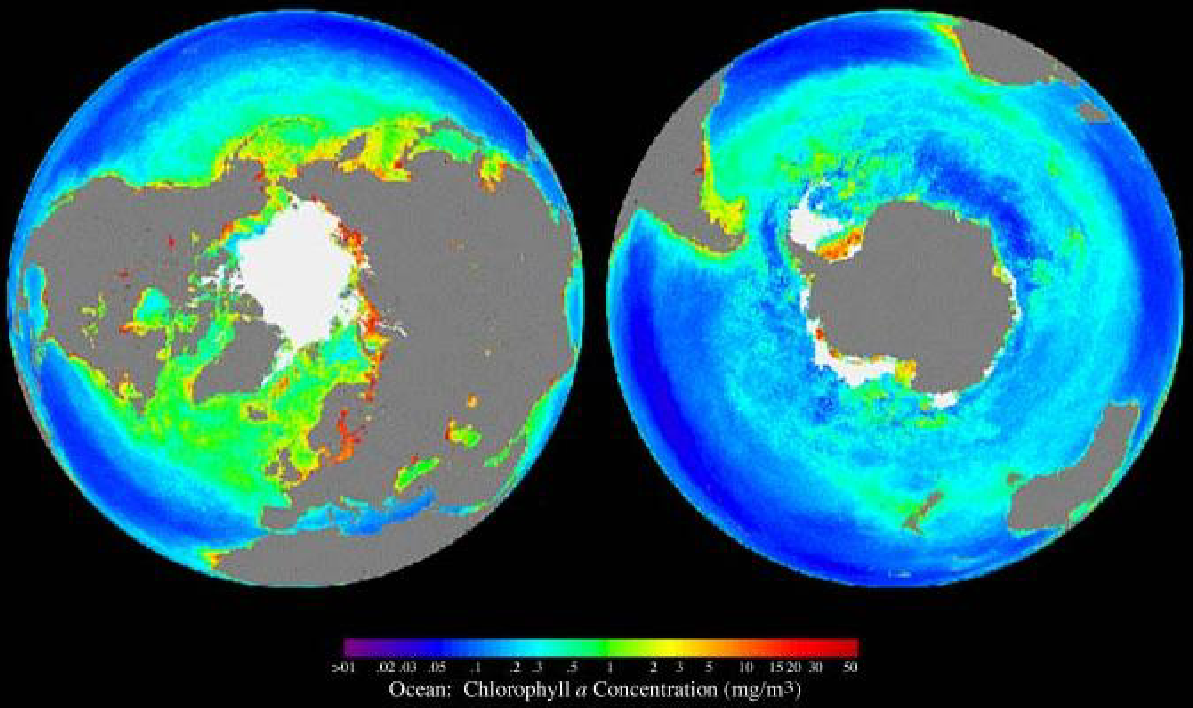
Phytoplankton blooms in high latitude systems



Sam Laney

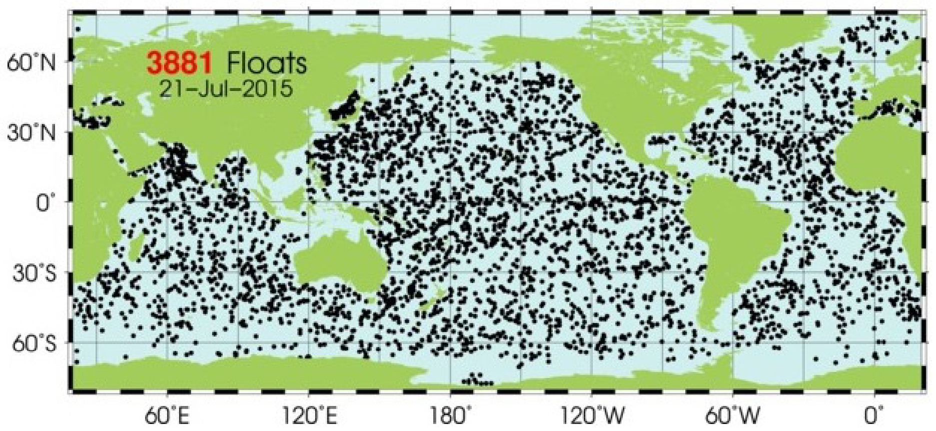
Biology Department

Woods Hole Oceanographic Institution

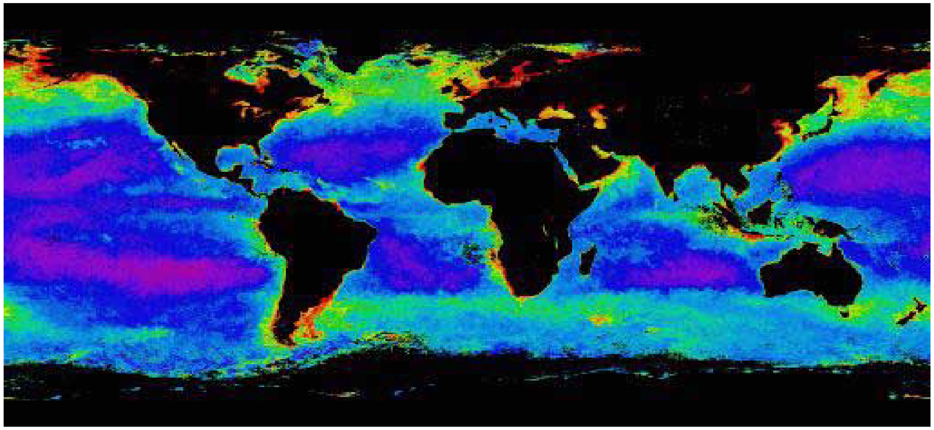
High-latitude oceans

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

“Global” ocean drifter array



“Global” ocean chl distributions

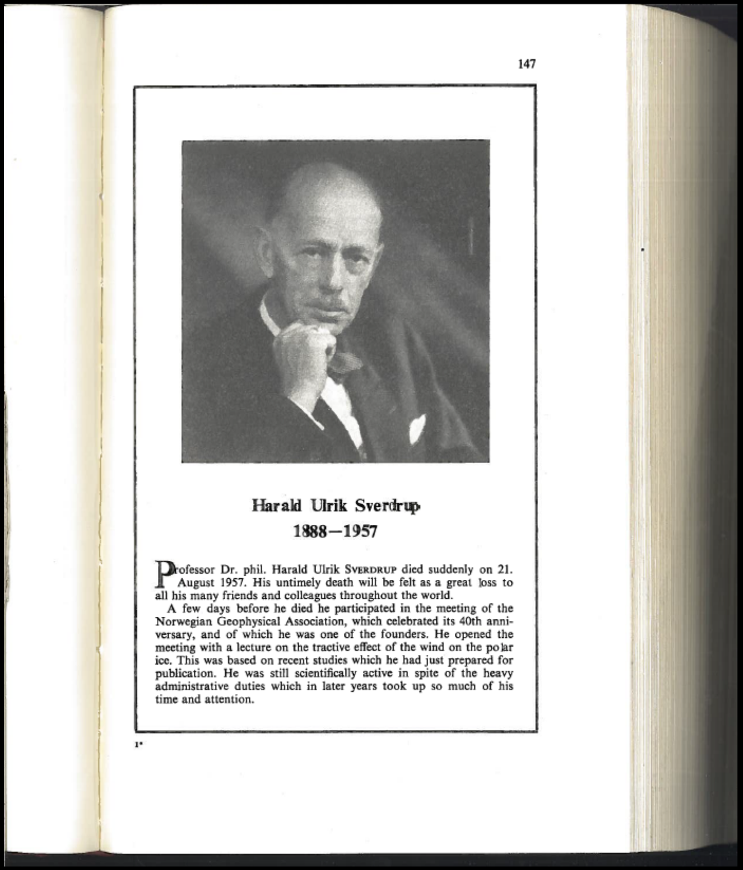


- *Especially so where there is substantial or perennial sea ice cover*
- *Regards phytoplankton & blooms → some unique ecological aspects*
- *Complex ocean ecosystems unfamiliar to many*

Often think of Harald Sverdrup w.r.t. CDH & North Atlantic bloom

But he was an accomplished polar ocean scientist

Obituary *J. Cons. Int. Explor. Mer (1957)*



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Harald Ulrik Sverdrup

1888—1957

Professor Dr. phil. Harald Ulrik SVERDRUP died suddenly on 21. August 1957. His untimely death will be felt as a great loss to all his many friends and colleagues throughout the world.

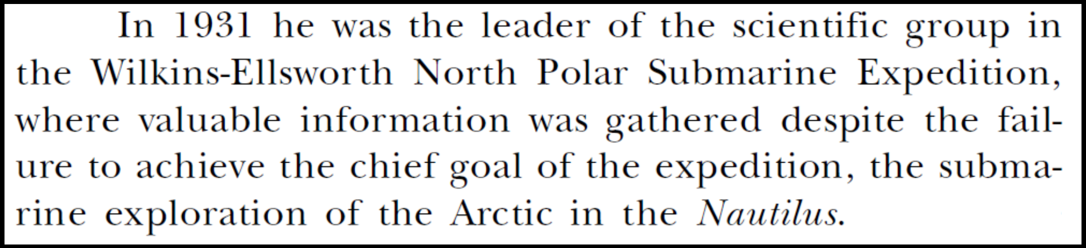
A few days before he died he participated in the meeting of the Norwegian Geophysical Association, which celebrated its 40th anniversary, and of which he was one of the founders. He opened the meeting with a lecture on the tractive effect of the wind on the polar ice. This was based on recent studies which he had just prepared for publication. He was still scientifically active in spite of the heavy administrative duties which in later years took up so much of his time and attention.

