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# 1 Exploring controls on the timing of the phytoplankton bloom in western 2 Baffin Bay, Canadian Arctic

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## 23 Abstract

24 In the Arctic Ocean the peak of the phytoplankton bloom occurs around the period of sea ice break-up.  
25 Climate change is likely to impact the bloom phenology and its crucial contribution to the production  
26 dynamics of Arctic marine ecosystems. Here we explore and quantify controls on the timing of the spring  
27 bloom using a one-dimensional biogeochemical/ecosystem model configured for coastal western Baffin  
28 Bay. The model reproduces the observations made on the phenology and the assemblage of the  
29 phytoplankton community from an ice camp in the region. Using sensitivity experiments, we found that  
30 two essential controls on the timing of the spring bloom were the biomass of phytoplankton before bloom  
31 initiation and the light under sea ice before sea ice break-up. The level of nitrate before bloom initiation  
32 was less important. The bloom peak was delayed up to 20 days if the overwintering phytoplankton  
33 biomass was too low. This result highlights the importance of phytoplankton survival mechanisms during  
34 polar winter to the pelagic ecosystem of the Arctic Ocean and the spring bloom dynamics.

## 35 1 Introduction

36 Baffin Bay is an important gateway between the Arctic Ocean and the Northwestern Atlantic. Each year  
37 during the sea ice retreat, the phytoplankton spring bloom leads to biomass increasing by orders of  
38 magnitude, from its lowest values at the end of winter to a peak in summer (Perrette et al., 2011). Because  
39 phytoplankton forms the basis of the Arctic marine trophic network (Legendre and Rassoulzadegan,  
40 1995), understanding the controls of the timing of the bloom is critical, especially given the shortness of  
41 the productive season. A mismatch between primary and secondary producers in the peak of activity and  
42 recruitment may decrease production at the higher trophic levels of the polar marine ecosystems (Søreide  
43 et al., 2010; Leu et al., 2011), and even impact the export of organic matter via the biological carbon  
44 pump (Henson et al., 2023). The biological carbon pump refers to mechanisms that export organic carbon  
45 from the ocean's surface to its interior, where it may be sequestered (Boyd et al., 2019; Henson et al.,  
46 2023). Mismatch events have occurred in Arctic environments, but they could increase in frequency and  
47 intensity owing to climate change (Søreide et al., 2010). Some of the largest effects of climate change  
48 globally occur in the Arctic (Gutiérrez et al., 2021; Rantanen et al., 2022). Moreover, as people living  
49 along western Baffin Bay rely partly on subsistence harvest (Kenny and Chan, 2017), unexpected changes  
50 in biological production may negatively impact their access to local fishery and marine mammal stocks,  
51 and ultimately their food security.

52 Arctic phytoplankton bloom dynamics are split between three periods separated by two crucial days: the  
53 pre-bloom period, the day of the bloom initiation, the growth period, the day of the bloom peak and the  
54 post-bloom period (Sakshaug, 2004; Carmack and Wassmann, 2006; Wassmann and Reigstad, 2011).  
55 During the pre-bloom period, very low light prevents significant population growth even though nutrient  
56 concentrations are high. Snow accumulation allows a transmittance of less than 1% through snow-covered  
57 sea ice, but as soon as snow starts to melt transmittance increases to between 2% and 10%, thus allowing  
58 the start of the growth period (Ardyna et al., 2020a). For instance, a bloom initiation was detected by  
59 floats under 100% sea ice cover as early as February in Baffin Bay (Randelhoff et al., 2020). Data from  
60 biogeochemical-Argo floats in the Greenland Sea show that neglecting under-ice blooms would have  
61 resulted in the underestimation of the annual net community production of phytoplankton by 52% (Mayot  
62 et al., 2018). The controls of the bloom initiation appear to be linked to the optical characteristics of the  
63 ice and snow cover, and to the physiological response of phytoplankton to severe light limitation, as was  
64 also observed in the Southern Ocean (Hague and Vichi, 2021). The middle of the growth period is  
65 associated with melt ponds increasing the proportion of irradiance reaching the water column by up to 25-  
66 31%. The growth period ends with the formation of the marginal ice zone when transmittance in the water  
67 column reaches 40 to 60%. At this point, the absence of limitation by either light or nutrients produce  
68 favourable conditions for exponential growth until the bloom peak is reached (Wassmann and Reigstad,  
69 2011). The initial stock of phytoplankton biomass at the onset of the growth period plays a role in the  
70 timing of the bloom peak for the Southern Ocean (e.g., Sakshaug et al., 1991) and the Arctic Ocean  
71 (Christian et al., 2022). The post-bloom period follows in response to nutrient depletion and grazing  
72 pressure. This period is characterised with a negative or near equilibrium biomass accumulation rate. In  
73 the Arctic Ocean, nutrient depletion is thought to exert a stronger control than grazing (Sakshaug, 2004;  
74 Randelhoff et al., 2019).

75 Here we use a complex ecosystem model within an idealised one-dimensional (1-D) water column  
76 representative of the conditions in Baffin Bay to better understand the crucial processes controlling the

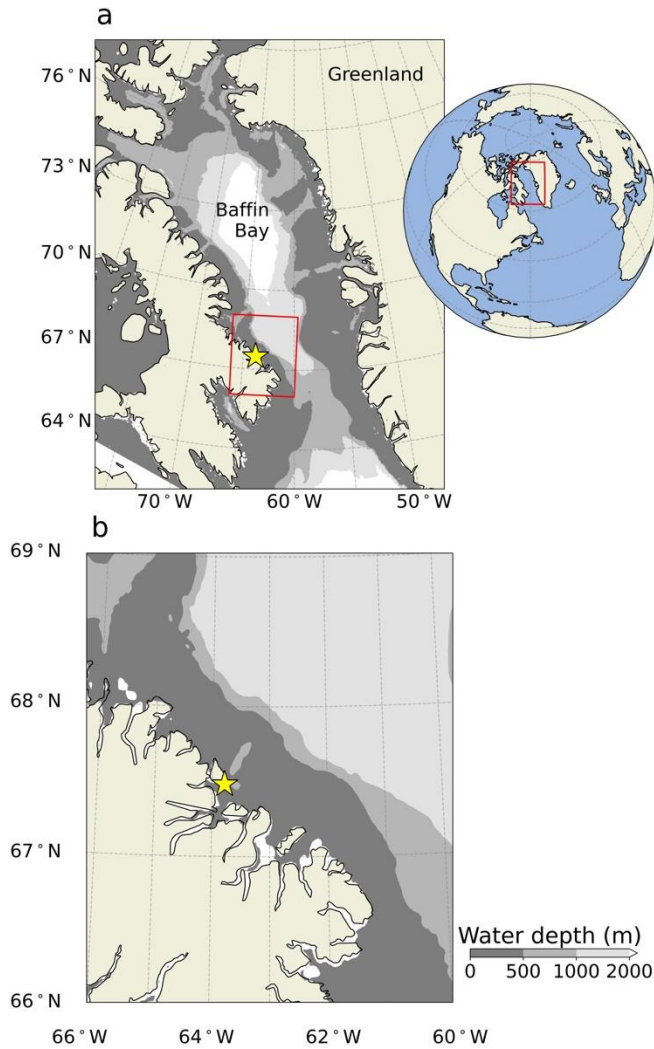
77 timing of the spring bloom. In particular, we consider the role of light, nutrients and overwintering  
78 phytoplankton biomass in the phenology of the spring bloom. Light is thought to control bloom initiation  
79 (Ardyna et al., 2020b), while nitrate is the limiting nutrient in Baffin Bay where its eventual decrease is  
80 thought to cause the end of the bloom (Randelhoff et al., 2019). The phytoplankton standing stock at the  
81 end of the winter is also relevant (Sakshaug et al., 1991; Christian et al., 2022). There remain many  
82 questions on how phytoplankton survive over winter. Here we ask how important this survival is to the  
83 spring bloom dynamics relative to the other controls. To this end, we conducted sensitivity experiments to  
84 better understand and quantify the controls exerted by light, nutrient level and overwintering  
85 phytoplankton biomass at the end of winter.

## 86 2 Materials and methods

### 87 *2.1 Ice camp*

88 The model simulations were configured to represent the location of the ice camp of the Green Edge  
89 mission in western Baffin Bay at (67.48°N, 63.79°W; Figure 1; see Oziel et al., 2019, for details) that  
90 provided rich datasets on oceanographic, biogeochemical and ecological properties of the site (Massicotte  
91 et al., 2019; 2020; see Data S3 in Benoit-Gagné et al., 2024). The camp was on seasonal landfast sea ice  
92 near Qikiqtarjuaq (Nunavut, Canada) with a water depth of 360 m (Massicotte et al., 2020). It will be  
93 referred to as the Qikiqtarjuaq ice camp from here onward. Field observations were collected at the ice  
94 camp in 2016 from April 27 to July 22.

95 During the camp, 134 variables were measured including snow thickness, ice thickness, underwater  
96 photosynthetically active radiation (PAR, 400 to 700 nm), nitrate and silicic acid concentrations,  
97 chlorophyll *a* (Chl *a*) and depth of the mixing layer (in both Oziel et al., 2019, and Massicotte et al.,  
98 2020). Notations and units mentioned in the main text are described in Table S1. Additionally, there were  
99 estimates of the carbon biomass for several plankton taxonomic categories (in both Grondin, 2019, and  
100 Massicotte et al., 2020) from an Imaging FlowCytobot (IFCB; Olson and Sosik, 2007; Sosik and Olson,  
101 2007; Moberg and Sosik, 2012; Laney and Sosik, 2014). The IFCB combines microscopy and flow  
102 cytometry to produce high-speed images of phytoplankton cells. These images can be used to identify  
103 species for cells larger than 10  $\mu\text{m}$  and to identify broader taxonomic groups for cells between 3  $\mu\text{m}$  and  
104 10  $\mu\text{m}$ . Further information is available in Appendix A5.



105

106 **Figure 1. Maps of Baffin Bay and the study site.** The yellow star marker represents the Qikiqtarjuaq sea  
 107 ice camp location (Oziel et al., 2019). a) Map of Baffin Bay. b) Map of the area around the Qikiqtarjuaq  
 108 sea ice camp (enlarged from the red box in panel a). Bathymetry from Jakobsson et al. (2012; see Data S1  
 109 in Benoît-Gagné et al., 2024).

## 110 2.2 Numerical model

### 111 2.2.1 Model description

112 The biogeochemical/ecosystem model follows from Dutkiewicz et al. (2021) but was modified here for  
 113 the Arctic Ocean. We present a brief overview of the simulated functional groups and the size classes.  
 114 Details can be found in Dutkiewicz et al. (2015; 2020) and Appendix A1. Versions of this ecosystem  
 115 model have been run and tested in 1-D configurations that were not specific for the Arctic Ocean  
 116 (Hickman et al., 2010; Wu et al., 2021).

117 In this study, the numerical planktonic ecosystem included 26 phytoplankton types (Figure 2a) divided  
 118 into four biogeochemical functional groups, each defined by a few physiological features.  
 119 Picophytoplankton were the smallest (1.4  $\mu\text{m}$  and 2.0  $\mu\text{m}$  equivalent spherical diameter, *ESD*), diatoms

120 (6.6–154  $\mu\text{m}$ ) required silicic acid, and mixotrophic dinoflagellates (6.6–228  $\mu\text{m}$ ) were capable of  
 121 photosynthesis as well as grazing on other plankton. An additional group of "other nanophytoplankton"  
 122 were analogs of all other phytoplankton types of similar size that were neither diatoms nor mixotrophic  
 123 dinoflagellates (for example, haptophytes such as coccolithophores or *Phaeocystis*). The phytoplankton  
 124 types differed from one another by their maximum growth rate ( $P_{max}^C$ ; Figure 2b) and their half saturation  
 125 for growth on nitrate ( $k_{NO_3}$ ; Figure 2c) and were allometrically (i.e., using a relationship between cell size  
 126 and the parameter) assigned within functional groups (Dutkiewicz et al., 2020; 2021). The half saturation  
 127 for growth on silicic acid ( $k_{Si(OH)_4}$ ), on phosphate ( $k_{PO_4}$ ), on iron ( $k_{Fe}$ ) and on ammonium ( $k_{NH_4}$ ) for  
 128 each type was calculated from the corresponding  $k_{NO_3}$  as described in Appendix A1.2. The photosynthetic  
 129 parameters of the model diatom analogs corresponded well to laboratory observations from Arctic  
 130 diatoms (Figure S1).

