Phytoplankton blooms in high latitude systems

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High-latitude oceans

Our understanding of high-latitude oceans far lags that of lower latitudes

- Especially so where there is substantial or perennial sea ice cover
- Regards phytoplankton & blooms → some unique ecological aspects
- Complex ocean ecosystems unfamiliar to many

“Global” ocean drifter array

“Global” ocean chl distributions

OCB – Woods Hole, MA, July 22 2015
Often think of Harald Sverdrup w.r.t. CDH & North Atlantic bloom

But he was an accomplished polar ocean scientist

- 1918-1925 Chief Sci. on Amundsen’s North Polar Expedition on *Maud*
- 1931 Chief Sci. on Wilkins’ *Nautilus* North Polar Expedition
- 1934 glaciology, West Spitzbergen
- <1936-48 Director Scripps; WWII>
- 1948 Director, Norwegian Polar Institute
- <1953 minor paper, vernal blooms*>
- 1957 Helped Norway establish Antarctic sovereign territory

*almost polar
Very little in his obituaries about 1931 *Nautilus* Expedition

In 1931 he was the leader of the scientific group in the Wilkins-Ellsworth North Polar Submarine Expedition, where valuable information was gathered despite the failure to achieve the chief goal of the expedition, the submersine exploration of the Arctic in the *Nautilus*.
Science plan:

- 3 scientists, with Sverdrup Chief Sci.
- Hydrography, magnetometry, sonic depth, bottom sampling with a winch
- Chemistry: N, P, pH
- Prof. Hardy’s ‘Continuous Plankton Recorder’ (didn’t work; prototype?)
- Spectrograph to measure under-ice spectral $E_d$ (didn’t work; no data)
the scientists did not hesitate to
join the expedition in spite of the probable deficiencies of the vessel.

“March-May 1931 in harbor NYC, quartermaster
overboard & drowned…mid-Atlantic…engines
broke…SOS…towed to England for repairs.”

“28 June…up and running…to Norway to pick
up <scientists>…23 August…600 miles from
North Pole…another setback …submarine
missing its diving planes.”

“…one setback after another…”

“…headed for England…forced to take refuge in
Bergen…suffered serious damage…received
permission from <US Navy> to sink the vessel in
a Norwegian fjord…sunk outside of Bergen.”

(“…Wilkins secretly felt that his mission was
deliberately sabotaged by a crew member…”)
What if this expedition had been successful?

1931 - Sverdrup likely would have encountered an under-ice algal bloom

*Nautilus* would arrive at the pole at just the right time

- Underway spectrograph → observed selective penetration of green wavelengths
- CPR → collected diatoms: chains & colonies
- Chemistry → indicated depleted nutrients (N,P).

_Not a vernal bloom. Would this have altered Sverdrup’s interest in high-latitude blooms & factors that drive them? Sverdrup + blooms in 1930s?*_
Very early (earliest?) application of Sverdrup’s CDH was at high latitudes:

- Blooms in & around Bear Island, Norway
- Truly ‘high latitude’ 74°30’N, 19°E
- Examined timing of ice-edge blooms (in April) vs. open-ocean ‘vernal’ blooms, (in May-June), using the CDH framework.
Arctic ice-edge blooms (Apr) vs. Atlantic open-ocean (May-June)

“Stabilization” sensu Sverdrup was by “spring heating of the surface layer” or by “spring run-off”. Marshall added a high-latitude factor: melted sea ice.
Perspectives on high-latitude blooms since Marshall (1957)

I. The photosynthetic environment at high latitudes
   • ‘Accidents of geography’, insolation & sea ice

II. A primer on some types of high-latitude blooms
   • Polynyas, ice-edge blooms, & under-ice blooms
   • Under-ice blooms at the highest Arctic latitudes

III. Some high-latitude ecophysiology worthy of more study

IV. Gaining better insight into high-latitude blooms
I. What’s different about oceans at high latitudes?

“High-latitude ocean” depends on your perspective.
Highly variable insolation on seasonal & sub-seasonal scales

- High-latitudes experience low irradiance due to planet’s curvature.
- Summer: longer day-lengths compensate for lower intensity

Insolation: over the month of April, a **tenfold increase**!