1*

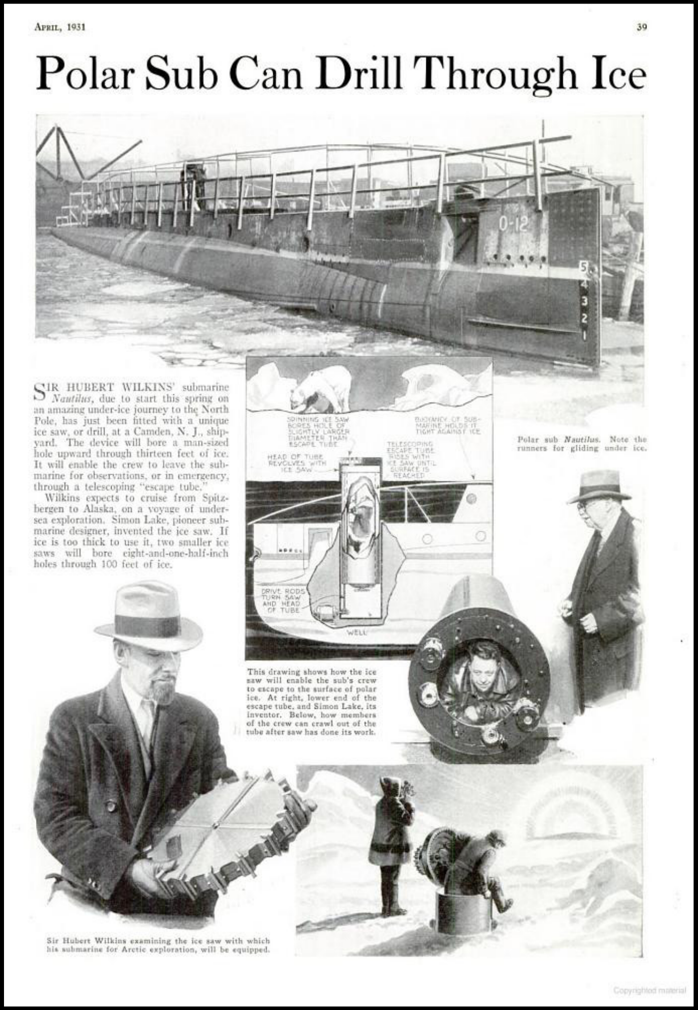
- 1918-1925 Chief Sci. on Amundsen's North Polar Expedition on *Maud*
- 1931 Chief Sci. on Wilkins' *Nautilus* North Polar Expedition
- 1934 glaciology, West Spitzbergen
- <1936-48 Director Scripps; WWII>
- 1948 Director, Norwegian Polar Institute
- 195? Visited Norwegian Antarctic Stn.
- <1953 minor 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 submarine exploration of the Arctic in the *Nautilus*.



APRIL, 1931 39

Polar Sub Can Drill Through Ice

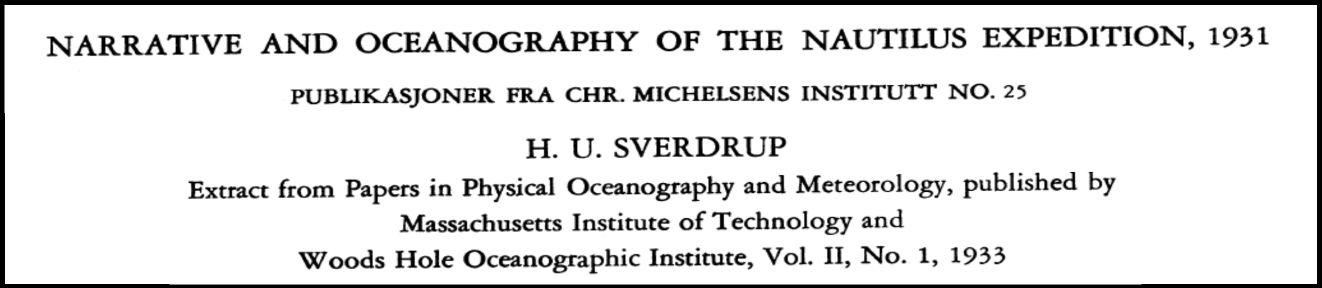
SIR HUBERT WILKINS' submarine *Nautilus*, due to start this spring on an amazing under-ice journey to the North Pole, has just been fitted with a unique ice saw, or drill, at a Camden, N. J., shipyard. The device will bore a man-sized hole upward through thirteen feet of ice. It will enable the crew to leave the submarine for observations, or in emergency, through a telescoping "escape tube."

Wilkins expects to cruise from Spitzbergen to Alaska, on a voyage of undersea exploration. Simon Lake, pioneer submarine designer, invented the ice saw. If ice is too thick to use it, two smaller ice saws will bore eight-and-one-half-inch holes through 100 feet of ice.

Polar sub *Nautilus*. Note the runners for gliding under ice.

This drawing shows how the ice saw will enable the sub's crew to escape to the surface of polar ice. At right, lower end of the escape tube, and Simon Lake, its inventor. Below, how members of the crew can crawl out of the tube after saw has done its work.

Sir Hubert Wilkins examining the ice saw with which his submarine for Arctic exploration, will be equipped.


NARRATIVE AND OCEANOGRAPHY OF THE NAUTILUS EXPEDITION, 1931

PUBLIKASJONER FRA CHR. MICHELSENS INSTITUTT NO. 25

H. U. SVERDRUP

Extract from Papers in Physical Oceanography and Meteorology, published by
Massachusetts Institute of Technology and
Woods Hole Oceanographic Institute, Vol. II, No. 1, 1933

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)

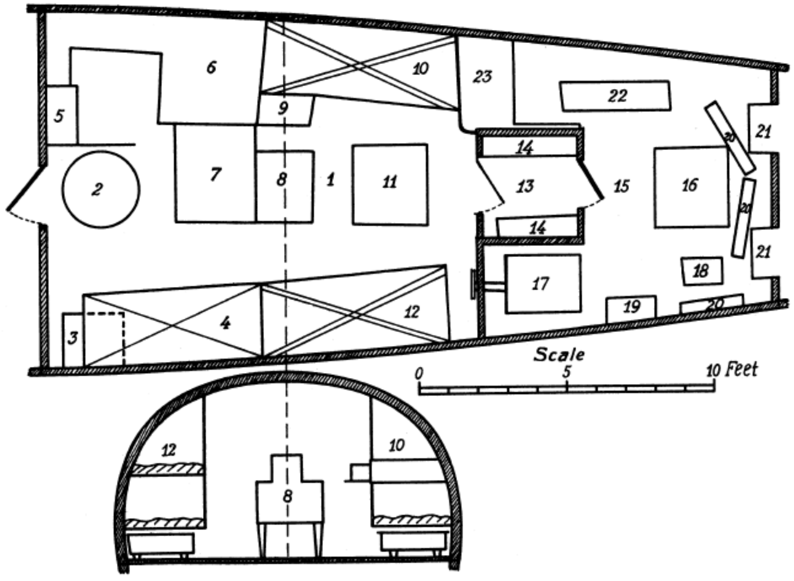
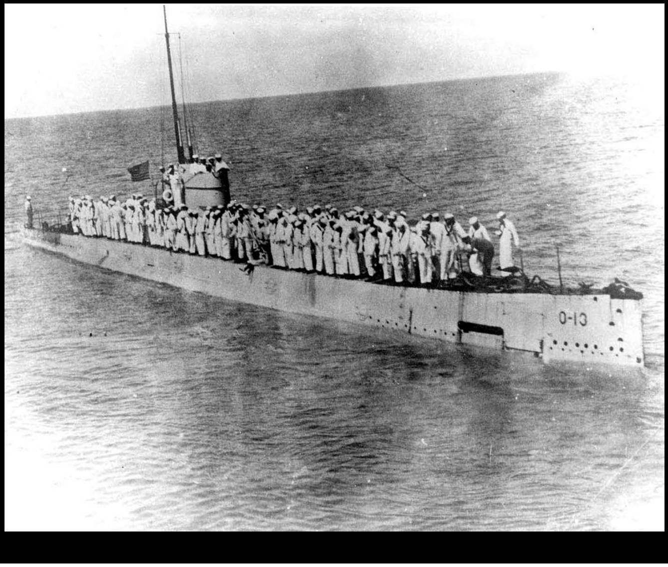


FIG. 1.—Plan of the compartment for the scientists, and of the diving compartment

1 Living room and laboratory.
2 Ice-drill.
3 Motor and winch for ice-drill.
4 Berth (Dr. Villinger). Boxes under berth for bottles with chemical solutions.
5 Sonic depth-finder.
6 Radio station.
7 Table for colorimeter and titration apparatus. Boxes under table with glassware and distilled water.
8 Gravity apparatus.
9 Shelf for chronometers.
10 Berths. (Sir Hubert Wilkins and Mr. R. Meyers, radio expert.)
11 Table built of boxes for water samples.
12 Berths. (Dr. Sverdrup and Mr. Soule.) Magnetic instruments under lower berth.
13 Air lock.
14 Boxes for water samples and bottom samples.
15 Diving compartment.
16 Diving hatch.
17 Hydrographic winch.
18 Pulley.
19 Boxes for water samples.
20 Racks for water bottles.
21 Torpedo tubes.
22 Bottom samplers.
23 Small air lock.

the scientists did not hesitate to join the expedition in spite of the probable deficiencies of the vessel.