131 Subscript  $j$  refers to a specific phytoplankton type and subscript  $k$  refers to a zooplankton type.  $C_j$  is the  
 132 biomass of phytoplankton  $j$  and  $Z_k$  is the biomass of zooplankton  $k$ . The source and sinks of the biomass  
 133 (in carbon) of each phytoplankton type  $j$  ( $S_{C,j}$ ) are calculated such that

$$134 \quad 1. \quad S_{C,j} = P_{max,j}^C \gamma^R \gamma^T \gamma^I C_j - m_{p,j} \gamma^T C_j - \sum_k [g_{jk} Z_k] - \frac{\delta \omega_{p,j} C_j}{\delta z}.$$

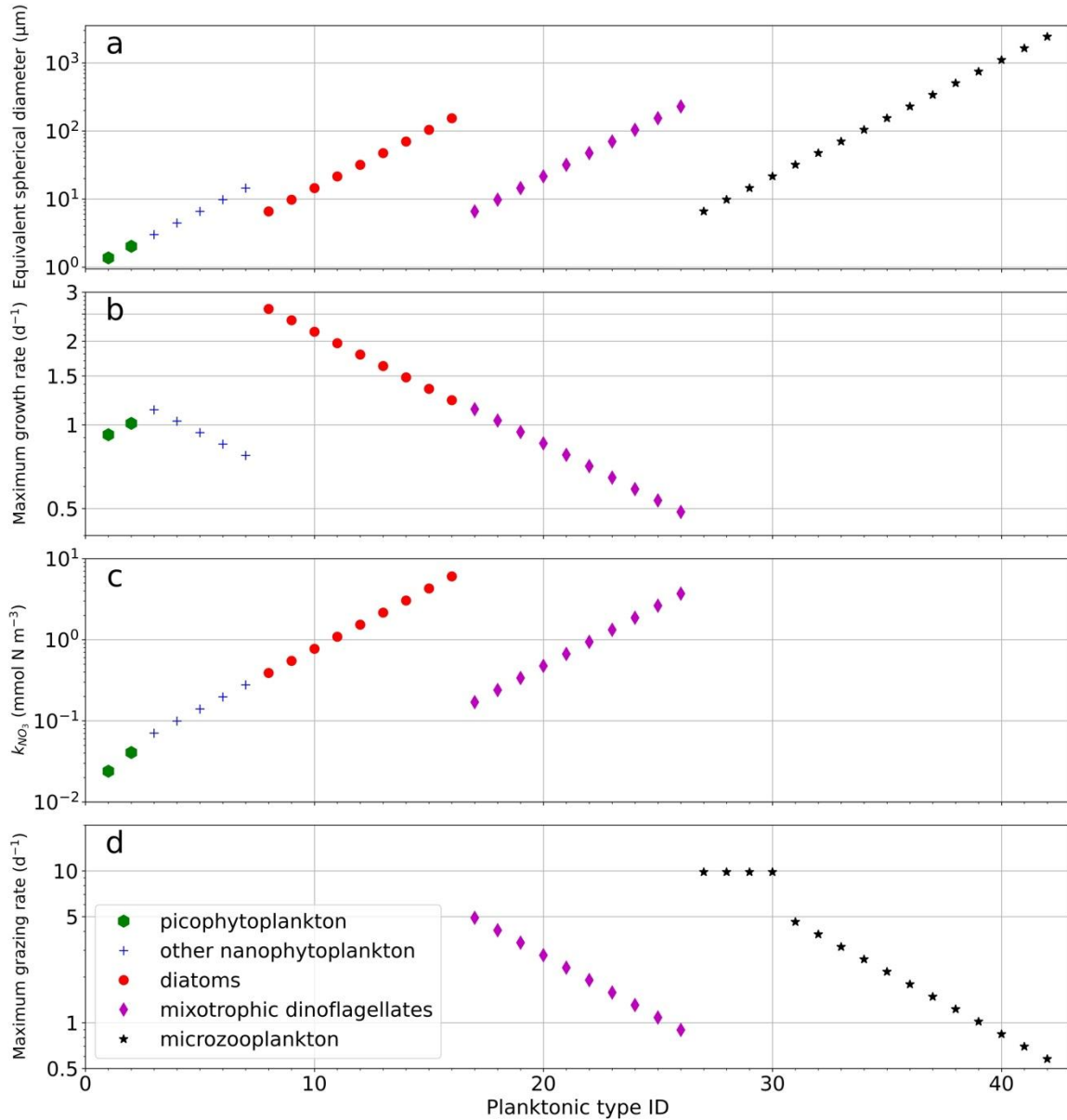
135 The first right-hand term represents biosynthesis. The limitation for growth by nutrients, temperature and  
 136 light ( $\gamma^R$ ,  $\gamma^T$ ,  $\gamma^I$ , respectively) is between 0 (e.g., a lack of light) and 1 (e.g., unlimiting light). The  
 137 calculations of  $\gamma^R$ ,  $\gamma^T$  and  $\gamma^I$  are described in Appendices A1.2, A1.3 and A1.4, respectively. The second  
 138 term represents the compounded losses of biomass due to respiration, senescence, viral lysis and  
 139 excretion. The relative impacts of these processes were not resolved individually. Instead, a bulk  
 140 estimation of these loss processes is calculated from a constant "mortality" rate at 30°C ( $m_{p,j}$ ) of 0.1 d<sup>-1</sup>.  
 141 The third term represents grazing (see Appendix A1.5 for the calculation of the grazing rate of  $j$  by  $k$ ,  $g_{jk}$ ).  
 142 The fourth term represents the sinking with a constant sinking rate ( $\omega_{p,j}$ ) of 0.07 m d<sup>-1</sup> for  
 143 picophytoplankton, 0.36 m d<sup>-1</sup> for diatoms and 0.23 m d<sup>-1</sup> for dinoflagellates and other  
 144 nanophytoplankton. The second and third terms were set to 0 when  $C_j$  dropped below a threshold of  
 145 minimum biomass for phytoplankton  $j$  ( $C_{min,j}$ ) of 10<sup>-2</sup> mmol C m<sup>-3</sup> to simulate survival in winter.  
 146 However, sinking and mixing could still dilute the biomass of phytoplankton  $j$  below this threshold. The  
 147 model includes explicit parameterization of Chl  $a$ , such that each phytoplankton has a dynamic Chl:C  
 148 ratio that alters due to acclimation following Geider et al. (1997; 1998). For the equations and more  
 149 details, the reader is referred to Dutkiewicz et al. (2015).

150 We also consider 16 zooplankton numerical types differing in size, resulting in a marine ecosystem  
 151 containing a complex planktonic community. The maximum grazing rate of the grazers ( $g_{max}$ ) depends on  
 152 their biogeochemical functional group (mixotrophic dinoflagellates or microzooplankton) and their size  
 153 following an allometric relationship. These  $g_{max}$  values are parameterized from the observations by  
 154 Taniguchi et al. (2014) and Jeong et al. (2010; Figure 2d). The four smallest microzooplankton are an  
 155 exception, with a  $g_{max}$  independent of their size (following a lack of observed allometric relationship  
 156 between these smallest types, as in Taniguchi et al., 2014).

157 We used a 1-D configuration representing the specific location of the ice camp in Baffin Bay. The  
 158 configuration had 75 levels ranging in thickness from 1 m near the surface to 6 m near the bottom (which  
 159 was 360 m). Temperature, salinity and vertical turbulent diffusivity ( $K_z$ ) were provided as offline forcing

160 fields. They were generated with a 1-D simulation of the LIM 3.6 sea ice model (Rousset et al., 2015)  
161 coupled to the ocean component of the general circulation model NEMO 3.6 (Madec et al., 2017).  
162 Hereafter these offline forcing fields will be referred to as NEMO-LIM3 (Data S4 in Benoît-Gagné et al.,  
163 2024). The modelled vertical diffusion,  $K_z$  was evaluated by comparing with two different metrics of the  
164 vertical mixing: the depth of the mixing layer and the depth of the equivalent mixed layer ( $h_{BD}$ ). The term  
165  $h_{BD}$  is the depth of the "buoyancy deficit" as in Randelhoff et al. (2017). The depth of the mixing layer  
166 was measured at the ice camp only on June 23, 2016, and corresponded to a  $K_z$  around  $10^{-4} \text{ m}^2 \text{ s}^{-1}$ . The  
167 depth at which  $K_z = 10^{-4} \text{ m}^2 \text{ s}^{-1}$  was considered as the simulated mixed layer depth herein.

168 Preliminary experiments revealed that two major adjustments to Dutkiewicz et al. (2021) were required  
169 for the Arctic setup: setting a minimum threshold below which phytoplankton experienced no losses,  
170 especially during the harsh Arctic winter, and including light under sea ice. The sensitivity experiments  
171 that allowed us to choose the best parameters are presented in Sections 3.3 and 3.4, respectively.



172

173 **Figure 2. Parameters for each numerical type (each numerical species).** a) Size (equivalent spherical  
 174 diameter, ESD). b) Maximum growth rate ( $P_{\max}^C$ ). c) Half saturation for growth on nitrate ( $k_{NO_3}$ ). d)  
 175 Maximum grazing rate ( $g_{\max}$ ).

### 176 2.2.2 Configuring the reference simulation

177 The initial conditions of nitrate, silicic acid and phosphate were prescribed from in situ observations in  
 178 2015 and 2016 (Massicotte et al., 2020). Data could be averaged between mid-April and end of May in  
 179 the two years (Figure 3a and Data S2 in Benoît-Gagné et al., 2024) because the observed nutrients were  
 180 constant during this time (Figures 4c and S2a, b and c for 2016; not shown for 2015) and the stable sea  
 181 ice conditions were likely responsible for this stability in the nutrient profiles during winter. There is no  
 182 advection in a 1-D model, which prevents the supply of nutrients to the surface layer of the water column

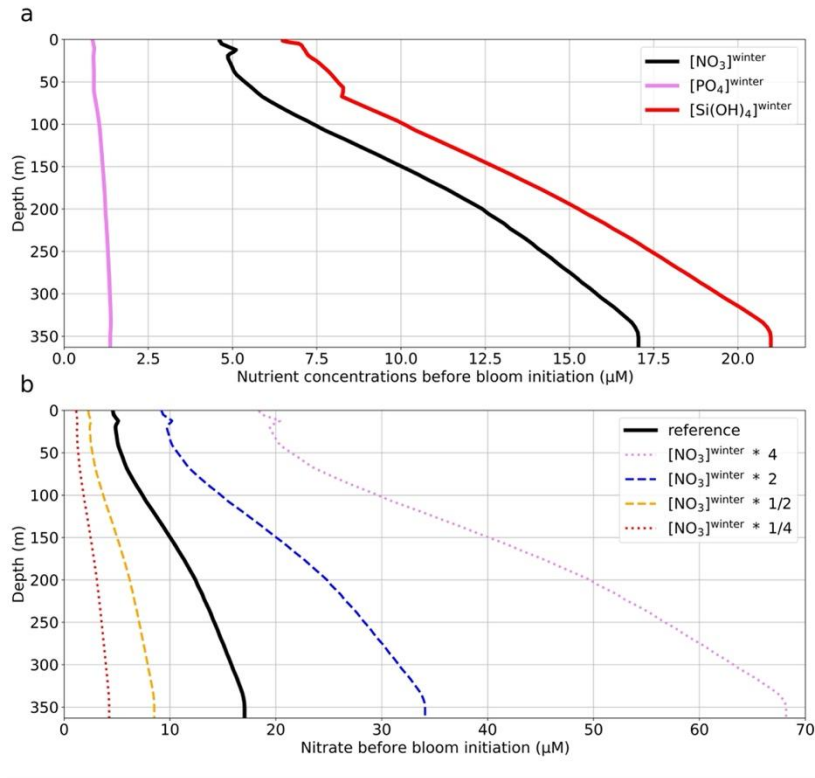


183 and results in their depletion. Compensation for the non-existing lateral advection and the absence of  
184 nutrient inputs by river runoff in the model was then necessary. The solution selected was the relaxation  
185 (reinitialization) of simulated nitrate, silicic acid and phosphate concentrations from January 1 to May 15  
186 to in situ observations from mid-April to the end of May, during the ice-covered period at the ice camp. A  
187 relaxation coefficient of  $1/30 \text{ d}^{-1}$  was used. No relaxation occurs after May 15, 20 days before the start of  
188 snow melt and biological activity in the water column, according to the in situ ice camp data (Oziel et al.,  
189 2019, their Figure 10). A sensitivity experiment on the level of winter nitrate is presented in Section 3.6.

