1981 to 2010 according to the present-day level. The position of the simulated river mouth was similar to the observation point (figure 1(a)). The simulated river discharge in the model was within a relatively acceptable range except for Kolyma (figure 1(b)).

3. Results

3.1. Impact of river discharge in present-day climate simulation

In the present-day climate simulation, the dominant response to the additional river discharge in spring (April-May) is a decrease in phytoplankton, except for the Laptev and East-Siberian coastal region, where a large amount of freshwater input and nutrients are supplied (figure 2(a)). Within the time span of the spring season, the afore-mentioned phytoplankton response is amplified throughout the season and, therefore, the feature is more salient in May (figure S2). Note that most negative chlorophyll concentration (CHL) anomaly patterns in spring appeared over the marginal ice zone (MIZ) (figure 3(a)).

There are a couple of mechanisms for the sea ice increase over the MIZ by additional river discharge. Firstly, the additional freshwater content throughout the Arctic Ocean increases sea ice by lowering surface salinity (Hellmer 2004, Bintanja *et al* 2013) which has a higher freezing point, allowing for better sea ice formation. Secondly, the Arctic basin's increased sea surface height (SSH) due to the supplied water mass may help the ice formation (figure S3). Additional river discharge weakens the SSH gradient, preventing hot and salty seawater inflow outside the Arctic Ocean. These results are consistent with other model experiments

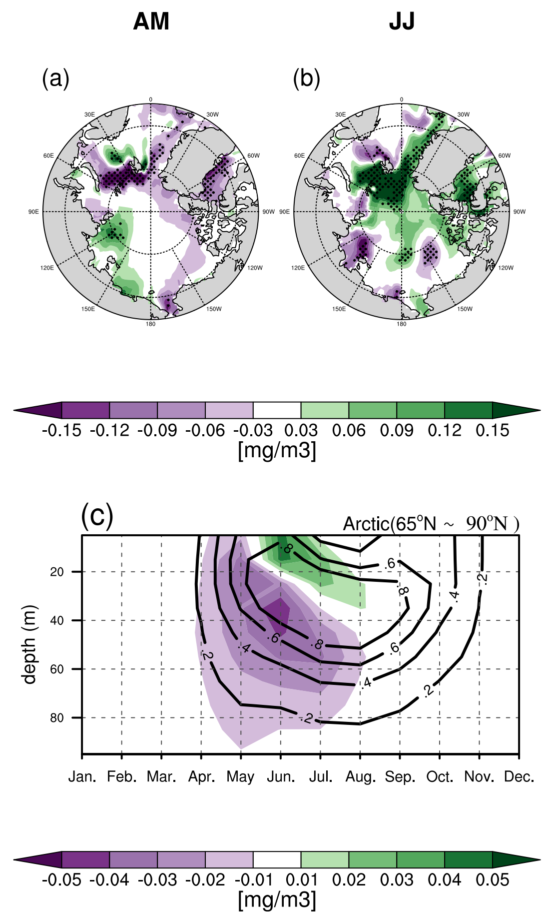

Figure 2. Chlorophyll concentration in the present-day climate simulation for (a) spring (April–May) and (b) summer (June–July) on the upper ocean (0–20 m). The shaded area indicates the difference between FWadd(P) and CTRL(P) of chlorophyll concentration. Black dots represent significant values of chlorophyll concentration at the 95% confidence level; (c) Vertical structure of monthly climatologies in the present-day (CTRL(P); contour) and the difference between FWadd(P) and CTRL(P) (shading) of the simulated chlorophyll in the Arctic Ocean (area averaged in latitude: 65° N–90° N, longitude: 180° E–180° W).