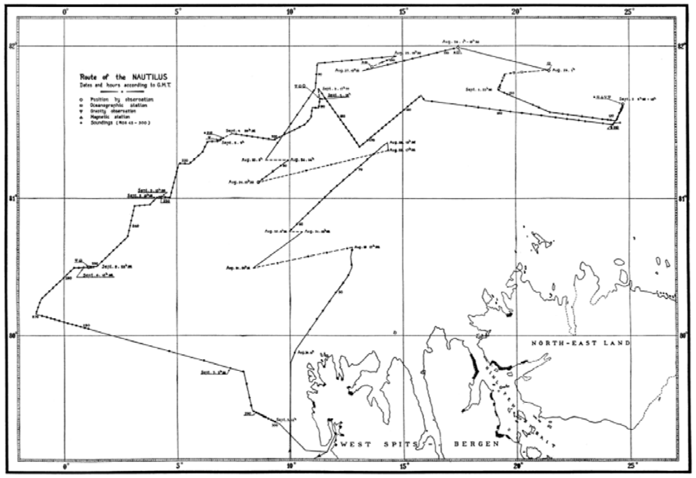


FIG. 2.—Chart of the route of the *Nautilus*

"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."

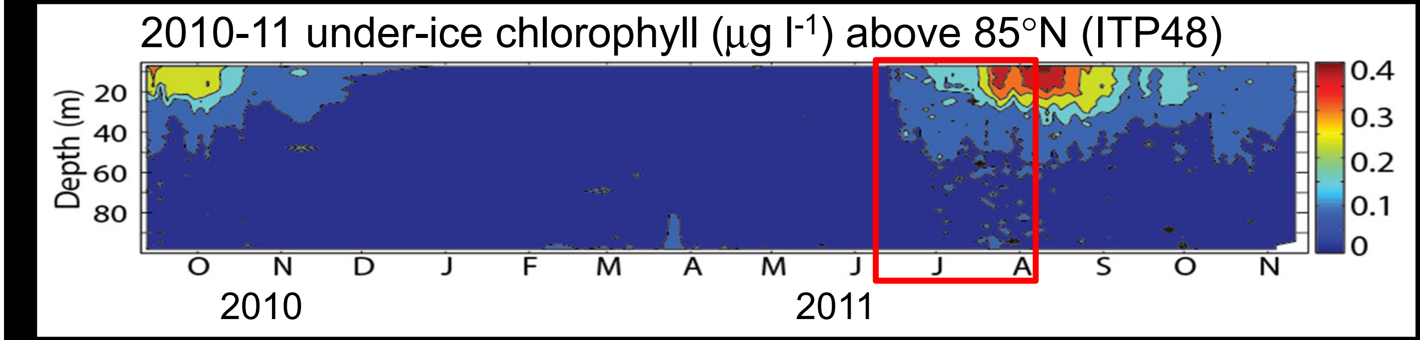
"…one setback after another…"

"…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…")

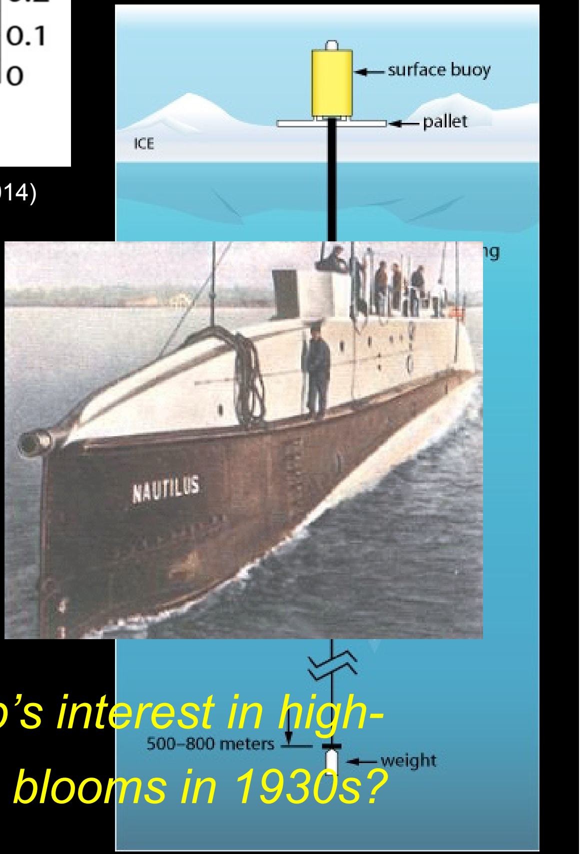
What if this expedition had been successful?

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


2010-11 under-ice chlorophyll ($\mu g\ l^{-1}$) above 85°N (ITP48)

Laney et al. (2014)

Ice-Tethered Profiler (ITP)

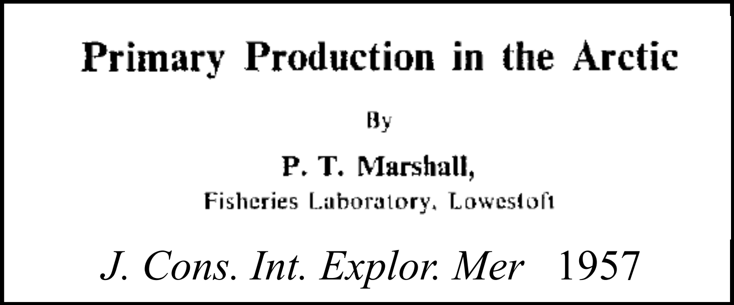


Nautilus would arrive at the pole at just the right time

- 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?

Sverdrup + high-latitude blooms had to wait to 1957



Primary Production in the Arctic

By

P. T. Marshall,

Fisheries Laboratory, Lowestoft

J. Cons. Int. Explor. Mer 1957

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.

Bear Is.

Weather Station 'M'

Arctic ice-edge blooms (Apr) vs. Atlantic open-ocean (May-June)

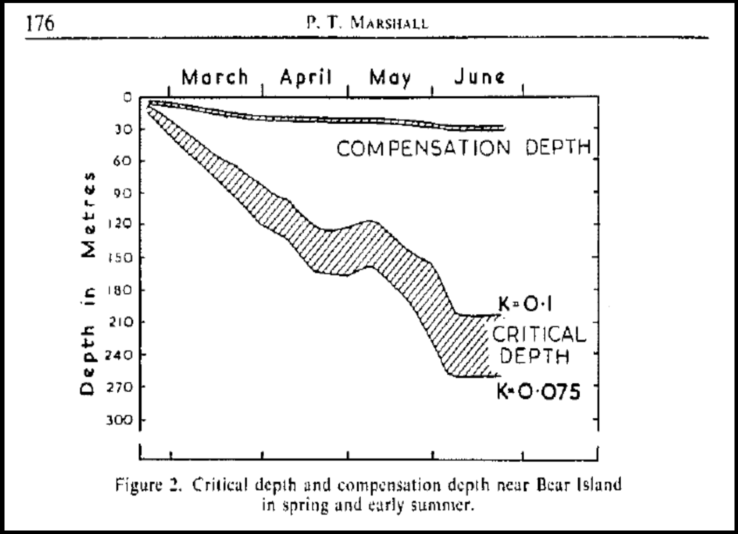

176 P. T. MARSHALL

Figure 2. Critical depth and compensation depth near Bear Island in spring and early summer.

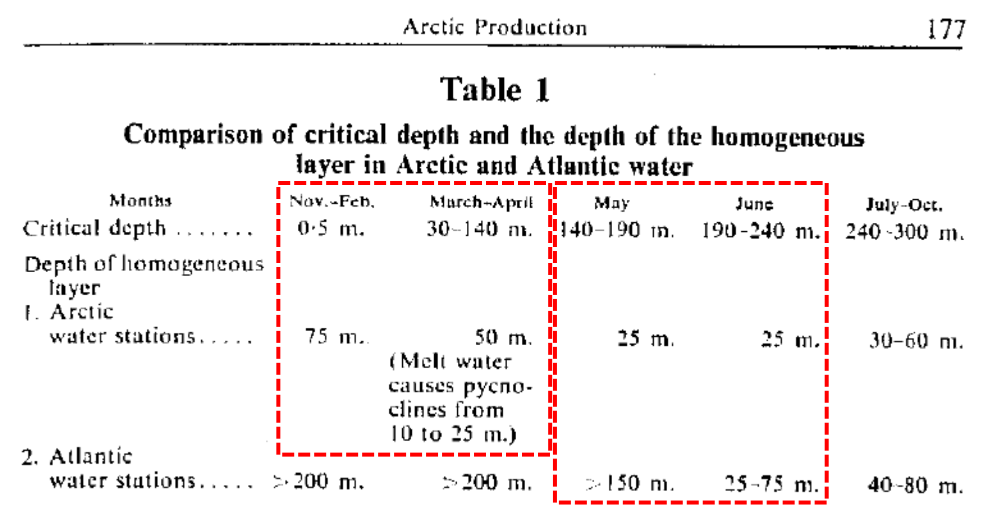
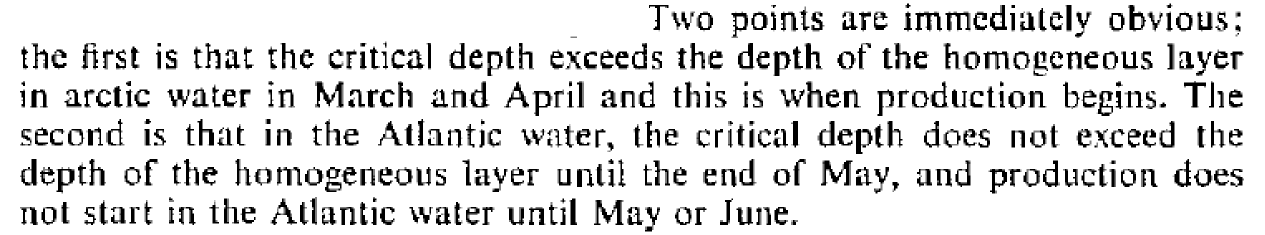

Arctic Production 177

Table 1

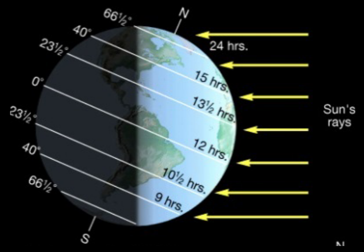
Comparison of critical depth and the depth of the homogeneous layer in Arctic and Atlantic water

Months	Nov.–Feb.	March–April	May	June	July–Oct.
Critical depth	0·5 m.	30–140 m.	140–190 m.	190–240 m.	240–300 m.
Depth of homogeneous layer					
1. Arctic water stations.	75 m.	50 m. (Melt water causes pycnoclines from 10 to 25 m.)	25 m.	25 m.	30–60 m.
2. Atlantic water stations.	>200 m.	>200 m.	>150 m.	25–75 m.	40–80 m.