190 Model output from a 10-year spin-up period was used to provide initial conditions of ammonia, nitrite,  
191 total iron and dissolved organic and particulate organic matter. The same initial spin-up model results  
192 provided the total phytoplankton biomass ( $\text{mmol C m}^{-3}$ ). This initial spin-up biomass was then divided  
193 equally between the 26 numerical phytoplankton types to be used as initial conditions for the reference  
194 simulation. The spin-up model output also provided the total zooplankton biomass which, again, was  
195 divided equally between the 16 numerical zooplankton types for initial conditions. At initialization, Chl *a*  
196 is acclimated to light, temperature and nutrients following Geider et al. (1998). But Chl *a* and the Chl:C  
197 ratio are calculated dynamically at each time step of the model.

198 The model time step was 1 h. The "reference" simulation was run forward for another 10 years with  
199 repeating forcing fields. Model results shown are from the last year of simulation. The phytoplankton  
200 established a regular pattern after 2 years, such that we can assume a "quasi-steady state" by year 10, at  
201 which time the initial conditions were no longer influencing the simulation results.

202 Before the sea ice break-up on July 18, the observed downwelling plane PAR just below sea ice in photon  
203 density flux,  $E_{d,i}(z = 0^-, \text{PAR}[Q])$ , was converted to the scalar PAR just below sea ice in photon density  
204 flux,  $E_{0,i}(z = 0^-, \text{PAR}[Q])$ , as described in Appendix A2.1. Observations from the Qikiqtarjuaq ice camp  
205 (Matthes et al., 2019) were used to estimate the conversion factors. After the sea ice break-up, the  
206 downwelling shortwave radiation just above surface in energy units,  $E_s(z = 0^+, \text{SW})$ , from Smith et al.  
207 (2014) was transformed into the scalar PAR just below open water in photon density flux,  $E_{0,w}(z = 0^-,$   
208  $\text{PAR}[Q])$ , as described in Appendix A2.2.  $E_{0,i}(z = 0^-, \text{PAR}[Q])$  and  $E_{0,w}(z = 0^-, \text{PAR}[Q])$  were used as  
209 forcing fields (Data S5 in Benoît-Gagné et al., 2024). The scalar PAR at each depth ( $E_0$ ) was calculated  
210 from  $E_{0,i}(z = 0^-, \text{PAR}[Q])$  before the sea ice break-up and from  $E_{0,w}(z = 0^-, \text{PAR}[Q])$  after the sea ice  
211 break-up as described in Appendix A2.3.



212

213 **Figure 3. Nutrient concentrations between January 1 and May 15.** The solid lines are the in situ  
 214 nutrient concentrations at the Qikiqtarjuaq sea ice camps averaged between mid-April and end of May in  
 215 2015 and 2016. They are also the nutrient concentrations between January 1 and May 15 for the reference  
 216 simulation (EXP-0). a) Nitrate ( $[\text{NO}_3]_{\text{winter}}$ , black), silicic acid ( $[\text{Si}(\text{OH})_4]_{\text{winter}}$ , red) and phosphate  
 217 ( $[\text{PO}_4]_{\text{winter}}$ , purple) concentrations between January 1 and May 15. b) Nitrate concentration ( $[\text{NO}_3]_{\text{winter}}$ ,  
 218 black) between January 1 and May 15. The dotted and dashed lines are the nitrate concentrations between  
 219 January 1 and May 15 for the sensitivity simulations EXP-3 (Table 1). Note the different x-axis scales  
 220 between panels a) and b).

### 221 2.2.3 Simulations

222 Model evaluation was performed by comparing the results of a reference simulation (EXP-0, Table 1;  
 223 Data S6 in Benoît-Gagné et al., 2024) with in situ observations from the ice camp. We explored the tenth  
 224 year of the reference simulation by segmenting it into: pre-bloom, bloom initiation and growth phase, and  
 225 bloom peak. The day of the bloom initiation is defined as the last day of a 7-day positive accumulation  
 226 period (following Boss and Behrenfeld, 2010). The bloom peak is defined as the day of maximum Chl *a*.  
 227 We conducted a series of sensitivity experiments (Table 1) to explore the controls of the bloom timing:  
 228 the magnitude of the biomass before the bloom initiation (EXP-1), treatment of light under sea ice (EXP-  
 229 2) and nitrate concentration before the bloom initiation (EXP-3).

230 **Table 1. Table of sensitivity experiments<sup>a</sup>**

Variable	EXP-0	EXP-1	EXP-2	EXP-3
Minimum biomass	$10^{-2}$	$0, 10^{-3}, 10^{-1}, 10^0$	$10^{-2}$	$10^{-2}$
Light under sea ice	Light under snow and ice	Light under snow and ice	Opaque under snow, opaque under snow and ice	Light under snow and ice
Winter nitrate	Same	Same	Same	Differing

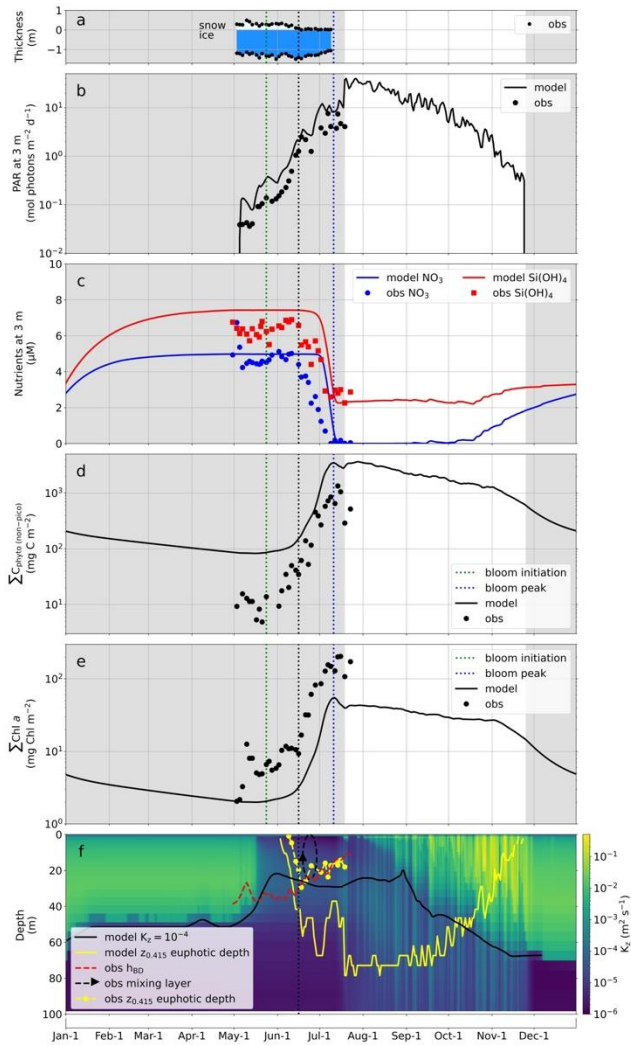
231 <sup>a</sup>The units of the minimum biomass are  $\text{mmol C m}^{-3}$  for each phytoplankton type.

## 232 3 Results

### 233 3.1 Ice camp observations

234 This section describes the observations measured at the ice camp and presented with dots on Figures 4  
 235 and 5. At the sea ice camp, snow melt occurred during the first half of June (Figure 4a and Oziel et al.,  
 236 2019). Sea ice became thinner and melt ponds were created from the middle of June until the full sea ice  
 237 break-up on July 18. The sea ice break-up necessarily led to the end of the ice camp campaign. The  
 238 increase in the underwater light field in June and July (Figure 4b) corresponded to a decrease in the  
 239 observed nutrient concentrations (Figure 4c) and an increase in vertically integrated phytoplankton  
 240 biomass ( $\sum C_{\text{phyto}}$ , 0–100 m; Figure 4d) and chlorophyll *a* ( $\sum \text{Chl } a$ , 0–100 m; Figure 4e).

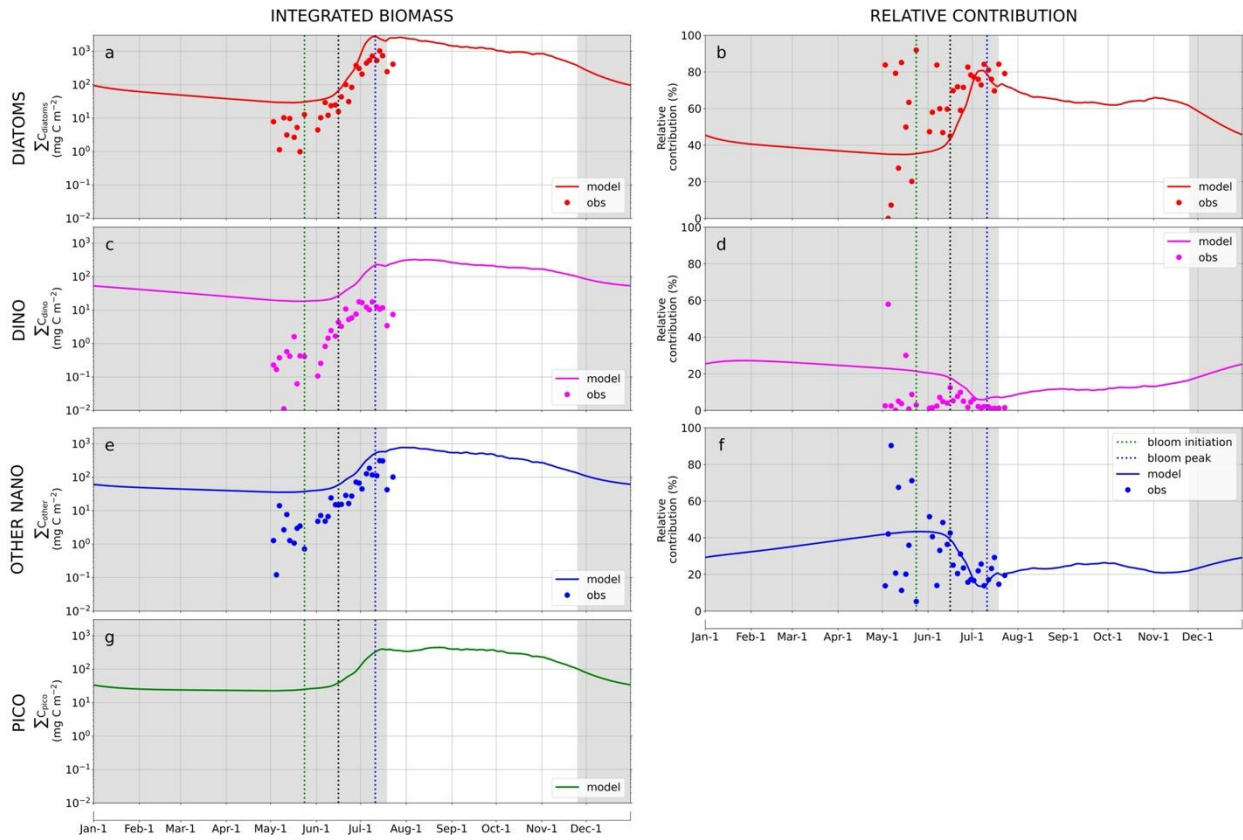
241 The early peak of accumulation rate of  $\sum \text{Chl } a$  on May 9 was likely due to the flushing of sea ice algae  
 242 from the melting ice. Hence, we considered the date of bloom initiation as May 27 (Figure S3 and Table  
 243 S2), a date similar to the date calculated in Oziel et al. (2019). After the snow had melted during the first  
 244 half of June,  $\sum C_{\text{phyto}}$  and  $\sum \text{Chl } a$  increased significantly in mid-June causing a drawdown in nutrients. The  
 245 highest  $\sum \text{Chl } a$  observed was on July 15, right before the sea ice cover disappeared at the ice camp.  
 246 Although  $\sum \text{Chl } a$  may have reached a value higher than that of July 15 after the end of the ice camp  
 247 campaign, for the purposes of this study we assume July 15 as the "peak" of the bloom. From the  
 248 underwater light field, the depth of a "reference isolume" at  $0.415 \text{ mol photons m}^{-2} \text{ d}^{-1}$  ( $z_{0.415}$ ) was  
 249 calculated (Letelier et al., 2004; Boss and Behrenfeld, 2010; Oziel et al., 2019). The significant increase  
 250 in  $\sum \text{Chl } a$  in mid-June was correlated to the shoaling of this reference isolume (Figure 4e and f). This  
 251 isolume followed the observed equivalent mixed layer depth ( $h_{BD}$ , as in Randelhoff et al., 2017; Figure  
 252 4f).