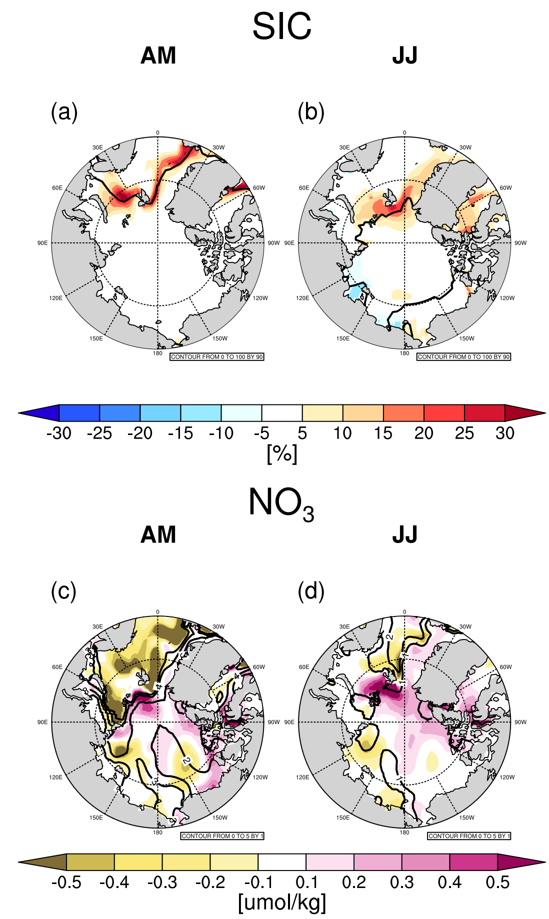

Figure 3. Difference of sea ice concentration (SIC) (shaded) and the averaged sea ice extent (SIC > 15%) on CTRL(P) (contour) between FWadd(P) and CTRL(P) of (a) spring and (b) summer. And, the difference of nitrate(NO_3) (shaded) between FWadd(P) and CTRL(P) and the averaged NO_3 on CTRL(P) (contour) of spring (c) and (d) summer.

that examined additional river discharge in the Arctic Ocean (Nummelin *et al* 2016). The increased sea ice caused by the additional river discharge blocked more sunlight, limiting phytoplankton's growth.

During the summer, additional river discharge played the opposite role, increasing the phytoplankton, especially over Eurasian Basin (figure 2(b)). We refer to the Eurasian Basin, where the spring and summer anomaly pattern changes are most significant, as a 'hotspot' for phytoplankton in the dominant response region to river forcing. Compared to June, the CHL anomaly pattern in July was weaker and moved towards the center of the Arctic Ocean as the sea ice moved toward the center of the Arctic Ocean (figure S2).

In general, the explosive growth of phytoplankton which is so called as a 'chlorophyll bloom,' is observed in spring where sea ice melts significantly. The increased chlorophyll consumes nitrate, which is a major nutrient in the Arctic Ocean, and leads to the nitrate depletion in the following summer (Lim *et al* 2019b). However, FWadd experiment exhibited poor spring phytoplankton growth and this, in turn, increased available nitrate in the phytoplankton hotspot in summer significantly (figure 3(d)). Therefore, increased sea ice concentration due to the additional fresh water delayed the chlorophyll bloom timing (figure 2(c)). The upper ocean chlorophyll bloom in summer by following better conditions of having both solar input from surface and nitrate consumption in FWadd above 20 m. At the subsurface, it is stratified by additional discharge, and sunlight is absorbed by the upper chlrophyll bloom (figure S4). So, subsurface CHL below 30 m depth has been decreased.

Another reason for summer nitrate increases could be increased sea ice (figure 3(b)). Sufficient summer light and shallow sea ice do not limit the light required for phytoplankton growth. Although the mixed layer becomes shallow due to the stratification effect of river water inflow, the effect is insignificant in summer (figure 4; no figure in autumn and winter).

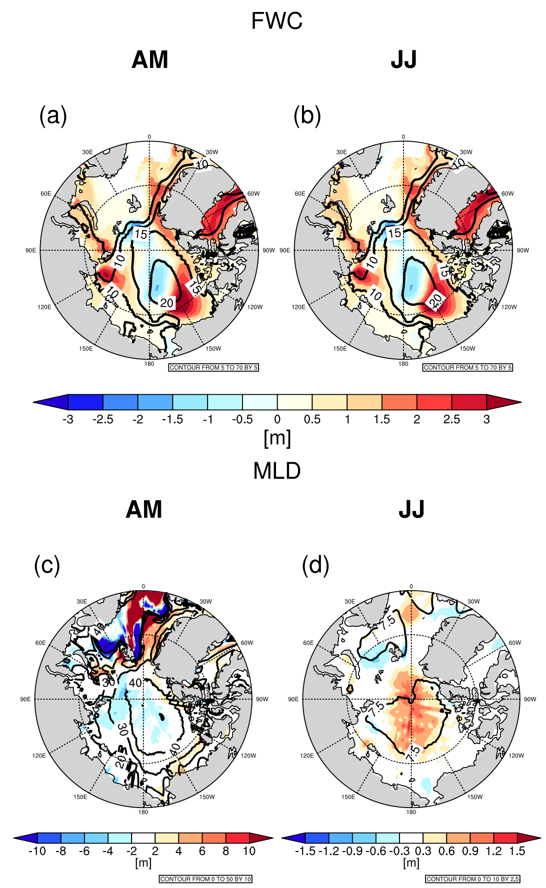

Figure 4. Difference between FWadd(P) and CTRL(P) for (a) spring and (b) summer freshwater content (FWC) (shaded) and averaged FWC on CTRL(P) (contour), (c) spring and (d) summer mixed layer depth (MLD). The FWC was calculated using the following integral with a reference salinity (S_{ref}) of 34.8 psu. $S(z)$ is the salinity of z. $\text{FWC} = \int_z^0 \frac{S_{\text{ref}} - S(z)}{S_{\text{ref}}}\,\text{dz}$.