Two points are immediately obvious; the first is that the critical depth exceeds the depth of the homogeneous layer in arctic water in March and April and this is when production begins. The second is that in the Atlantic water, the critical depth does not exceed the depth of the homogeneous layer until the end of May, and production does not start in the Atlantic water until May or June.

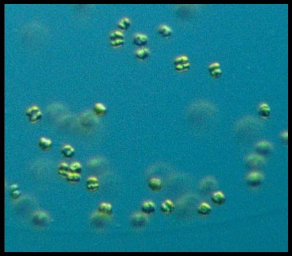
"Stabilization" *sensu* Sverdrup was by "spring heating of the surface layer" or by "spring run-off". Marshall added a high-latitude factor: melted **sea ice**.

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

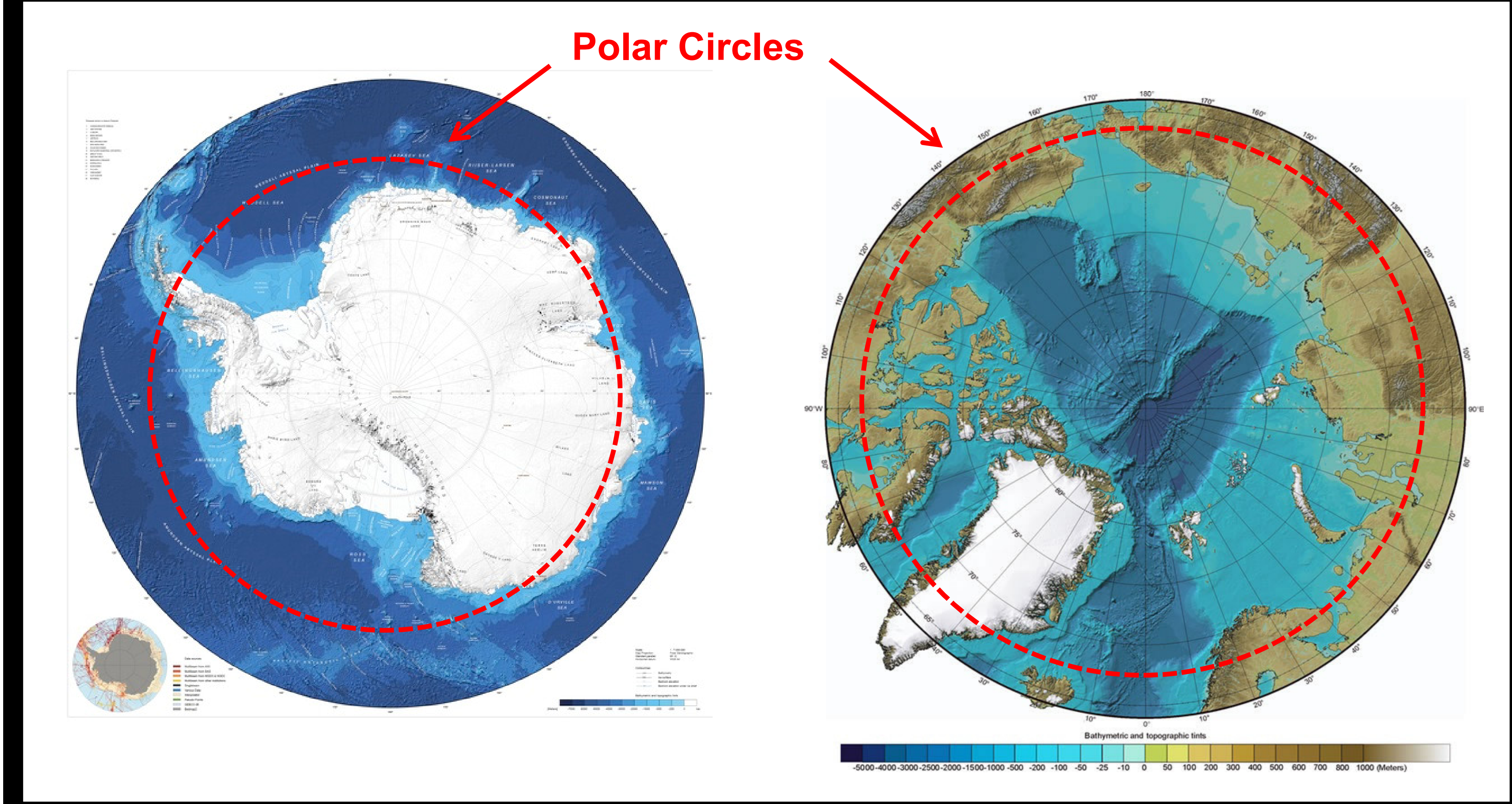


III. Some high-latitude ecophysiology worthy of more study

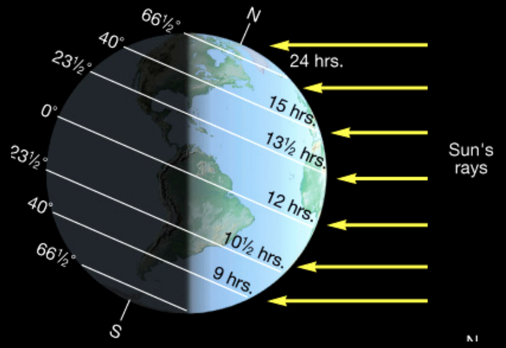
IV. Gaining better insight into high-latitude blooms

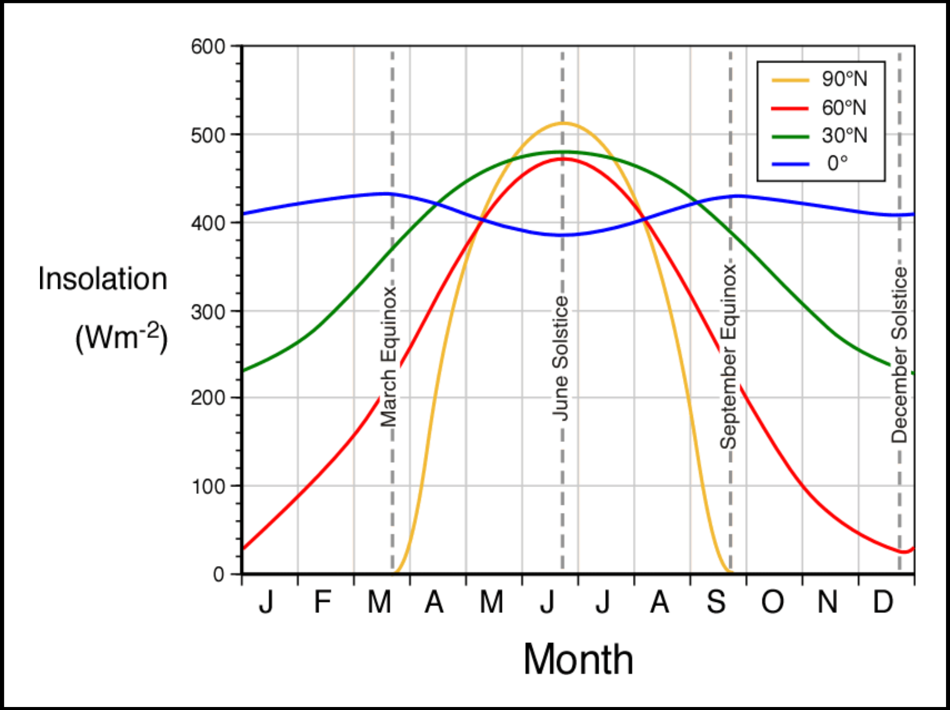
I. What’s different about oceans at high latitudes?