253

254 **Figure 4. Model output and observations for total phytoplankton.** a) Observed snow and ice  
 255 thickness. b) Surface daily photosynthetically active radiation (PAR) at 3 m. Black dots are in situ daily  
 256 downwelling plane PAR. Solid black line is the model daily scalar PAR from the MIT General  
 257 Circulation Model (MITgcm). c) Surface nitrate concentration and silicic acid concentration at 3 m. Dots  
 258 are in situ nutrient concentrations. Lines are the modelled nutrient concentrations from MITgcm. d)  
 259 Vertically integrated biomass of phytoplankton (0–100 m). Dots are in situ biomass. The line is the model  
 260 biomass from MITgcm. Note that picophytoplankton is not included in the analysis of the integrated  
 261 biomass as this group was not part of the observations. e) Vertically integrated Chl *a* (0–100 m). Dots are  
 262 in situ Chl *a*. The line is the model Chl *a* from MITgcm. f) Physical variables. The background is the  
 263 model vertical turbulent diffusivity ( $K_z$ ) from NEMO-LIM3. The depth at which model  $K_z = 10^{-4} \text{ m}^2 \text{ s}^{-1}$  is  
 264 the black solid line. The depth of the model reference isolume at  $0.415 \text{ mol photons m}^{-2} \text{ d}^{-1}$  ( $z_{0.415}$ ) from  
 265 MITgcm is the yellow complete line. The depths of the observed equivalent mixed layer ( $h_{BD}$  as in  
 266 Randelhoff et al., 2017) is the red dashed line. The depth of the observed mixing layer measured on June  
 267 23, 2016, as described in Oziel et al. (2019), is the black dashed arrow. The depth of the observed  
 268 reference isolume at  $0.415 \text{ mol photons m}^{-2} \text{ d}^{-1}$  ( $z_{0.415}$ ) is the yellow dashed line. The vertical green, black  
 269 and blue dotted lines are the dates of the simulated bloom initiation, the snow melt completion and the

270 simulated bloom peak, respectively. The grey shading represents the time of year before the sea ice break-  
 271 up and after the sea ice freeze-up.

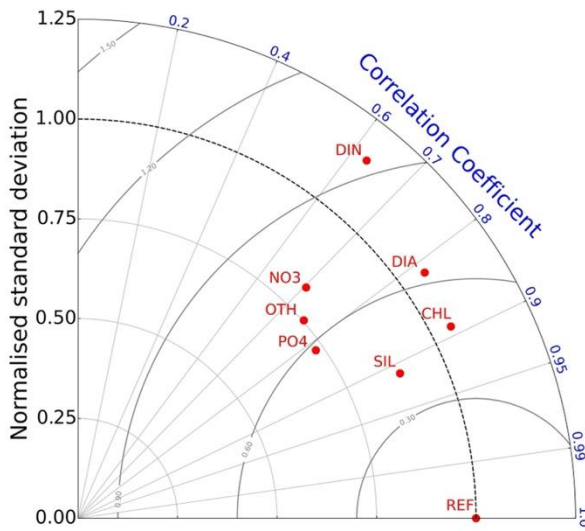


272  
 273 **Figure 5. Model output and observations by phytoplankton group.** Vertically integrated biomass of  
 274 each functional group (0–100 m, left). Relative contribution of each functional group to the total  
 275 (diatoms+dinoflagellates+other nanophytoplankton) biomass (right). a) Integrated biomass of diatoms. b)  
 276 Relative contribution of diatoms. c) Integrated biomass of dinoflagellates. d) Relative contribution of  
 277 dinoflagellates. e) Integrated biomass of other nanophytoplankton. f) Relative contribution of other  
 278 nanophytoplankton. g) Integrated biomass of picophytoplankton. Picophytoplankton carbon biomass was  
 279 not measured during the ice camp, as the Imaging FlowCytobot is not capable of imaging these smaller  
 280 cells. The vertical green, black and blue dotted lines are the dates of the simulated bloom initiation, the  
 281 snow melt completion and the simulated bloom peak, respectively. The grey shading represents the time  
 282 of year before the sea ice break-up and after the sea ice freeze-up.

283

284 **3.2 Reference simulation**

285 The model was evaluated by comparing the simulated variables with observations. A Taylor diagram for  
286 the observational time series summarises the resulting statistics (Figure 6). The correlation coefficient  
287 (angular position) and normalised standard deviation (radial position) are performed on log-normalised  
288 fields. The correlation coefficient of the nutrient concentrations was greater than 0.7 for each nutrient.  
289 Observed  $\Sigma$ Chl *a* was particularly well captured by the model with a correlation coefficient of 0.89.  $\Sigma$ Chl  
290 *a* variability was also well captured with a normalised standard deviation of 1.05. The model captures the  
291 diatoms and other nanophytoplankton biomass well (correlation coefficients of 0.82 and 0.75,  
292 respectively), and slightly worse for the dinoflagellates (correlation coefficient of 0.63). We discuss the  
293 time series of the reference simulation further in terms of three phases: pre-bloom (before May 23),  
294 bloom initiation and growth, and bloom peak on July 10.



295 **Figure 6. Taylor diagram.** Taylor diagram evaluating the model with the observations at the  
296 Qikiqtarjuaq ice camp in 2016. The angular position indicates the correlation coefficient between model  
297 and observed values. The radial position is their normalised (by observed standard deviation) standard  
298 deviation. Statistics are performed on log-normalised fields. CHL indicates Chl *a* concentration obtained  
299 by high-performance liquid chromatography; DIA, diatoms; DIN, dinoflagellates; NO3, nitrate; OTH,  
300 other nanophytoplankton; PO4, phosphate; SIL, silicic acid; REF, perfect match between model and  
301 observations.  
302

303 **3.2.1 Pre-bloom period**

304 This section describes the observed and simulated quantities before the simulated bloom initiation  
305 represented by the vertical green dotted line on May 23 in Figures 4 and 5. In both model and  
306 observations, snow melt had not yet started (Figure 4a) and simulated underwater PAR was low (Figure  
307 4b). Simulated surface nutrient concentrations were high (Figure 4c), matching observations. Simulated  
308 integrated biomass (0–100 m,  $\Sigma C_{\text{phyto}}$ ) and simulated integrated Chl *a* (0–100 m,  $\Sigma$ Chl *a*) were low  
309 (Figure 4d and e, respectively). The simulated biomass was higher than observed, though the simulated  
310 Chl *a* (2 mg Chl m<sup>-2</sup>) was on the lower bound of the observed values of Chl *a* (2–23 mg Chl m<sup>-2</sup>).

### 311 3.2.2 Bloom initiation and growth period

312 The bloom initiation occurred on May 23 in the reference simulation, 4 days before the observations  
313 (Figure 4e). A steep increase in the underwater PAR between bloom initiation and the complete melt of  
314 the snow cover on June 15 (Figure 4b) caused a slow growth period of both observed and simulated  
315  $\sum C_{\text{phyto}}$  and  $\sum \text{Chl } a$  (Figure 4d and e, respectively). This increase in biomass was not enough to decrease  
316 the nutrient concentrations significantly. In both model and observations, the depth of the reference  
317 isolume increased (Figure 4f).

318 The disappearance of the snow cover on June 15 (black dotted vertical line on panels a and b of Figure 4)  
319 allowed the underwater PAR to increase enough to cause a fast growth period (Figure 4a and b). This fast  
320 growth period is visible in both observed and simulated  $\sum C_{\text{phyto}}$  and  $\sum \text{Chl } a$  between the complete melt of  
321 the snow cover on June 15 and the simulated bloom peak on July 10 (blue dotted vertical line on panels d  
322 and e of Figure 4). Simulated and observed nitrate was depleted at the end of this fast growth period, but  
323 not silicic acid (Figure 4c). During the fast growth period, the reference isolume was deeper than  
324 observed (Figure 4f). We discuss this discrepancy in Section 3.2.3.

325 The simulated biomass of the diatoms increased at the same time as the observations, though the model  
326 overestimated the biomass at the start and end of the growth period (Figure 5a). Similarly, the simulated  
327 biomass of the other nanophytoplankton increased at the same time as the observations, though the  
328 biomass was too high over the full season (Figure 5e). The model captured the relative contributions (%)  
329 of diatoms and other nanophytoplankton (Figure 5b and f, respectively) during this period. In particular,  
330 the fast growth period between the disappearance of the snow cover and the bloom peak was associated  
331 with a change in the phytoplankton assemblage from other nanophytoplankton dominance to diatoms.

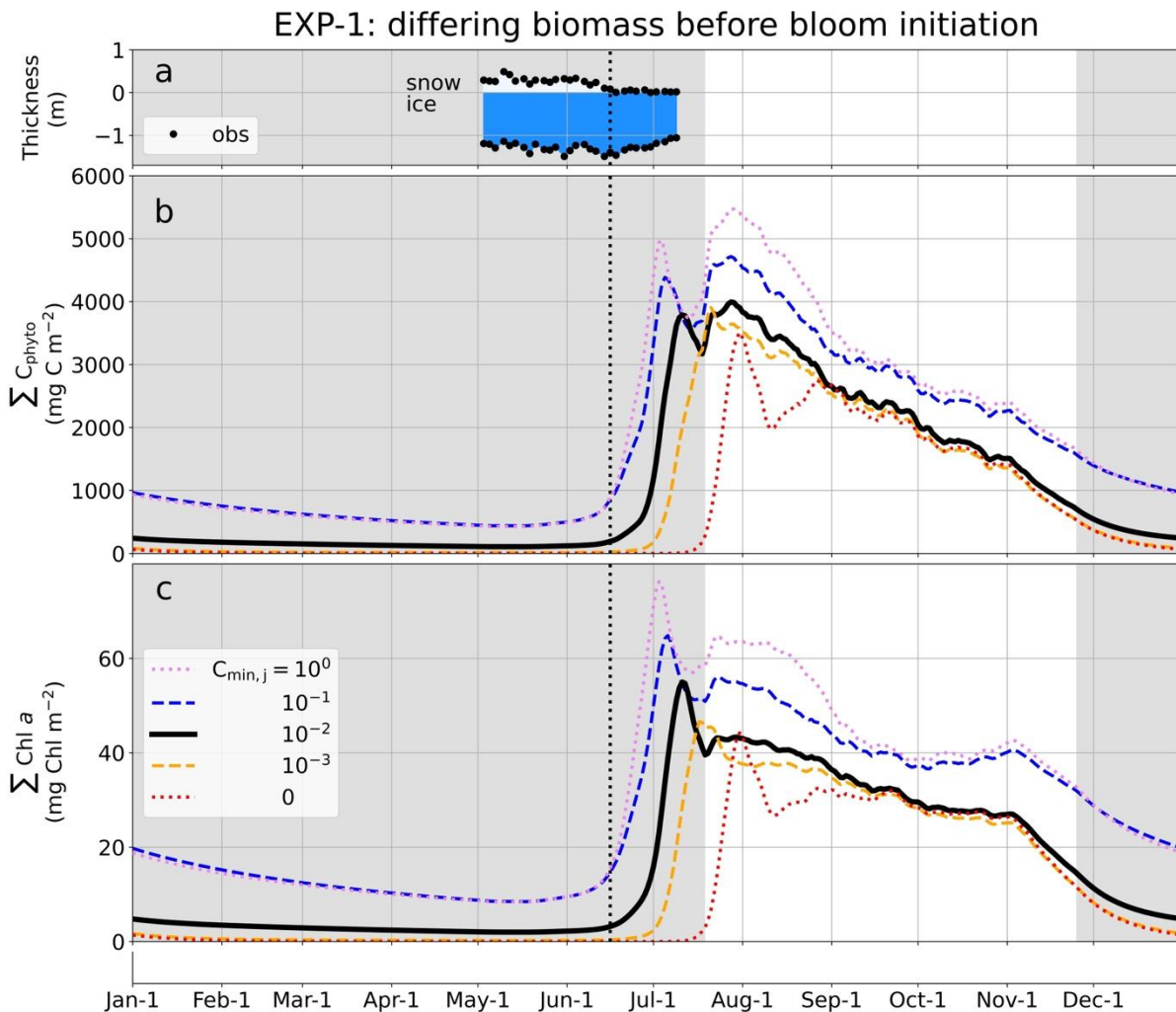
### 332 3.2.3 Bloom peak

333 The depletion of simulated surface nitrate inhibited the growth of phytoplankton after July 10. The steep  
334 increase in surface PAR associated with the sea ice break-up of July 18 led to photoacclimation of the  
335 numerical phytoplankton. This decrease in the Chl:C ratio after the sea ice break-up caused a decoupling  
336 between  $\sum C_{\text{phyto}}$  and  $\sum \text{Chl } a$ . The  $\sum \text{Chl } a$  peak occurred on July 10, 5 days before the observations.  
337  $\sum C_{\text{phyto}}$  from the IFCB continued to increase reaching a maximum on July 27 due to the decoupling.  
338 Following previous studies of the Qikiqtarjuaq sea ice camp (Oziel et al., 2019; Massicotte et al., 2020),  
339 maximum  $\sum \text{Chl } a$  rather than maximum  $\sum C_{\text{phyto}}$  was defined as the bloom peak.