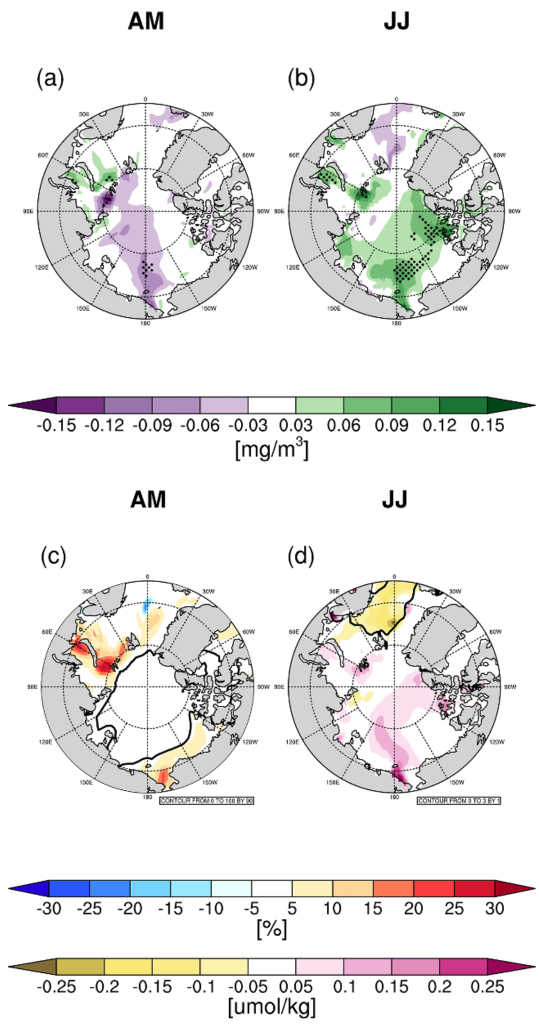

Figure 5. Differences between the FWadd(F) and CTRL(F) of the simulated (a) spring chlorophyll, (b) summer chlorophyll, (c) spring sea ice concentration, and (d) summer nitrate. In (a) and (b), black dots represent significant values of chlorophyll concentration at the 95% confidence level. The climatologies in the CTRL(F) of (c) sea ice extent (SIC > 15%) and (d) nitrate (Contour).

This is because the freshwater inflow from sea ice melting in summer is much larger than from river discharge (Peralta-Ferriz and Woodgate 2015, Hordoir *et al* 2022). Because of the mixed layer characteristics in summer, the decrease in sea ice melting water can causes vertical mixing with the deep ocean, increases nutrients, and may affect phytoplankton growth. As a result, the phytoplankton hotspot is formed due to a significant increase in nutrients due to surplus nutrients in spring and reduced sea ice melting effect in summer.

3.2. Impact of river discharge in future

In the previous subsection, we analyzed the effects of additional river discharge on phytoplankton in the present-day climate. This subsection analyzes the impact of additional river discharge on phytoplankton under the future climate simulation. In the future climate simulation, the dominant response of phytoplankton to additional river discharge was a decrease in spring and an increase in summer, similar to the present-day climate simulation. However, in contrast to the increase in phytoplankton mainly in the Eurasian Basin in the present-day climate, in the future climate, phytoplankton was extended to the Canada Basin.

The future Arctic Ocean is expected to become more stratified than present-day climate conditions by melting ice and strengthening the hydrological cycle (Haine *et al* 2015). Most models project that, in the future, surface nitrate will decrease due to the stratification of the Arctic Ocean (Vancoppenolle *et al* 2013). The CTRL(F) results are consistent with the previous studies mentioned above: a significant decrease in surface nitrate and phytoplankton was simulated compared with the CTRL(P).

In the future climate simulation, the increase in river discharge resulted in a decrease in spring phytoplankton (figure 5(a)). As in the present-day simulation results, the phytoplankton is decreased by increased sea ice in the future simulations. However, compared with the results of the present-day climate simulations, negative CHL anomaly patterns appeared in the Kara and Chukchi Seas, which are generally close to the interior of the Arctic Ocean. Because the sea ice extent was significantly reduced in the future compared to the present-day 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-day climate simulation.

As in the simulation of the present-day climate, an increase in river discharge led to an increase in summer phytoplankton. A wider reaction was shown in the Canada Basin than in the Eurasian Basin (figure 5(b)). The positive anomaly in the Eurasian Basin, Canada Basin, and East-Siberian-Chukchi Sea is the primary CHL anomaly pattern in June (figure S6). However, the positive anomaly in the Eurasian Basin was narrow, and the anomaly in the Canada Basin was wide (figure S6). In July, the anomaly intensity weakened, and the pattern shifted toward the center of the Arctic Ocean, compared to June.

