The Influence of Meltwater on Phytoplankton Blooms Near the Sea-Ice Edge

Conner W. Lester^{1,1}, Till Jakob Wenzel Wagner^{2,2}, Dylan E McNamara^{3,3}, and Mattias Rolf Cape^{4,4}

¹Duke University ²UNCW ³University of North Carolina Wilmington ⁴University of Washington

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Abstract

Annual sea-ice edge phytoplankton blooms occur throughout the Arctic during the spring melt period. Our study considers how phytoplankton spring blooms may depend on sea-ice meltwater. We extend the classic Fisher reaction-diffusion equation to consider a time- and space-varying death rate that represents the role of meltwater in the system. Our results indicate that blooms peak at a characteristic distance from the ice edge where (i) meltwater is still concentrated enough to stratify the upper ocean such that the phytoplankton are confined near the surface and (ii) phytoplankton have been exposed to sufficient sunlight to allow for maximum growth. The results are qualitatively similar to satellite data of a large bloom observed in Fram Strait in May 2019. Our findings support the idea that sea-ice meltwater is of central importance for Arctic phytoplankton blooms.

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C. W. Lester^{1,2}, T. J. W. Wagner¹, Dylan E. McNamara¹, M.R. Cape³

 ⁴ ¹Department of Physics and Physical Oceanography/Center for Marine Science, University of North ⁵ Carolina Wilmington, Wilmington, NC, United States
 ⁶ ²Division of Earth and Ocean Sciences, Nicholas School of the Environment, Duke University, Durham, ⁷ NC, United States
 ⁸ ³Applied Physics Laboratory, University of Washington, Seattle, WA, United States

Key Points:

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10	• Observations show that sea-ice edge phytoplankton concentrations are spatially
11	correlated with sea-ice meltwater.
12	• We present an idealized model of phytoplankton dynamics where the influence of
13	meltwater and sunlight is parameterized in phytoplankton growth and death rates
14	• Model output captures key characteristics of observed phytoplankton blooms in
15	Fram Strait, highlighting the role of meltwater in bloom development.

Corresponding author: C. W. Lester, conner.lester@duke.edu

16 Abstract

Phytoplankton blooms occur annually at the sea-ice edge throughout the Arctic during 17 the spring melt period. Our study considers how these spring blooms may depend on 18 sea-ice meltwater, focusing on the role of horizontal mixing and advection. We extend 19 the classic Fisher reaction-diffusion equation to consider a time- and space-varying death 20 rate that represents the role of meltwater in the system. Our results indicate that blooms 21 peak at a characteristic distance from the ice edge where (i) meltwater is concentrated 22 enough to stratify the upper ocean such that the phytoplankton are confined near the 23 surface and *(ii)* phytoplankton have been exposed to sufficient sunlight to allow for op-24 timized growth. The results reproduce key characteristics of a large bloom observed in 25 Fram Strait in May 2019. Our findings support the idea that sea-ice meltwater is of cen-26 tral importance in setting the spatial patterns of Arctic phytoplankton blooms. 27

²⁸ Plain Language Summary

In the Arctic, each spring the appearance of the sun awakens the region's ecosys-29 tem. In particular, the blooming of phytoplankton – which form the base of the Arctic 30 marine food web — is an early phenomenon that depends on the availability of sunlight. 31 In this study we present a model that supports the idea that sunlight alone is not enough 32 to drive large plankton blooms in the open ocean: an influx from sea-ice meltwater is 33 also needed. This meltwater (which is fresh and light) acts to maintain an ocean surface 34 35 layer that is thin and separated from the ocean below. The plankton are confined to this surface layer where they can absorb plentiful sunlight and grow into large blooms. Our 36 model sheds light on this central role of sea-ice meltwater for the growth of Arctic phy-37 toplankton. 38

³⁹ 1 Introduction

Springtime in the Arctic Ocean is marked by large-scale algal growth events, known
as phytoplankton blooms. Phytoplankton form the base of the trophic food web and their
blooming constitutes a key phenomenon in the seasonal cycle of the Arctic ecosystem
(Wassmann & Reigstad, 2011; Behrenfeld & Boss, 2014; Leu et al., 2015). Algae blooms
also impact ocean-atmosphere dynamics through primary production and associated carbon dioxide uptake (Wassmann & Reigstad, 2011).