340 The simulated maximum magnitude of  $\sum \text{Chl } a$  of  $55 \text{ mg Chl m}^{-2}$  was underestimated relative to the  
341 observations of  $204 \text{ mg Chl m}^{-2}$ . The fact that the simulated  $\sum C_{\text{phyto}}$  was equal to or above the  
342 observations (Figure 4d) but that the simulated  $\sum \text{Chl } a$  was below the observations (Figure 4e) was  
343 indicative of an underestimation of the Chl:C ratio. This underestimated Chl  $a$  also led to light penetrating  
344 too deep in the simulation (Figure 4f). The trend of the simulated mixed layer depth ( $K_z = 10^{-4} \text{ m}^2 \text{ s}^{-1}$ )  
345 differed from the trend of the observed equivalent mixed layer depth ( $h_{BD}$ , as in Randelhoff et al., 2017)  
346 that was shoaling from 40 m to 10 m during this period of time. Despite underestimating the Chl  $a$   
347 concentration, the temporal trends correlated well with the observations (Figures 4 and S2) and the  
348 subsurface chlorophyll maximum was captured (Figure S2). The biomass of the dinoflagellates was  
349 overestimated particularly after the bloom peak (Figure 5c).

350 **3.3 The role of biomass before bloom initiation**

351 We conducted a series of sensitivity experiments (Table 1) to explore controls of the bloom timing. In the  
 352 model a minimum biomass threshold ( $C_{min,j}$ ) was set below which a phytoplankton type experiences no  
 353 losses such as grazing, maintenance or cell death to account for overwinter survival. In the reference  
 354 simulation (EXP-0),  $C_{min,j}$  was set to  $10^{-2}$  mmol C m<sup>-3</sup> for each phytoplankton type. This parameterization  
 355 allowed the model to maintain winter Chl *a* like that observed at the ice camp (Figure 4e) and in other  
 356 regions of the Arctic Ocean (see Section 4 for more discussion). In the first set of sensitivity experiments  
 357 (EXP-1; Figures 7 and S4), this threshold was either increased ( $C_{min,j} = 10^0$  and  $10^{-1}$  mmol C m<sup>-3</sup>) or  
 358 decreased ( $C_{min,j} = 10^{-3}$  mmol C m<sup>-3</sup> and 0). A higher biomass before bloom initiation ( $C_{min,j} = 10^0$  and  $10^{-1}$   
 359 mmol C m<sup>-3</sup>) caused an earlier bloom peak on July 2 (-8 days) and July 5 (-5 days), respectively. A  
 360 lower biomass before the bloom initiation ( $C_{min,j} = 10^{-3}$  mmol C m<sup>-3</sup> and 0) delayed the bloom peak more  
 361 substantially to July 16 (+6 days) and July 30 (+20 days), respectively.



362

363 **Figure 7. Sensitivity simulations for total phytoplankton: EXP-1 prescribed minimum biomass.** The  
 364 minimum biomass ( $C_{min,j}$ ) was prescribed at 0,  $10^{-3}$ ,  $10^{-2}$ ,  $10^{-1}$  and  $10^0$  mmol C m<sup>-3</sup> for each of the 26  
 365 numerical phytoplankton types. The minimum biomass for the reference simulation was  $10^{-2}$  mmol C m<sup>-3</sup>



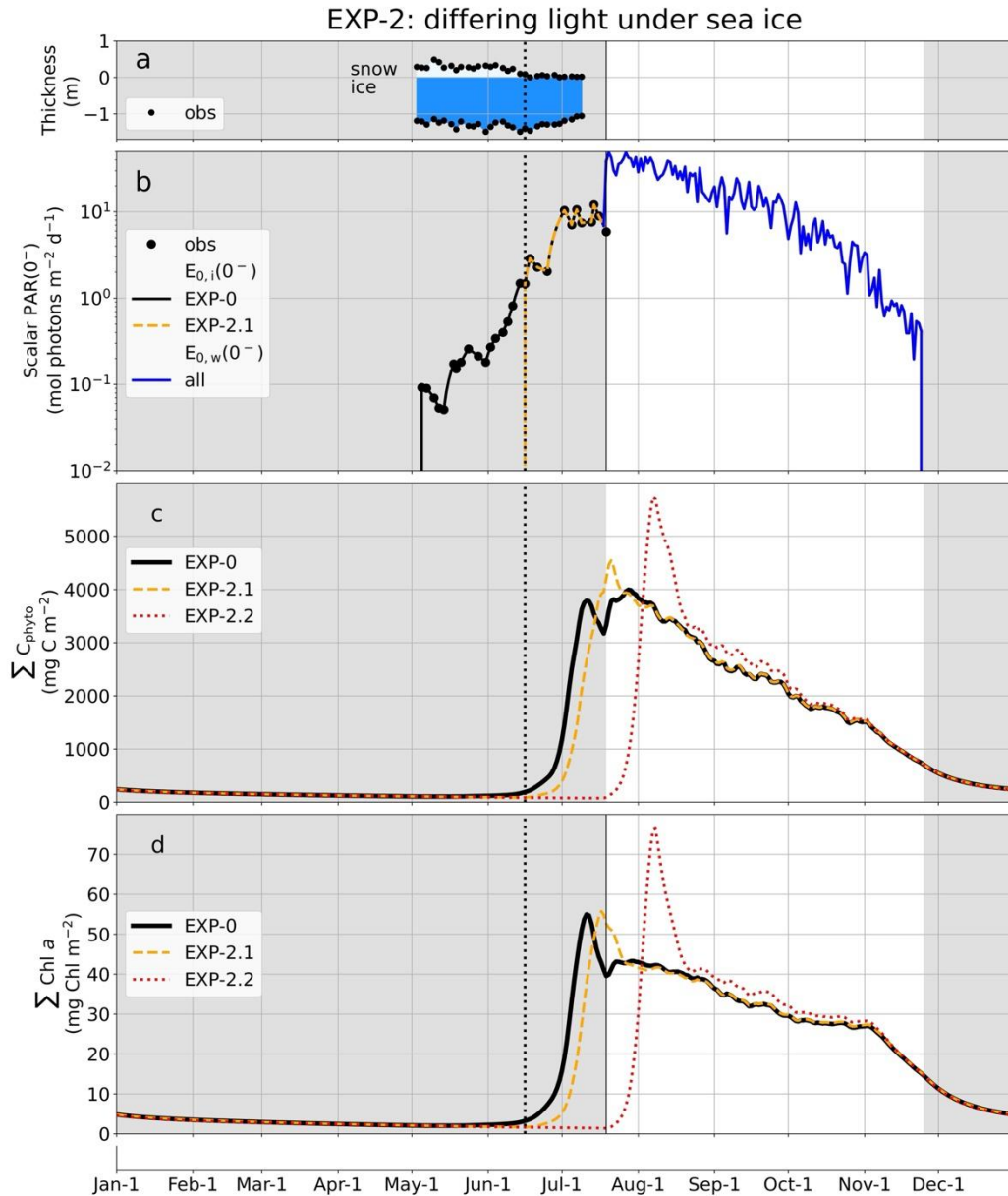
366 (solid black line). This solid black line is the same output as shown in Figure 4d and e for the reference  
367 simulation. a) Observed snow and ice thickness. b) Vertically integrated biomass of phytoplankton (0–  
368 100 m). c) Vertically integrated Chl *a* (0–100 m). The vertical black dotted line is the date of the snow  
369 melt completion. The grey shading represents the time of year before the sea ice break-up and after the  
370 sea ice freeze-up.

371 *3.4 The role of light under sea ice*

372 In the second set of sensitivity experiments (EXP-2), we explored the importance of light in controlling  
373 bloom timing. In the reference simulation (EXP-0), the observed light just below sea ice, both for snow-  
374 covered sea ice and bare sea ice, was used as input for the model (Figures 8 and S5). In EXP-2.1, snow  
375 was considered opaque so that light just below snow-covered sea ice was set to 0 (Figure 8b). In EXP-2.2,  
376 both snow-covered sea ice and bare sea ice were considered opaque such that in this experiment there was  
377 no light below sea ice, both snow-covered sea ice and bare sea ice.

378 Removing light under snow-covered sea ice (EXP-2.1) delayed the bloom initiation to June 22 (+30 days)  
379 and the bloom peak to July 16 (+6 days; Figure 8c and d). Removing light under all sea ice (EXP-2.2)  
380 caused greater delays: in this case, the bloom initiation was delayed until July 25 (+63 days) and the  
381 bloom peak occurred only on August 7 (+28 days).

382



383

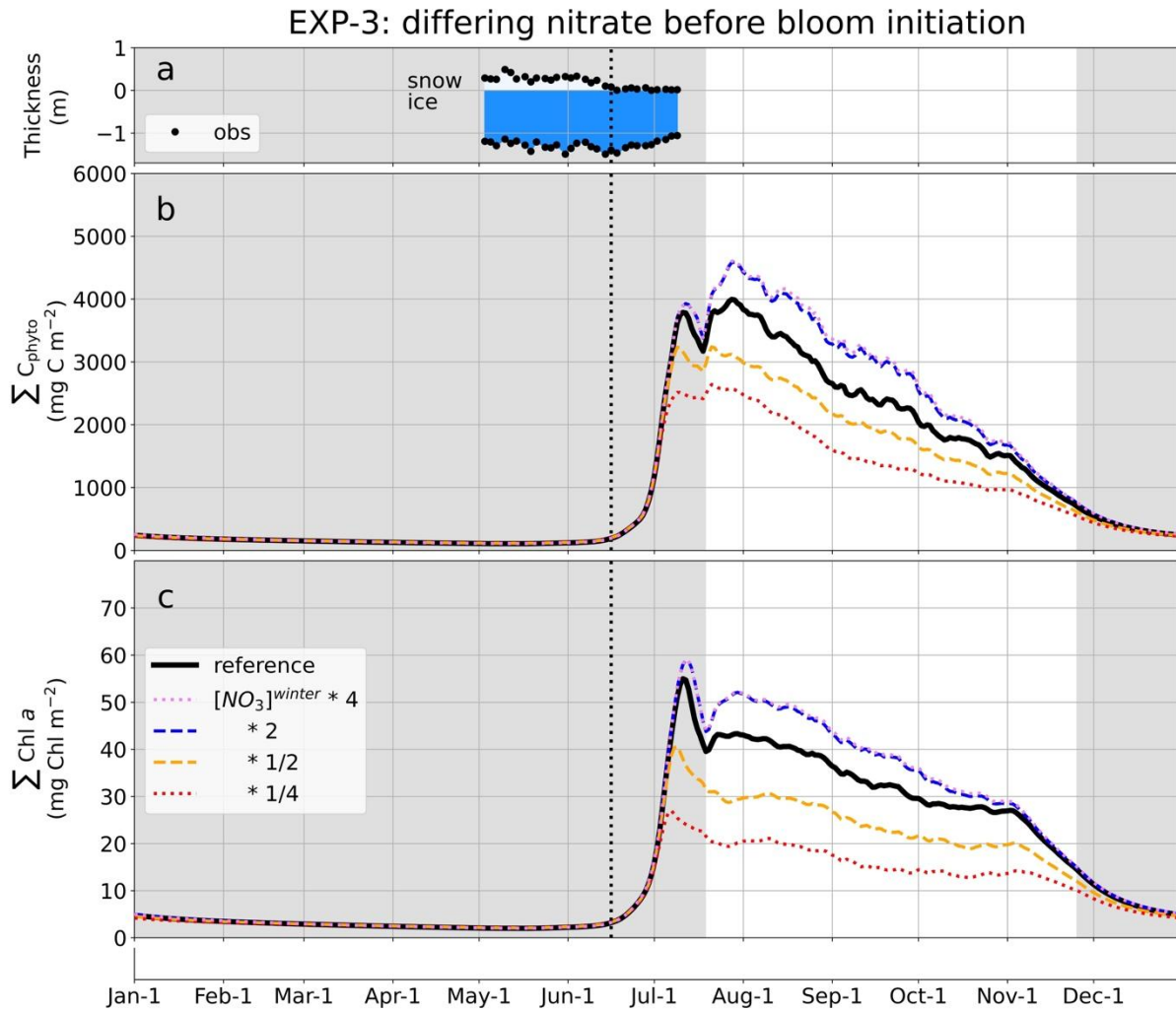
384 **Figure 8. Sensitivity simulations for total phytoplankton: EXP-2 with differing light under sea ice.**  
 385 EXP-0 (reference simulation, solid black line) had light under snow-covered sea ice and under bare sea  
 386 ice. EXP-2.1 (orange dashed line) had no light under snow-covered sea ice but had light under bare sea  
 387 ice. EXP-2.2 (red dotted line) had no light under snow-covered sea ice and no light under bare sea ice;  
 388 this line is not visible on panel b because its value was 0 and the y-axis is logarithmic. All the simulations  
 389 had the same light under open water (solid blue line in panel b). a) Observed snow and ice thickness. b)  
 390 Scalar photosynthetically active radiation (PAR) irradiance just below the surface given as input to the  
 391 model,  $E_0(0^-)$ . The scalar PAR irradiance is just below sea ice,  $E_{0,i}(0^-)$ , until July 18 and just below open  
 392 water,  $E_{0,w}(0^-)$ , after July 18. Black dots are observed in situ scalar PAR irradiance just below sea ice. c)  
 393 Vertically integrated biomass of phytoplankton (0–100 m). d) Vertically integrated Chl *a* (0–100 m). The

394 vertical black dotted line is the date of snow melt completion. The grey shading represents the time of  
395 year before sea ice break-up (left) and after sea ice freeze-up (right).

