PAN-ARCTIC VIEW OF ICE-EDGE PHYTOPLANKTON BLOOMS

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ABSTRACT

Blooms are known to occur in the Arctic Ocean immediately following the melting of the sea-ice, but a collection of individual observations from research ships cannot give the broad view as to how often they occur and how long they last. We combine passive microwave observations of sea-ice and visible light determinations of chlorophyll concentration to achieve this wider perspective. Defining the Marginal Ice Zone (MIZ) as the period within 20 days of ice melt, we note that an ice-edge bloom can be detected in 89% of locations for which adequate chlorophyll observations exist. In 80% of these cases the ice-edge bloom peaks within 20 days of the region becoming durably ice-free, with this value rising to more than 90% for some individual regional seas. The ice-edge bloom is usually short, with roughly half ending by the end of the MIZ period.

1. INTRODUCTION

Phytoplankton in the seasonal ice zone of the Arctic Ocean are generally thought to undergo a period of intense growth i.e. bloom immediately after the ice melt, when a freshwater layer provides strong stratification, enabling a shallow "ice edge" bloom. In some cases, if storms or other processes have mixed further nutrients up into the photic zone, a second bloom may appear later in the year, when solar heating provides a period of thermal stratification allowing the open water bloom found in most of the rest of the world's oceans. There are a number of reports of in situ observations of such ice edge blooms, indicating their occurrence in the Bering Sea [2], Chukchi Sea [3] and the Barents Sea [4] amongst others. These indicate that the phenomenon occurs in many diverse areas, but the observations are by nature limited in space and time, and thus do not imply that it is ubiquitous.

Thus very few papers to date have looked at the ice-edge bloom in a pan-Arctic context, quantifying how much of the region is affected and whether their contribution to total productivity in the Arctic is significant. One of the few exceptions is Pabi et al. [5] who quantify pan-Arctic primary production from satellite and differentiate between marginal-ice zones and open-water areas, thus implicitly addressing ice-edge blooms. Here we make a fresh look at the phenomenon of Arctic ice edge blooms, using satellite data to provide a consistent view across the whole Arctic. The data sets are described in section 2, with the following section looking at the issues concerning definitions of "ice-free" regions and "bloom conditions". Section 4 then collates the statistics to give the pan-Arctic view.

2. DATA SOURCES

This work makes use of two very different sources of data — passive microwave observation of sea-ice coverage, and visible light measurements of the phytoplankton bloom. These sources are described below.

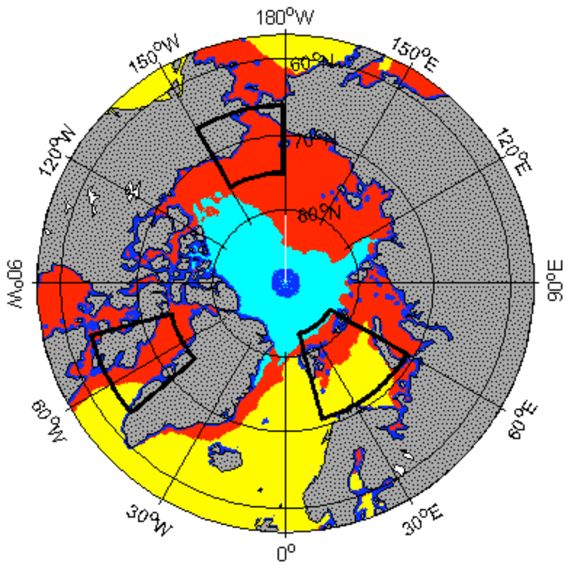

Figure 1. Ice coverage during 2007, from OSISAF data. Yellow indicates permanently open water, light blue the multi-year ice and the red region is the area of seasonal ice cover, which is the region discussed in this paper. [Dark blue indicates no data due to very high latitude or presence of coast in microwave footprint.].