“High-latitude ocean” depends on your perspective



Highly variable insolation on seasonal & sub-seasonal scales





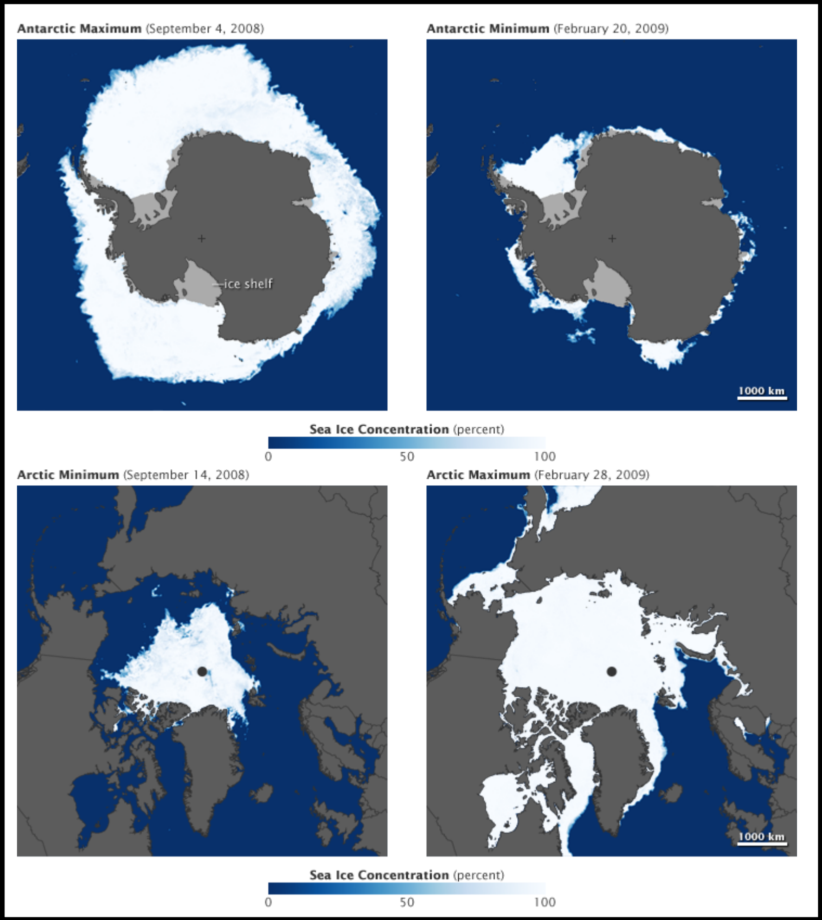
- High-latitudes experience low irradiance due to planet's curvature.
- Summer: longer day-lengths compensate for lower intensity

Insolation: over the month of April, a <u>tenfold increase</u> !

(Important corollary: over August, a tenfold <u>decrease</u>)

CDH → rapid day-to-day changes in critical depth

Sea ice → several direct effects on photosynthetic environment



earthobservatory.nasa.gov

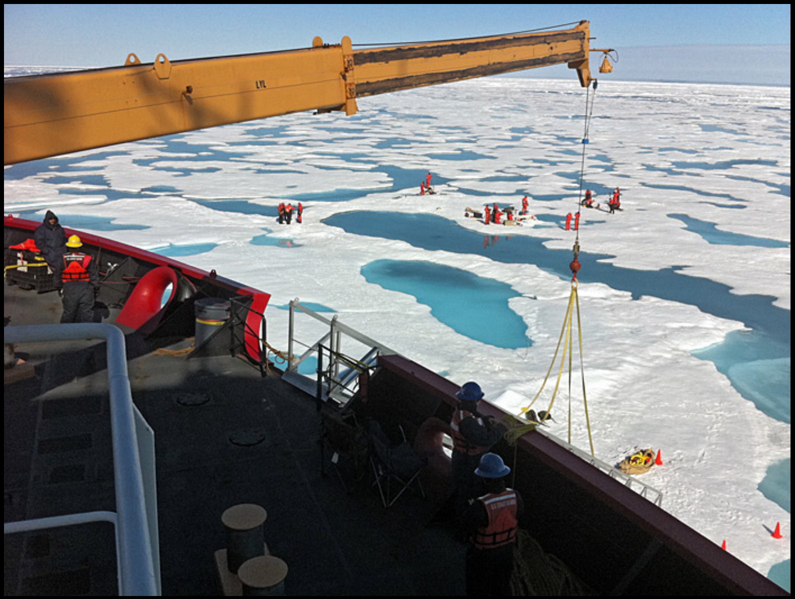
1. Insulates ocean from wind stress.

   (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

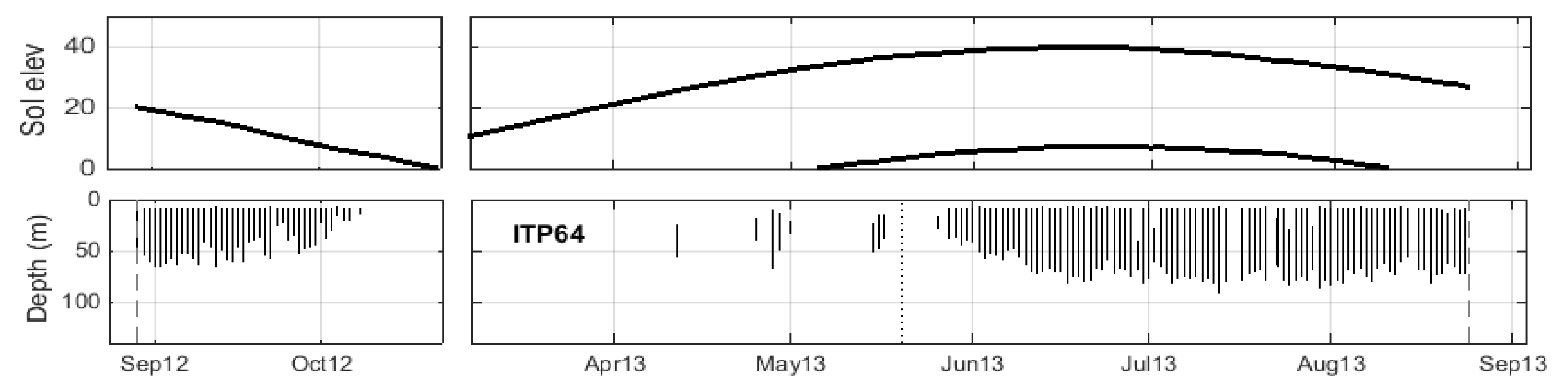


- Ice: 1.3-2.5 m^{-1} (1 m removes 80% PAR)
- Snow: 16-45 m^{-1} (15 cm snow removes 90% of PAR)
- Highly variable optically (time & space)
- Any biota in ice may alter light as well

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)



Laney *unpubl.*

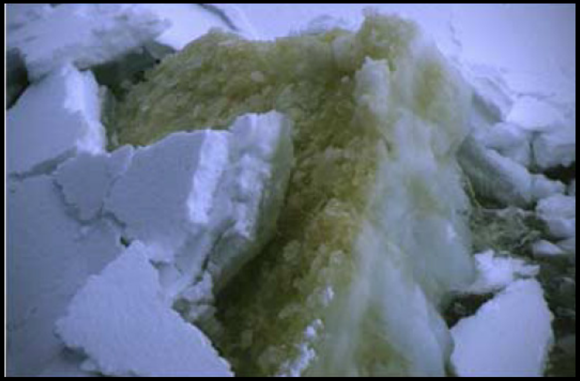
Delays light entering into the ocean, by several months

Major factor establishing short growing seasons under ice

An important additional (indirect) effect of sea ice

Provides habitat for an immediately adjacent, very different ecosystem

nature.ca



Ackley et al. 2008

- Arctic → thicker ice (2-3 m); combination of 1st- & multi-year ice. Ice algae on or close to bottom of ice.
- Antarctic → thinner ice (1-2 m); primarily 1st year ice. Algae often in internal layers.
- Ice algae bloom earlier
  - → shades water column below
- When ice melts → pulse of ice algae falling through water column. Seeding or sediment?

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
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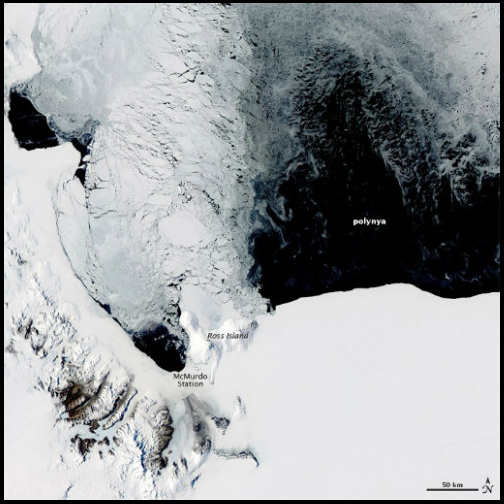
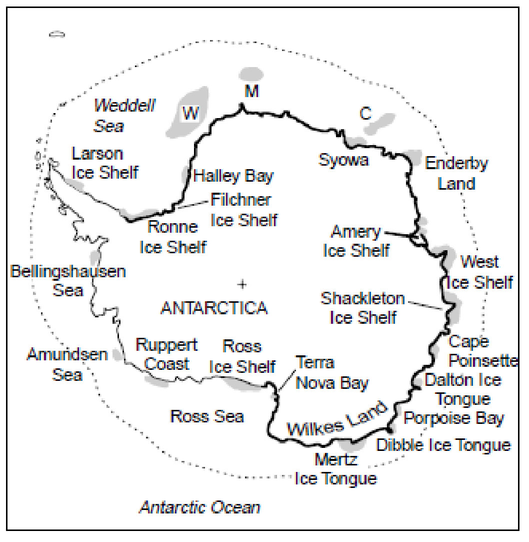
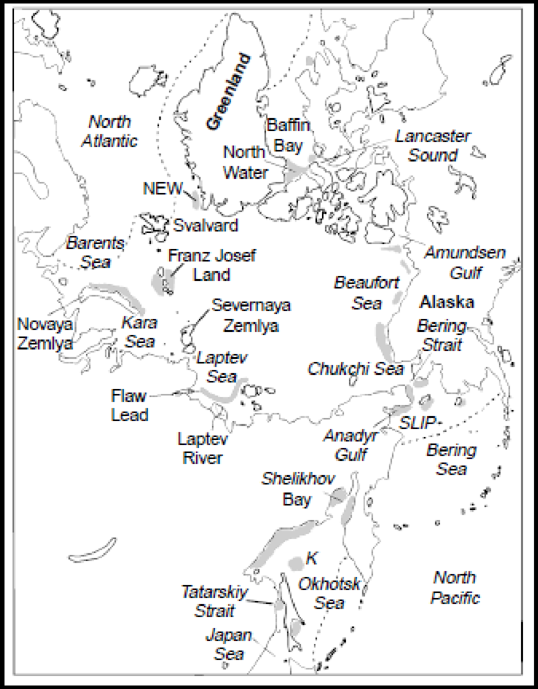
High-latitude blooms part 1: coastal polynya blooms

