Responses to Reviewer 1:

Minor comments:

L120-125 It would be useful to also detail how sea-ice influences light limitation in the model. Is NPP permissible under sea ice? If so, does this depend on thickness, snow cover etc?

- Thank you for your comment. Yes, NPP occurs below sea ice in the water column. In the model, sea ice thickness determines the light entering the surface layer below the ice. Our model used the approach developed by Long et al. (2015). The model does not use the grid-cell mean irradiance to compute phytoplankton light limitation terms. Instead, it computes light limitation across different categories of ice thickness present within a grid cell, then averages the limitation terms across the grid cell. This approach acknowledges that light penetration varies significantly with the thickness of the sea ice, providing a more nuanced and accurate representation of light availability under the ice.
- In the revised manuscript, we added the following text (L127-L130): "Considerable spatial heterogeneity exists in sea ice thickness, which affects light available for phytoplankton growth below sea ice. Following the approach of Long et al (2015), our model calculates phytoplankton growth limitation terms for the distribution of sea ice thicknesses present within the model grid cell, and then averages these values over the grid cell to estimate the average light limitation in the grid cell."

L161-163. I don't understand this. Do the authors mean that atmospheric greenhouse gas concentrations are held constant in these simulations so the impact of acidification for example is not simulated? The prescribed CORE-II fluxes (e.g. heat and freshwater fluxes) are presumably affected by anthropogenic climate change. Or have these forcings been modified in some way?

- Thank you for your comment. The COREv2 dataset encompasses a comprehensive set of air-sea fluxes, including momentum, heat, and freshwater, spanning from 1948 to 2009 at monthly resolution. The historical climate signal is indeed embedded within the atmospheric reanalysis data and satellite-derived flux measurements used to force the model. However, because the seasonal-to-interannual variability in the CORE-II forcing is large compared with the longer-term climate signal, we considered that our simulations are more appropriate for studying seasonal to interannual variations. Therefore, we focused on the seasonal and interannual changes in light, temperature, and nutrients. In the revised manuscript, we removed the confusing sentence "It is not a simulation forced by increasing greenhouse gas emissions, and as such, our analyses focus on seasonal to interannual rather than decadal-to-centennial changes forced by anthropogenic greenhouse gas emissions." and replaced it with, (L167-L169): "Though the CORE-II forcing captures the historical climate signal, we instead focus on seasonal-to-interannual variability because it is the larger signal compared to climate change during this time period."

L202 Is NO3 the only limiting nutrient in the Arctic domain or the only nutrient that is assessed?

- The model simulates transformation and transport of nitrogen, phosphorus, iron, and silicate. We identified the most limiting nutrient for each phytoplankton type (following Leibig's Law of the Minimum (Equation 2 shown below)) and used this information to compare nutrient limitation with limitations imposed by light and temperature (as shown in Figure 5 of our manuscript). In the Arctic Ocean model, nitrate was the predominant limiting nutrient for phytoplankton growth in most places and times (see figure below), consistent with other modeling studies (Manizza et al. 2023). Because of this, we elected to focus primarily on nitrate.
  Equation 2: ${\gamma_i}^N = min(N_{N,i}^{lim}, \; N_{P,i}^{lim}, N_{Fe,i}^{lim}, N_{Si,i}^{lim})$
- In the revised manuscript, we added a supplemental figure showing that nitrate is the most widely limiting nutrient in this region across all groups of phytoplankton (see figure below). This figure also shows that iron limitation is important in summer in the subpolar portions of the North Atlantic Ocean. Additionally, we updated the description in Figure 5 to include "Nitrate was the most limiting nutrient for phytoplankton growth for most regions and seasons (Supp. Fig. S2)."

