Increase in the frequency and extent of sub-ice phytoplankton blooms in the Arctic Ocean

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Phytoplankton are a fundamental component of Earth's oceanic ecosystem and carbon cycle. These photosynthetic organisms inhabit the upper layers of the sunlit ocean, converting carbon dioxide into the organic compounds that sustain oceanic life. Through their growth and decay, they form the foundation of the oceanic food web and constitute a major sink for atmospheric CO_2[1]. Phytoplankton populations undergo periods of exponential growth, known as "blooms", which occur seasonally in many of the world's oceans[2]. In 2011, a phytoplankton bloom was observed underneath a region of the Arctic fully covered by sea ice[3]. This was unexpected because sea ice is typically understood to transmit limited solar radiation to the ocean below. To understand the likelihood and location of sub-ice blooms, we develop a critical-depth model for regions of the ice-covered Arctic ocean. This model incorporates the increased transmission of solar radiation through regions of sea ice that are

covered by melt ponds, which collect in topographic lows on the ice surface as it melts. We find that the conditions that permit sub-ice blooms exist over a large portion of the modern Arctic. The large spatial extent of these regions has only existed over the preceding 10-20 years, driven by thinning Arctic sea ice and an increase in melt pond coverage. Our results demonstrate that these large biological events may be both possible and likely in regions that previously were not considered regions of photosynthetic activity. Projections of a thinner Arctic sea ice cover in a warming world suggests that the likelihood and extent of sub-ice phytoplankton blooms will increase in the future.

As Arctic sea ice has retreated, satellite observations indicate that so has the timing of Arctic phytoplankton blooms. In some regions, summer-time blooms initiated by the retreat of the sea ice edge can occur up to 50 days sooner in 2009 than in 1997[4]. The sharp decline in the minimum sea ice extent has enabled new secondary phytoplankton blooms in ice-free regions where surface wind stresses lead to strong vertical mixing[5]. The 2011 observation of a "massive" phytoplankton bloom under sea ice in the Chukchi sea, however, has challenged the notion that the timing of phytoplankton blooms is tied to the seasonal retreat of the ice, and that they occur only in open water.

A possible explanatory factor for the observation of sub-ice blooms is the recent thinning of Arctic sea ice[8], reducing the attenuation of solar radiation. Melt ponds, which have a low albedo and form on the sea-ice surface from melting snow and ice in the spring and summer, cover larger areas on thinner ice, and may help transmit sufficient light through the thinner Arctic ice cover to sustain primary production even when the sea surface is fully ice-covered[9]. The focus of this study is to understand the likelihood, distribution and trend of phytoplankton blooms that may occur in sea-ice covered regions. We develop a model of sub-ice phytoplankton blooms that is based on the Sverdrup critical depth hypothesis[10], accounting for both the increased transmission of radiation due to the formation of melt ponds on the ice, and the transmission of solar radiation through sea ice. We examine how these factors determine the initiation of sub-ice blooms, apply our model to a set of representative climate conditions, and compare our results to observations made during the Chukchi bloom of 2011. Finally, we examine the evolving potential for sub-ice blooms over the period 1986-2015 and suggest possible future changes under Arctic climate change conditions. We find that the thinning of sea ice over this period has lead to a profound shift in the availability of light underneath sea ice, leading to an many-fold increase in the extent and likelihood of sub-ice phytoplankton blooms.

A Sub-Ice Critical Depth Model The simplest, oldest, most widely-used model for describing the timing and initiation of light-limited phytoplankon blooms is the Sverdrup critical depth hypothesis[10]. The critical depth hypothesis has been examined, updated, and expanded in many oceanographic settings[11–13], though it offers a simplistic treatment of biology and ocean mixing[14,15]. It asserts that phytoplankton populations live in, and are continuously mixed through, the ocean mixed layer, growing in proportion to the availability of light and dying at a uniform rate. Blooms occur when the mixed layer shoals above what is termed the "critical depth", where cumulative population growth and decay rates are balanced. The time evolution of the cumulative population of phytoplankton, $\mathcal{P}(D)$, over a mixed layer of depth D, is described by the equation,