### 396 *3.5 The role of nitrate before bloom initiation*

397 To explore the importance of the winter pool of nitrate on the timing of the bloom peak, a third set of  
398 sensitivity simulations considered different winter nitrate concentrations (EXP-3; Table 1). In the  
399 reference simulation EXP-0, the winter nutrients were relaxed to in situ observations at the Qikiqtarjuaq  
400 sea ice camps averaged between mid-April and end of May in 2015 and 2016 (Figure 3a). In the  
401 sensitivity simulations EXP-3 (Figures 9 and S6), the winter nitrate concentrations were instead relaxed to  
402 1/4, 1/2, 2 and 4 times that in the reference simulation (Figure 3b).

403 Decreasing nitrate by a factor of 2 or 4 decreased the magnitude of the bloom peak from 55 mg Chl m<sup>-2</sup> to  
404 40 mg Chl m<sup>-2</sup> and 27 mg Chl m<sup>-2</sup>, respectively (Figure 9c). This decrease, in turn, caused a bloom peak  
405 slightly earlier on July 8 (-2 days) and July 6 (-4 days), respectively. The change in timing was much less  
406 than one would expect from the change in nutrients. Conversely, increasing nitrate before the bloom  
407 initiation by a factor of 2 or 4 increased marginally the magnitude of the bloom peak from 55 mg Chl m<sup>-2</sup>  
408 to 59 mg Chl m<sup>-2</sup> in both cases. Consequently, the bloom peak was barely delayed to July 11 (only +1  
409 day).



410

411 **Figure 9. Sensitivity simulations for total phytoplankton: EXP-3 prescribed pre-bloom nitrate**  
 412 **concentrations.** Nitrate concentrations before the bloom initiation ( $[\text{NO}_3]^{\text{winter}}$ ) were prescribed at 4, 2,  
 413 1/2 and 1/4 times that in the default simulation (solid black line). This solid black line is the same output  
 414 as shown in Figure 4d and e for the reference simulation. a) Observed snow and ice thickness. b)  
 415 Vertically integrated biomass of phytoplankton (0–100 m). c) Vertically integrated Chl *a* (0–100 m). The  
 416 vertical black dotted line is the date of snow melt completion. The grey shading represents the time of  
 417 year before sea ice break-up (left) and after sea ice freeze-up (right).

#### 418 4 Discussion

419 Our study has shown that the overwintering biomass was an important control on the timing of the bloom  
 420 peak (EXP-1; Figure 7). When the biomass before bloom initiation was lower than observed there was a  
 421 delay in the peak Chl *a*. The simulated Chl *a* before the bloom initiation achieved with the  $C_{\text{min},j}$  of the  
 422 reference simulation (EXP-0) was between  $10^{-2}$  and  $10^{-1}$  mg Chl  $\text{m}^{-3}$ , like the observed Chl *a* in May at  
 423 the Qikiqtarjuaq ice camp (Figure S7). Randelhoff et al. (2020) measured Chl *a* with gliders in offshore  
 424 Baffin Bay during the winters 2017–2018 and 2018–2019. Their values were also between  $10^{-2}$  and  $10^{-1}$

425 mg Chl m<sup>-3</sup> (their Figure 2e), supporting that a numerical winter Chl *a* above 10<sup>-2</sup> mg Chl m<sup>-3</sup> was  
426 realistic. The impact of pre-bloom biomass on the timing of the phytoplankton bloom peak is not  
427 surprising and has also been highlighted for ice algal growth and bloom timing (Mortenson et al., 2017;  
428 Haddon et al., 2024).

429 In our model, a value range of 10<sup>-2</sup> to 10<sup>-1</sup> mg Chl m<sup>-3</sup> for Chl *a* before bloom initiation was achieved by  
430 halting any further losses from metabolism, grazing or other mortality (terms 2 and 3 in Equation 1) when  
431 the biomass of one type of phytoplankton dropped below  $C_{min,j}$ . This parameterization was necessary to  
432 maintain an overwintering biomass, but is obviously an extreme oversimplification of complex processes  
433 controlling the survival of phytoplankton communities during winter. The numerical  $C_{min,j}$ , however,  
434 could compensate for excessive phytoplankton sinking and dilution in the model and could also represent  
435 the missing three-dimensional features of the sea ice such as production in leads. This simple  
436 implementation of a threshold biomass is the minimum parameterization needed in a biogeochemical  
437 model to mimic the particular conditions of the Arctic. It might also apply to the Austral Ocean given  
438 polar night there as well. A similar parameterization has been implemented by several model studies  
439 (Mortenson et al., 2018; Christian et al., 2022; Bertin et al., 2023; Haddon et al., 2024), but none of the  
440 studies provided detailed documentation of the impacts. Chl *a* in the oligotrophic subtropical gyres falls  
441 between 10<sup>-2</sup> and 10<sup>-1</sup> mg Chl m<sup>-3</sup> (Kuhn et al., 2023), similar to winter observations in Baffin Bay. These  
442 Chl *a* values suggest that carbon biomass is low and comparable in both systems. However, these two  
443 systems differ in the seasonality of the zooplankton predation, as the pressure of zooplankton grazing is  
444 continuous in oligotrophic tropical gyres. Therefore, using a parameterization that stops grazing in  
445 oligotrophic tropical gyres would not be appropriate, and  $C_{min,j}$  should not be used globally. A simple  
446 workaround could be an empirical relationship between the latitude and the  $C_{min,j}$  threshold, while a more  
447 comprehensive solution could be the decomposition of the linear mortality into various loss terms, each  
448 one mechanistically formulated (e.g., senescence, viral lysis of phytoplanktonic cells, etc.).

449 However, a clearer understanding of what maintains the overwintering biomass is needed for newer and  
450 better parameterizations. By implementing a realistic overwintering biomass and demonstrating its  
451 importance, this study is a first step in its mechanistic implementation. This implementation would  
452 benefit from the results of laboratory experiments at extremely low light. For example, the limitation for  
453 growth by light ( $\gamma^I$ ) could be modified in winter to allow more phototrophy at low levels (Kvernvik et al.,  
454 2018; Hancke et al., 2018). The mortality term ( $m_{p,j}$ ) could be reduced in winter to represent reduced  
455 metabolism (Lacour et al., 2019; Kennedy et al., 2020; Joli et al., 2024) and sparing consumption of  
456 storage lipids (Morin et al., 2020). In winter, mixotrophy (Vader et al., 2015; Błachowiak-Samołyk et al.,  
457 2015; Marquardt et al., 2016; Kvernvik et al., 2018; Stoecker and Lavrentyev, 2018; Johnsen et al., 2020)  
458 could be enhanced or osmotrophy (Wen et al., 2002; Lavoie et al., 2018; Johnsen et al., 2020) could be  
459 activated. Winter grazing by zooplankton could be reduced by modifying the limitation of grazing by  
460 temperature ( $\gamma^T$ ) in winter to represent the negligible losses to herbivorous grazing (Frost, 1993; Rose  
461 and Caron, 2007) or by implementing diapause on mesozooplankton (Baumgartner and Tarrant, 2017).  
462 Another strategy of survival during the polar night is resting stage formation (Johnsen et al., 2020).

463 Several studies have reported that Arctic diatoms can survive in the dark for months and start  
464 photosynthesis rapidly (within a few hours) when light returns (e.g., Lacour et al., 2019; Kennedy et al.,  
465 2020; Morin et al., 2020; Handy et al., 2024): a finding that has been confirmed in situ in Svalbard  
466 (Kvernvik et al., 2018). Both field experiments and laboratory experiments suggest that photosynthesis

467 can occur at very low light from 0.17 to 1  $\mu\text{mol photons m}^{-2} \text{s}^{-1}$  (Geider et al., 1986; Hancke et al., 2018;  
468 Kvernvik et al., 2018). Accumulation of biomass generally does not occur until higher light levels  
469 between 1.2 and 2.3  $\mu\text{mol photons m}^{-2} \text{s}^{-1}$  are available (Geider et al., 1986; Ardyna et al., 2020b).  
470 However, biomass accumulation has been observed to occur at levels lower than previously thought, for  
471 example, in February in offshore Baffin Bay shortly after the winter solstice (Randelhoff et al., 2020).  
472 Recent field observations (Ardyna et al., 2020b; Randelhoff et al., 2020) show that even in Arctic marine  
473 ecosystems, blooms can start before stratification occurs, which is coherent with the dilution recoupling  
474 hypothesis (Behrenfeld, 2010; Behrenfeld and Boss, 2018). Importantly, the minimum light thresholds for  
475 photosynthesis and a positive accumulation rate remain uncertain. Further laboratory experiments with  
476 extremely low irradiances are needed.

477 The importance of under-ice PAR in triggering the initiation of the under-ice bloom is better understood  
478 (Ardyna et al., 2020a; 2020b). With the absence of light under snow-covered sea ice (EXP-2.1) and the  
479 absence of light under any sea ice (EXP-2.2), the bloom peak was delayed significantly (+6 and +28 days,  
480 respectively).

481 Finally, the magnitude of the bloom peak was only slightly affected by the winter pool of nitrate (EXP-3,  
482 Figure 9). Nitrate concentration before the bloom initiation had no effect on the initiation of the bloom  
483 and was only a modest control on the timing of the bloom peak. Because the accumulation of  
484 phytoplankton was exponential, a linear variation in winter nitrate and thus the magnitude of the bloom at  
485 its peak did not change the date of the bloom peak by much.

486 The model used in this study did not include a sympagic component. Previous modelling studies have  
487 shown some influence of ice algal production on the magnitude of the phytoplankton bloom in Arctic  
488 marine ecosystems (Hayashida et al., 2017; Mortenson et al., 2017). These studies suggested that seeding  
489 of phytoplankton production by ice algae sloughing from the sea ice in spring influenced the timing of  
490 both the bloom initiation and bloom peak by a few days. However, a review of in situ studies showed that  
491 only when extreme meteorological events trigger mass release of ice algae into the water column is  
492 seeding from sea ice an important control of the timing of under-ice blooms (Ardyna et al., 2020a).  
493 Another observation that may be interpreted as against seeding by ice algal sloughing is that the genera of  
494 polar diatoms observed in the winter water column (Vader et al., 2015; Kvernvik et al., 2018) are also  
495 those found in the spring phytoplankton bloom (Hoppe, 2022). Another impact of sea ice algae on  
496 phytoplankton production involves a shading effect. In simulations, ice algal shading can have a strong  
497 impact on the timing of the phytoplankton bloom under the ice when ice algal biomass is high (Castellani  
498 et al., 2017; Hayashida et al., 2019). In this study, observed PAR just below the (real) sea ice, and thus  
499 including the shading impact of sea ice algae, was used as a forcing field. Further research on the impact  
500 of sea-ice algae is warranted but is beyond the scope of this study.

501 The physical variables at the location of the ice camp were close to the conditions of offshore western  
502 Baffin Bay (Appendix 6.4). The conditions at the ice camp followed the dynamics described for offshore  
503 areas with phytoplankton bloom initiation occurring while there was still ice (Randelhoff et al., 2019;  
504 2020). The processes at the ice camp and in western Baffin Bay (of which the ice camp is representative)  
505 are typical of an outflow shelf environment. Seasonal sea ice cover fosters sizable pelagic blooms as soon  
506 as sea ice becomes translucent due to the deepening of the euphotic zone and the shoaling of the mixed  
507 layer depth (Randelhoff et al., 2019) in a manner similar to other outflow shelf environments of the Arctic

508 Ocean, such as the Canadian Arctic Archipelago and the East Greenland shelf (Ardyna et al., 2020a).  
509 These outflow shelves are expected to react similarly to climate change (Ardyna and Arrigo, 2020). Thus,  
510 we believe that our study has broader implications than the single location studied here, although our  
511 study is specific to the polar regions.