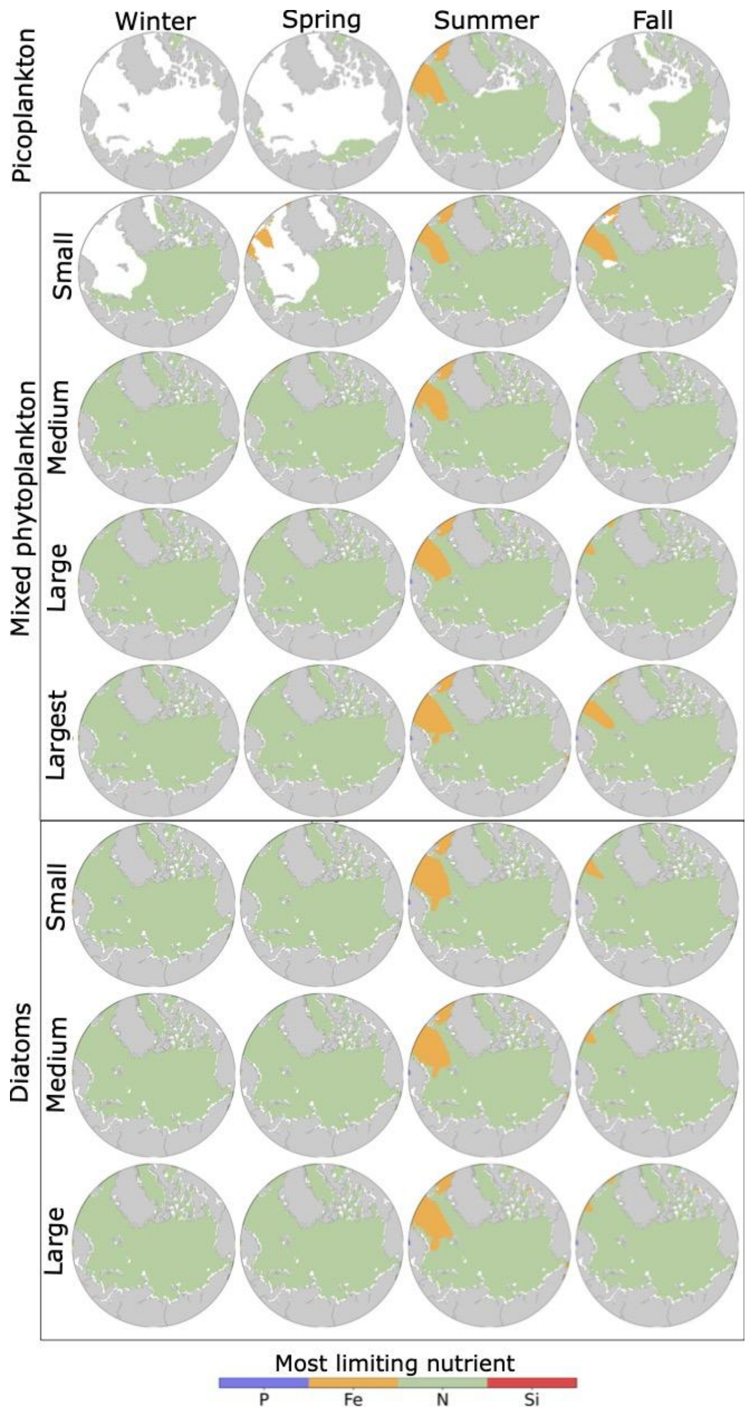

Figure S2. Most limiting nutrient for each phytoplankton group in the Arctic Ocean. The most limiting nutrients (Phosphate (purple), Iron (yellow), Nitrate (green), and Silica (red)) for each phytoplankton type were averaged over the three months in each season, averaged over 1990-2009. White regions represent areas where no nutrient is limiting. Silica was only considered for diatoms.

L270-272. It is difficult to reconcile this text with what I can interpret from Figure 3. Few if any of the subregions seem to exhibit peaks in observed and simulated chlorophyll in the same month. In the East Siberian Sea, Chukchi Sea and Beaufort Sea the simulated peak appears to be 2-3 months later.

- In response to your comment as well as similar concerns from Reviewers 2 and 3, we have modified the satellite and model Chl comparisons, and now use a satellite ocean color algorithm to estimate chlorophyll tailored for the Arctic Ocean developed by Lewis and Arrigo (2020; https://doi.org/10.1029/2019JC015706). The Lewis and Arrigo approach uses a large bio-optical database from the Arctic Ocean to generate estimates of chlorophyll specific to the Arctic Ocean. We have recreated Figures 2 and 3 with this satellite chlorophyll estimate.