$$\frac{\partial \mathcal{P}(D)}{\partial t} = (G(D) - L(D))\, \mathcal{P}(D), \tag{1}$$

where $G(D)$ (units s^{-1}) is the cumulative specific (per plankter) growth rate up to a depth D, and $L(D)$ (units s^{-1}) is similarly the cumulative specific population loss rate up to a depth D. Equation. 1 implies that the phytoplankton population grows exponentially (a "bloom") when growth exceeds loss ($G(D) - L(D) > 0$).

The growth rate G(D) of phytoplankton populations depends on converting solar radiation in the 400-700 nm range, known as photosynthetically available radiation (PAR), into energy. In a region covered by sea ice of thickness h, the PAR at a depth z below the ice is

$$I_i(z) = I_0(1 - \alpha_i)e^{-\kappa_i h}e^{\kappa_w z}, \tag{2}$$

where I_0 is the PAR incident on the ice surface (units Wm^{-2}), α_i is the albedo of bare ice, κ_w (units m^{-1}) is the attenuation coefficient of seawater, κ_i (units m^{-1}) is the attenuation coefficient of sea ice, and z is negative downwards. (A list of model parameters are provided, see Methods, Extended Data Table 1).

For ponded ice, with surface albedo given by α_w, the incoming radiation absorbed at the pond surface is $(1 - \alpha_w)I_0$. The radiation is then attenuated through the pond and ice to reach the ocean below. The PAR under a melt pond, $I_m(z)$, at a depth z for ice of thickness h and a melt pond of depth h_p is

$$I_m(z) = I_0 e^{-\kappa_i h} e^{-\kappa_w h_p}(1 - \alpha_w)e^{\kappa_w z}. \tag{3}$$

A typical attenuation coefficient of seawater is about (0.1 m^{-1}), whereas the typical attenuation coefficient of light in ice is about (1 m^{-1}), thus attenuation of solar radiation through a melt pond is small compared to attenuation through ice, and we take $e^{-\kappa_w h_p} \approx 1$ in eq. 3.

We assume that phytoplankton populations are well-mixed laterally on scales larger than the typical spacing of melt ponds, and respond to a weighted average of the PAR by melt pond area fraction ϕ. The total PAR $I(z)$ underneath ponded ice of thickness h is,

$$
\begin{aligned}
I(z) &= \phi I_m(z) + (1-\phi) I_i(z), \\
&= I_0(1-\alpha_w)e^{-\kappa_i h}\left[\phi + (1-\phi)\alpha^*\right] e^{\kappa_w z},
\end{aligned}
\tag{4}
$$

where $\alpha^* \equiv \frac{1-\alpha_i}{1-\alpha_w}$.

Phytoplankton growth at depth z is assumed linearly related to the light intensity $I(z)$ with a proportionality coefficient μ (units m J^{-1}). Phytoplankton decay is assumed uniform, independent of z, at a rate Γ (units m^{-1} s^{-1}). The ratio of these two terms $\Gamma^{-1}\mu$ is termed the "compensation irradiance", and is set to be equal to 4.5 W/m^2 (Methods, Extended Data Table 1).

To elucidate the leading order controls on blooms, we define a nondimensional surface forcing parameter, $\beta \equiv \Gamma^{-1}\mu I_0(1-\alpha_w)e^{-\kappa_i h}$. This is the ratio of the PAR that penetrates through bare ice, $I_0(1-\alpha_w)e^{-\kappa_i h}$, to the PAR at the depth of zero net rate of change of the population, $\Gamma\mu^{-1}$. Let $x \equiv \kappa_w D$, the mixed layer depth nondimensionalized by the attenuation coefficient of PAR in water. The condition $G(D) - L(D) = 0$ for no population rate of change corresponds to

$$
S(\phi, x, \beta) \equiv \beta(1-e^{-x})\left[\phi + (1-\phi)\alpha^*\right] - x = 0. \tag{5}
$$

Equation (5) defines a critical threshold $S(\phi, x, \beta) = 0$ for phytoplankton blooms.