## 512 5 Conclusion

513 Our study has shown that phytoplankton biomass at the end of winter is a key parameter for accurately  
514 modelling the spring phytoplankton bloom in a seasonal sea ice zone. Though a minimum threshold  
515 biomass parameterization has been used in previous studies, to our knowledge this study provides the first  
516 published sensitivity analysis. Our study also agrees with earlier results about the necessity of a  
517 reasonable representation of light transmittance through sea ice, especially for bare sea ice compared to  
518 snow-covered sea ice. Here we have shown that winter biomass and light under sea ice are comparably  
519 important controls for the timing of the bloom peak (+20 days when no winter biomass and +28 days  
520 when no light under sea ice). Research campaigns so far have generally concentrated efforts on measuring  
521 light in the water and have not focused on measuring winter biomass. Our results have shown that both  
522 observations will be important for further understanding of the spring phytoplankton bloom. This study  
523 highlights the need for field and laboratory experiments to gain a more precise understanding on the  
524 acclimation and adaptations by phytoplankton to maintain a balance between biomass growth and losses  
525 during the harsh Arctic winter. A better characterization of the underwater light field during the polar  
526 night will also be worthwhile, as darkness is never complete because of moonlight among other reasons  
527 (Cohen et al., 2020). Only with a better understanding of the mechanisms of survival of phytoplankton  
528 during winter we will be able to parameterize this aspect more realistically in models. Better models of  
529 Arctic ecosystems are urgently needed as this region has warmed four times faster than the global average  
530 since 1979, a phenomenon known as Arctic amplification (Rantanen et al., 2022). The crude  
531 parameterization of a minimum phytoplankton biomass threshold is, however, an initial step towards  
532 more accurately representing the timing of the bloom peak.



## 533 6 Appendix

### 534 6.1 A1 Biogeochemical/ecosystem model

535 Only an overview of the model is presented here. More detail and equations can be found in Dutkiewicz  
536 et al. (2015; 2020) and at [https://darwin3.readthedocs.io/en/latest/phys\\_pkgs/darwin.html](https://darwin3.readthedocs.io/en/latest/phys_pkgs/darwin.html) (accessed May  
537 30, 2024). See Tables S3, S4 and S5 for the units of the variables, the values of the constants and the  
538 coefficients for allometric scaling, respectively.

#### 539 6.1.1 A1.1 Phytoplankton growth

540 The carbon-specific photosynthesis rate of phytoplankton ( $P^C$ ) is dependent on maximum growth rate  
541 ( $P^C_{max}$ ; Figure 2b) and limitation for growth by nutrients, temperature and light ( $\gamma^R$ ,  $\gamma^T$ ,  $\gamma^I$ , respectively,  
542 between 0 and 1) such that

$$543 \quad 2. \quad P^C = P^C_{max} \gamma^R \gamma^T \gamma^I.$$

544 A limitation for growth of 0 means no growth because there are no nutrients, for example, or no light. A  
545 limitation for growth of 1 means no limitation for growth. The limitation for growth by nutrients,  
546 temperature and light is described in Appendices A1.2, A1.3 and A1.4, respectively.

#### 547 6.1.2 A1.2 Nutrient limitation for growth

548 The half saturation for growth on nitrate ( $k_{NO_3}$ ; Figure 2c) is modelled as in Dutkiewicz et al. (2020)  
549 using the model Monod formulation of growth rate (Follows et al., 2018):

$$550 \quad 3. \quad k_{NO_3} = K_{NO_3} \frac{P^C_{max} Q_N^{min}}{V_{NO_3}^{max}}.$$

551 The cell nutrient uptake half saturation constant on nitrate ( $K_{NO_3}$ ; Figure S8a) is dependent on size but not  
552 on group as

$$553 \quad 4. \quad K_{NO_3} = a_{K_{NO_3}} V^{b_{K_{NO_3}}},$$

554 where  $a_{K_{NO_3}}$  and  $b_{K_{NO_3}}$  are coefficients for allometric scaling and  $V$  is the cell volume. The maximum  
555 growth rate ( $P^C_{max}$ ; Figure 2b) is dependent both on size  $V$  and on group  $g$  as

$$556 \quad 5. \quad P^C_{max} = a_{P^C_{max,g}} V^{b_{P^C_{max,g}}},$$

557 where  $a_{P^C_{max,g}}$  and  $b_{P^C_{max,g}}$  are the coefficients for allometric scaling dependent on group  $g$ . The cell  
558 minimum stoichiometric quota of nitrogen relative to carbon ( $Q_N^{min}$ ; Figure S8b) is dependent on size but  
559 not on group as

$$560 \quad 6. \quad Q_N^{min} = a_{Q_N^{min}} V^{b_{Q_N^{min}}},$$

561 where  $a_{Q_N^{min}}$  and  $b_{Q_N^{min}}$  are coefficients for allometric scaling. The cell nutrient uptake rate of nitrate  
562 relative to carbon ( $V_{NO_3}^{max}$ ; Figure S8c) is dependent on size but not on group as

563 7.  $V_{NO_3}^{max} = a_{V_{NO_3}^{max}} V_{NO_3}^{b_{V_{NO_3}^{max}}}$ ,

564 where  $a_{V_{NO_3}^{max}}$  and  $b_{V_{NO_3}^{max}}$  are coefficients for allometric scaling. The cell elemental C:N:Si:P:Fe  
 565 stoichiometry is 120:16:16:1:0.001. (Only diatoms have silicon.) The half saturation for growth on silicic  
 566 acid ( $k_{Si(OH)_4}$ ) is computed using this stoichiometry as

567 8.  $k_{Si(OH)_4} = k_{NO_3} \times \frac{16}{16} = k_{NO_3}$ .

568 The half saturation for growth on phosphate ( $k_{PO_4}$ ) is computed similarly as

569 9.  $k_{PO_4} = k_{NO_3} \times \frac{1}{16}$ .

570 The half saturation for growth on iron ( $k_{Fe}$ ) is computed similarly as

571 10.  $k_{Fe} = k_{NO_3} \times \frac{1}{16000}$ .

572 The half saturation for growth on ammonia ( $k_{NH_4}$ ) is computed with a factor of 1/2 because  
 573 phytoplankton preferentially use ammonia:

574 11.  $k_{NH_4} = k_{NO_3} \times \frac{1}{2}$ .

575 The most limiting nutrient determines the value of the nutrient limitation for growth ( $\gamma^R$ , between 0 and 1)  
 576 as

577 12.  $\gamma^R = \min\left(\frac{R_{NO_3} + R_{NO_2}}{R_{NO_3} + R_{NO_2} + k_{NO_3}} e^{-\sigma_{NH_4} R_{NH_4}} + \frac{R_{NH_4}}{R_{NH_4} + k_{NH_4}}, \frac{R_{Si(OH)_4}}{R_{Si(OH)_4} + k_{Si(OH)_4}}, \frac{R_{PO_4}}{R_{PO_4} + k_{PO_4}}, \frac{R_{Fe}}{R_{Fe} + k_{Fe}}\right)$ ,

578 where  $\sigma_{NH_4}$  is the coefficient for ammonia inhibition of nitrogen uptake and  $R_{NO_3}$ ,  $R_{NO_2}$ ,  $R_{NH_4}$ ,  $R_{Si(OH)_4}$ ,  
 579  $R_{PO_4}$  and  $R_{Fe}$  are the concentrations of nitrate, nitrite, ammonia, silicic acid, phosphate and iron,  
 580 respectively.

### 581 6.1.3 A1.3 Temperature limitation for growth

582 Temperature modulation for growth ( $\gamma^T$ , between 0 and 1) is calculated from the ambient temperature ( $T$ )  
 583 as in Dutkiewicz et al. (2015):

584 13.  $\gamma^T = \tau_T \exp\left(A_T \left(\frac{1}{T} - \frac{1}{T_N}\right)\right)$ ,

585 where  $\tau_T$  is a normalisation factor for temperature function,  $A_T$  is a constant and  $T_N$  is the reference  
 586 temperature. The interval of ambient temperature in the forcing fields of the simulation was  $-1.8^\circ\text{C}$  to  
 587  $2.9^\circ\text{C}$ . Following Equation 13, the interval of modification of growth rate by temperature was 0.27 to 0.34.  
 588 The term  $\gamma^T$  was the same for all plankton types.

### 589 6.1.4 A1.4 Light limitation for growth

590 Light limitation for growth ( $\gamma^I$ , between 0 and 1) follows Geider et al. (1998) as described in Dutkiewicz  
 591 et al. (2015):

592           14.  $\gamma^I = 1 - \exp\left(\frac{-\alpha^{chl} E_0 \theta}{P_{max}^C \gamma^R \gamma^T} \frac{1}{M_C} \frac{24h}{d}\right)$ ,

593 where  $\alpha^{chl}$  is a constant linear initial slope of the Chl *a*-specific photosynthesis versus irradiance curve in  
 594 nutrient-replete conditions (Figure S1b),  $E_0$  is the scalar PAR,  $\theta$  is the Chl:C ratio,  $P_{max}^C$  is the maximum  
 595 growth rate (Figure 2b),  $\gamma^R$  is the nutrient limitation for growth,  $\gamma^T$  is the temperature modulation for  
 596 growth and  $M_C$  is the molar mass of carbon. The last two factors of Equation 14 are required to correctly  
 597 convert the units of  $\theta$  and  $\alpha^{chl}$ . The production of new Chl *a* follows Geider et al. (1997) and Geider et al.  
 598 (1998) as described in Dutkiewicz et al. (2015).

599 **6.1.5 A1.5 Grazing**

600 Grazing follows from Dutkiewicz et al. (2020) as

601           15.  $g_{jk} = g_{max,k} \gamma^T \frac{\sigma_{jk} B_j}{G_k} \frac{G_k^2}{G_k^2 + k_p^2}$ .

602 The subscript *j* is the prey, and the subscript *k* is the predator. The term  $g_{jk}$  is the grazing rate. The  
 603 maximum grazing rates ( $g_{max,k}$ ; Figure 2d) are from observations (Jeong et al., 2010; Taniguchi et al.,  
 604 2014). The term  $\sigma_{jk}$  is palatability,  $B_j$  is prey biomass and  $G_k$  is the palatability-weighted total  
 605 phytoplankton biomass as

606           16.  $G_k = \sum_j \sigma_{jk} B_j$ .

607 The grazing half saturation rate ( $k_p$ ) is a constant.

## 608 6.2 A2. Scalar photosynthetically active radiation

609 In this section, we provide a description of the calculation of the scalar PAR at each depth. Appendix  
610 A2.1 describes the calculation of the scalar PAR just below the surface when the surface was sea ice  
611 before July 18. Appendix A2.2 describes the calculation of the scalar PAR just below the surface when  
612 the surface was open water from July 18. Appendix A2.3 describes the calculation of the scalar PAR at  
613 each depth from the scalar PAR just below the surface. Equations from Appendix A2.3 were used the  
614 whole year. See Tables S6 and S7 for the units of the variables and the values of the constants,  
615 respectively.