In certain regions of the Arctic there has been a recent increase in the intensity of 46 phytoplankton blooms (Lewis et al., 2020). Cherkasheva et al. (2014) have found that 47 this increase is particularly notable near the sea-ice edge. During typical winter-spring 48 transitions, the sympagic environment of the sea-ice edge is populated by algae commu-49 nities that, under favorable conditions, grow rapidly into blooms (Leu et al., 2015). Cen-50 tral factors in determining the magnitude and spread of these blooms are the availabil-51 ity of nutrients and sunlight, and the stratification of the upper ocean. In the spring, in-52 creasing solar irradiance in the Arctic not only provides sunlight for photosynthesis, but 53 also drives melting of sea ice. Although meltwater is typically nutritionally sparse, it cre-54 ates a stably stratified ocean surface layer that constrains phytoplankton in the euphotic 55 zone, making it a key factor in bloom development (Waniek et al., 2005; Cherkasheva 56 et al., 2014; Janout et al., 2016; Mayot et al., 2018, 2020). 57

The link between meltwater and algae blooms is illustrated by Landsat 8 satellite imagery which shows strong spatial correlations between phytoplankton concentrations and low sea surface temperatures near, or below, 0°C (Figure 1) – an indicator for high meltwater concentrations. Concerns about future changes in the sea-ice cover and its role in altering spring bloom dynamics have further motivated recent field efforts (Cherkasheva et al., 2014; Arrigo & van Dijken, 2015). Although such observational work and the satellite images of Figure 1 suggest a dynamic relation between phytoplankton blooms and



Figure 1. Landsat 8 images of an evolving ice-edge phytoplankton bloom taken in Fram Strait (sea ice is shown in grey/white). Svalbard is seen in the far right of both images. Left column (a,c) shows chlorophyll-a (mg m⁻³), right column (b,d) SST (°C). Top (a,b): May 26, 2019. Bottom (c,d): May 30, 2019. Bloom regions used in the data analysis (see text) are outlined by dashed boxes.

sea-ice melt, our understanding of the role meltwater plays in sea-ice edge phytoplank ton blooms remains incomplete.

Most research to date on this topic has aimed at resolving the vertical processes 67 that govern stratification-bloom interactions, often using one-dimensional single column 68 models (A. Taylor, 1988; Jin et al., 2007; Mellard et al., 2011). Previous studies have found 69 that phytoplankton blooms occur when the surface mixed layer shoals to a critical depth 70 in the spring (Sverdrup, 1953), when turbulent mixing is insufficient to remove the plank-71 ton from the surface (Huisman et al., 1999), or when the balance between phytoplank-72 ton division and grazer consumption is perturbed (Behrenfeld & Boss, 2014). Stratifi-73 cation of the upper ocean due to meltwater from sea ice may therefore play a central role 74 in determining whether a bloom is initiated and how large it will grow. This hypothe-75 sis is supported by anecdotal observational evidence of striking correlations between blooms 76 and meltwater, as discussed above. However, while vertical processes have been stud-77 ied in some detail, the influence of horizontal mixing and advection of meltwater on early 78 bloom development and the resulting spatial characteristics of ice-edge blooms have re-79 ceived less attention. 80

Previous efforts to model horizontal distributions of spring blooms in the open ocean 81 invoke mechanisms that drive stratification through eddy (Omand et al., 2015; Mahade-82 van et al., 2012) or ocean-front (J. R. Taylor & Ferrari, 2011) formations. In a similar 83 vein, here we model horizontal features of spring blooms near the sea-ice edge that arise due to the stratifying effects of meltwater input. Namely, we present an idealized model 85 that accounts for phytoplankton death and growth rates in a way that is physically mo-86 tivated by the ice-edge environment during the spring melt period. The model builds on 87 previous work using the Fisher reaction-diffusion equation as a representation of open-88 ocean plankton dynamics (Birch et al., 2007). Specifically, we parameterize the role of 89 meltwater and associated surface stratification which retains phytoplankton in the eu-90 photic zone and thus provides enhanced growing conditions near the ice edge. 91