2.1. Sea-ice

The microwave emission properties of sea-ice are very different from open water, allowing, in principle, an easy division between the two. However, even at the highest relevant microwave frequencies the footprint of the sensors is of order 25 km. Consequently during the melt period, as the ice begins to break up, the recorded emission will be from a mix of ice and water. We examined two data products — from OSISAF (Ocean and Sea-Ice Space Application Facility) and NSIDC (National Sea-Ice Data Center) — both of which provided estimates of sea-ice concentration on a daily basis. Fig. 1 shows the region of seasonal ice cover i.e. the region between maximal extent and the multi-year ice. We interpolate these ice concentration data to that of the ocean colour observations (section 2.2) using a nearest neighbour approach.

2.2. Chlorophyll concentration

A number of ocean colour sensors — SeaWiFS, MODIS, MERIS — can provide chlorophyll estimates over the Arctic. For all instruments there are no observations during the Arctic winter, as the algorithms assume the Sun is significantly above the horizon to give the source of light. However, the lack of such data is not a problem, as ice melt requires solar input too. In this work we have used SeaWiFS data available from NASA/GSFC on a 9 km x 9 km grid. The ocean colour algorithm to correct for atmospheric attenuation and then derive chlorophyll concentrations assumes the whole sensor footprint is uniform ocean: appreciable concentrations of sea-ice would invalidate these assumptions. In the product used here, chlorophyll concentrations were set to null based on a monthly sea-ice climatology; the recently revised product uses actual NSIDC real-time data [6], thus strongly advising against bloom investigation in ice-contaminated waters.

3. DEFINITIONS OF ICE AND BLOOM CONDITIONS

3.1. Time of ice melt

Phytoplankton may grow in conditions where ice concentration is 50% or more; however they will not be detectable from satellites. Given that the chlorophyll algorithms are only robust for sea-ice concentration ≤10%, we follow Pabi et al. [5] in using that threshold to define "ice-free".
At a given location the sea-ice concentration does not always decrease monotonically throughout the melt season. Conditions may allow a partial re-freeze, or more ice could be borne into the region by currents and/or winds. We define the location to be "ice-free" when the concentration is durably below 10% i.e. it remains so for at least 20 days (to fit our definition of the end of the MIZ). This is illustrated in Fig. 2, where the ice concentration first drops below 10% on day 160, but more ice appears within a week, and it only drops durably below 10% on day 166. We then consider the conditions in the ensuing 20 days probably to have a shallow surface freshwater layer, and thus be fertile for any ice edge bloom.

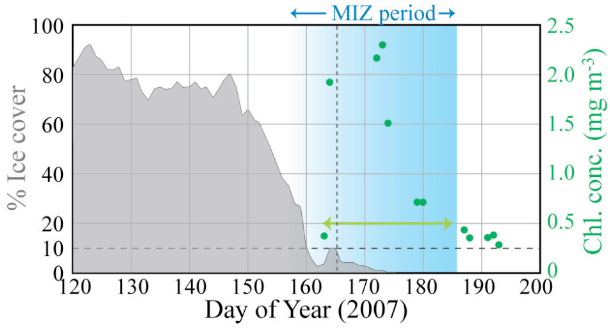

Figure 2. Illustration of data coverage for a location in the Baffin Bay, showing our definitions of MIZ period and of existence of ice-edge bloom. MIZ period is up to 20 days after ice concentration durably below 10%. A bloom is registered when chlorophyll concentration exceeds 0.5 mg m^{-3}.

