INTERANNUAL VARIABILITY IN PRIMARY PRODUCTION IN THE ARCTIC USING EC-EARTH CLIMATE MODEL

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Index

Abstract

Generally, the climate is not stable. Superimposed on long-term trends are short-term climate variations. Climate variability is the result of natural fluctuations that take place on various time-scales and can amplify or obscure trends in climate change. Similar patterns of variability can be found in algae concentration in the Arctic, but the drivers of this variability have yet to be determined. Changes in climate can influence this algae variability, so to examine the variability in primary production, long-term datasets are needed that do not exhibit long-term trends. Because long-term and complete observational records do not exist, the Earth System Model (ESM) EC-Earth was used. Using this model, a dataset of climate and ocean biochemistry using a pre-industrial climate with constant forcing was generated. Following the results of earlier research, the focus of the analysis was mainly on the interaction between sea ice cover (proxy for light availability), planktonic primary production and nitrate concentration. Based on the results of the pre-industrial model simulation, the extent of the sea ice cover, and hence light availability, was the main factor limiting the growth of algae. This suggests that sea ice is the most likely climate variable driving the variability in planktonic primary production. However, over the last few decades, sea ice in the Arctic region has reduced both in surface area and in thickness. The expectation is that this trend will continue in the future. Therefore, we anticipate that in the future the variability of algae in the Arctic may be affected more by nutrient availability. However, our finding that the strength of the interactions between primary production and the different abiotic factors strongly varied with the season, geographic location and depth, may complicate this conclusion.

Introduction

Since the mid-1990’s the Arctic is warming twice as fast as other regions in the world, which has resulted in a decline of Arctic sea ice. The last few decennia sea ice in the Arctic region has reduced both in surface area and in thickness. The summer months show the fastest rate of decline in sea ice extent, with the highest rate in September (-13.0% decade $^{-1}$, -2.7% decade $^{-1}$ in March). The reduction in sea ice thickness is mostly the result of the loss of older and thicker multiyear ice: 75% of sea ice cover consisted of multiyear ice in 1985 in comparison to just 30% in 2017 (Serreze and Meier, 2019). This thinner sea ice is also more vulnerable to breaking and earlier onset of seasonal melting, which results in enhanced light availability in the waters below the ice (Moline *et al.*, 2008). Between 1979 and 2013, the melting season in the Arctic has increased by 5 days per decade and a onset of the seasonal melt ~2 days earlier each decade (Stroeve *et al.*, 2014).

Primary Production
Microalgae growth in the Arctic is strongly connected to the presence of sea ice. The presence of sea ice determines light availability, while nutrients (NO_3, Fe and Si) determine if algae can grow (Zohary *et al.*, 2014). The timing of the seasonal melting of the sea ice determines when the spring blooms start (pelagic system) and the thickness determines if it is possible for the algae to grow under the sea ice (sympagic system). Thinning of the sea ice cover in the last decades has increased the amount of sympagic primary production, but predictions of future sea ice loss will probably nullify this effect (Horvat *et al.*, 2017; Tedesco, Vichi and Scoccimarro, 2019). At the same time the increase in open water area, as a result of the decline in sea ice extent, has caused a rise in pelagic algae (phytoplankton). However it is yet uncertain if this trend will continue or if nutrient limitation will inhibit this increased primary production (Vancoppenolle *et al.*, 2013; Arrigo and van Dijken, 2015; Lewis, van Dijken and Arrigo, 2020). Also, the shift of seasonal melting of sea ice happening earlier in

spring has resulted in earlier spring blooms. This shift in spring bloom timing could possibly result in a mismatch between algae and their grazers and higher trophic levels (Leu *et al.*, 2011; Post, 2017).

The lengthening of the open water season has also the potential to cause a shift in the algae community composition. Because of a longer open water season, there will be a longer period of time of nutrient depletion. When this happens the algae community will shift from larger diatom species to nano- or picoplankton species and this will have consequences downwards the food web (Hahn-Woernle, Dijkstra and Woerd, 2014; Zohary *et al.*, 2014). Climate change can also influence nutrient availability by influencing the stratification of the Arctic ocean and so the mixed layer depth. The Arctic ocean is strongly stratified during summer as a result of melting sea ice. The resulting shallow mixed layer depth prevents the depleted nutrients at the surface to be supplemented from the lower water layers and increased sea ice melting could possibly strengthen this stratification. However, the increased inflow of warm saline Atlantic water of the past few years can weaken the stratification of the Arctic ocean (Lind, Ingvaldsen and Furevik, 2018). While a deeper mixed layer depth may increase the upwelling of nutrients from lower water depth, the turbulence of the water will not allow for much light penetration so algae will grow poorly. Finally, there is also uncertainty about the transport of nutrients to the Arctic. While some models show a increased inflow of nutrients and increasing photosynthetic levels. Other models predict that nutrient levels will not increase and algae growth will be limited by nutrients (Vancoppenolle *et al.*, 2013).

Climate Variability and Variability in Primary Production

Superimposed on long-term trends are short-term climate variations. Climate variability is the result of natural fluctuations that take place on various time-scales and can amplify or obscure trends in climate change. The variability of a system is difficult to predict because of its chaotic nature. Also, different time-scales can be the result of different drivers, for example, interannual variability in Arctic temperature is mostly driven by atmospheric heat transport, while decadal variability is more connected to oceanic circulation (Reusen, van der Linden and Bintanja, 2019). Research done on variability in the Arctic has mostly focused on precipitation, temperature and sea ice cover extent (van der Linden, Bintanja and Hazeleger, 2017; Reusen, van der Linden and Bintanja, 2019; Bintanja *et al.*, 2020; Labe, 2020). While research on primary production has mostly used averaged values and did not take variability into account (Arrigo and Van Dijken, 2011; Chavez, Messié and Pennington, 2011; Vancoppenolle *et al.*, 2013; Arrigo and van Dijken, 2015; Tedesco, Vichi and Scoccimarro, 2019; Lewis, van Dijken and Arrigo, 2020). Research directed towards the impact of climate variability on primary productivity has been largely lacking and therefore this study will focus on interannual variability of primary production and its abiotic drivers. By trying to understand variability, it could be possible to link variables (e.g. primary production) to climate variables without having to use long-term datasets. By doing so it can be determined what processes play a role and help to better predict climate variability. To analyse variability one needs long-term datasets that are, preferably, not influenced by climate change (i.e. long-term trends). Climate change can affect variability which makes it harder to distinguish between a changing climate and variability (Brown *et al.*, 2017). Long-term pre-industrial observational records for the Arctic do not exists, and for that reason we will use the Earth System Model (ESM) EC-Earth to analyse the variability of primary production in the Arctic in a long simulation with constant forcing.

Methods

EC-Earth Model

For the analyses, we used EC-Earth version 3 (ECE3), which is a fully coupled atmospheric-ocean global climate model developed in a consortium of Earth-system scientists from ten different European countries (Hazeleger *et al.*, 2012). ECE3 uses the Integrated Forecasting System with cycle 36R4 (IFS CY36R4) created by the European Center for Medium-Range Weather Forecasts (ECMWF) to model the atmosphere. It runs at T225 spectral resolution and has 91 vertical levels. The ocean system is modelled by the Nucleus for European Modelling of the Ocean version 3.6 (NEMO 3.6); NEMO has a resolution of 1^{0} and has 75 vertical levels (Rousset *et al.*, 2015). Incorporated into NEMO is the Pelagic Interactions Scheme for Carbon and Ecosystem Studies version 2 (PISCES-v2) and the Louvain la Neuve sea ice model version 3 (LIM3) (Vancoppenolle *et al.*, 2012; Aumont *et al.*, 2015). PISCES simulates ocean biochemistry including algae and LIM3 is a dynamic-thermodynamic sea ice model. A description of the ECE3 model is still in progress; a recent paper describing the differences between ECE2 and ECE3 was used to get the necessary information (Wyser *et al.*, 2019). ECE3 will be used to carry out simulation in the framework of CMIP6 and the next generation of the KNMI climate scenario's for the Netherlands.