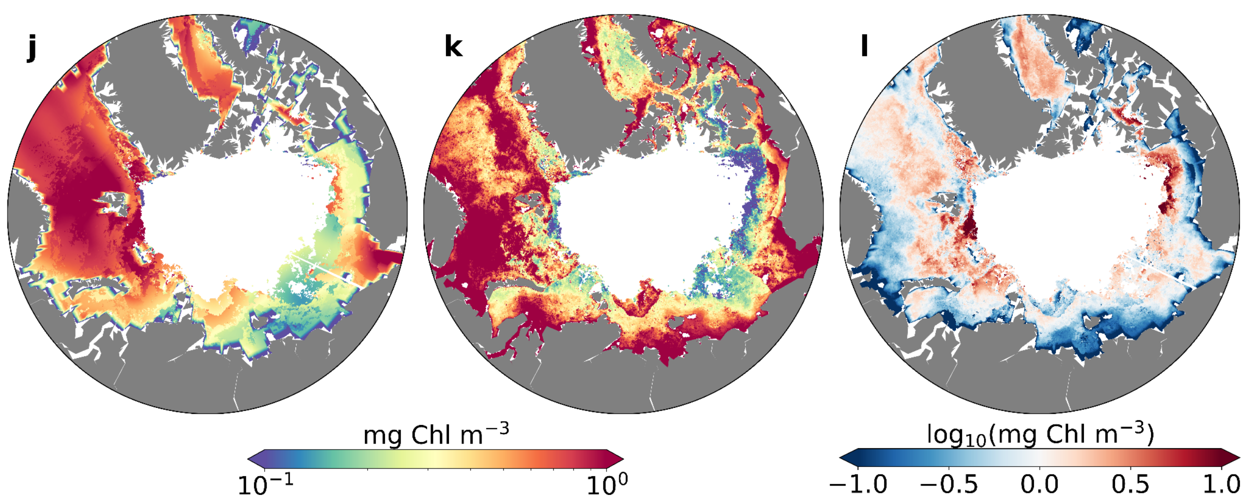

Figure 2 (*just the chlorophyll portion*). Annual average model (j) and satellite (k) surface chlorophyll, and difference between model minus satellite (log_{10} mg Chl m^{-3}).

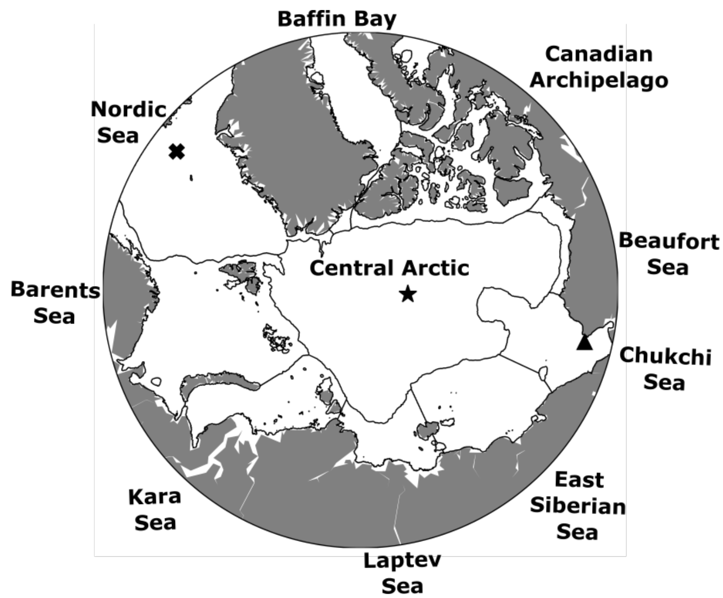

Figure 1. Map of the Arctic Ocean divided into ten sections included in the analysis, following Lewis & Arrigo (2020) regional mask. Additionally, symbols represent three grid cells selected throughout the Arctic Ocean for growth limitation analysis. The cross symbol shows the Western Nordic Seas (*68.5*^{o}N, *348*^{o}E), the star symbol shows the central Arctic Ocean location (*85.5*^{o}N, *200*^{o}E), and the triangle symbol shows the Chukchi Sea location (*68.5*^{o}N, *168*^{o}W).