92 2 Plankton Model

Birch et al. (2007) simulated phytoplankton dynamics using the Fisher equation (Fisher, 1937; Kolmogorov et al., 1937) with a spatially variable growth rate and an incompressible velocity field:

$$P_t + \mathbf{u} \cdot \nabla P = \gamma(\mathbf{x})P - \nu P^2 + \kappa \nabla^2 P, \tag{1}$$

where $P(\mathbf{x}, t)$ is phytoplankton concentration, **u** is the velocity field, $\gamma(\mathbf{x})$ is a spatially variable growth rate, ν is a constant death rate, and κ is a constant diffusivity.

⁹⁸ Birch et al. (2007) present equation (1) in the context of open-ocean plankton dy-⁹⁹ namics with the goal of deriving bounds on total plankton biomass. The model as pre-¹⁰⁰ sented by Birch et al. (2007) has no explicit dependencies on nutrient limitations or pre-¹⁰¹ dation. Nonetheless, plankton are able to reach a nontrivial steady state with rich tran-¹⁰² sient dynamics dependent on stirring magnitude $|\mathbf{u}|$ and diffusivity κ .

Here, we modify equation (1) to study the dependence of phytoplankton blooms 103 on meltwater near a sea-ice edge. To simulate phytoplankton-meltwater dynamics we in-104 clude space and time dependence for the death rate ν in equation (1). Our hypothesis 105 is that ν broadly reflects the effects that meltwater has on phytoplankton bloom devel-106 opment, namely that when meltwater is concentrated the death rate is lowered as phy-107 toplankton are kept near the surface. The phytoplankton growth rate γ is broadly de-108 pendent on sunlight availability, nutrient abundance and predation, and is typically a 109 function of space and time as well. 110

Beyond the central role of the mixed layer, bloom dynamics are controlled by nu-111 trient availability and grazing pressure from zooplankton (Truscott & Brindley, 1994; Hup-112 pert et al., 2002; Behrenfeld & Boss, 2014). We note that blooms near the marginal ice 113 zone may not be nutrient limited in the early spring as recent winter ice growth and as-114 sociated salt rejection drive vertical convection and upward-mixing of nutrients from depth 115 (Mayot et al., 2018). Here, we are primarily interested in the dynamical effects that hor-116 izontal mixing and advection of meltwater have on the evolution of blooms. In order to 117 isolate these effects, we take other factors impacting the system, such as nutrient and 118 light availability and grazing pressure, to be fixed. This can be approximated by tak-119 ing the growth rate γ to be constant. Since we are focusing on the early stages of the 120 bloom, the assumption that the system is not nutrient limited appears justified. Sim-121 ilarly, since we are considering a time-scale of only a few days near the initiation of the 122 bloom, sunlight availability can be assumed to be approximately constant. 123

With these modifications to equation (1), the model takes the form:

$$P_t + \mathbf{u} \cdot \boldsymbol{\nabla} P = \gamma P - \nu(\mathbf{x}, t) P^2 + \kappa \nabla^2 P, \qquad (2)$$

$$\nu_t + \mathbf{u} \cdot \boldsymbol{\nabla} \nu = \alpha \nu + \kappa \nabla^2 \nu. \tag{3}$$

Equation (2) is equivalent to (1) aside from γ now being constant and $\nu(\mathbf{x}, t)$ varying

in space and time (γ and ν only take positive values). Note that equation (2) and (3)

contain the same velocity field **u** and diffusivity κ . This presupposes that phytoplank-126 ton are passive tracers which are advected and diffused at the same rate as the surface 127 water in which they reside. The term $\alpha\nu$ in equation (3) causes exponential growth of 128 ν (α being a positive constant). When ν reaches an upper bound ν_{max} , we set $\alpha = 0$. 129 The constant ν_{max} is interpreted as the open-ocean background death rate (when there 130 is no meltwater). The term $\alpha\nu$ can be interpreted as a proxy for wind-driven vertical mix-131 ing, where vertical mixing is suppressed near the ice edge and increases as you move to-132 ward open water. From here forward we will refer to α as the vertical mixing rate. 133