Simulation

The simulation was carried out using pre-industrial (PI) climate (1850) forcing, with atmospheric CO_2 and other forcing agents kept constant in time. This version of the model did not include land vegetation and feedbacks between ocean biogeochemical and atmosphere/ocean physics, so PISCES was driven by the physics included in NEMO/LIM3. After the initial spin-up to reach quasi-equilibrium, the model was set to simulate a few hundred years of output in a constant PI climate. Because of unknown problems with section of the output and erroneous postprocessing, we could only use 57 consecutive years for our analysis. This time series consists of monthly mean values, and exhibited no trends.

Analyses

The output of the run was analysed using Python version 3.8.1. (Van Rossum and Drake, 2009). Variables that were analysed were sea ice cover, netto downward shortwave radiative flux at sea water surface (later called surface shortwave flux), ocean nitrate concentration, silicate concentration, and chlorophyll-a concentration as a proxy for primary production. If a variable had a depth dimension, the mean over the first 18 levels (38 meter) was calculated and used. Within our dataset most of the processes concerning primary production took place in this water layer, so only the first 38 meters were included in our analysis. For all the variables the mean and standard deviation (the interannual variability) were calculated for the Arctic region between 65-90 ^{0} North to find spatial differences in variability. For the selected area of high variability, we calculated correlations between various variables to quantify the strength of their interaction. Because a correlation analysis cannot determine causality and the physics governing the various links, the empirical limitation functions as proposed by Vancoppenolle *et al.* (2013) were evaluated. This method calculates the factors that limit chlorophyll-a concentration. The two possbile limiation factors are nitrate concentration and sea ice cover (as a proxy for light availability). The sea ice limitation is a function of the area covered by sea ice (S_{dom}) and the lotal area(S_{dom}). :

$$Lim\,Sie = \frac{S_{dom} - S_{PIZ}(y)}{S_{dom}} \tag{1}$$

The nitrate limitation is a hyperbolic function with NO_3 the nitrate concentration in a year and k^{NO3} (k^{NO3} = 1.6 mmol/m^3) the halfsaturation concentration for nitrate by algae (Sarthou *et al.*, 2005).

$$Lim\,NO_3 = \frac{NO_3(y)}{k^{NO_3} + NO_3(y)} \qquad (2)$$

The total emperical limitation was calculated:

$$Lim = Lim\,NO_3 * Lim\,Sie \qquad (3)$$

When the limitation values is close to 0 the limitation is strong and when it is close to 1 the limitation is weak. Because interactions in the Arctic change during the seasons, we will calculate the values for the different seasons. The correlation between the different limitation formulas and primary production will also be calculated, it is expected that the concentration of chlorophyll-a will follow the same pattern as their limiting factor. When calculating the correlation normalised integrated primary production was used (IPP*). Which is the chlorophyll-a concentration (mg/m^3) of the area divided by the mean chlorophyll-a concentration.

$$IPP^*(y) = \frac{IPP(y)}{IPP(mean)} \qquad (4)$$

Results

Mean values

The EC-model simulated multiple variables for the entire globe. For the Arctic region (65-90^{o}N), the average (mean) values of climate variables were calculated to get a general overview of the area. The average value was the mean over 57 years and the standard deviation was the variability between the different years. For the Arctic region, the average air temperature at 2 metre was 256.5 ± 4.9 K (-15.7 ^{o}C) and the perennial ice zone was 12.06 ± 0.46 million km^2. In Comparison, the present day temperature of the Arctic is circa 262.2 K and the perennial ice zone is on average between 6-7 million km^2. The variables chlorophyll-a, nitrate and surface shortwave flux have respectively mean values of 0.16 ± 0.01 mg/m^3, 4.15 ± 0.05 mmol/m^3, 17.79 ± 1.56 W/m^2 (Table 1, figure 1).

Variability

A region between Greenland, Iceland and Norway in the Norwegian Sea/southern Barents Sea showed much higher variability than other regions in the Arctic and was therefore chosen for a more in-depth study (Figure 2). The region of interest was located along the sea ice margin, between 65^o-80^{o}N and between 20^{o}W-25^{o}E. It had an average air temperature of 259.6 ± 6.7 K and an average perennial ice cover of 1.38 ± 0.22 million km^2 (with the 1-sigma uncertainties representing the interannual variability). Chlorophyll-a concentration was 0.29 ± 0.04 mg/m^3, nitrate concentration was 4.09 ± 0.13 mmol/m^3 and the surface shortwave flux was 38.06 ± 5.48 W/m^2 (Table 1, Figure 3). As with the values calculated for the entire Arctic (65-90^{o}N), the average was the mean calculated over 57 years and the standard deviation was the variability between the different years. The interannual variation of the aforementioned variables were up to 4 times higher in the selected area than the average variation of the entire Arctic. Furthermore, the reason for choosing this area was that multiple variables that were identified for possible drivers of variability in primary production showed high variability in the same area. Sea ice cover, surface shortwave radiation, nitrate concentration and chlorophyll-a concentration variability peaked in the same general region. The spatial location and the magnitude of the variability of this area was not constant and changed with the seasons.

For the variables that had a depth dimension (NO_3- and chlorophyll-a concentration), it was possible to make depth plots (figure 4) . These plots showed a cross-section of the ocean along the 0° longitude, the cross-section intersected the area with high variability to gain more insight in what was happening below the surface. The average values of both variables started to change during spring, which was also the season in which the sea ice margin started to melt and moved northwards (Appendix A). The concentration in chlorophyll-a increased during spring and summer and decreased again during autumn. Possibly as a result of the sea ice area extending again and the sea ice edge moving towards the south. The nitrate concentration decreased during summer and autumn, because this decrease happened in the same spatial location as the increase of chlorophyll-a it was assumed that the nitrate was consumed by the algae. Most of the variability was located north and below the area with the highest (chlorophyll-a) or lowest concentrations (nitrate). Both the average and the variability plots, showed a northwards movement when sea ice margin moved northwards during spring and summer and a southwards movement when the sea ice margin moved towards the south during autumn. It was hypothesised that the variability in chlorophyll-a concentration and nitrate concentration followed the melting sea ice edge. That in years with more melting the sea ice margin would move further upwards towards the north, allowing for more light to be available at higher latitudes. Chlorophyll-a concentrations could increase at higher latitudes because there was more light available and the nitrate concentration in the same area would decrease because it was consumed by algae. The opposite would happen in years in which there was less melting of the sea ice, resulting in different situations each year depending on the extent of the seasonal melt.