Figure 1(a-c) shows a typical seasonal cycle of the parameters used in the model. Mixed layer depths are from a combination of observational sources from the Chukchi Sea[16] (Fig. 1a). Solar irradiance data is the NCEP-2 reanalysis climatology at 72.5°N 170°W[17], and ice thickness is a representative Arctic Basin seasonal cycle over the period 2000-2012[18] (Fig. 1b). Melt pond fraction is taken as the 2012 Arctic mean seasonal cycle from a stand-alone simulation of sea ice model CICE[19] including a model for the evolution of melt ponds[20,21] (Fig. 1c). For these values, a light-limited bloom is possible during the period from June and August (green plots in Fig. 1a-c), corresponding to the period of maximum solar insolation, maximum melt pond fraction, and minimum mixed layer depth, a period that typically is before the seasonal ice edge retreats. Values representative of the 2011 bloom are displayed as green circles in Fig. 1(a-c), with hashed boxes indicating ranges of mixed layer depth (20-30 meters), ice thickness (.8-1.2 m), and melt pond fraction (30%-40%) observed during the cruise[22]. This parameter range permits the formation of a light-limited bloom during the observed period, beginning as early as mid-June, when the bloom was observed.

Arctic Change and Sub-Ice Blooms Arctic sea ice has changed dramatically over the past several decades. The large-scale thinning of sea ice observed in the submarine and satellite record[8] as well as the increase in melt pond fraction seen in observations and model simulations[21,23] suggests that the potential for sub-ice blooms has evolved, as well. We first assess the model sensitivity to changes in the mixed-layer depth of $\pm$12m from the reference seasonal cycle shown in Fig. 1(d).

The critical melt pond fraction required for a bloom (Methods) is plotted in Fig. 1(e) for the reference seasonal cycle (black), a shallower mixed layer (blue), and a deeper mixed layer (red). The timing of a bloom is controlled by the intersection of these curves with the seasonal cycle of melt pond fraction. Dashed curves show departures from this seasonal cycle by $\pm 50\%$, reflecting the considerable interannual variability in melt pond fraction[21]. Phytoplankton populations in shallow mixed layers spend a relatively larger proportion of time in well-illuminated regions, and so a reduction in the mixed layer depth parameter x leads to an earlier bloom onset. Fig. 1(d) suggests that fairly large changes in mixed layer depth ($\pm$20m) correspond to fairly modest changes in bloom onset of around half a month.

The model indicates that blooms are very sensitive to sea-ice thickness (Fig. 1e). Even a modest variation of the reference seasonal cycle of sea ice thickness (black curve) by ± 0.40m (red and blue curves) produces a change in the timing of blooms of over one month, though this range of thickness variation is smaller than the observed changes in Arctic sea-ice thickness[8]. Thinner ice attenuates less light and permits blooms as early as mid-May, even before melt ponds begin to form. By contrast, thicker ice attenuates more light and permits no blooms, even for the upper range of melt pond fraction. As sea ice has thinned in the recent decades, this sensitivity suggests that blooms under ponded sea ice are a relatively recent phenomenon that may have been unlikely in the recent past when Arctic sea ice was substantially thicker.

To test this hypothesis, we examine a combination of model and reanalysis data over the period 1986-2015 to describe the recent trend of sub-ice phytoplankton blooms in the Arctic. Daily sea ice thickness, ice concentration, and melt pond fraction are from a stand-alone simulation of sea ice model CICE[19] including a model for the evolution of melt ponds[20,21]. Mixed layer depths are from a climatology including ARGO float and ice-tethered profile data[24]. Due to the sparsity of data on the evolution of the Arctic mixed layer, we use the same annual cycle of mixed layer depth for each year. Solar irradiance data is from the NCEP-2 reanalysis[17]. All data is interpolated to a .5° by .5° grid for latitudes greater than 60° N, and a temporal resolution of one day.