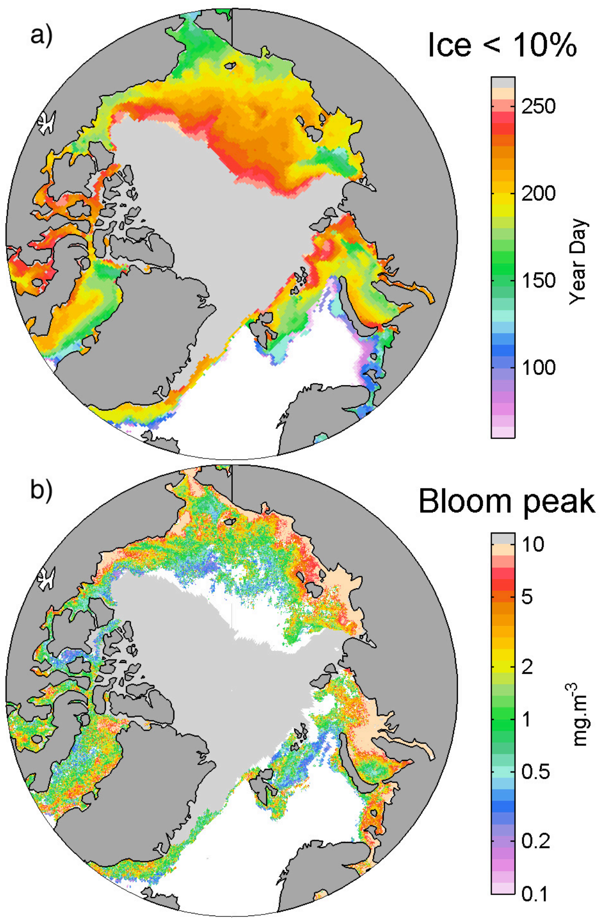

Figure 3. Ice and chlorophyll statistics for 2007. a) Date when "ice-free"; b) Bloom peak in the ensuing 20 days. Light grey shows multi-year ice; white indicates lack of data, either open ocean (so no MIZ period) or lack of any ocean colour observations in the correct time frame.

Fig. 3a shows the date during 2007 when each location becomes ice-free. The earliest melting (before day 100) occurs in the N. Atlantic, with the Bering Sea and Baffin Bay also becoming ice-free before the end of June.

3.2. Detection of bloom

The chlorophyll data record is patchy, as the view of the ocean may be obscured by clouds, low-lying fog (common just after ice-melt) or, of course, sea-ice. In many locations the peak of the bloom will have a concentration of between 1 and 10 mg m^{-3}. We define bloom conditions as that period when chlorophyll concentration ≥ 0.5 mg m^{-3}. Sometimes there are long periods without observations, such that interpolation is required to identify when the 0.5 mg m^{-3} threshold is exceeded. The example shown in Fig. 2 illustrates another complication: a few measurements indicate that the bloom had commenced before durably ice-free. However, for some pixels such early observations documenting the start of the bloom may not be available, due to being flagged as ice-contaminated. Fig. 3b shows the amount of chlorophyll at the peak of the ice-edge bloom, where the values are the maxima during the MIZ period i.e. a different interval for each pixel, tied to the time of ice melt (Fig. 3a).

The highest bloom concentrations in the MIZ period are noted along the coasts of Alaska and Russia. For the latter, at least, it is believed that estimates may be contaminated by the presence of sediment and/or CDOM (coloured dissolved organic matter) in the riverine outflow.

4. COLLATED STATISTICS OF THE ARCTIC ICE-EDGE BLOOM

As shown in Fig. 2, the availability of ocean colour observations of the sea is somewhat intermittent. Perrette et al. [6] noted that for around half of locations there were at least 3 days of observations within the MIZ period, though for some regions (predominantly those of early ice-melt or northernmost areas) there may be no records in the MIZ period for 2007. Polar plots showing timing of onset of bloom and its termination (not shown) appear speckled and are complicated to interpret because of the gappy record of chlorophyll observations. Therefore we now aggregate the statistics on the timing of the onset and termination of the bloom (Tab. 1). The second column gives the likelihood, provided there are at least 3 observations in the MIZ period, that at least one corresponds to a bloom. This is 89% globally, but with strong variations between different regions.

Combining the data on timing of the bloom peak, we note that, globally, nearly 80% of locations showing an ice-edge bloom have the peak either before the ice concentration drops below 10% or within 20 days of that. For a number of the regional seas the proportion of blooms with such an early peak is even higher (Tab. 1). Indeed, in many cases the bloom has terminated (chlorophyll concentration < 0.5 mg m^{-3}) by the end of the MIZ period. The regional variation of these statistics is likely to be strongly affected by the availability of nutrients, and by when the ice-melt occurs, as that governs the solar angle and thus the amount of photosynthetically available radiation (PAR).

Region	Bloom, given ≥ 3 obs	Peak < day 0	day 0 < Peak < day 20	Terminate < day 20
Global	89	30	52	50
Baffin	96	27	68	68
Barents	77	44	46	77
Chukchi	95	31	63	62

Table 1. Percentage of 2007 pixels with at least 3 chlorophyll observations during the MIZ period, and from those percentage of blooms starting before location ice-free, or during the next 20 days, plus percentage of blooms terminating within those 20 days.