We take the velocity field $\mathbf{u} = (u, v)$ to be the stochastic two-dimensional field used by Birch et al. (2007), with slight modifications to mimic stirring at an ideal seaice edge:

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$$\mathbf{u}(\mathbf{x},t) = \begin{cases} U(c+(1-c)\cos(k_m y + \phi_x), \ 0) & \text{for } n\tau \le t < (n+1/2)\tau, \\ U(c, \ \cos(k_m x + \phi_y)) & \text{for } (n+1/2)\tau \le t < (n+1)\tau, \end{cases}$$
(4)

where $(x, y) \in [0, \ell)$. The piecewise velocity field alternates on a given decorrelation time period τ with an imposed constant advection away from the ice edge of magnitude cU, such that space-time averages are $\langle u \rangle = cU$ and $\langle v \rangle = 0$. The positive constant c is added to insure mean advection away from the ice edge boundary; the wave number $k_m = 2\pi m/\ell$, where ℓ is the domain length scale; and ϕ_i is a phase shift randomly chosen between 0 and 2π each period.

Boundary conditions are applied to equations (2) and (3) that reflect sea-ice melt-144 water and phytoplankton conditions at and near the sea-ice edge at the beginning of the 145 melt season. At the ice edge (x = 0), we supply the domain with a constant influx of 146 low death rate (ν_0) and low phytoplankton concentration (P_0). This influx is balanced 147 by an equally constant outflux at $x = \ell$. The domain is thus non-periodic in x. The 148 perpendicular boundaries are periodic at $y = (0, \ell)$. A snapshot of a typical spun-up 149 model state is seen in Figure 2. We initialize the model with the uniform background 150 density $P = P_0$ and maximum death rate ν_{max} (i.e., no meltwater). In all simulations, 151 c = 0.5, m = 1, and $\nu_{max} = 20\nu_0$. After several time steps a bloom develops near 152 the influx boundary, the magnitude of which is bounded by the carrying capacity K =153 γ/ν_0 . 154

The model is characterized by three dimensionless parameters: (i) The Péclet number – the ratio of the diffusive time scale ℓ^2/κ to the advective time scale ℓ/U : Pe $\equiv U\ell/\kappa$;



Figure 2. Snapshot of converged model state. Shown are phytoplankton concentration P rescaled by the carrying capacity K (left) and death rate ν rescaled by ν_0 (right). Here, Da = 20, $\alpha/\gamma = 0.05$, and $k = 5 \times 10^{-6}$.

(ii) The Damköhler number – the ratio of the advective time scale to the biological growth 157 time scale: Da $\equiv \gamma \ell/U$; (iii) The ratio α/γ of the vertical mixing rate α and growth rate 158 γ . For the following analysis it is convenient to further define the characteristic diffu-159 sivity $k \equiv 1/(\text{Da Pe}) = \kappa/\gamma \ell^2$. 160

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2.1 Limit of no horizontal diffusion

Here, we consider environmental conditions where diffusive time scales are much 162 larger than advection time scales (Pe $\rightarrow \infty$). To explore this limit we set $\kappa = 0$ in equa-163 tions (2) and (3). In this case, we can readily solve for the steady-state plankton con-164 centration for a given advective field. Considering the idealized flow field $\mathbf{u} = \langle \mathbf{u} \rangle / c =$ 165 (U,0), the zero-diffusion equivalents of equations (2) and (3) can be written as: 166

$$U\frac{dP}{dx} = \gamma P - \nu P^2,\tag{5}$$

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$$U\frac{d\nu}{dx} = \alpha\nu. \tag{6}$$

This is solved to give plankton concentration as a function of distance from the ice edge 168 x: 169

$$P(x) = \frac{e^{\frac{1x}{U}}}{\frac{\nu_0}{\gamma + \alpha} (e^{\frac{x}{U}(\gamma + \alpha)} - 1) + \frac{1}{P_0}}.$$
(7)