(Important corollary: over August, a **tenfold decrease**)

**CDH** → rapid day-to-day changes in critical depth
Sea ice → several direct effects on photosynthetic environment

1. Insulates ocean from wind stress. (wind-driven mixing is weak)

2. Ice melts & freezes: affects stability of ocean layer immediately below surface ice cover (~20 m)

3. Blocks sunlight from entering the ocean
Sea ice with surface snow – transmits light poorly

- Ice: 1.3-2.5 m\(^{-1}\) (1 m removes 80% PAR)
- Snow: 16-45 m\(^{-1}\) (15 cm snow removes 90% of PAR)
- Highly variable optically (time & space)
- Any biota in ice may alter light as well
Sea ice: melting takes time; delays illumination of water column

Under-ice PAR data: 12 month ITP in Canada Basin (~80° to 74°N)

Top: Solar elevation daily min & max (degrees, computed)
Bottom: Depth of measurable PAR (light penetration, m, measured)

Delays light entering into the ocean, by several months

Major factor establishing short growing seasons under ice

Laney unpubl.
An important additional (indirect) effect of sea ice

*Provides habitat for an immediately adjacent, very different ecosystem*

- Arctic $\rightarrow$ thicker ice (2-3 m); combination of 1st- & multi-year ice. Ice algae on or close to bottom of ice.

- Antarctic $\rightarrow$ thinner ice (1-2 m); primarily 1st year ice. Algae often in internal layers.

- Ice algae bloom earlier $\rightarrow$ shades water column below

- When ice melts $\rightarrow$ pulse of ice algae falling through water column. Seeding or sediment?

Acknowledgments

Ackley et al. 2008

nature.ca
I. The photosynthetic environment at high latitudes
   • ‘Accidents of geography’, insolation, & sea ice

II. A primer on some types of high-latitude blooms
   • Polynyas, ice-edge blooms, & under-ice blooms
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Perspectives on high-latitude blooms since Marshall (1957)
High-latitude blooms part 1: coastal polynya blooms

Katabatic winds push sea ice offshore → strong blooms


Amundsen Sea Polynya International Research Expedition (ASPIRE: Yager et al. 2012)
Coastal polynya blooms $\rightarrow$ photosynthetic niches

Diatoms $\rightarrow$ highly pigmented, strongly self-shade; assoc. with mixing $< 40$ m  
(Sakshaug & Holm-Hansen 1984)

Phaeocystis $\rightarrow$ lower chl, can survive deeper mixing: 60-80 m  
(e.g. Olsen et al. 2003)

Amundsen Sea polynya 2007-8 & 2010-11 (Delmont et al. 2014)

- Diatoms in stratified edges of polynya
- Phaeocystis in better-mixed polynya center

Reflects photosynthetic niches within the nominal ‘bloom’: partitioning of multiple, co-blooming, disparate taxa.

Not always just diatoms & Phaeocystis
High-latitude blooms part 2: ice-edge blooms

- A belt ~ 20-100 km wide from ice edge
- A highly-stratified MIZ $\rightarrow$ diatoms
- Less stratified (later) $\rightarrow$ *Phaeocystis*
- Large fraction of yearly production
- Diatom blooms can be rapid & escape predation $\rightarrow$ contribute to export

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arctic.noaa.gov

Laney unpubl.
Ice-edge blooms widespread where ice cover is seasonal

perrette et al. 2011
1. ‘Prebloom growth’ → low light, low biomass
2. ‘Ice-edge bloom’ → rapid growth in MIZ, high algal biomass
3. ‘Post-bloom deep-chlorophyll max’
4. Oligotrophic post-bloom surface layer
Numerous studies examined other aspects of ice-edge blooms

- Winds & currents moving the ice edge?
- Ice-edge transects surface waters already nutrient depleted?
- Upwelling at the ice edge?
- Fe limitation & fertilization?
- Seeding of bloom initially, by populations introduced by sea ice?
- Termination: solely nutrients & light, or attack by bacteria?
High-latitude blooms part 3: under-ice blooms far from ice edge

Massive Phytoplankton Blooms Under Arctic Sea Ice


15 JUNE 2012 VOL 336 SCIENCE www.sciencemag.org

Under-ice
No bloom         bloom

K. Frey, Clark University

NASA ICESCAPE 2011
coastal Arctic, Chukchi Sea

~120 km

Arrigo et al. 2014
**2011 bloom: biomass, composition, growth rates, & productivity**

**Table 3**

Photosynthetic Parameters of Phytoplankton at the surface and the SCM from the under-ice bloom (bloom) and adjacent open water (non-bloom).