Ross Sea



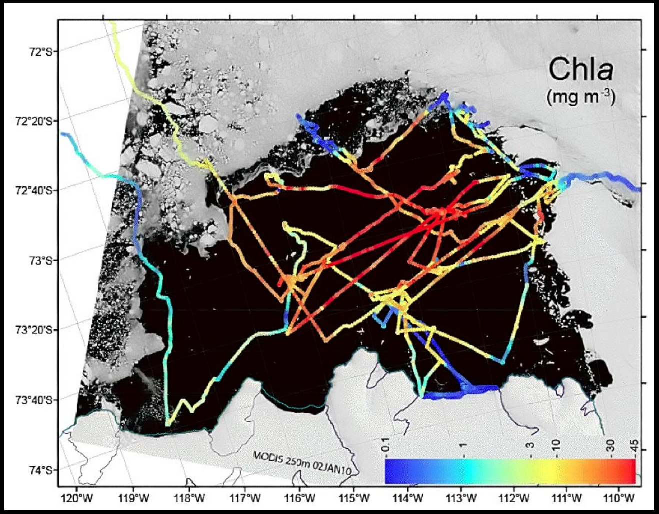
thewatchers.adorraeli.com





Martin (2001)

Amundsen Sea



marine.rutgers.edu

Katabatic winds push sea ice offshore → strong blooms

Ross Sea Polynya Project (RSPP, 1994-96. Smith & Asper 2001; Garrison et al. 2003)

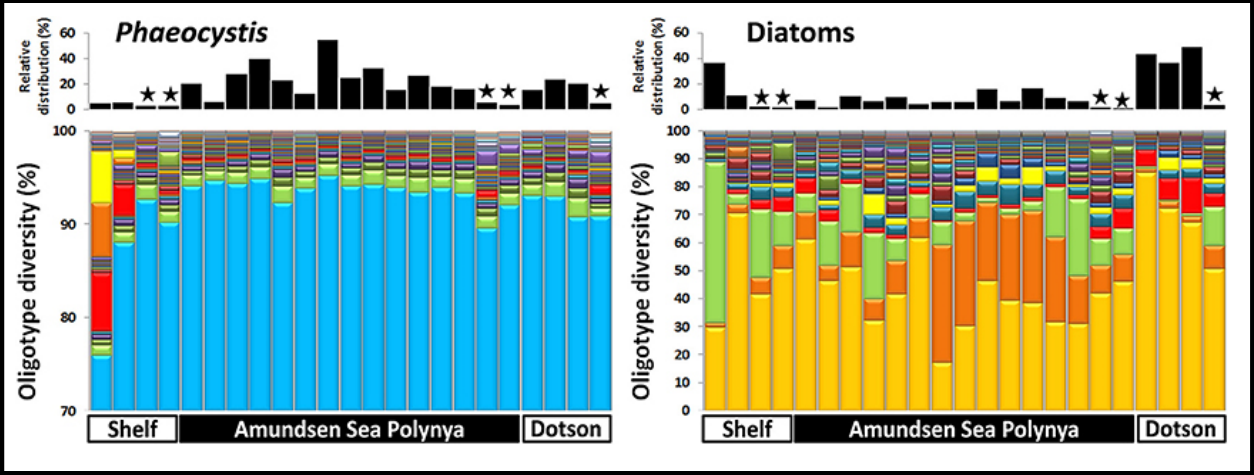
Amundsen Sea Polynya International Research Expedition (ASPIRE: Yager et al. 2012)

Coastal polynya blooms → photosynthetic niches

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

Phaeocystis → 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)

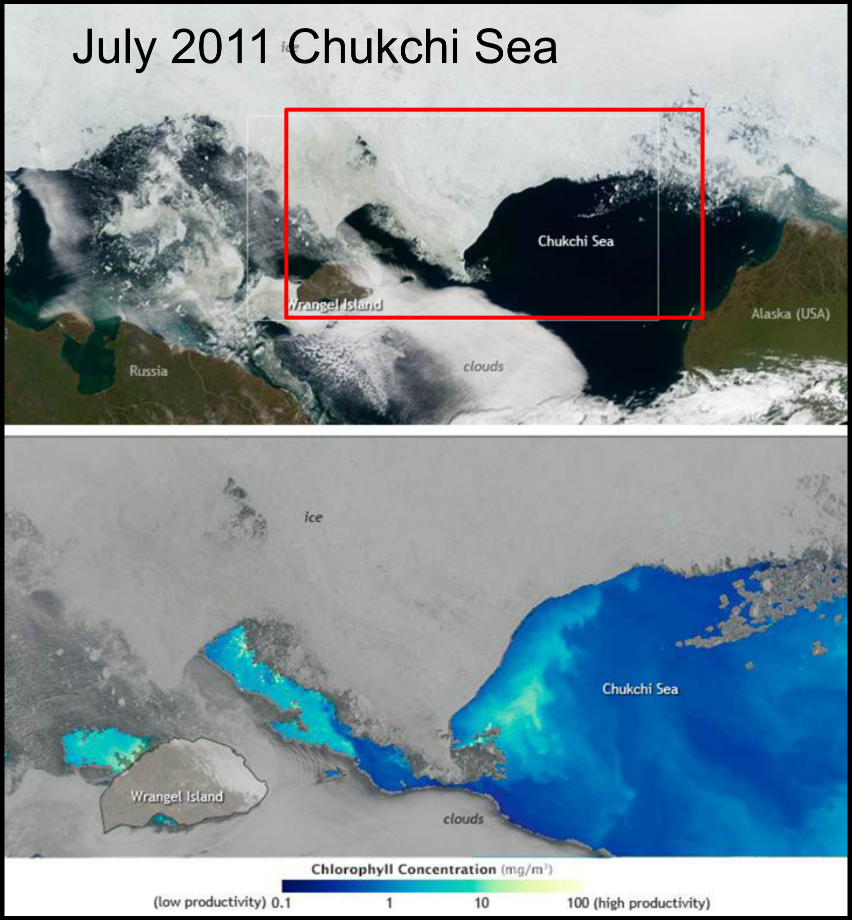


Delmont et al. 2014

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

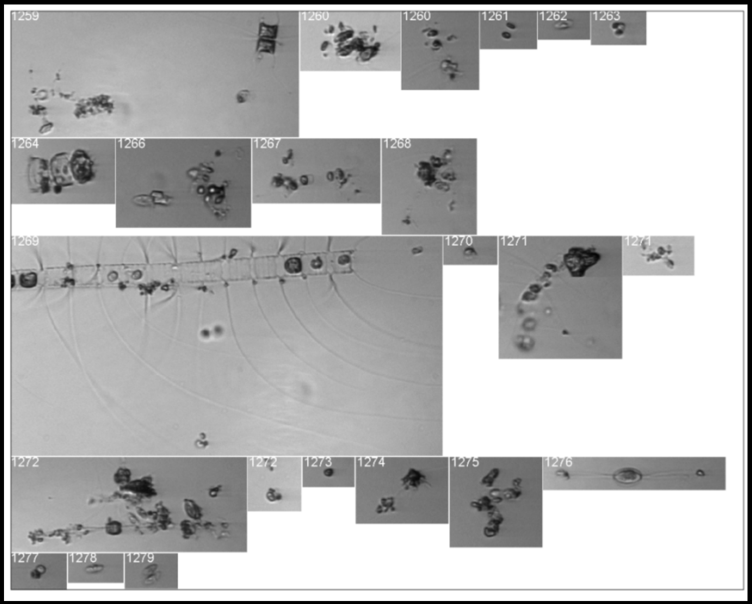
Reflects photosynthetic niches within the nominal 'bloom': partitioning of multiple, co-blooming, disparate taxa.
Not always just diatoms & *Phaeocystis*