Here, no bound is imposed on ν (i.e., $\alpha = 0$ for $\nu = \nu_{max}$ no longer applies) and $P \rightarrow \infty$ 170 0 as $\nu, x \to \infty$. This can be interpreted as the open-ocean background concentration 171 of phytoplankton being zero. 172

The solution P(x) in equation (7) highlights the spatial dynamics that may be ex-173 pected of a bloom in this idealized environment. Namely, P(x) has the intuitive shape 174 of a heavy tailed distribution, where phytoplankton grow rapidly from a small initial value 175 close to the ice edge boundary, peak, and decay slowly away from the ice edge. This "bloom 176 curve" is sensitive to the parameters α/γ and Da (Figure 3a,b). For instance, as the ra-177 tio of vertical mixing to phytoplankton growth rate (α/γ) gets larger the death rate in-178 creases more quickly with x, which reduces the bloom magnitude and spread (Figure 3a). 179 This can be interpreted as larger vertical mixing rates destabilizing and mixing the sur-180 face waters more efficiently, resulting in a less intense bloom. And as the ratio of the bi-181 ological growth versus advective time scales (Da) decreases the bloom grows spatially, 182 spanning a larger range in x, and its peak P_{max} is pushed further from the x = 0 bound-183 ary (Figure 3b). That is, a large influx of meltwater from the ice edge allows for a spa-184 tially large bloom to occur, peaking at a greater distance from the ice edge because of 185 the increased advection speed. 186

3 Phytoplankton Meltwater Dependence 187

Equation (7) provides insight into the spatial behavior of an ice edge bloom sub-188 ject to an idealized velocity field. However, real-world phytoplankton blooms are sub-189 ject to highly variable horizontal velocities, resulting in large fluctuations of phytoplank-190 ton concentration with distance from the ice edge (Figure 1). Since P(x) depends ex-191 plicitly on the velocity field \mathbf{u} , a comparison between model output and observations (where 192 **u** is not known) is made difficult. However, since the advection rates for P and ν are the 193 same in equations (2) and (3), we can obtain a solution $P(\nu)$, for negligible diffusion, that 194 is invariant of **u**: 195

$$P(\nu) = \frac{\nu^{\frac{1}{\alpha}}}{\frac{1}{\gamma + \alpha} (\nu^{\frac{\gamma}{\alpha} + 1} - \nu_0^{\frac{\gamma}{\alpha} + 1}) + \frac{\nu_0^{\frac{\gamma}{\alpha}}}{P_0}}.$$
(8)

This solution represents the phytoplankton concentration as a function of death rate (melt-196 water) and produces similar shaped bloom curves as P(x) (Figure 3c,d). The velocity 197



Figure 3. Top row: Rescaled phytoplankton concentration as a function of distance from the ice edge P(x) on model parameters. (a) Analytic solutions of P(x) for different values of α/γ . Here, Da = 10. (b) Analytic solutions of P(x) with varying Da. Here, $\alpha/\gamma = 0.1$. Bottom row: Rescaled phytoplankton concentration as a function of rescaled death rate $P(\nu)$. (c) Analytic solutions of $P(\nu)$ in the limit of no diffusion (equation 8), for different values of the characteristic growth rate α/γ . Inset: dependence of peak bloom value P_{max} on α/γ , with $P_{max} \rightarrow K$ as $\alpha/\gamma \rightarrow 0$ and $P_{max} \rightarrow P_0$ as $\alpha/\gamma \rightarrow \infty$. (d) Numerical steady state solutions for the full model (equations 2 and 3), for different values of dimensionless diffusivity k. Solutions found by binning ν and averaging the P values in each bin, represented by $\langle P \rangle$. The analytic solution for k = 0 (equation 8) is shown as the solid black line. Inset: P_{max} as a function of k, approaching P_0 as $k \rightarrow \infty$. Here, $\alpha/\gamma = 0.1$.

¹⁹⁸ invariance of $P(\nu)$ is due to our initial assumption that phytoplankton are passive trac-¹⁹⁹ ers and are advected at the same rate as the meltwater they reside in. Without the ex-²⁰⁰ plicit dependence on horizontal motion, $P(\nu)$ allows us to qualitatively compare our model ²⁰¹ results to observational data (see below).