Correlation Analysis

It has been established by earlier research that chlorophyll-a concentration is primarily related to light availability (hence sea ice cover) and nutrient concentration (nitrate being the most important). To test if the variability of chlorophyll-a in any way relates to the variability in other variables, the correlation coefficient was calculated. The variables that were compared to chlorophyll-a were nitrate concentration, sea ice cover and surface shortwave influx (figure 5). Surface shortwave flux was included to get a more direct measurement for the interaction between light availability and chlorophyll-a, so it could be compared to the more indirect measurement sea ice cover provided. Because the strength of the variability changes through the year, the correlation coefficient was calculated for the different seasons. Chlorophyll-a concentration and nitrate concentration (figure 5b) had strong negative correlation throughout most of the seasons, with the strongest in summer (-0.94) and the weakest in winter (-0.25). Spring, summer and autumn had similar correlations, the correlation in autumn was weaker, but it was still a relatively strong negative correlation. Although the correlation was relatively constant for those seasons, the chlorophyll-a and nitrate concentrations were not. In spring nitrate concentrations were high and there were low chlorophyll-a concentrations, during summer chlorophyll-a concentrations started to increase and nitrate concentrations decreased. In autumn, the situation was reversed again with chlorophyll-a concentration decreasing and nitrate concentration increasing. The correlation between chlorophyll-a and surface shortwave radiative flux (figure 5c) was the strongest in spring (0.94) and summer (0.96), during which both shortwave flux and chlorophyll-a concentrations were increasing. In autumn the correlation was also strong (0.84), only the situation was the opposite of spring and summer with both shortwave flux and chlorophyll-a concentration decreasing. The correlation between chlorophyll-a and sea ice cover (figure 5a) was the strongest in spring (-0.58), which was the season when the sea ice started to melt. Overall, the correlation between those two variables was rather weak. The sea ice cover did start to extent again in autumn, but this did not correlate with the decrease in chlorophyll-a concentration that also took place in autumn. All the variables showed no correlation with chlorophyll-a during winter. A possible explanation for this could be that chlorophyll-a concentration levels were very low during winter months with almost no variability. It should be noted that although a correlation can indicate that there is a connection, it cannot be used to determine cause and effect. A correlation can also not quantify the strength of the link between chlorophyll-a and different variables. So, to gain more insight in what drives variability in primary production we use Vancoppenolle's empirical limitation analysis.

Empirical Limitations

To determine the strength of the processes behind the variability of chlorophyll-a concentration, the limiting factor for primary production were calculated. This was done by calculating the empirical limitation formulas of nitrate concentration (Lim_{NO3}) and sea ice cover (Lim_{SIE}), which was a proxy for light availability. The limitation that was the closest to zero was then determined as the limiting factor. The overall limitation (Lim) was calculated by $Lim = Lim_{NO3} * Lim_{SIE}$ to determine how strongly primary production was limited. The closer the Lim is to zero, the stronger the limitation. The mean of the limitations over 57 years were: $Lim_{NO3} = 0.72$, $Lim_{SIE} = 0.43$ and $Lim = 0.31$ (figure 6). It can be concluded that primary production is mostly limited by the presence of sea ice and that overall the limitation is quite strong. The strength of the sea ice limitation was highly depended on the season and on the spatial location. The limitation of sea ice on the growth of chlorophyll-a was the strongest during winter and spring when the sea ice area was at its largest and the weakest during summer and autumn when the sea ice cover was at its smallest. During all the seasons the limitation was the strongest in the north where most of the sea ice was located and weakest in the south were there was no sea ice. The nitrate limitation was rather constant during the seasons, with it becoming somewhat stronger during autumn. In autumn, the sea ice area is the smallest and chlorophyll-a was not as strongly limited by it. Therefore, nitrate concentration became a more important factor for limiting chlorophyll-a concentration. To find out how primary production further related to the limitations, the correlation coefficient between normalised integrated primary production (IPP*) and the three limitations were calculated (figure 7). The correlation between IPP* and Lim_{NO3} was -0.67, IPP*, and between IPP* and Lim_{SIE} it was 0.30. For both the correlations the strength of them changed depending on the season, though, overall the correlations were rather weak. The correlation between IPP* and Lim_{NO3} was overall negative and had the strongest correlation in summer (-0.74). The correlation between IPP* and Lim_{SIE} was overall positive, but very weak. The strongest correlation was in spring (0.4). In spring there was also a band of very strong positive correlations, but because the surrounding area only had very weak correlations the overall correlation of the area was very low. Overall the correlations were not very strong, which made it difficult to draw conclusions with certainty. However, if indeed there was a negative correlation between Lim_{NO3} and IPP*, it would mean that when chlorophyll-a concentrations were low, they could not consume all the nutrients and so were not limited by the nitrate concentration. If the chlorophyll-a concentration did become high enough to consume all the nutrients, nitrate would start to limit the growth. However, within this dataset the chlorophyll-a concentration did not become high enough to be limited by nitrate concentration. Before they reached high enough concentration levels, they were limited in growth by the sea ice. The correlation analysis between Lim_{SIE} and IPP* seemed to indicate a positive correlation. That would mean that when the sea ice cover was large, it would limit the production of chlorophyll-a and the chlorophyll-a concentrations were low. When the sea ice extent was small, it would no longer limit the growth of algae and chlorophyll-a concentration could increase.

Table 1: Mean and Standard Deviation values of the Arctic region and the study area over 57 years

Variables	**Unit**	**Mean** *Lat:* 65:90 *Long:* -180:180	**SD** *Lat:* 65:90 *Long:* -180:180	**Mean** *Lat:* 65:80 *Long:* -20:25	**SD** *Lat:* 65:80 *Long:* -20:25
2 Meter Temperature	Kelvin	256.5	4.89	259.6	6.74
Sea Ice Cover Perennial Ice Zone	Km^2	12.06e-6	0.46e-6	1.38e-6	0.22e-6
Surface Net Downward Shortwave Flux	W/m^2	17.79	1.556	38.06	5.478
Mixed Layer Depth	Meter	57.76	14.0	68.56	19.36
Chlorophyll-a Concentration	mg/m^3	0.1579	0.0103	0.2864	0.0354
Nitrate Concentration	$mmol/m^3$	4.146	0.04872	4.088	0.1327
Phosphorus Concentration	$mmol/m^3$	0.3782	0.002718	0.3474	0.008124
Silicate Concentration	$mmol/m^3$	8.587	0.06322	3.726	0.07089
Dissolved Iron Concentration	$mmol/m^3$	0.001746	1.154e-05	0.001255	3.346e-05