High-latitude blooms part 2: ice-edge blooms


July 2011 Chukchi Sea

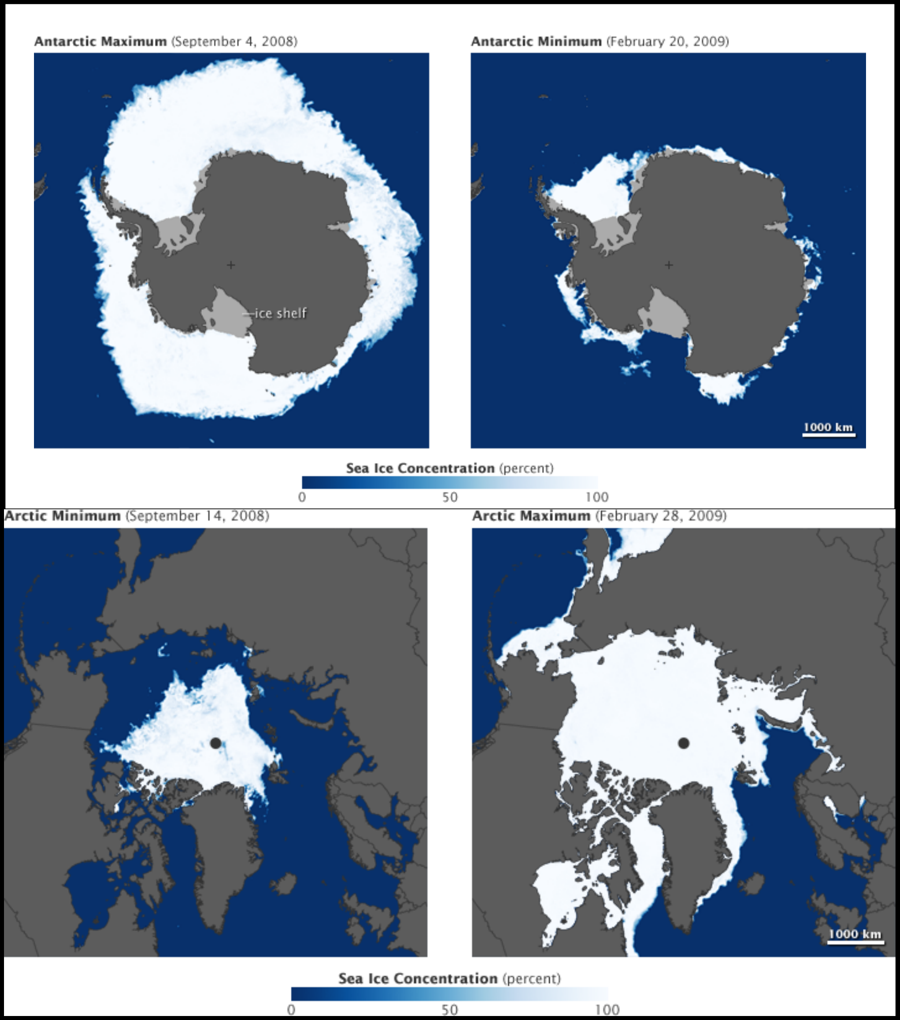
arctic.noaa.gov

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

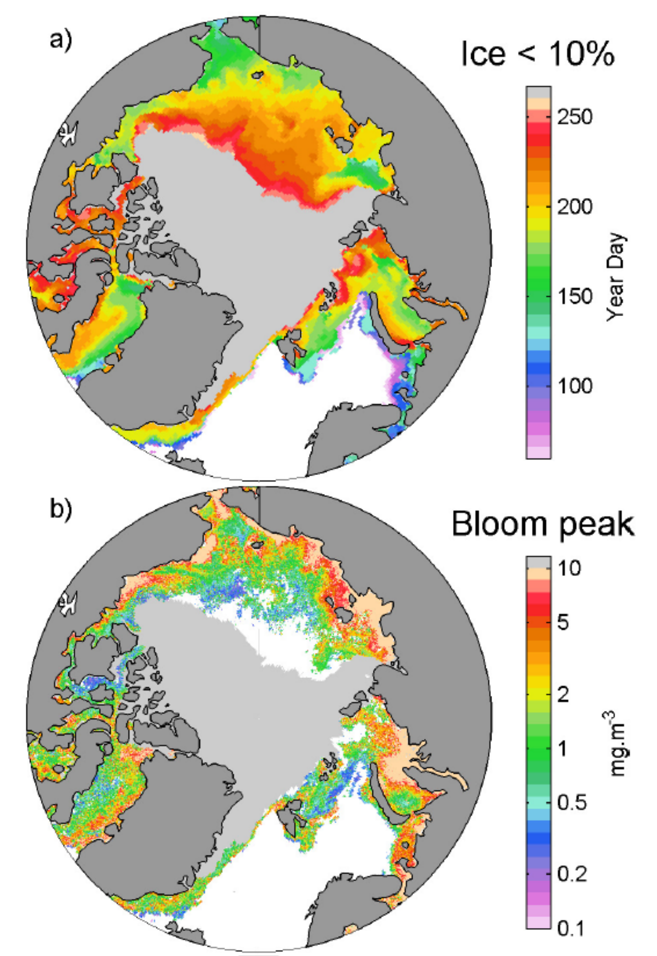


Laney *unpubl.*

Ice-edge blooms widespread where ice cover is seasonal



earthobservatory.nasa.gov



Perrette et al. 2011

Canonical model for genesis & fate of ice-edge blooms

sensu Sakshaug & Skjoldal 1989

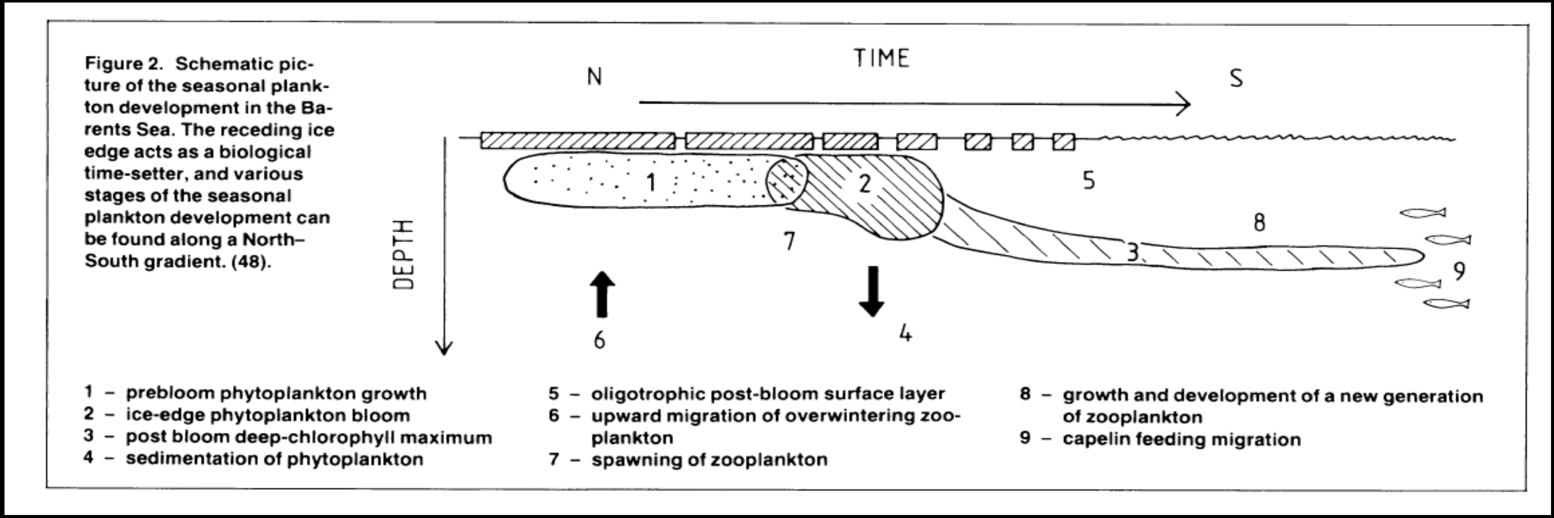


Figure 2. Schematic picture of the seasonal plankton development in the Barents Sea. The receding ice edge acts as a biological time-setter, and various stages of the seasonal plankton development can be found along a North–South gradient. (48).

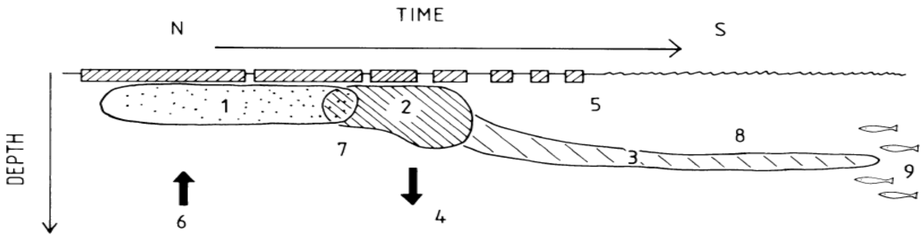
1 – prebloom phytoplankton growth
2 – ice-edge phytoplankton bloom
3 – post bloom deep-chlorophyll maximum
4 – sedimentation of phytoplankton
5 – oligotrophic post-bloom surface layer
6 – upward migration of overwintering zooplankton
7 – spawning of zooplankton
8 – growth and development of a new generation of zooplankton
9 – capelin feeding migration

Sakshaug & Skjoldal 1989

1. *'Prebloom growth' → low light, low biomass*
2. *'Ice-edge bloom' → rapid growth in MIZ, high algal biomass*
3. *'Post-bloom deep-chlorophyll max'*
5. *Oligotrophic post-bloom surface layer*

Numerous studies examined other aspects of ice-edge blooms

Figure 2. Schematic picture of the seasonal plankton development in the Barents Sea. The receding ice edge acts as a biological time-setter, and various stages of the seasonal plankton development can be found along a North–South gradient. (48).