²⁰² $P(\nu)$ is controlled by the parameter α/γ (Figure 3c). When α/γ is small (i.e., when ²⁰³ vertical mixing is low or growth rate is high) the phytoplankton maximum P_{max} is large ²⁰⁴ at low values of ν . In the limit $\alpha/\gamma \to 0$ the death rate becomes spatially constant at ²⁰⁵ ν_0 , allowing the bloom to reach full carrying capacity, with $P_{max} \to K$. When α/γ is ²⁰⁶ large (i.e., when vertical mixing is high or growth rate is low) $\nu(P_{max})$ is pushed towards ²⁰⁷ high values of ν and P_{max} is reduced, approaching the background concentration P_0 ev-²⁰⁸ erywhere in the limit $\alpha/\gamma \to \infty$.

To explore the influence of non-zero horizontal diffusion on the phytoplankton concentration we numerically solve equations (2) and (3) with varying values of κ (Figure 3d). As expected, as diffusivity κ increases the bloom peak P_{max} is suppressed. In the limit $\kappa \to \infty$ the bloom peak vanishes and the plankton population in the domain homogenizes at P_0 . In the limit $\kappa \to 0$, on the other hand, the plankton bloom follows the zero-diffusivity curve described by the analytic solution above (equation 8). We note that equation (3) models the death rate as exponentially increasing with time and space. This gives rise to the asymptotic decay in the phytoplankton concentration as ν grows large (Figure 3c,d). Qualitatively similar shapes for $P(\nu)$ to those in Figure 3 are found if the death rate ν increases in any fashion with \boldsymbol{x}, t . That is, the bloom curve $P(\nu)$ does not change its qualitative shape as long as equation (3) has the form: $\frac{D\nu}{Dt} = f(\nu)$, with the conditions that $f(\nu) \ge 0$ and $f(\nu) = 0$ iff $\nu > \nu(P_{max})$.

Therefore, the exponential growth of equation (3), $\frac{D\nu}{Dt} = \alpha\nu$, represents just one possible functional form that is compatible with the observational data (see below). The physical interpretation here is that sea-ice meltwater is increasingly vertically mixed out of the surface layer with time and distance from the ice edge; the exact spatiotemporal dependence of this mixing however is beyond the scope of this study.

3.1 Comparison to Observations

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The modeled $P(\nu)$ (equation 8, Figure 3c,d) suggests a dynamical interpretation of observed ice edge blooms (Figure 1). Because $P(\nu)$ is not dependent on the horizontal stirring scheme (and weakly dependent on diffusion; Figure 3d) it provides a simple framework for us to interpret key bloom characteristics that may be present in bloom data – characteristics we may expect to be approximately independent of horizontal stirring as well.

The scenes in Figure 1 are from high spatial resolution (30m) satellite imagery, taken May 26 and 30, 2019, by the NASA/USGS Landsat 8 mission in the Arctic region of Fram Strait. This imagery captures horizontal ocean surface data from the top several meters of the water column. We consider sea-surface temperature (SST) and chlorophyll-a (chla) as rough proxies for sea-surface meltwater and phytoplankton concentrations, respectively. Namely, low values of SST correspond to high meltwater concentration (low ν) and high values of chl-a to high phytoplankton concentration (high P).

To get at the relationship between phytoplankton and meltwater in the satellite 240 data we compute binned averages of chl-a as a function of SST for the main bloom re-241 gions in Figure 1 (outlined by dashed boxes). The results reveal two distinct regimes, 242 present in both scenes: a positive correlation for low SST and a negative correlation for 243 higher SST (Figure 4). In regions where SST is low and meltwater concentration is high 244 the positive correlation between chl-a and SST suggests that in this region the algae grow 245 as they are transported away from the ice edge. In regions where SST is high (i.e., low 246 meltwater concentration) the negative correlation between chl-a and SST suggests that 247 the growth-favoring stratification is lost as meltwater is mixed vertically, and algae lev-248 els drop to a background value of chl-a present in the open ocean. 249

Note that both curves in Figure 4 show similar mean chl-a concentrations ($\langle chl_{251} \rangle \approx 0.4 \text{mg m}^{-3}$) at low SST ($\approx -1.8^{\circ}$ C) near the ice edge. This suggests a relatively unchanged level of algae near the sea ice between May 26 and May 30. Similarly, the chla levels in the warm water limits are comparable for the two scenes ($\langle chl-a \rangle \approx 0.25 - 0.3 \text{mg m}^{-3}$), indicating that this may be a background level of algae in the region during this period.