At each ocean gridpoint, we calculate whether an under-ice bloom is permitted using Eq. 5. To restrict our interest to only sub-ice blooms, grid cells with less than 80% ice concentration are excluded from the calculation. Regions with less than 80% ice concentration are typically defined as "marginal ice zones"[25], and often used to study the onset of phytoplankton blooms in polar ice-free regions[26,27]. The focus of this study is on regions with a high ice area coverage where open-ocean processes, such as wind-driven vertical mixing, are less important. The binary data on whether conditions permit a bloom at each grid location is averaged over the calendar months May, June, and July, and over the time periods from 1986-1995, 1996-2005, and 2006-2015. Figure 2 shows the results of this calculation, indicating the likelihood over each time period and month that a given day in a given location would permit a sub-ice bloom. Estimated sensitivity ranges (for details, see Methods) are given as Extended Data Tables 2 and 3.

Sea ice conditions in May that would support sub-ice blooms are not present across the Arctic for any of the three decades (Fig. 1a-c). Exceptions are the southern section of Baffin Bay, which experiences higher solar insolation in May as well as relatively thin ice, and the lower-latitudes of the European Arctic and Kara Sea near the marginal ice zone, where the sea ice is thin. These regions experience appropriate conditions for a bloom with likelihoods of once per 20 days. There are no days that support a bloom in the Chukchi Sea in May over the entire time period.

There is a significant change in the potential for sub-ice blooms for the month of June (Fig. 2d-f) over the considered time period. In 1986-1995, small regions of the European and Russian Arctic near the ice edge permitted blooms. These regions expand in extent, and the likelihood of blooms increases over the period from 1996-2005, with this expansion continuing from 2006-2015 (Fig. 2f). In the most recent decade, a majority of the Russian Arctic permits a June bloom, with frequencies reaching a maximum of once per 3 days in the East Siberian Sea. The region of the Chukchi Sea where a sub-ice bloom was observed in 2011 (red box, Fig. 2d-f) is notable as it also experiences a large increase in bloom likelihood. During 1986-1996, conditions did not support sub-ice blooms. Over the period from 1996-2006, the appropriate conditions arose once out of every 10 days in June. From 2006-2015, conditions were appropriate roughly once in every 5 days. The massive sub-ice bloom observed in the Chukchi Sea in 2011[3] was therefore only possible during the most recent two decades, and became most likely in the past 10 years. Similar increases in bloom likelihood occur throughout the Arctic during July (Fig. 2g-i), with conditions that support blooms reaching to the interior of the Arctic, all the way to the pole from 2006-2015, with the likelihood of permitting a bloom approaching once in 5 days across the Russian Arctic.

As Arctic conditions have become more bloom-friendly over the past three decades, the spatial extent of bloom-permitting regions in the central Arctic Ocean has increased dramatically.

To evaluate this change, we define 'bloom-permitting regions" to be all regions with a bloom likelihood of at least once in 14 days that occupy the greater Arctic Ocean, which we define to be all ocean points north of 70°N, excluding Baffin Bay. The data in these locations are averaged by area, with the fraction of the Arctic Ocean that is bloom-permitting shown in Table. 1. As discussed previously, blooms are unlikely in May, representing 1% or less of the Arctic region in all decades. The total fraction of the Arctic permitting June under-ice blooms has increased dramatically over the period 1986-2015, from 2.6% over the period 1986-1995 up to 16.2% over the period 2006-2015. In July, the effect is even greater, with an increase from 6.5% of the Arctic permitting blooms in July 1986-1996 to 27.0% over the period 2006-2015.