An alternative way to look at this is to collate the statistics as a function of time of ice melt (Fig. 4). The top set of histograms (Fig. 4a) summarises the number of locations becoming ice-free at a given time (light grey), with medium grey indicating those for which there are sufficient (≥3) ocean colour observations in the ensuing 20 days. This shows that a large proportion of the seasonal ice zone loses its ice cover around day 180 (mid-summer), and that up day 200 well over half such points have the required minimum of 3 chlorophyll observations in the MIZ period. The black bars in Fig. 4a show how many of these pixels develop an ice-edge bloom in the MIZ period. For each time interval up to day 200, more than half of those locations becoming durably ice-free demonstrate a clear immediate bloom. Of those for which adequate observations exist, ice-edge blooms occur on 89% of occasions. However, regions becoming ice-free after day 210 usually offer poor opportunities for bloom observation, and a lower likelihood of one occurring within the next 20 days (despite the greater insolation).

The second panel (Fig. 4b) shows when the bloom peak occurs relative to ice-melt. For approximately 52% of reliably-detected blooms, the peak occurs in the 20 days following the waters becoming durably ice-free. Early on in the year, there are almost no blooms peaking before ice concentration is durably <10% (shown in blue), but a high occurrence of blooms peaking more than 20 days after initiation (red). This is probably due to the low light levels, such that growth is relatively slow and nutrient supply not quickly exhausted. In contrast, at the end of the melt season (days 220-250) more than half of blooms peak before ice concentration is reliably < 10%.

The third panel (Fig. 4c) shows a similar story for when the ice-edge bloom terminates (chlorophyll level drops below 0.5 mg m^{-3}). In the early part of the year (up to day 130), more than half of the blooms detected are relatively slowly growing and persistent, with bloom conditions still existing after 30 days; after day 130 the ice-edge blooms are much more shortly-lived, with more than half ending within 15 days of ice melt.

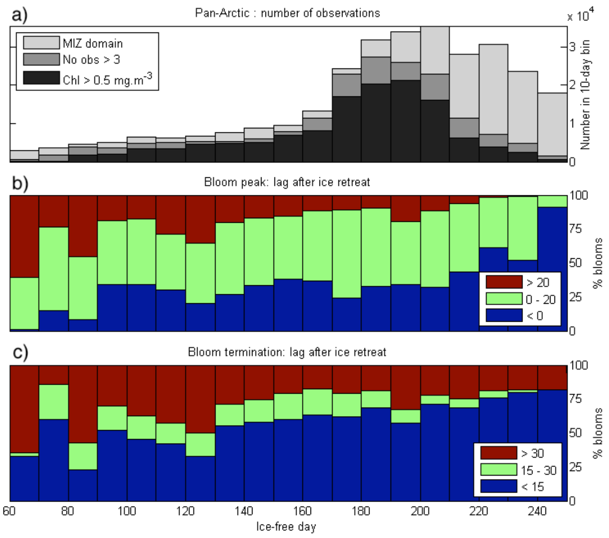

Figure 4. Summary of ice-melt and phytoplankton bloom statistics for 2007, grouped in 10-day bins. a) Availability of observations, including in black locations becoming ice-free, and showing a clear ice-edge bloom. b) Timing of peak of ice-edge bloom, relative to first ice-free day at location (expressed as % of observations). c) Timing of end of bloom, relative to first ice-free day at location (expressed as % of observations).

In some cases, the ice edge bloom may be being succeeded by an open ocean bloom, without a clear termination separating them. This could happen if, as the halocline breaks down, mixing occurs to a greater depth bringing further nutrients into the photic zone, but with a sharp enough thermal barrier below, so that phytoplankton are not mixed too deep. In situ observations would be able to distinguish them, as the open water bloom tends to occur much deeper in the water column. However, one of the clear results from this analysis is that in order to make the required in situ observations (e.g. to determine which phytoplankton species are dominating, and effects at higher trophic levels), the research ship needs to reach the location early within the MIZ period else it is likely that the bloom will be waning.