<table>
<thead>
<tr>
<th></th>
<th>$P_m$ ($\mu$g Chl a m$^{-2}$)</th>
<th>$\alpha^*$ ($\mu$g Chl a m$^{-2}$)</th>
<th>$E_k$ ($\mu$mol photons m$^{-2}$ s$^{-1}$)</th>
<th>$\mu$ (day$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Surface</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bloom</td>
<td>1.35 (0.30)</td>
<td>0.021 (0.006)</td>
<td>67.6 (22.4)</td>
<td>0.85 (0.47)</td>
</tr>
<tr>
<td>Non-bloom</td>
<td>0.68 (0.11)</td>
<td>0.011 (0.003)</td>
<td>67.9 (25.1)</td>
<td>0.05 (0.02)</td>
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<tr>
<td><strong>SCM</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bloom</td>
<td>1.45 (0.38)</td>
<td>0.027 (0.007)</td>
<td>54.9 (10.0)</td>
<td>0.92 (0.30)</td>
</tr>
<tr>
<td>Non-bloom</td>
<td>0.74 (0.17)</td>
<td>0.013 (0.005)</td>
<td>64.0 (31.9)</td>
<td>0.24 (0.23)</td>
</tr>
<tr>
<td><strong>All</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bloom</td>
<td>1.40 (0.33)</td>
<td>0.024 (0.007)</td>
<td>61.2 (18.0)</td>
<td>0.89 (0.39)</td>
</tr>
<tr>
<td>Non-bloom</td>
<td>0.71 (0.14)</td>
<td>0.012 (0.004)</td>
<td>66.0 (26.6)</td>
<td>0.15 (0.18)</td>
</tr>
</tbody>
</table>

$^a$ Mean ± standard deviation.

$P_m$ = mg C m$^{-2}$ Chl a hr$^{-1}$, $\alpha^*$ = mg C mg$^{-1}$ Chl a hr$^{-1}$, $E_k$ (umol photons m$^{-2}$ s$^{-1}$)$^{-1}$, $\mu$ (day$^{-1}$).

Arrigo et al. 2014

**Taxa different from under-ice bloom observed by Gradinger (1996)**

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Details of 2011 under-ice bloom composition

Imaging FlowCytobot
Bloom & non-bloom taxa

Laney & Sosik 2014
Beginning to examine higher order taxonomic complexity in bloom beyond just ‘bloom’ and ‘diatom bloom’

Under-ice bloom composition → complex distributions

Laney & Sosik 2014

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Under-ice production too high for a ‘typical’ ice-edge bloom

Possible explanations:

- Ice-edge bloom advecting back under ice?
- Ice pack itself moving over ice-edge bloom?
- Sinking ice-algal export?
- Advection from elsewhere in the Chukchi?
Putative explanation: transient melt ponds

Melt ponds better transmit insolation into water column below

Phytoplankton trapped in winter water under-ice → suddenly released from light limitation → perfect conditions.

Ponds are ephemeral. Their role in Arctic production not well understood.
High-latitude blooms part 4: blooms at the highest latitudes

I.e., in perennially ice-covered regions of the Arctic Ocean

- Where sea ice only loses snow cover & thins, but does not melt away
- Growth season very short: ~ 6 weeks
- Mixed-layer depths typically very shallow (10-20 m), shoaling in Jul-Aug:
  - Diatoms bloom in the upper 10 m in July, with early melting of snow cover
  - Can be secondary peaks, e.g. Oct (e.g., Gran 1904, Fortier et al. 2002)

Composite of ~5600 ITP profiles in Canada Basin (Toole et al. 2010)
Ice-Tethered Profilers

Automated instrument system to obtain & transmit upper ocean water property profiles under perennial sea ice in the polar oceans, multiple times daily over months to years.
### 8 ‘bio-optical’ ITPs deployed in Aug / Sept 2011-2013

7 of these ITPs collected profiles for at least 100 days

<table>
<thead>
<tr>
<th>ITP</th>
<th>days</th>
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<th># profs</th>
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<td>72</td>
<td>107</td>
<td>1196</td>
<td>242</td>
<td>¾</td>
<td>✓</td>
</tr>
</tbody>
</table>

Two systems: 1 year chl data
One also: 1 year light data
Seasonal trends in depths & timing of blooms

2011-2015: 8 ITPs outfitted with chl fluorometers (NSF AON)

Central Arctic (Transpolar Drift) vs. Canada Basin (Beaufort Gyre)

Laney et al. 2014
Late spring event: Start of bloom? Release of sea ice algae?

Laney et al. 2014
Day-to-day trends in \( \text{chl} \)

1-2 week changes in the time derivative of \( \text{chl} \) →

Bloom? Local growth or loss within euphotic zone?

Vertical fluxes through it?