Because both scenes were collected in the same region only four days apart it is rea-256 sonable to assume that they represent different stages of the same bloom event. The ear-257 lier date (Figure 4, blue) shows the earlier, less developed stage while the later date (red) 258 shows the more developed stage at which point the peak chl-a value has roughly dou-259 bled. The earlier scene exhibits its highest chl-a in rather cold waters (SST $\approx -1^{\circ}$ C) near 260 the ice edge and an approximately linear increase of chl-a from the ice edge to this peak. 261 As the bloom grows more mature, the positive correlation between meltwater and chl-262 a extends to $SST \approx 0^{\circ}C$, which suggests that conditions are more advantageous for al-263 gae growth with increasing distance from the ice edge up to waters with 0° C. One ex-264



Figure 4. Observed chl-a versus SST from the regions outlined in Figure 1 (dashed boxes). Here, May 26 data is shown in blue and May 30 data in red. The large dots show averages of chl-a in SST bins (600 bins with width 0.01° C). Also plotted are 10^{6} randomly selected pixels from each scene (blue and red point clouds). We ignore values of chl-a < 0.16 mg m⁻³ and > 4 mg m⁻³ and SST values < -1.8° C, which are likely satellite measurement anomalies. We note that the general shapes of the blue and red curves above are robust for different sized and oriented bounding boxes in Figure 1.

planation for this correlation is that the algae grow as they are advected away from the
ice edge (by sub-mesoscale eddies, Figure 1) while confined to the meltwater-stratified
shallow surface layer and exposed to an abundance of sunlight. The peak of the bloom
therefore moves further into warmer waters and increases in maximum value.

The different slopes in the SST-chl-a relation for low SST ($< -.5^{\circ}$ C) between the two scenes may be (at least in part) due to differences in vertical mixing rates. A larger vertical mixing rate and weakened stratification in the later scene would explain the suppression of bloom growth (red curve), while the steeper slope for the earlier stage (blue curve) may indicate quiescent conditions with little vertical mixing and rapid algae growth.

At the later stage of the bloom, conditions appear to be optimized for 0 < SST <1.4°C, where peak (chl-a) concentrations are approximately constant at $\approx 1 \text{ mg m}^{-3}$. We note that from MODIS data (NASA Goddard Space Flight Center, 2018 Reprocessing) we estimate this event to be the largest spring bloom in Fram Strait since MODIS started observing ocean surface color in 2002 (not shown).

For SST values higher than those at the chl-a peaks, we observe roughly linear decreases in chl-a in both cases which level off at $\approx 0.25-0.3 \text{ mg m}^{-3}$. This may be due to a loss of stratification with decreasing meltwater concentration in the surface layer. The steeper slope of the later stage may again indicate enhanced vertical mixing during that period.

The satellite-derived chl-a curves share similarities with major features in the model of $P(\nu)$ above (Figure 3c,d). As a bloom evolves in the model there is an initial growth phase at low ν associated with the influx of low phytoplankton concentration P_0 and low death rate ν_0 into the domain. This is analogous to the low chl-a and low SST values near the ice edge as seen in the data (Figures 1 and 4), where low SST indicates a meltwaterstratified shallow surface layer, associated with low phytoplankton death rate. Away from the model influx boundary, P and ν grow according to their respective growth rates, γ and α . In regions of high ν , the plankton concentration decays towards a steady-state value, the background plankton concentration. At an early stage of bloom evolution the bloom peak P_{max} is small and concentrated in regions of low ν . As the bloom intensifies P_{max} shifts towards higher values of ν , similar to the data (Figure 4).