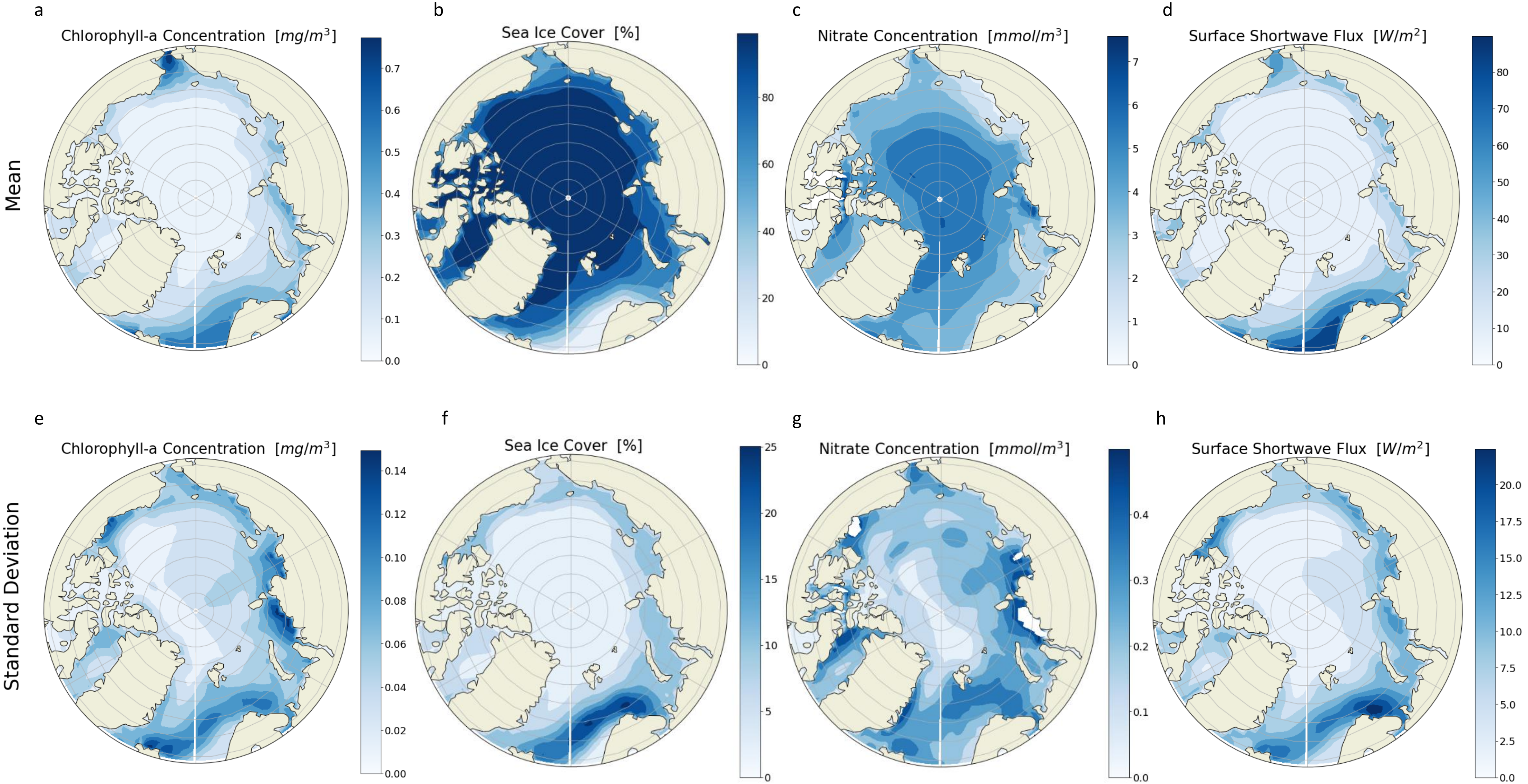


Figure 1: The mean (a-d) and the standard deviation (e-h) of the variables chlorophyll-a, sea ice cover, nitrate concentration and surface shortwave flux. The dark blue coloured areas in the SD plots indicate areas of high interannual variability

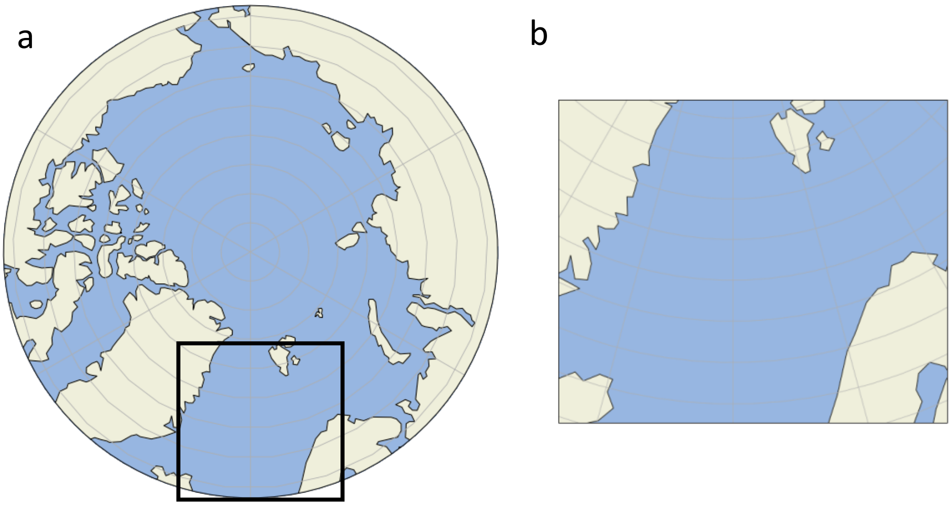


Figure 2: Arctic region and study area. (a) is the Arctic region as described in this research (65-90 ^{o}N). (b) is the region of high variability on which the analysis where performed (65^{o}-80^{o}N, 20^{o}W-25^{o}E).

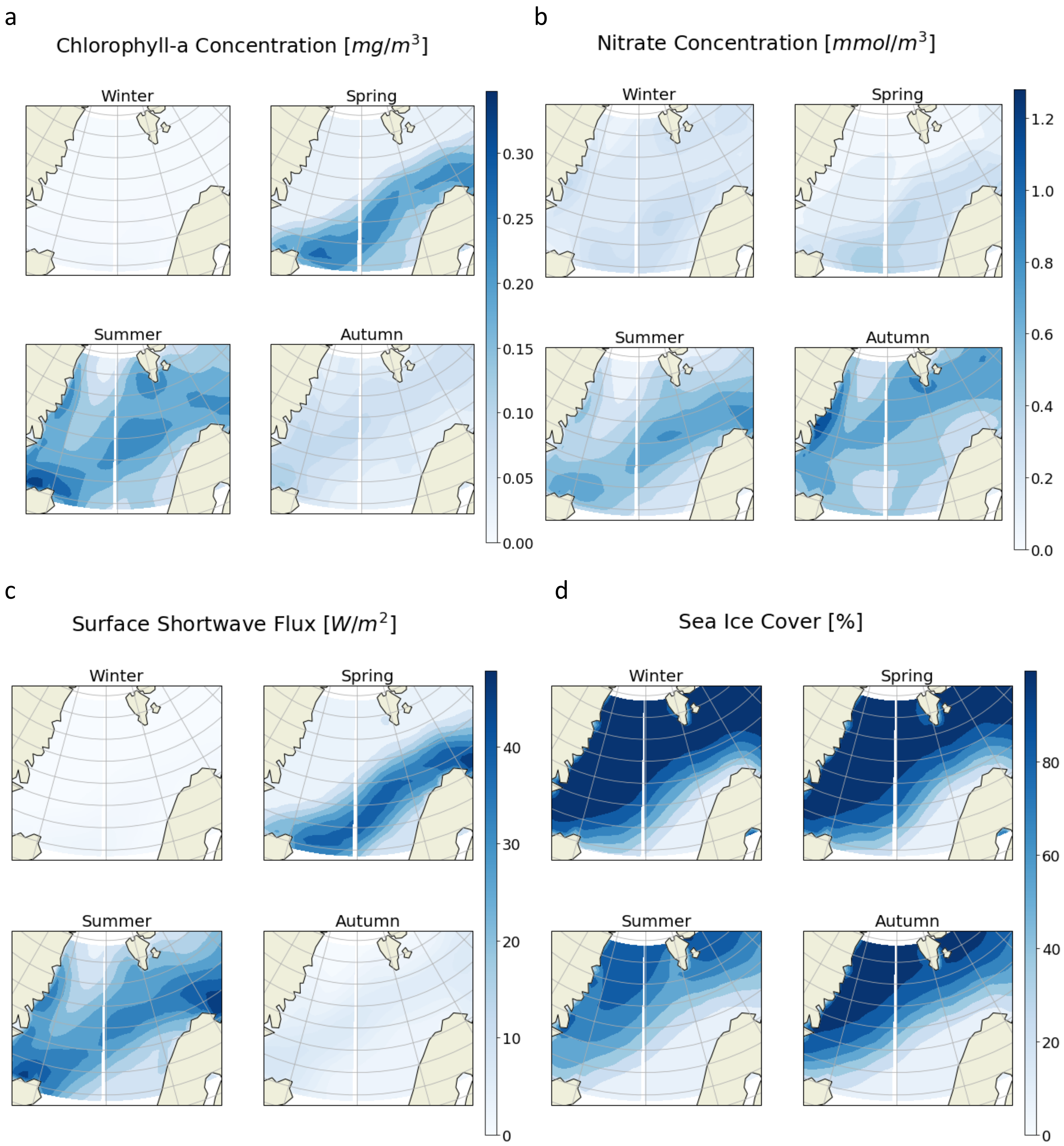


Figure 3: The standard deviation plots of the study area for the variables chlorophyll-a concentration (a), nitrate concentration (b), surface shortwave flux (c) and sea ice cover (d). The dark blue coloured areas in the SD plots indicate areas of high interannual variability