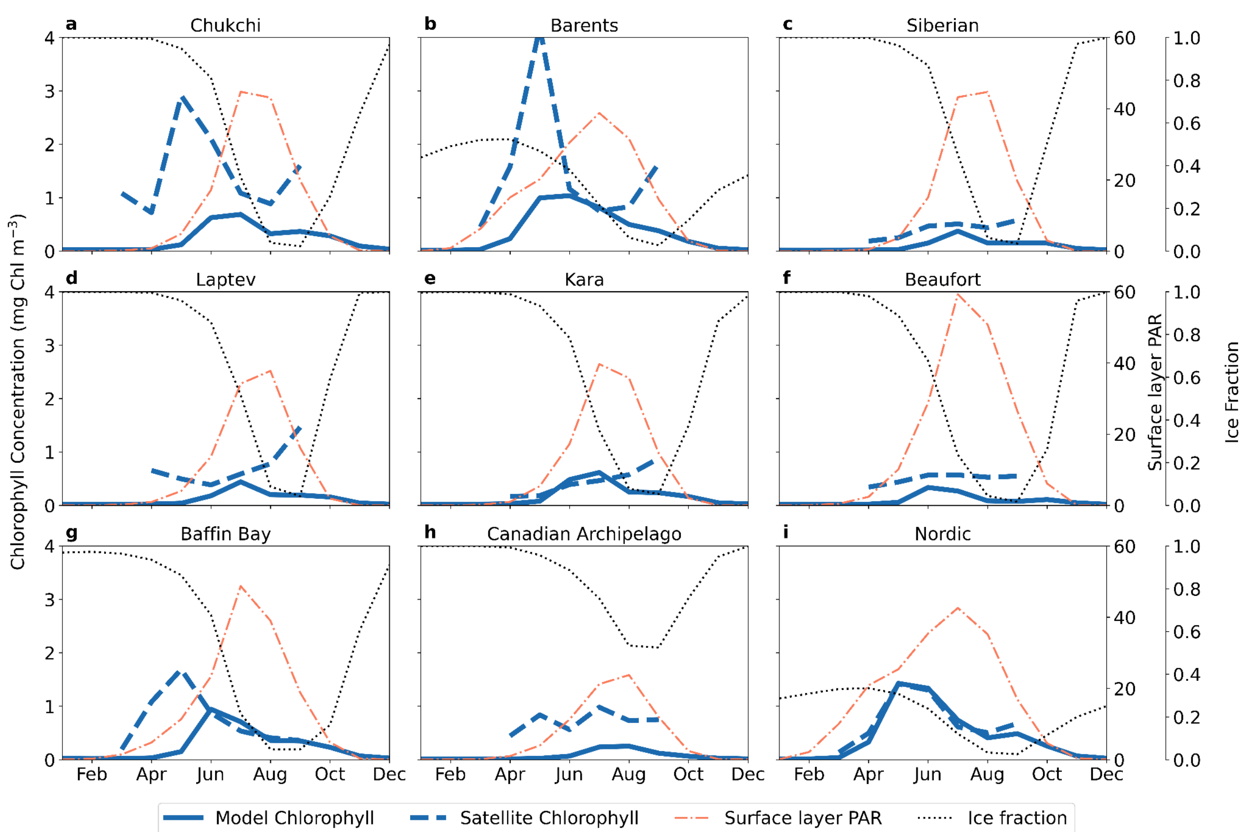

Figure 3. Modeled and satellite estimates of seasonal variability in surface chlorophyll. The solid blue lines depict the modeled monthly-averaged chlorophyll at the surface layer (10 m), while the dashed blue lines represent the satellite-derived (Lewis & Arrigo 2020) surface chlorophyll. Additionally, the black line shows modeled monthly-averaged ice fraction, and the thin red line represents the average photosynthetically active radiation (PAR) over the surface layer (10 m) (W m^{-2}). Seasonal cycles are displayed for nine different regions: the Chukchi Sea (a), Barents Sea (b), Siberian Sea (c), Laptev Sea (d), Kara Sea (e), Beaufort Sea (f), Baffin Bay (g), Canadian Archipelago (h), and Nordic Sea (i).

- We have also modified the text as follows:
- L260-L264: "MARBL-SPECTRA generally underestimated surface chlorophyll along coastal waters above the Russian continental shelves compared to satellite-based chlorophyll estimates using an ocean color algorithm tailored for the Arctic Ocean developed by Lewis et al. 2020 (Fig. 2l). This underestimation can be attributed to inaccuracies of the satellite estimates from the atmospheric correction scheme, sensor calibration, or bio-optical algorithms, which were not optimized to account for the presence of colored dissolved organic matter (CDOM) in coastal waters (Siegel et al.,2013, 2002; Mustapha et al. 2012)."