Frequent profiling → insight into a bloom’s rapid dynamics

ITP48 – Central Arctic

\[
\begin{align*}
-205 & \quad -91 & \quad -996 \text{ profiles} \\
\text{4 profiles day}^{-1} \text{ Mar-Oct} & \quad \text{1.5 profiles day}^{-1} \text{ Nov-Feb} & \quad \text{All profiles: 25 cm vertical resolution}
\end{align*}
\]

Laney et al. 2014
Controls on dChl/dt in the euphotic zone

Are Δ in chl (growth?) followed by ↑ in # spikes at depth? (export?)

- Under-ice annual trends not as simple as ‘bloom → export’
- Dynamics of ice algae sedimenting through: needs more study.
Bloom dynamics: light availability (timing, magnitude, variability)

Light availability: One of the least-well constrained aspects of bloom dynamics in the deep central Arctic
Many high-latitude phytoplankton have overwintering strategies whose ecological role in bloom genesis & dynamics remain largely unexamined.

Healy 2011 ‘Winter’ cruise: Chukchi Sea, Nov-Dec (NSF-OPP)
Chaetoceros resting stages (spores)

Laney unpubl.
Phaeocystis also has a complex life cycle, involving colony formation.

A case where $1 + 1 \neq 2$!!

E.g., Shields & Smith (2009):

Cells & colonies differ $\alpha$, $P_{\text{max}}$

Solitary cells & colonies likely play different roles during bloom

Phenotype-level modeling:

Fig. 7. Conceptual diagram of the temporal sequence of Phaeocystis antarctica growth rates, environmental variables (iron and irradiance) and biomass for both colonial and solitary forms. $E_{\text{irr}}$, surface irradiance; $[Fe]$, iron concentrations; $B_{\text{col}}$, biomass of colonies; $\mu_{\text{col}}$, growth rate of colonies; $B_{\text{sc}}$, biomass of solitary cells; $\mu_{\text{sc}}$, growth rate of solitary cells.
Many basic aspects of high-latitude blooms remain unclear:

- How long is the growing season? When does it start, end?
- Where do blooms occur (vertically, spatially) & when?
- Esp. in the Arctic: ice algae - phytoplankton interactions?

→ Difficult to predict effects on polar ecology & biogeochemistry

Three avenues for improving our knowledge about HLAT blooms:

- Arctic: historical observations not easily obtained in the West
- Application of autonomous systems & remote sensing
- Using observations to constrain & improve models
Last decade: new insight through satellite remote sensing

Understanding distribution, timing, & magnitude of ice-edge & polynya blooms

Near-ubiquity of ice-edge blooms in the Arctic

M. Perrette¹,³, A. Yool³, G. D. Quarm³, and E. E. Popova³

Perrette et al. 2011

Are phytoplankton blooms occurring earlier in the Arctic?

M. KAHRU, V. BROTAS, M. MANZANO-SARABIA, and B. G. MITCHELL

Kahru et al. 2010

Impact of a shrinking Arctic ice cover on marine primary production

Kevin R. Arrigo, Gert van Dijken, and Sudeshna Pabi

Arrigo et al. 2008

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New insight using high-latitude ecosystem models

Using models to examine timing & forcing of under-ice blooms

Central Arctic (Transpolar Drift)  Canada Basin (Beaufort Gyre)

BIOMAS model

ITP tracks & BIOMAS model mesh

Zhixuan Feng (WHOI)

Collaborative Research: Changing Seasonality of the Arctic: Alteration of Production Cycles and Trophic Linkages in Response to Changes in Sea Ice and Upper Ocean Physics

Jinlun Zhang and Mike Steele (University of Washington)
Yvette H. Spitz (Oregon State University)
Carin J. Ashjian (Woods Hole Oceanographic Institution)
Robert G. Campbell (University of Rhode Island)

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Harald Sverdrup’s legacy & impact regards high-latitude blooms

On Conditions for the Vernal Blooming of Phytoplankton.

By
H. U. Sverdrup,
Norisk Polarinstitute, Oslo.


Primary Production in the Arctic

By
P. T. Marshall,
Fisheries Laboratory, Lowestoft

Polar Sub Can Drill Through Ice

Sir Hubert Wilkins' submarine, the Norland, is being equipped with a unique ice saw, or drill, at Camden, N. J., shipyard. The device will enable the vessel to travel through 13 feet of ice, and allows the crew to escape in an emergency through a telescoping 'escape tube.'

Wilkins expects to explore the Arctic in the Norland. As a proponent of underwater excavation, Sir Leonard, pioneer submarine designer, invented the ice saw. It is made of two separate sleds which can cut through 10 feet of ice.