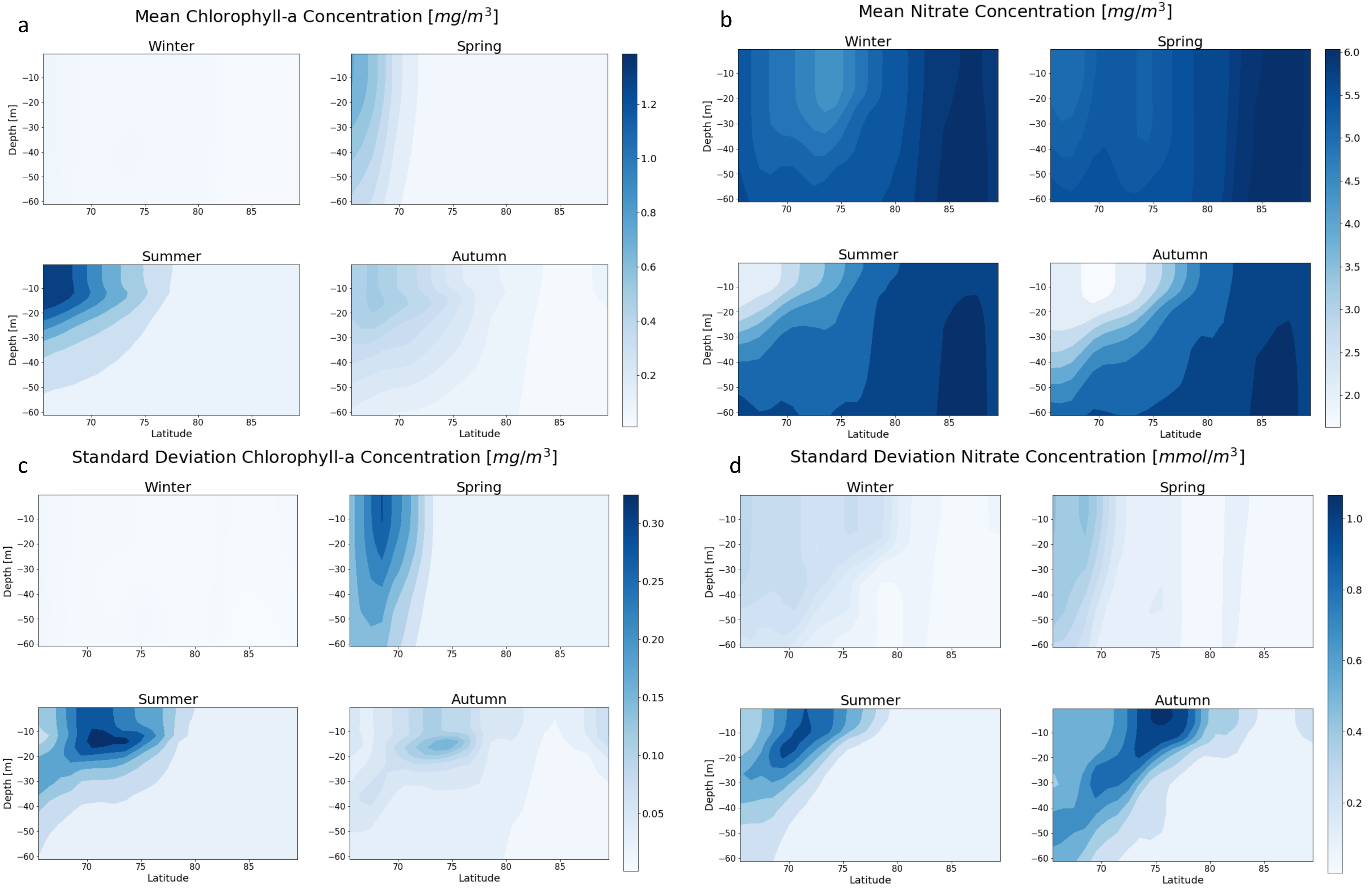
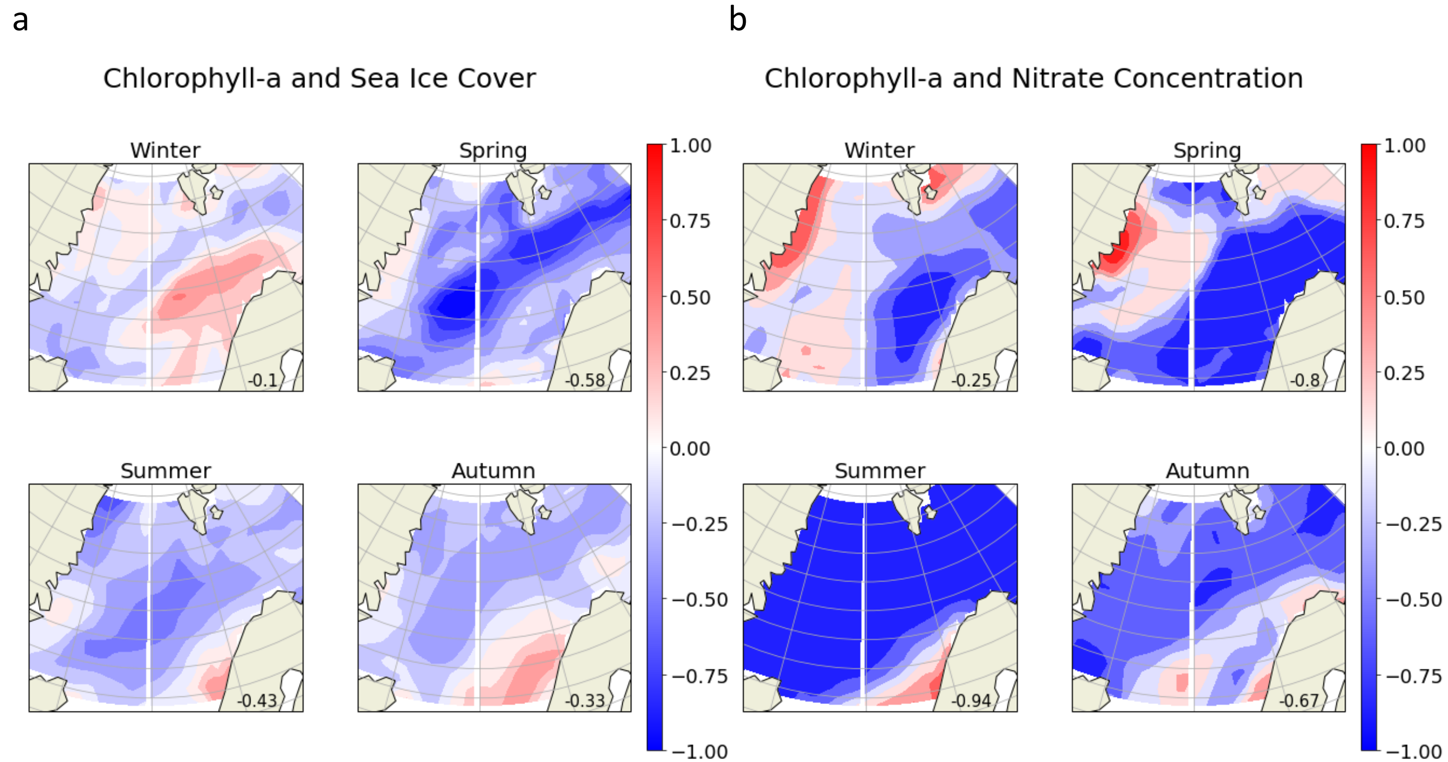