- L273- 277: "Comparison between satellite and model chlorophyll is difficult due to known challenges of remote sensing in the Arctic Ocean, including but not limited to clouds, sea ice, and organic matter in the water column (Li et al. 2024, Gregg and Casey, 2007, Mikelsons and Wang, 2019). However, we further assessed the performance of MARBL-SPECTRA by comparing the seasonality of surface chlorophyll in different regions of the Arctic Ocean with satellite chlorophyll estimates tailored to the Arctic Ocean (Lewis and Arrigo, 2020) (Fig. 3).
- L279-L290: "With the exception of the Chukchi (Fig 3a) and Barents Seas (Fig 3b), model and satellite chlorophyll magnitudes were qualitatively similar. The satellite and model seasonal phenology of chlorophyll were similar in some regions (e.g., the Nordic Sea (Fig. 3i)) but shifted in others (e.g., Baffin Bay (Fig. 3g), Barents Sea (Fig. 3b))) due to temporal discrepancies between model and remotely sensed Arctic Ocean in timing of sea ice retreat. MARBL-SPECTRA simulated a summer peak in chlorophyll during July in the Siberian (Fig.3c), Laptev (Fig. 3d), Kara (Fig. 3e) Seas and Canadian Archipelago (Fig. 3h), coinciding with the highest average photosynthetically active radiation (PAR) over the surface layer and a rapid decrease in sea ice fraction. In the Barents Sea (Fig. 3b) and Baffin Bay (Fig. 3g), MARBL-SPECTRA simulated a peak in chlorophyll concentrations of lower magnitude than the satellite estimate, and with a month delay. Comparing the Central Arctic region with satellite-based estimates was challenging due to the limited chlorophyll information available, as this area remains mostly covered by ice throughout the year."

While in the Barents Sea the seasonal cycles of observed and simulated chlorophyll almost appear to be anticorrelated. What explains the winter peak in observed chlorophyll in the Barents Sea? Presumably there is insufficient light availability to sustain this? Is this an artifact of variable observational coverage? In which case it might be best to only do pairwise comparisons of models and obs.

- In our updated comparison between model chlorophyll and satellite chlorophyll, estimated using an algorithm tailored to the Arctic Ocean (Lewis and Arrigo, 2020), we observe that the previously noted peak in chlorophyll during the winter months in the Barents Sea is no longer present. This suggests that the peak may have been due to biases in the earlier satellite product we used.

Figure 5. I'm surprised that in the Central Arctic light limitation isn't more extensive in summer. It would be useful to add an evaluation of simulated sea ice extent/thickness. Maybe in Figure 2. Overestimation of seasonal sea ice variability might help explain this and as the authors mention in their discussion, this is an issue that has been previously identified with CORE-II forced simulations.

- Figure 5 shows the most limiting factor. This does not mean that phytoplankton growth in the Central Arctic isn't inhibited by light, only that nutrient limitation is stronger. However, we appreciate your suggestion to include model data on sea ice fraction, and have included it in the revised manuscript.

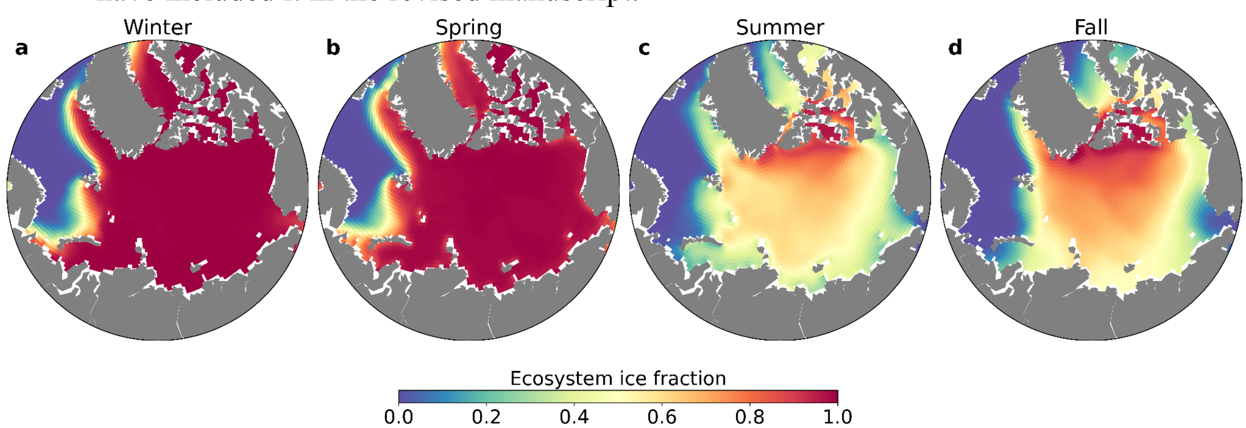

Figure S1. Ecosystem ice fraction in winter (a, December-February), spring (b; March-May), summer (c; June-August), and fall (d; September-November), averaged over 1990-2009.