To attribute these changes to trends in sea ice evolution and melt pond fraction, we first fix the melt pond fraction ϕ at the mean 1986-1995 values. When ϕ is fixed, the trend in sea ice thickness alone causes 9.5% of the Arctic to permit blooms in June of 2006-2015, and 18.6% in July of 2006-2015. Next, sea ice thickness is fixed at the 1986-1995 values, with melt pond fraction varying. With the thickness trend is suppressed, the fraction of the Arctic that supports sub-ice blooms is 7.1% in June and 5.3% in July. In June, the responsibility for the increased spatial coverage of bloom-permitting regions in the period 2006-2015 may be due to a combination of the increase in melt pond fraction and the thinning of sea ice. In July, the thinning sea ice is likely most responsible, with melt pond fraction alone leading to less blooms in July 2006-2015 than in July 1986-2015. These increasing trends are despite a diminishing Arctic sea ice pack in summer months that leads to a smaller proportion of the Arctic that is "ice-covered". When the ice concentration field (which determines whether a grid point is considered to be ice-covered or

Figure 1: **Example seasonal cycles of climate variables, timing of sub-ice blooms, and model sensitivity**. (a-c): example time series of (a) mixed layer depth parameter x, (b) sea ice thickness parameter β, and (c) melt pond fraction ϕ. Green correspond to times in which the region permits a sub-ice bloom. Green dots and grey boxes correspond to the average observed values and reported ranges observed during the 2011 bloom[3]. (d,e) Sensitivity of curves of the melt pond fraction required to support a bloom for perturbations of the seasonal cycle seen in (a-c). Green shaded region is the area under the reference curve of mixed layer depth in (c). (*d*) mixed-layer depth changes of $\pm$20m ($x = x_{ref} \pm 1$); (*e*) ice thickness changes of ± 0.40m (corresponding to $\beta = .5\beta_{ref}$ or $\beta = 2\beta_{ref}$). When the critical pond depth curve intersects the green curve, a bloom is permitted. Dashed black curves plot $\pm 50\%$ changes in the seasonal cycle of melt pond fraction.

not) is fixed at 1986-1995 values, the fraction of the Arctic that blooms is 21.7% in May, 24.7 % in June, and 41.5% in July for the period 2016-2015.

In the future, as Arctic sea ice continues to thin, the frequency and extent of June and July blooms may increase further. If the melt pond fraction continues to increase as well, we expect June sub-ice blooms to further increase in frequency. We conclude that there is an increased potential for summer-time sub-ice blooms in the Arctic which is driven mainly by the decreasing trend in Arctic sea ice thickness, aided by the increasing proliferation of melt ponds on sea ice. For observational scientists intending to observe these blooms, the indications of high-probability bloom regions in the southern Chukchi Sea and in the Russian Arctic may prove useful for cruise planning.

1 Acknowledgements

Years	May % area	June % area	July % area
1986-1995	0.2%	2.6%	6.5%
1996-2005	0.8 %	7.6 %	18.1%
2006-2015	0.6%	16.2 %	27.0%
ϕ fixed (06-15)	0.9%	9.5%	18.6%
h fixed (06-15)	0.4%	7.1%	5.3 %
c fixed (06-15)	2.2%	27.4 %	48.7%

Table 1: **Statistics of the likelihood of sub-ice blooms in the Arctic Ocean**. The Arctic is defined as the region with latitudes greater than $> 70°$N, excluding Baffin Bay. Percentage by area refers to the fraction of the Arctic that has greater than 80% ice concentration and permits blooms, with a frequency greater than once in 14 days. ϕ fixed, h fixed, and c fixed refer to runs in which the melt pond fraction, sea ice thickness, or ice concentration field is fixed at the 1986-1996 values, with bloom statistics displayed only for the decade 2006-2015.

Figure 2: **Spatial map of the likelihood of sub-ice phytoplankton blooms over time** . (a-c) Shading indicates the frequency of days in May, from 1986-1995 (a), 1996-2005 (b), and 2006-2015 (c), where a sub-ice bloom is permitted. (d-f) Same as (a-c) but for June. (g-i) Same as (a-c) but for July. Red boxes in (d-f) indicate the region of the 2011 cruise.