Unlike the present-day climate simulation, summer nutrient changes due to additional river discharge were only related to a spring phytoplankton bloom. The nitrate positive anomaly pattern in summer was similar to the CHL negative anomaly pattern in spring, showing the same mechanism as the present-day climate simulation (figure 5(d)). 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. However, the increased positive CHL anomaly caused by summer ice is weakened in future simulations (figure S7). It is because the future mixed layer is shallow, the melting of much sea ice in May. Therefore, the mechanism of increased ice-induced vertical mixing will occur in May instead of in June. However, the impact of nutrients is small as May is still the period when light limitations dominate.

The summer hotspots shift the seasonal evolution of the MIZ from May to June is remarkably different in the present-day and future. In the present-day 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 future climate in the Beaufort and East Siberian-Chukchi sea. These results suggest that future sea ice distribution changes may shift summer phytoplankton hotspots.

4. Summary and discussion

We studied how the increase in Arctic river discharge, which was the large model uncertainty in most CMIP6 models, affects spring and summer phytoplankton in the present-day and future climates. In the present-day climate simulation, additional river discharge in spring decreased phytoplankton near the Eurasian Basin due to the block of light by the increased sea ice. In summer, additional river discharge increased phytoplankton, mainly in the Eurasian Basin, by the nutrients not consumed in the spring and the increased mixed layer depth due to reduced sea ice melting water. In the future climate simulation, similar to the present-day climate simulation, phytoplankton decreases in spring and increases in summer. However, major phytoplankton variability occurs in the Canada Basin, not in the Eurasian Basin. We suggest that the shift of the significant response region of phytoplankton in future climates is due to the shift of the MIZ in the future.

It should be noted, when interpreting our results, that the model used in this study, GFDL-CM2.1-TOPAZ, overestimates the river volume of 0.1 Sv (CTRL(P), 0.14 Sv). It is also useful to consider that the additional river forcing of 0.03 Sv is weaker than the additional forcing due to global warming (figure S8).

In the comparison with the observed data (figure 1(b)), careful interpretation is needed. Note that the observed data in figure 1(b) are from the upper layer of the river observed at specific river mouth. However, model data comes from gridded averaged values.

Previous studies have revealed that future phytoplankton could enhance the AA (Park *et al* 2015). It has been suggested that phytoplankton blooming in early spring could enhance AA by melting sea ice, transferring more ocean heat to the atmosphere, and reducing Arctic Ocean albedo (Lim *et al* 2019a, 2019b). However, as shown in our study, an increase in river discharge may weaken the effect of biogeophysical feedback owing to a decrease in phytoplankton. Therefore, when quantitatively analyzing the effects of biogeophysical processes on Arctic warming, we suggest that both precise forcings of the freshwater input and more realistic sea ice response ice are needed. In this regard, 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 sensitively depends on the distribution of sea ice concentration both in the present and future.

Note that we still do not have a state-of-art ESM that realistically captures the complex biogeophysical feedback between the Arctic environment and ecosystem (Vancoppenolle *et al* 2013, Tagliabue *et al* 2021). Although it may vary for specific regions and variables, the multi-model ensemble mean of typical historical run is reported to be better for CMIP6 than CMIP5 (Davy and Outten 2020, Thorarinsdottir *et al* 2020). However, it exhibits even greater uncertainty in many variables, especially in the biogeochemistry category, such as phytoplankton biomass (Tagliabue *et al* 2021). The physical understanding gained in this study, therefore, can be useful for developing a better simulation of complex interactions among physical, hydrological, and biological processes in the Arctic.

Due to the expected permafrost thawing in the future, additional nutrients input by river discharge has to consider in the future simulation of Arctic environmental and ecosystem change (Fichot *et al* 2013, Turetsky *et al* 2019, Terhaar *et al* 2021). Although the Arctic Ocean is expected to become more stratified, an increase in river discharge and riverine nutrients may increase the phytoplankton in the shelf break (Ardyna *et al* 2017). The mechanisms of nutrients for the additional river discharge become more and more complex. Therefore, future modeling studies should consider the positive and negative effects of river discharge and riverine nutrients using more sophisticated biogeochemical models and evaluate their impact.

In this study, we do not consider the temperature of rivers due to global warming. In recent years, the temperature of rivers has been increasing globally (Liu *et al* 2020). Park *et al* (2020) suggested that increasing river water temperature could cause positive feedback in the Arctic climate. In future research, we plan to quantify the sensitivity to the riverine heat.

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, desalination due to Greenland glacial dynamics, which is not considered in this study, may also affect phytoplankton (Arrigo *et al* 2017, Kwiatkowski *et al* 2019). It will be more valuable if additional research is conducted by combining several desalination processes in the Arctic Ocean, which was not considered in our experiment.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

Acknowledgments

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