Figure 4: The cross-section plots along the 0⁰ longitude, 65-90⁰ latitude and the first 60 meters below ocean surface. The plots show the mean (a,b) and the standard deviation (c,d) of the variables chlorophyll-a and nitrate concentration. Dark colours within the SD plots depict areas with high interannual variability.



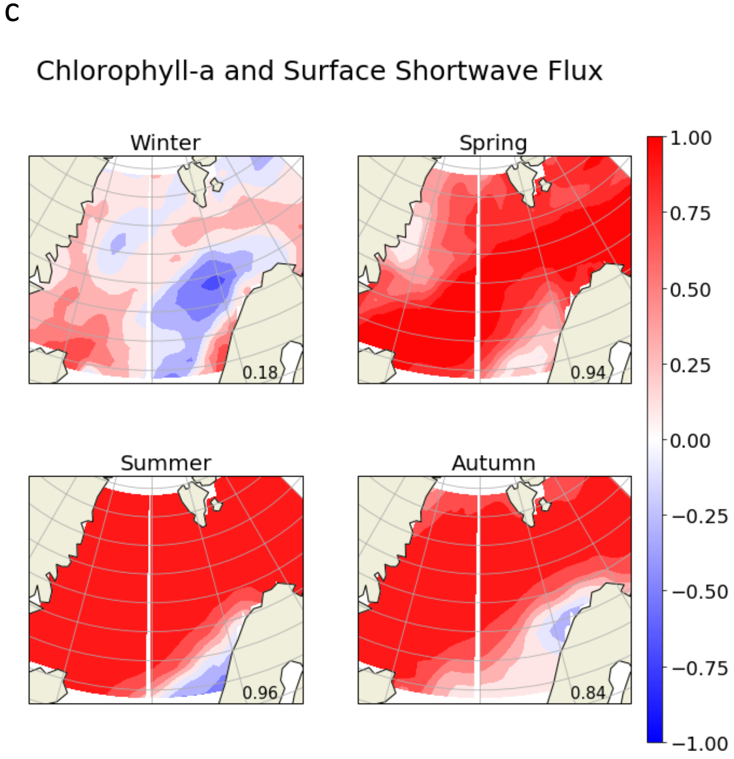
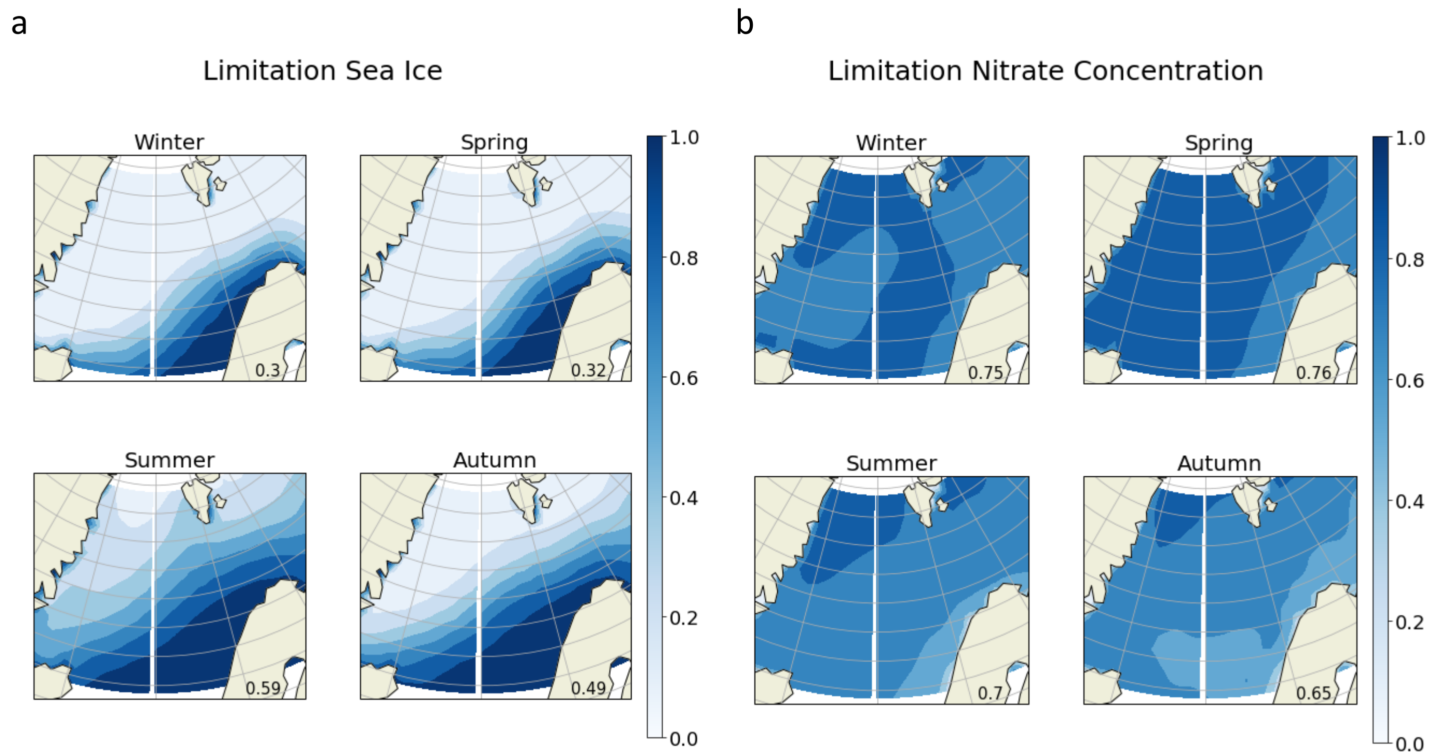


Figure 5: Correlation between chlorophyll-a and the variables sea ice cover (a), nitrate concentration(b) and surface shortwave flux (c). The correlation coefficient was calculation for each grid cell within the study area. In the bottom right corner of each plot the correlation coefficient for the entire area was included.