From the analysis in Section 2.1 we know that bloom growth and intensity depends 295 on the ratio α/γ (equation 8, Figure 3c). Namely, if α/γ is small – i.e. when the sim-296 ulated death rate is small compared to the biological growth rate – $P(\nu)$ grows quickly 297 in regions of low ν resulting in a more intense bloom, and if α/γ is large then $P(\nu)$ grows 298 slowly at low ν . This is in agreement with the interpretation above regarding the rate 299 at which chl-a grows at low SST (Figure 4). However, our model only considers a con-300 stant vertical mixing rate α for a single bloom whereas our interpretation of the data above 301 suggests that the vertical mixing rate may change substantially as the bloom evolves. 302

We note that the variations in chl-a growth at low SST in the data could also be 303 a result of changes in phytoplankton growth rate. This could be caused, for example, by 304 variations in sunlight availability. This effect can be captured by varying γ in our model. 305 Namely, if the early stage of the bloom in the data (Figure 4, blue) is experiencing a larger 306 growth rate γ , this would be analogous to decreasing α/γ . Lower α/γ in turn leads to 307 a steep bloom growth at low ν , or in the case of the data, low SST. Equivalently, the later 308 bloom stage (red) may be experiencing a smaller growth rate, therefore increasing α/γ 309 in the model and resulting in less steep bloom growth at low ν (SST). 310

4 Conclusions and Discussion

We have presented an idealized model with a number of paramaterized dynami-312 cal processes to investigate spatial and temporal characteristics of phytoplankton blooms 313 at the sea-ice edge. This builds on work by Birch et al. (2007), using a modified version 314 of the Fisher equation. Our model results suggest that ice edge blooms can be charac-315 terized by two distinct regimes: (i) Growth near the ice edge – as the phytoplankton are 316 advected away from the sea-ice edge and confined to a meltwater-stratified shallow sur-317 face layer, their growth is determined by the ratio of biological growth rate to vertical 318 mixing; (ii) Decay away from the ice edge – in regions beyond the peak bloom the phy-319 toplankton concentration decreases together with the meltwater concentration, since a 320 reduction in meltwater in the surface layer leads to weakened stratification and deeper 321 vertical mixing of the plankton. Eventually, when the meltwater is well mixed the phy-322 toplankton concentration returns to its background steady state levels present in the open-323 ocean. 324

The modeling results support a simple initiation mechanism for how meltwater helps 325 drive algae spring blooms near the marginal ice zone: During the spring melt period, the 326 marginal sea-ice zone features a highly stratified cold and fresh surface layer that is main-327 tained by meltwater influx and populated with sea-ice algae. Constrained in the euphotic 328 zone by the melt, the algae grow rapidly by photosynthesis into a phytoplankton bloom 329 that peaks at a certain distance from the ice edge. This initiation mechanism suggests 330 that blooms prosper in the stable environment provided by sea-ice meltwater and are dy-331 namically impacted by meltwater concentration. The model developed here provides a 332 framework to study the details of how these blooms evolve spatially and spread from near 333 the ice edge to the open ocean over time. 334

Our framework assumes that the system is (at least initially) not nutrient limited, which can be the case early in the season after winter ice formation and corresponding brine rejection have driven vertical convection and enriched the ocean surface layer with nutrients. Ice edge blooms that occur later in the year may be substantially impacted by nutrient depletion as well as predation (Wassmann & Reigstad, 2011). We note that the assumption of no nutrient limitation may hold better in Eastern Fram Strait – the region covered by the satellite scenes – than in other regions. In this region warm Atlantic Water is advected from the subtropics and may contain the nutrients needed to facilitate bloom development. This warm northward current can additionally drive the bloom as it also accelerates sea-ice melt (Randelhoff et al., 2018).

The hierarchical importance of phytoplankton blooms for a thriving ecosystem in 345 the Arctic is a driving motivator to understand how their dynamics vary with current 346 and future variations in sea-ice conditions. Under continued global warming, the spring 347 348 sea ice edge is projected to retreat further and further north. This suggests that regions that currently experience large meltwater fluxes in the spring may lose this source of strat-349 ifying freshwater, and the focus of phytoplankton spring blooms will migrate to increas-350 ingly high latitudes. This may have far-reaching impacts on the Arctic ecosystem as a 351 whole. 352

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