2 Methods

Parameters used to evaluate sub-ice blooms The compensation irradiance, μ/Γ is defined using data from the North Water Polynya[28], with units of mol quanta $\mathrm{m}^{-2}\mathrm{d}^{-1}$, and a range of 1.9 $\pm$ 0.3 mol quanta $\mathrm{m}^{-2}\mathrm{d}^{-1}$. The factor μ/Γ has been measured in the North Atlantic via satellite[13], with values in a similar range (1.3 $\pm$ 0.3), though to the authors' knowledge no similar measurements exist in the high Arctic. On the basis of this similarity, we assume the magnitude of this factor is relatively spatially uniform and in this range in the Arctic. The conversion factor from these units to W/m^2 is approximately 2.5 W/mol quanta d^{-1} for PAR from sunlight, so we approximate $\mu/\Gamma \approx 4.5$ W/m^2 as a representative value. The clear-water attenuation coefficient ranges from 0.09 m^{-1} to 0.16 m^{-1} for wavelengths in the range $(412, 555)$[29]. We choose .12 m-1 as a representative value.

Critical Melt Pond Fraction The threshold determining a bloom onset is given by the equality

$$x = \beta(1 - e^{-x})\left[\phi + (1 - \phi)\alpha^*\right].$$

This equality can be re-arranged to form a similar threshold for the melt pond fraction, which we term the critical melt pond fraction ϕ_{crit},

$$\phi_{crit} = \frac{1}{1-\alpha^*}\left(\frac{x}{\beta(1-e^{-x})} - \alpha^*\right).$$

Calculation of model sensitivity To assess the degree to which variability in melt pond fraction and sea ice thickness may influence the fraction of the Arctic which permits blooms, Extended Data Table 2 shows the lower and upper bounds for the total Arctic area fraction that permits blooms when the sea ice thickness field is increased or decreased by one standard deviation. Extended Data Table 3 shows the same, but for melt pond fraction. At each grid point and year day, the thickness and melt pond fraction fields are linearly detrended over the period 1986-2015. The standard deviation at each grid point is then calculated using this time series and subtracted to or added to the baseline melt pond fraction and ice thickness data. The bloom analysis is then performed on the new perturbed data to produce the bounds given in Extended Data Table 2 and 3.

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Variable	Description	Value
α_i	Albedo of bare ice	.7[19]
α_w	Albedo of melt ponds	.2[30]
κ_i	Extinction coefficient of sea ice	1.8 m^{-1} [31]
κ_w	Extinction coefficient of ocean water	.12 m^{-1} [29]
μ/Γ	Compensation irradiance	1.9 mol quanta $m^{-2}d^{-1}$ [28]

Table Extended Data Table 1: Model parameter values and sources

Thickness $\pm$ 1 standard deviation ranges			
Years	Range of May % area	Range of June % area	Range of July % area
1986-1995	(0.1,0.3)	(1.4,4.7)	(3.8,12.3)
1996-2005	(0.5,1.3)	(5.6,11.2)	(13.5,22.6)
2006-2015	(0.4,0.9)	(10.4,23.9)	(21.6,31.4)

Table Extended Data Table 2: Ranges of the percentage are of the Arctic ocean ($> 70°$N, excluding Baffin Bay) in which sub-ice blooms can occur, when sea ice thickness data is increased or decreased by one standard deviation (for details, see Methods).

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Melt Pond Fraction $\pm$ 1 standard deviation ranges			
Years	Range of May % area	Range of June % area	Range of July % area
1986-1995	(0.0,6.5)	(0.6,5.8)	(4.0,9.4)
1996-2005	(0.0, 8.8)	(3.8,11.6)	(13.9,20.7)
2006-2015	(0.1, 10.3)	(9.6,23.2)	(21.7,30.1)

Table Extended Data Table 3: Ranges of the percentage are of the Arctic ocean ($> 70°$N, excluding Baffin Bay) in which sub-ice blooms can occur, when the melt pond coverage data is increased or decreased by one standard deviation (for details, see Methods).