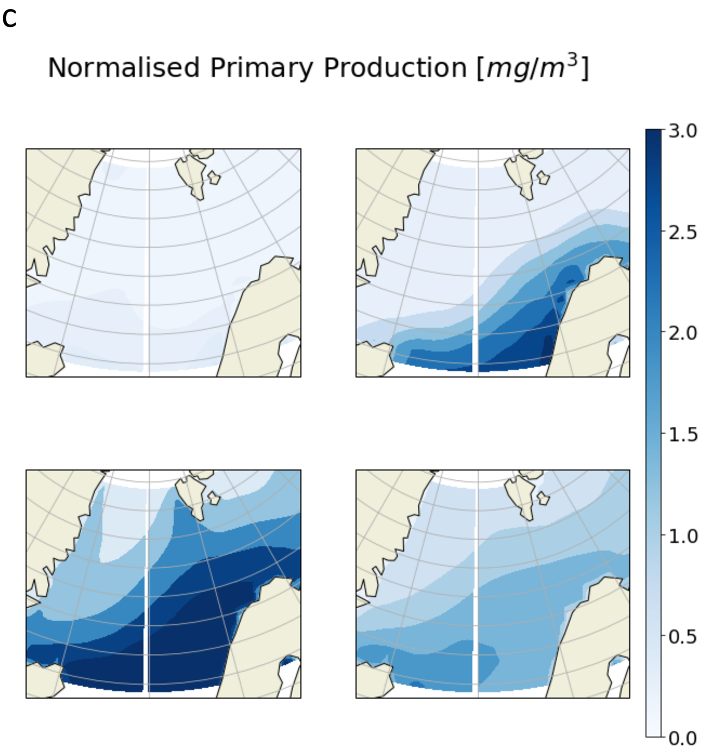


Figure 6: The limitation of chlorophyll-a concentration as a result of sea ice cover (a) and nitrate concentration. The limitation value was calculation for each grid cell within the study area. In the bottom right corner of each plot the limitation value for the entire area was included. (c) shows the normalised chlorophyll-a concentration.

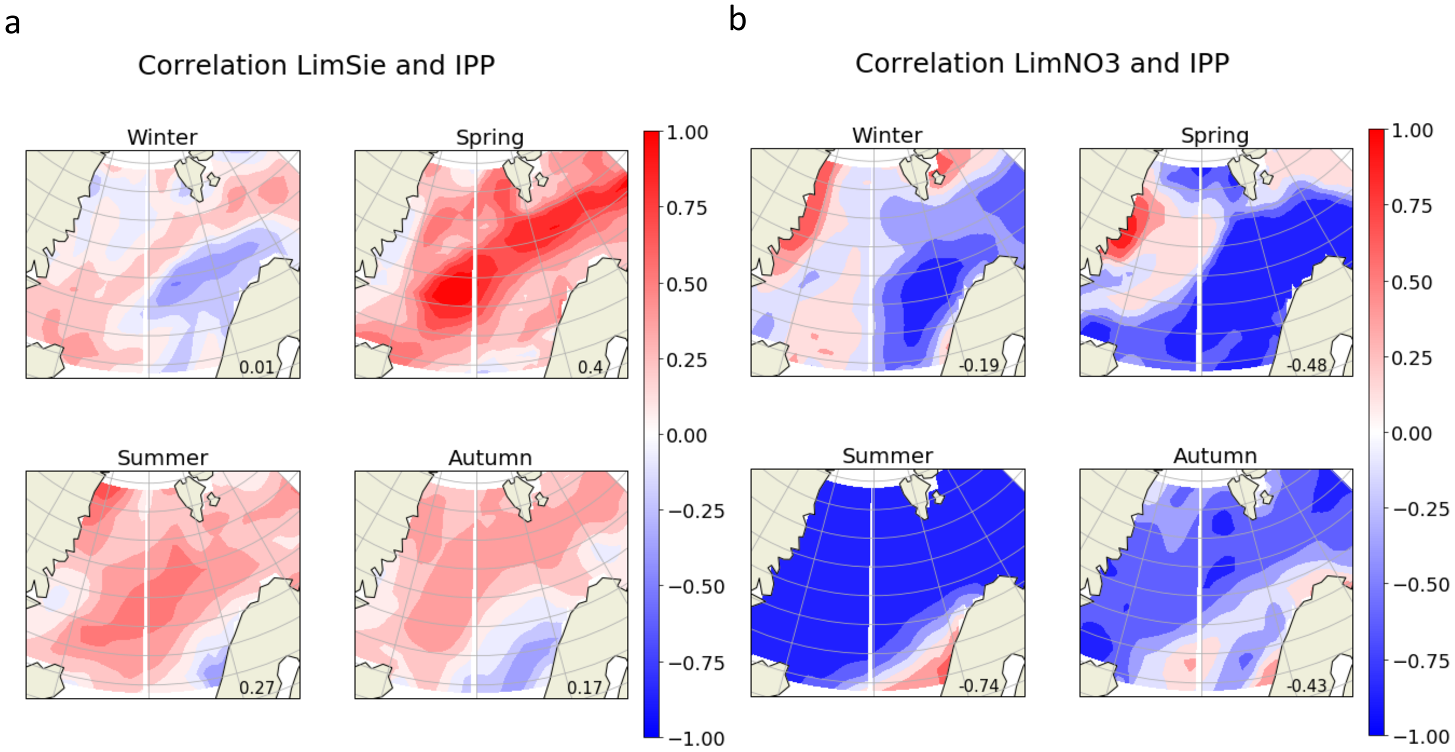


Figure 7: Correlation between the normalised chlorophyll-a and the sea ice limitation (a) and the nitrate limitation. The correlation coefficient was calculation for each grid cell within the study area. In the bottom right corner of each plot the correlation coefficient for the entire area was included.

Discussion

Within our dataset of the PI-climate in our selected region in the North Atlantic (where variability is relatively high), sea ice cover is the variable that primarily limits the concentration of chlorophyll-a. Based on this result and the results of the variability plots and the correlation analysis, it can be concluded that sea ice cover is the most likely driver of interannual variability in primary production in the Arctic.

To calculate the limitation of light on algae, sea ice was used as a proxy for light availability. However, despite being the limiting factor, the correlation between the sea ice limitation and the normalised primary production was rather weak. It was expected that the chlorophyll-a concentration would follow the same pattern as its limiting factor, resulting in a strong correlation. The weak correlation between normalised primary production and Lim_{sie}, could possibly be the result of the weak correlation between chlorophyll-a and sea ice. However, the correlation between surface shortwave radiation and chlorophyll-a was much stronger. So it would be interesting to develop a formula to analyse the limitation of surface shortwave flux on chlorophyll-a. The surface shortwave flux had a strong positive correlation with chlorophyll-a in the correlation analysis and it is also a more direct way of quantifying light availability instead of using a proxy like sea ice cover. Photosynthetically available flux could possibly be an even better variable to use, because it focuses on the spectrum of light that algae can use, but in the model it generally showed the highest values under the sea ice which might not be realistic. It should be kept in mind that even if sea ice cover is not the best proxy of light availability, it still should be included in future studies. Melting of the sea ice and the introduction of fresh water into the system drives the stratification of the Artic ocean and plays an important role in nutrient availability.

Nitrate concentration often had a stronger correlation with chlorophyll-a concentration than sea ice cover, despite being not the limiting factor. An explanation can be that sea ice cover is not a suitable proxy for light availability, but it can also partly be explained by the more complex interaction that algae have with nitrate. For algae to grow, the nitrate concentration has to be high enough, but the moment the algae start growing, they will consume the nitrate and nitrate levels will drop. At a certain point in time the algae will stop growing and the nitrate concentration can increase again. So the presence of algae can influence the nitrate concentration and nitrate concentration can in turn influence the growth of algae. Because of this circular process, the concentrations of algae and nitrate are strongly connected, resulting in a strong correlation between the two. In comparison, sea ice cover can influence the presence of algae, but the presence of algae does not influence the sea ice cover. Which makes it a more straightforward interaction.