Finally, in Fig. 5 we look once more in a global context at the timing of the bloom peak relative to when ice concentration falls below some threshold. It can be seen that using a 10% criterion there are a number of locations showing a chlorophyll peak up to 20 days prior. Even with a higher ice threshold of 30% there are still a few cases with bloom peaks 20 days ahead of that.

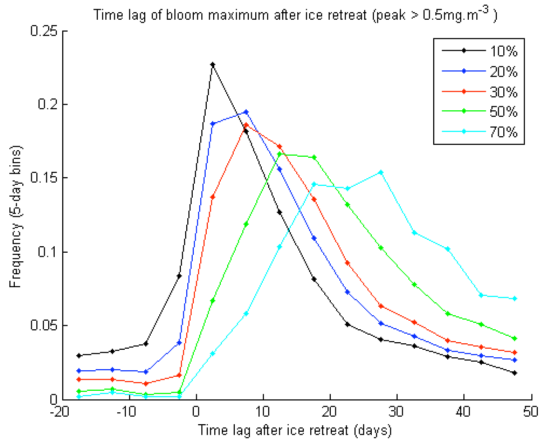

Figure 5. Histograms showing timing of bloom maximum relative to time of ice-melt, showing the effect of choosing different ice concentration thresholds to define start of growing conditions. [From OSISAF and SeaWiFS data.]

One factor is the definition of ice-free day, which in our case is best described by the last ice-covered day. Drifting or regrowth of new ice indeed leads to delaying the "ice-free day" until the time of durable retreat, and therefore leads to apparent early blooms when the ice-edge oscillates. In other cases the negative time-lag could be due to very different resolutions of the instruments for ice- and bloom-detection, so patches classified as "ice" by the microwave sensor may have patches on a smaller scale that are relatively ice-free and for which valid chlorophyll observations are returned. Alternatively, these "blooms" could be erroneous retrievals by an ocean colour algorithm that did not recognise the ice contamination. Obviously, changing the threshold to a higher sea-ice concentration leads to earlier dates for "ice-free" and thus greater lags for the timing of the bloom. More interestingly, the distribution of bloom timing relative to ice-free is narrowest for the 10% criterion, indicating that the date ice concentration falls below 10% is the best for predicting when the bloom will occur, acknowledging however that this distribution may be artificially truncated due to ice-contamination flagging.

5. SUMMARY AND IMPLICATIONS

An early phytoplankton bloom following the ice edge provides the early fodder for zooplankton and higher trophic levels; however, recording and quantifying the extent of this bloom is difficult. A number of ships have made in situ measurements, but it is not clear how representative these reported observations are of the general situation. In this paper we have looked at the ice edge bloom in a pan-Arctic context, documenting some of the challenges e.g. patchy ocean colour observations (due to clouds, fog and sea-ice), as well as the determination as to when the ocean is "ice-free". For the latter, we use the date for which ice concentrations are durable below 10%. This value corresponds to the maximum allowing ocean colour algorithms to function [6], gives dates reasonably consistent between OSISAF and NSIDC products, and accords with that used by Pabi et al. [5]. We define the MIZ period as up to 20 days after that date.

For those locations affording at least 3 observations in the MIZ period, 89% show a phytoplankton bloom (concentration $\geq$ 0.5 mg m^{-3}), with in many cases the bloom exceeding 2.5 mg m^{-3}. Of those locations showing a bloom, 30% peak before the region is durably "ice-free", with a further 52% in the ensuing 20 days. Indeed for some regions (e.g. Baffin Bay and Barents Sea) the bloom has usually terminated by the end of the MIZ period, indicating that to perform in situ sampling of such blooms research ships will have to be right near to the ice edge.

As these blooms are short, they may make only a moderate contribution to the total productivity of a region that is ice-free for a long-period and has an open water bloom when there is greater sunlight available. However, for many regions the mean productivity rate in the MIZ period exceeds that averaged over the rest of the growing season [7]. With the recent changes in amount of Arctic ice cover, there is great interest in understanding what the repercussions will be for plankton productivity and the health of the whole Arctic ecosystem.

6. ACKNOWLEDGEMENTS

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