### 616 6.2.1 A2.1 Scalar photosynthetically active radiation below sea ice

617 The downwelling plane PAR just below sea ice in photon density flux,  $E_{d,i}(z = 0^-, PAR[Q])$  (Data S5 in  
618 Benoit-Gagné et al., 2024), was measured as described in Oziel et al. (2019) and Massicotte et al. (2020).  
619 The average cosine ( $\mu_d$ ) was used to calculate the downwelling scalar PAR just below sea ice in photon  
620 density flux,  $E_{0d,i}(z = 0^-, PAR[Q])$ :

$$621 \quad 17. E_{0d,i}(z = 0^-, PAR[Q]) = E_{d,i}(z = 0^-, PAR[Q]) / \mu_d.$$

622 Following the observations of Matthes et al. (2019) at the Qikiqtarjuaq ice camp,  $\mu_d$  was set to 0.6 under  
623 snow-covered sea ice and to 0.7 under bare sea ice. The observations of Matthes et al. (2019) also allowed  
624 the conversion of  $E_{0d,i}(z = 0^-, PAR[Q])$  into the scalar PAR just below sea ice in photon density flux,  $E_{0,i}(z$   
625  $= 0^-, PAR[Q])$  (Figure 8b; Data S5 in Benoit-Gagné et al., 2024), as

$$626 \quad 18. E_{0,i}(z = 0^-, PAR[Q]) = E_{0d,i}(z = 0^-, PAR[Q]) 1.03.$$

### 627 6.2.2 A2.2 Scalar photosynthetically active radiation below open water

628 Downwelling shortwave radiation just above surface in energy units,  $E_s(z = 0^+, SW)$  (Figure S9a), was  
629 from Smith et al. (2014). The processing of  $E_s(z = 0^+, SW)$  followed that of the biogeochemical model  
630 PISCES (Aumont et al., 2015). The downwelling shortwave radiation just below open water in energy  
631 units,  $E_s(z = 0^-, SW)$  (Figure S9b), was calculated with an albedo for open water,  $\alpha_w = 0.066$ , as

$$632 \quad 19. E_s(z = 0^-, SW) = E_s(z = 0^+, SW) (1 - \alpha_w).$$

633 The scalar PAR just below open water in energy units,  $E_{0,w}(z = 0^-, PAR[W])$  (Figure S9c), was calculated  
634 using a factor of 0.43 as

$$635 \quad 20. E_{0,w}(z = 0^-, PAR[W]) = E_s(z = 0^-, SW) 0.43.$$

636 The visible spectrum was divided into three equal bands: blue, green and red. The scalar irradiances for  
637 each band just below open water in energy units,  $E_{0,w,\lambda}(z = 0^-, PAR[W])$  (Figure S9d), were considered  
638 equal as

$$639 \quad 21. E_{0,w,\lambda=blue}(z = 0^-, PAR[W]) = E_{0,w,\lambda=green}(z = 0^-, PAR[W])$$

$$640 \quad = E_{0,w,\lambda=red}(z = 0^-, PAR[W]) = E_{0,w}(z = 0^-, PAR[W]) / 3.$$

641 The scalar irradiances for each band just below open water in energy units were converted into the scalar  
 642 irradiances for each band just below open water in photon density flux  $E_{0,w,\lambda}(z = 0^-, PAR[Q])$  (Figure  
 643 S9e), as

$$644 \quad 22. E_{0,w,\lambda}(z = 0^-, PAR[Q]) = \frac{E_{0,w}(z=0^-, PAR[W]) \lambda 10^6}{hcN},$$

645 for  $\lambda = \text{blue} = 450 \text{ nm}$ ,  $\lambda = \text{green} = 550 \text{ nm}$  and  $\lambda = \text{red} = 650 \text{ nm}$ .  $E_{0,w,\lambda}(z = 0^-, PAR[Q])$  was added up to  
 646 get the scalar PAR just below open water in photon density flux,  $E_{0,w}(z = 0^-, PAR[Q])$  (Figure S9f, Data  
 647 S5 in Benoit-Gagné et al., 2024), as

$$648 \quad 23. E_{0,w}(z = 0^-, PAR[Q]) = \sum_{i=1}^3 E_{0,w,\lambda_i}(z = 0^-, PAR[Q]).$$

### 649 **6.2.3 A2.3 Scalar photosynthetically active radiation in the water column**

650  $E_{0,i}(z = 0^-, PAR[Q])$  was used for the forcing field for the scalar PAR just below surface in photon density  
 651 flux,  $E_0(z = 0^-, PAR[Q])$ , before sea ice break-up (before July 18).  $E_{0,w}(z = 0^-, PAR[Q])$  was used as the  
 652 forcing field for  $E_0(z = 0^-, PAR[Q])$  from the sea ice break-up (from July 18). The water column was  
 653 divided into 75 depth layers. The scalar PAR at depth  $z$  in photon density flux was computed with a Beer-  
 654 Lambert law as

$$655 \quad 24. E_0(z, PAR[Q]) = E_0(z = 0^-, PAR[Q]) \exp\left(-\int_0^z K_0(z') dz'\right),$$

656 where  $K_0$  was the diffuse vertical attenuation coefficient of scalar PAR.  $K_0$  was dependent on Chl  $a$   
 657 concentration (Chl  $a$ ) as

$$658 \quad 25. K_0 = K_w + K_{chl} Chl a,$$

659 where  $K_w$  was light absorption for pure seawater and  $K_{chl}$  was light absorption for Chl  $a$ . Coloured  
 660 dissolved organic matter and detrital matter were not considered in the calculation of  $K_0$ .

661 *6.3 A3. Adjustments to the observations specific for comparison to the model*

662 The measured PAR was the downwelling plane PAR ( $E_d$ ), while the model simulated the scalar PAR ( $E_0$ ).  
663 Matthes et al. (2019) found a conversion factor of approximately 1.4 from plane to scalar PAR within the  
664 upper 20 m at the Qikiqtarjuaq ice camp. Before June 27, there were observations of Chl *a* only down to  
665 40 m and extrapolation was necessary for the vertical integration to 100 m. Reaching 100 m was required  
666 after June 27 because a subsurface chlorophyll maximum was formed by that point. Extrapolation was  
667 achieved by considering that Chl *a* below 40 m was equal to Chl *a* at 40 m because, before June 27, Chl *a*  
668 remained unchanged with depth (Figure S2d). The depth of the mixing layer was measured during the ice  
669 camp only on June 23. The methods for the measurement of the equivalent mixed layer depth ( $h_{BD}$ ; as in  
670 Randelhoff et al., 2017), a measure distinct from the *depth of the mixing layer*, are described in Oziel et  
671 al. (2019). The equivalent mixed layer depth was smoothed with a moving average of 7 days.

672 *6.4 A4. Expedition Amundsen 2018*

673 The relatively deep water depth of 360 m at the ice camp suggested that this site may be representative of  
674 offshore western Baffin Bay, even though it was located only a few kilometres from the coast. Data from  
675 the 2018 expedition of the Canadian Coast Guard Ship (CCGS) *Amundsen* was used to test this  
676 hypothesis. Six stations including one at the Qikiqtarjuaq ice camp location were sampled from July 13 to  
677 July 24, 2018 (Leg 2b; Figure S10). Salinity and temperature measurements were acquired with a  
678 conductivity-temperature-depth sensor (CTD SBD911plus, SeaBird Scientific). The temperature-salinity  
679 diagram for each station showed that the oceanographic conditions in 2018 at the ice camp location  
680 (Station 5) were like the oceanographic conditions at the offshore stations (Stations 1 to 3; Figure S11).  
681 Thus, we believe that the ice camp location could be considered representative of western Baffin Bay,  
682 allowing this modelling study to be representative of this area as well.

683

684 *6.5 A5. Carbon biomass at the ice camp*

685 The materials and methods for the observation of carbon biomass at the ice camp Qikiqtarjuaq in 2016 is  
686 described in Grondin (2019) and Massicotte et al. (2020). Only a brief overview is presented here and  
687 illustrated in Figure S12. The 5 ml seawater samples were analysed with an Imaging FlowCytobot (Olson  
688 and Sosik, 2007; Sosik and Olson, 2007) manufactured by McLane®. The targeted size range was  
689 between 1  $\mu\text{m}$  and 150  $\mu\text{m}$ . Cells larger than 10  $\mu\text{m}$  could be identified to a finer taxonomic resolution  
690 than cells between 3  $\mu\text{m}$  and 10  $\mu\text{m}$  due to an image resolution of approximately 3.4 pixels  $\mu\text{m}^{-1}$ . The Chl  
691 *a* in vivo fluorescence with an excitation laser at 635 nm triggered image acquisition. The resulting  
692 greyscale images were processed with a MATLAB (2013b) code (Sosik and Olson, 2007;  
693 <https://github.com/hsosik/ifcb-analysis>, accessed May 29, 2024). This code extracted the regions of  
694 interest and their associated features with a random forest algorithm. Each region of interest had 231  
695 features (backscattering, Chl *a*, geometry, shape, symmetry, texture, etc.; see  
696 <https://github.com/hsosik/ifcb-analysis/wiki/feature-file-documentation>, accessed June 11, 2024). These  
697 regions and their features were then processed with the EcoTaxa application (Picheral et al., 2017) again  
698 using a random forest algorithm. The result was images annotated with one of the 35 taxonomic  
699 categories. The annotated images were converted to biovolumes (Moberg and Sosik, 2012). The  
700 biovolumes were converted to carbon (Laney and Sosik, 2014) using carbon-to-volume ratios (Menden-  
701 Deuer and Lessard, 2000). For the purposes of this study and evaluation of the model, the biomasses of  
702 the 35 taxonomic categories were binned into three functional groups: diatoms, mixotrophs and other  
703 nanophytoplankton (<https://github.com/maximebenoitgagne/timing/blob/main/timing.ipynb>, accessed  
704 June 11, 2024). Algaebase (Guiry and Guiry, 2022) helped in the classification of the IFCB categories  
705 into these groups (Table S8). The "other nanophytoplankton" included strictly autotrophic phytoplankton.  
706 More than 99% of the mixotrophs group were dinoflagellates, and as such we refer to this group as  
707 "mixotrophic dinoflagellates" in this study.

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## 983 Contributions

984 Conception and design: MBG, SD, FM.

985 Analysed data: MBG.

986 Interpreted data: MBG, SD, ID, CD, DD, LM, FM.

987 Acquisition and processing of temperature and salinity data during the CCGS Amundsen 2018  
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989 Processing of nutrient concentrations before May 15 from the Qikiqtarjuaq sea ice camps 2015 and 2016:  
990 GO.

991 NEMO-LIM3 modelling to provide offline physical forcing fields (temperature, salinity and mixing) for  
992 the MITgcm modelling: GO.

993 MITgcm modelling: MBG.

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### 1030 Competing interest

1031 The authors have declared that no competing interests exist.

### 1032 Supplemental material

1033 The file supplement.docx has been submitted with the present article. It contains the following  
1034 supplemental figures and tables.

- 1035 • **Figure S1.** Photosynthetic parameters.
- 1036 • **Figures S2.** Nutrient concentrations and chlorophyll *a*.
- 1037 • **Figures S3.** Accumulation rate.
- 1038 • **Figures S4.** Sensitivity simulations by phytoplankton groups and size classes: EXP-1 prescribed  
1039 minimum biomass.
- 1040 • **Figures S5.** Sensitivity simulations by phytoplankton groups and size classes: EXP-2 with  
1041 differing light under sea ice.
- 1042 • **Figures S6.** Sensitivity simulations by phytoplankton groups and size classes: EXP-3 prescribed  
1043 pre-bloom nitrate concentrations.
- 1044 • **Figure S7.** Mean biomass and chlorophyll *a* (0-40m).
- 1045 • **Figure S8.** Parameters controlling the half saturation for growth on nitrate for each numerical  
1046 type.
- 1047 • **Figures S9.** Processing of downwelling shortwave radiation just above the surface.
- 1048 • **Figure S10.** Maps of Baffin Bay and the study site including the expedition *Amundsen* 2018.

- 1049 • **Figure S11.** Observations of temperature and salinity during the expedition *Amundsen* 2018.
- 1050 • **Figure S12.** Materials and methods for the observation of the carbon biomass at the ice camp  
1051 Qikiqtarjuaq 2016.
- 1052 • **Figure S13.** Annual drift of nitrate.
- 1053 • **Table S1.** Notations mentioned in the Main Text.
- 1054 • **Table S2.** Features of the phytoplankton blooms at the Qikiqtarjuaq ice camps in 2015 and 2016.
- 1055 • **Table S3.** Notations mentioned in the Appendix A1.
- 1056 • **Table S4.** Constants and fixed parameters mentioned in the Appendix A1.
- 1057 • **Table S5.** Coefficients for allometric scaling (unitless) mentioned in Appendix A1.
- 1058 • **Table S6.** Notations mentioned in the Appendix A2.
- 1059 • **Table S7.** Constants and fixed parameters mentioned in the Appendix A2.
- 1060 • **Table S8.** Classification of the Imaging FlowCytobot (IFCB) taxonomic categories into the  
1061 biogeochemical groups of the model.

## 1062 Data Accessibility Statement

1063 Model output and other data for the generation of the figures are openly accessible in the data directory at  
1064 <https://github.com/maximebenoitgagne/timing/tree/v0.1.4> (Benoît-Gagné et al., 2024). DOI:  
1065 <https://doi.org/10.5281/zenodo.13287110>.

1066 The physical model used here is available through <http://mitgcm.org/>, and the generic ecosystem used in  
1067 this study is available through <https://gud.mit.edu/git/gud>. The specific modifications for the setup used  
1068 here, the code for the new options to the ecosystem code, all parameters values, and the code to generate  
1069 the figures are provided at <https://github.com/maximebenoitgagne/timing/tree/v0.1.4> (Benoît-Gagné et al.,  
1070 2024). DOI: <https://doi.org/10.5281/zenodo.13287110>. The code to generate the figures can be visualised  
1071 by opening the file `timing.ipynb`. The code to generate the supplemental figures can be visualised by  
1072 opening the file `timing_supmat.ipynb`.