Limitations of the study

For our study we used data simulated by a model and although EC-Earth is a state of the art Earth System Model, it is still a model trying to replicate earth system processes. When studying the present-day climate, data generated by a model is often compared to in situ observations to validate and verify the output of the model. However, because we studied the pre-industrial climate this was not possible and therefore it could be that model was not necessarily realistic. We also only studied interannual variability of primary production for the pre-industrial climate, which is quite different than present-day climate (lower temperatures, more sea ice). The interannual variability of the present-day climate may be different and drivers of the interannual variability of primary production may also be different in present-day climate. Lastly, our time-series was relatively short, therefore it was not possible to test for the potential influence decadal variability could have on our dataset.

Seasonality and Future Shift in Limitation

The interaction between primary production and different abiotic variables can change a lot depending on the season in the Arctic. These differences between the seasons should be taken into account when studying interannual variability, because it is likely that the drivers of interannual variability can change depending on the season. Even for the climate of 1850, there were years in which nitrate concentration was the limiting factor during autumn. Vancoppenolle *et al.* (2013) compared multiple climate models, in an attempt to understand what would happen to the limitation as a result of climate change. Depending on the inflow of nitrate into the Arctic and the ability of the algae to recycle nutrients (Lewis, van Dijken and Arrigo, 2020), primary production would be more limited by nitrate concentration when the sea ice extent started to decline. Based on these findings, it is likely that in the future, interannual variability of primary production will be driven by nitrate concentration instead of light availability. The shift will probably be gradual, starting with nitrate limitation in September when sea ice extent is at its minimum.

Future variability of primary production

This year, the minimum Arctic sea ice extent is the second lowest in 42 years of satellite records and the second time that minimum sea ice extent was below 4 million km^2 (Gautier, 2020). When more sea ice area gets susceptible to melting it is expected that the areas of high variability will increase and sea ice variability will become stronger (van der Linden, Bintanja and Hazeleger, 2017). With sea ice cover being the driver of the variability in primary production, algae will probably follow the same pattern as sea ice in the beginning. Until the sea ice area will become so small that its presences does not influence the growth of algae anymore. At that point the variability will be mostly driven by nutrient concentration and a system more similar to the Atlantic ocean will develop, which has lower levels of variability and is more constant. Besides sea ice cover, the variability in Arctic precipitation is also expected to increase (Bintanja *et al.*, 2020). However, how this may influence the variability of primary production is less clear. The increased input of fresh water from precipitation or rivers could possibly strengthen the stratification of the Arctic ocean, but without the fresh water input from the melting sea ice the Arctic ocean will become well-mixed instead of strongly stratified (Lind, Ingvaldsen and Furevik, 2018). The variability in Arctic temperature is expected to decrease as a result of increased temperatures during the winter months (Screen, 2014). Because this study focused on the variability of primary production in the pre-industrial climate, it could be considered for future studies to focus more on how the variability of primary production will change under Arctic warming.

Conclusion

Within the 1850 pre-industrial climate the magnitude of the interannual variability of primary production was highly dependent on the spatial location, with some areas showing almost no variability. A area within the Norwegian Sea/Southern Barents Sea showed a very clear pattern of high variability and was used for further analysis. Besides spatial location, the magnitude of the variability also highly depended on season. Because the growth of algae was primary limited by the presence of sea ice, it can be concluded that sea ice cover (and hence light availability) is the driver of interannual variability of primary production in the Arctic. However, for future studies is should be considered to use a more direct measurement of light availability (surface shortwave flux, photosynthetically available radiation).

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Appendix A

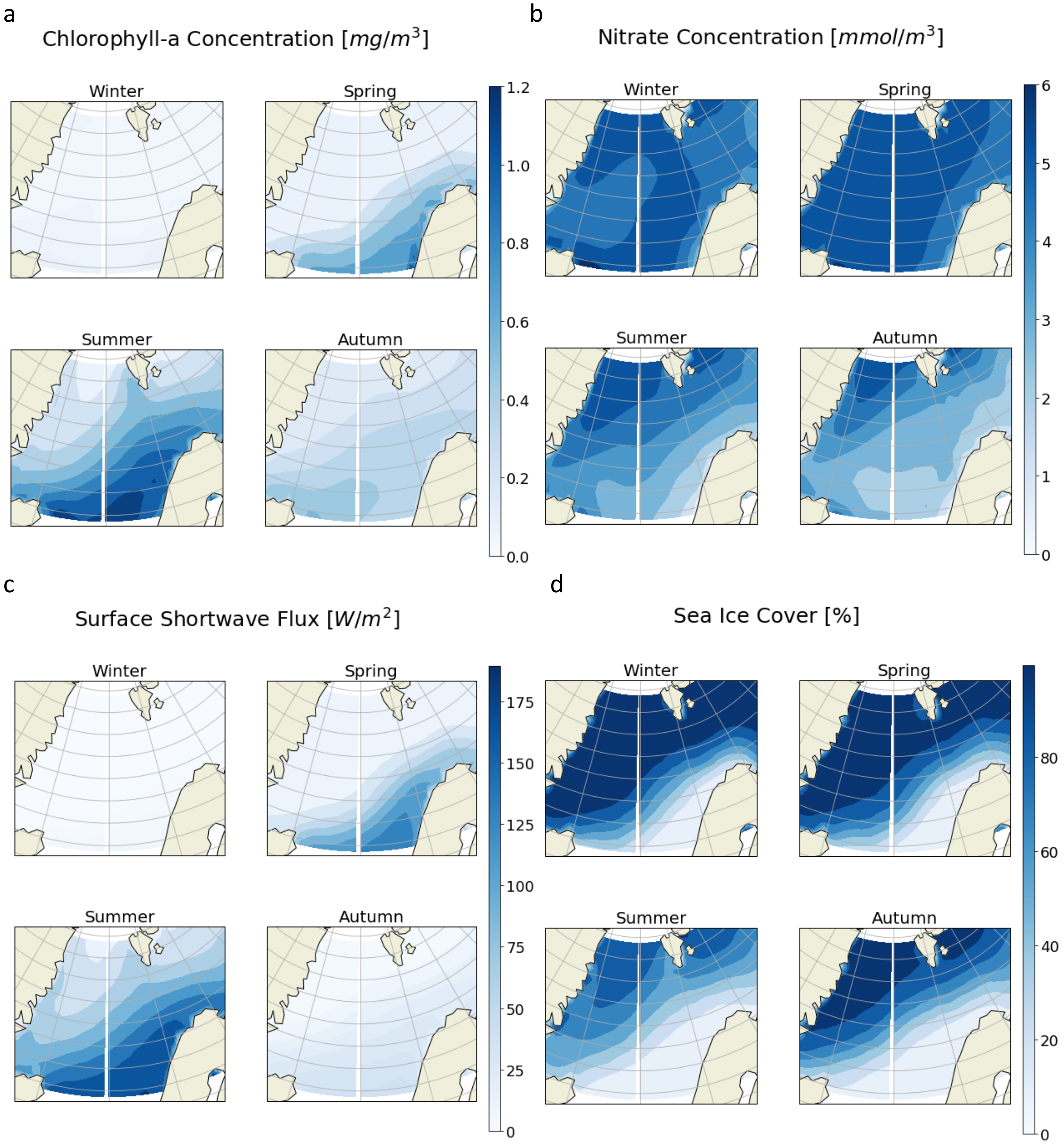

Figure 8: The average values over 57 years of the study area for the variables chlorophyll-a concentration (a), nitrate concentration (b), surface shortwave flux (c) and sea ice cover (d). The dark blue coloured areas in the SD plots indicate areas of high interannual variability