L365 does "added" just mean simulated here?

- Thank you for catching that, yes, we meant that larger phytoplankton were increased seasonally in simulations and modified the text to say "simulated to increase".

Figure 8 is quite difficult to interpret. I suggest avoiding the repetition of labels to allow you to increase the figure size. Why does summer sea ice not appear to be declining? Is this a shortcoming of the simulation setup as mentioned in line 478?

- Thank you for your comment. We updated Figure 8 by removing some of the yearly labels and making the y axes on the time series plots consistent so that it provides more clarity.

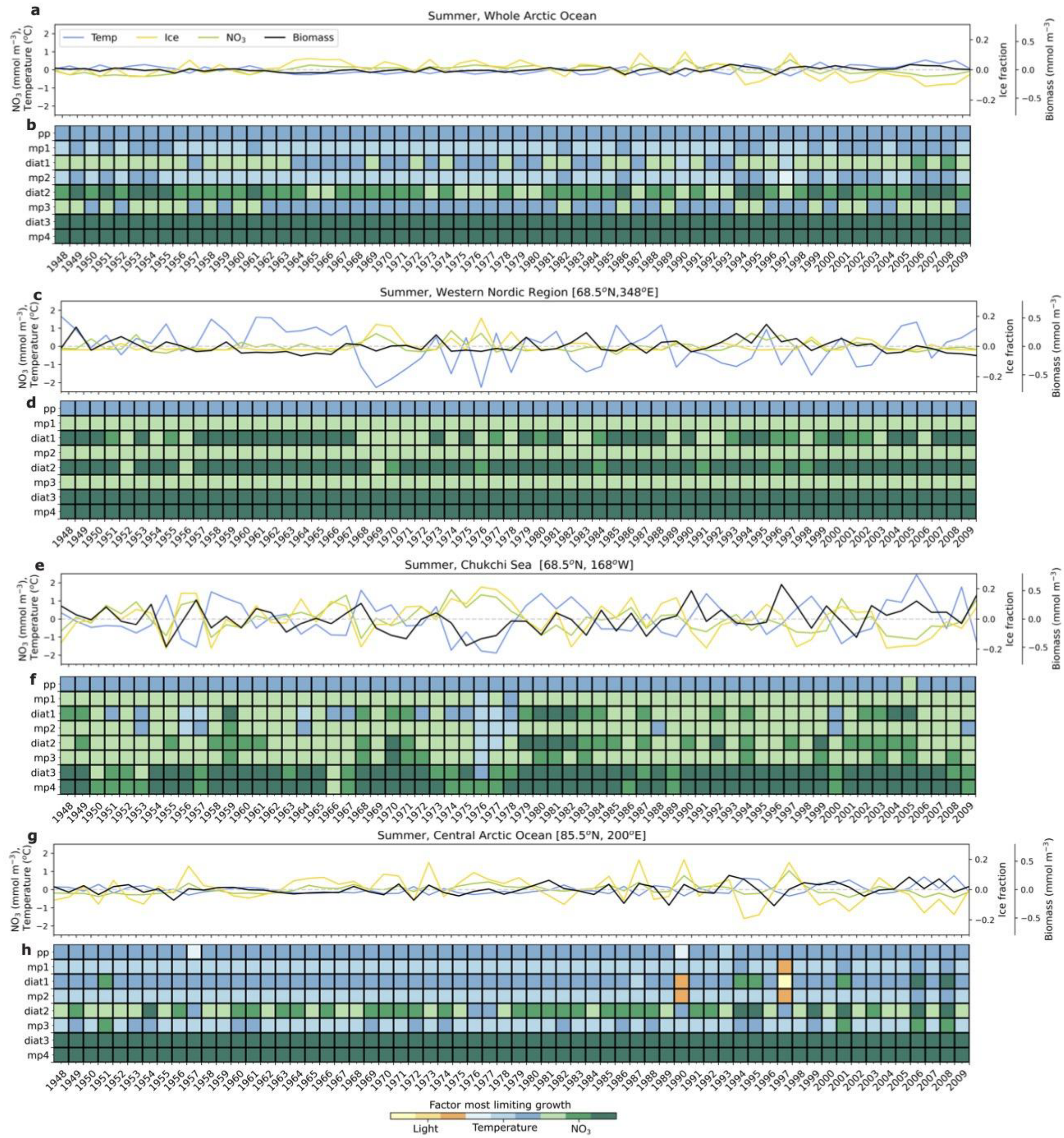

Figure 8. Summer anomalies from 1948-2009 in total phytoplankton biomass (mmol C m^{-3}; black line), nitrate (mmol N m^{-3}; green line), temperature (^{o}C; blue line), and sea ice fraction (yellow line) for the whole Arctic Ocean (a), and locations along the Western Nordic Seas [68.5^{o}N, 348^{o}E] (c), Chukchi Sea [68.5^{o}N, 168^{o}W] (e), and central Arctic

Ocean [85.5oN, 200oE] (g). Anomalies were calculated relative to monthly averages of the 62 year (1948-2009) climatology. Phytoplankton growth limitation in summer is shown for each zone in b, d, f, h. The colors in b, d, f, and h indicate the factor that is most limiting (temperature=blue, light=yellow, nitrate=green), where darker shades of each color represent greater limitation. Nutrient and light limitation terms were computed as biomass-weighted vertical averages of the top 100m. Temperature limitations were estimated using activation energy values for each phytoplankton type.

- The hindcast simulation showed modest reductions in sea ice extent, but these changes were not uniform across all specific regions and time periods. This is a known discrepancy with Arctic CORE-II forced models (Wang et al. 2016a, 2016b). This model limitation is why our analysis emphasized seasonal and interannual variability rather than focusing solely on a long-term decline in sea ice and associated changes in the plankton.

L433-437 It's not entirely clear to me why these regions are behaving differently. Can the authors expand a little here? Under diminished NO3 one would typically expect fewer large phytoplankton. Why is this not occurring in the Nordic Seas?

- Thank you, we have incorporated a more detailed description in this section to explain this behavior. This region in the western Nordic Sea is typically light-limited throughout the year. Therefore, reductions in ice cover decrease light limitation, allowing larger phytoplankton to utilize available nutrient resources more effectively. The observed decrease in nutrients may be due to an earlier phytoplankton bloom, which depletes nutrient concentrations earlier in the season. This pattern results in lower nutrient levels when averaged over the entire season.
- We will modify the text to how say:

  L454-L468: "Two distinct mechanisms of trophic change were evident in our analysis. In the central Arctic, the increase in zooplankton mean trophic level during years of elevated temperature, reduced ice fraction, and diminished NO_3 was caused by the earlier onset of phytoplankton and microzooplankton blooms, prompting mesozooplankton to graze on microzooplankton earlier in the year (Supp. Fig. S7). In contrast, during fall and winter, the inflow regions of the western Nordic Seas exhibited lower zooplankton mean trophic levels in years with higher temperatures and reduced ice coverage. These conditions were associated with overall declines in phytoplankton biomass (Supp. Figs. S3-S4), particularly among smaller phytoplankton (Supp. Fig. S6). This reduction in smaller phytoplankton led to a decline in microzooplankton, resulting in less grazing by mesozooplankton on microzooplankton. In the western Nordic Seas, the decreased phytoplankton biomass in fall and winter may have resulted from a chain reaction triggered by a strong phytoplankton bloom earlier in the season (e.g., spring, Supp. Figs. S3-S4), which quickly depleted available nutrients. In this typically light-limited region, reduced ice cover alleviated light limitation, allowing larger phytoplankton to utilize nutrients more effectively, leading to overall lower nutrient levels throughout the season.

These results align with observed regional differences in plankton dynamics throughout the Arctic due to earlier annual ice retreats and increased light availability (Song et al. 2021). They also emphasize how planktonic organisms exhibit varied responses to the same environmental changes, consistent with previous studies investigating the impacts of warming across trophic levels and functional groups within an ecological community (Edwards et al. 2004)."

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