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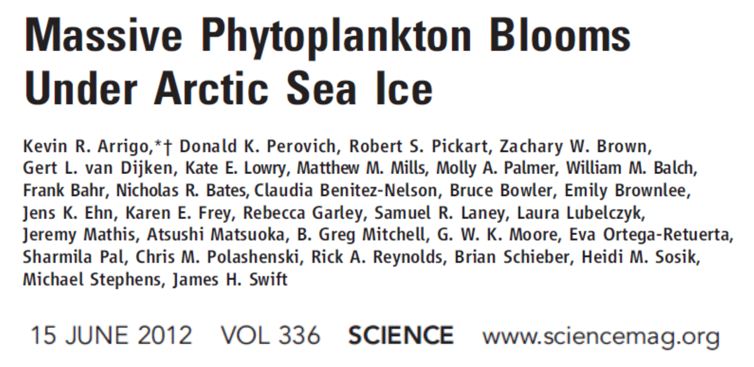
Sakshaug & Skjoldal 1989

- 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



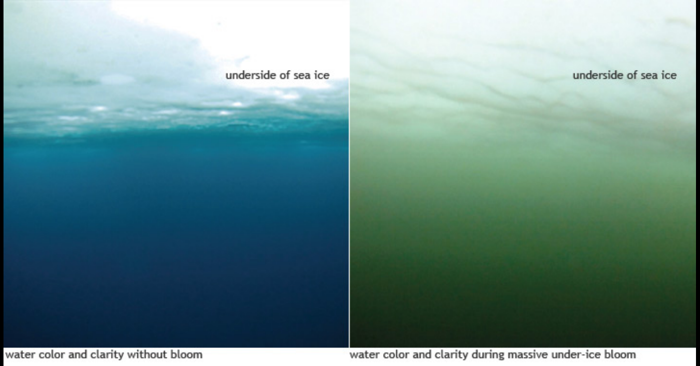
Massive Phytoplankton Blooms Under Arctic Sea Ice

Kevin R. Arrigo,*† Donald K. Perovich, Robert S. Pickart, Zachary W. Brown, Gert L. van Dijken, Kate E. Lowry, Matthew M. Mills, Molly A. Palmer, William M. Balch, Frank Bahr, Nicholas R. Bates, Claudia Benitez-Nelson, Bruce Bowler, Emily Brownlee, Jens K. Ehn, Karen E. Frey, Rebecca Garley, Samuel R. Laney, Laura Lubelczyk, Jeremy Mathis, Atsushi Matsuoka, B. Greg Mitchell, G. W. K. Moore, Eva Ortega-Retuerta, Sharmila Pal, Chris M. Polashenski, Rick A. Reynolds, Brian Schieber, Heidi M. Sosik, Michael Stephens, James H. Swift

15 JUNE 2012 VOL 336 **SCIENCE** www.sciencemag.org

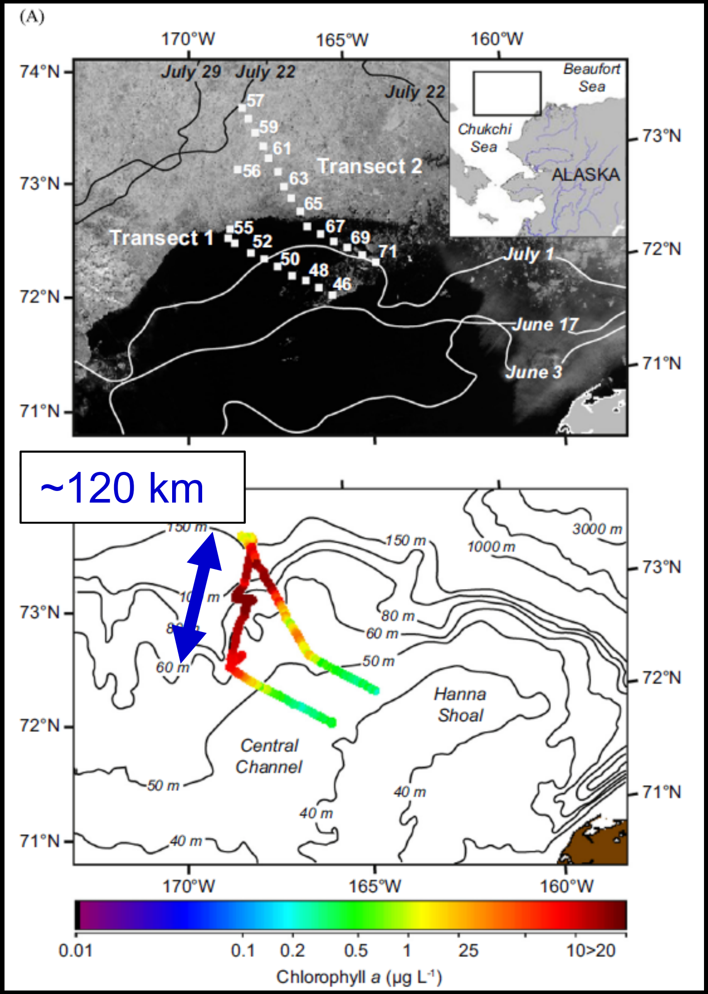
Under-ice

No bloom bloom



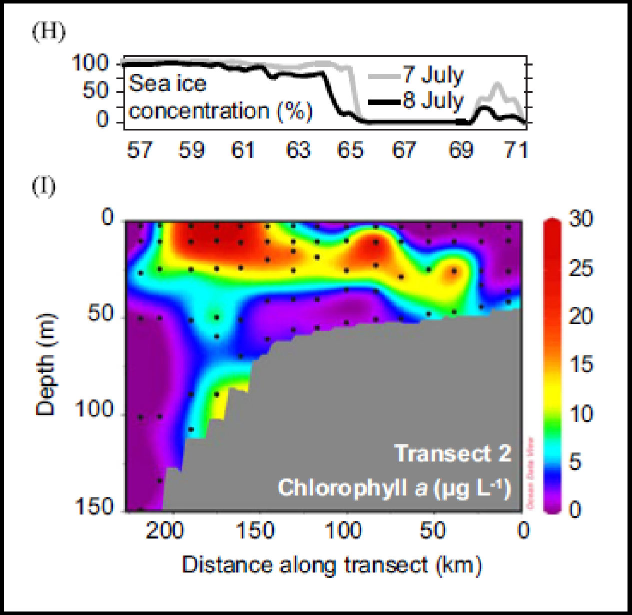
K. Frey, Clark University

NASA ICESCAPE 2011
coastal Arctic, Chukchi Sea



Arrigo et al. 2014

2011 bloom: biomass, composition, growth rates, & productivity



Arrigo et al. 2014

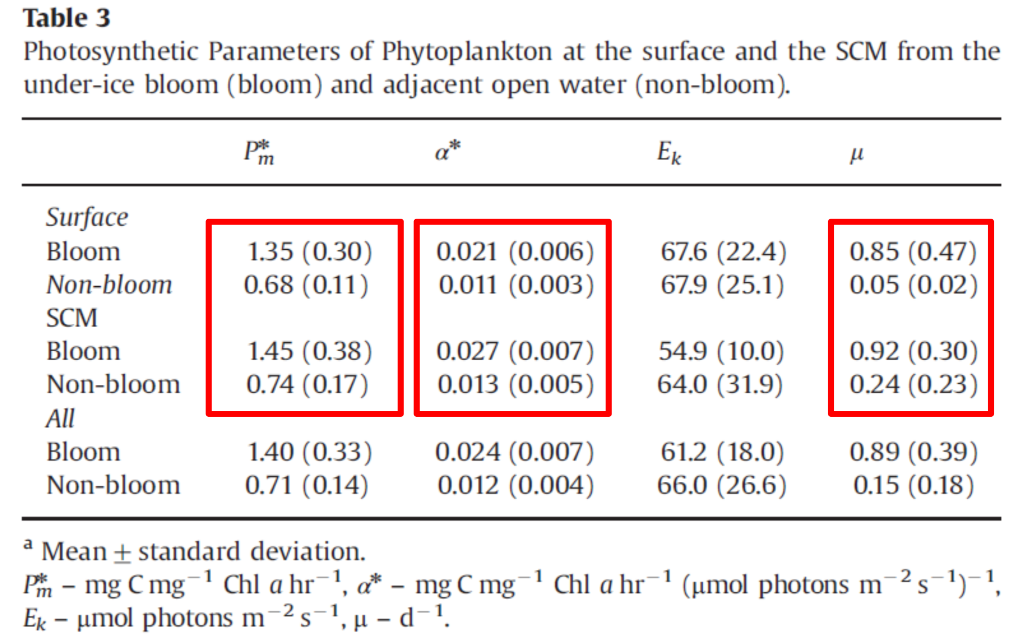


Table 3

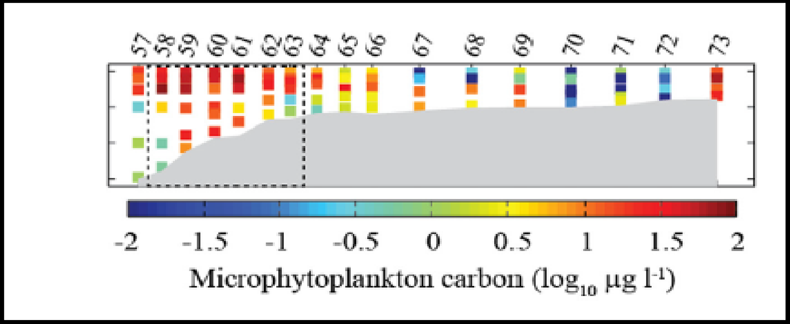
Photosynthetic Parameters of Phytoplankton at the surface and the SCM from the under-ice bloom (bloom) and adjacent open water (non-bloom).

	P^*_m	α^*	E_k	μ
Surface				
Bloom	1.35 (0.30)	0.021 (0.006)	67.6 (22.4)	0.85 (0.47)
Non-bloom	0.68 (0.11)	0.011 (0.003)	67.9 (25.1)	0.05 (0.02)
SCM				
Bloom	1.45 (0.38)	0.027 (0.007)	54.9 (10.0)	0.92 (0.30)
Non-bloom	0.74 (0.17)	0.013 (0.005)	64.0 (31.9)	0.24 (0.23)
All				
Bloom	1.40 (0.33)	0.024 (0.007)	61.2 (18.0)	0.89 (0.39)
Non-bloom	0.71 (0.14)	0.012 (0.004)	66.0 (26.6)	0.15 (0.18)

[a] Mean ± standard deviation.

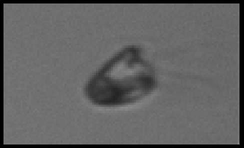
P^*_m – mg C mg^{-1} Chl *a* hr^{-1}, α^* – mg C mg^{-1} Chl *a* hr^{-1} (μmol photons m^{-2} s^{-1})$^{-1}$, E_k – μmol photons m^{-2} s^{-1}, μ – d^{-1}.

Arrigo et al. 2014

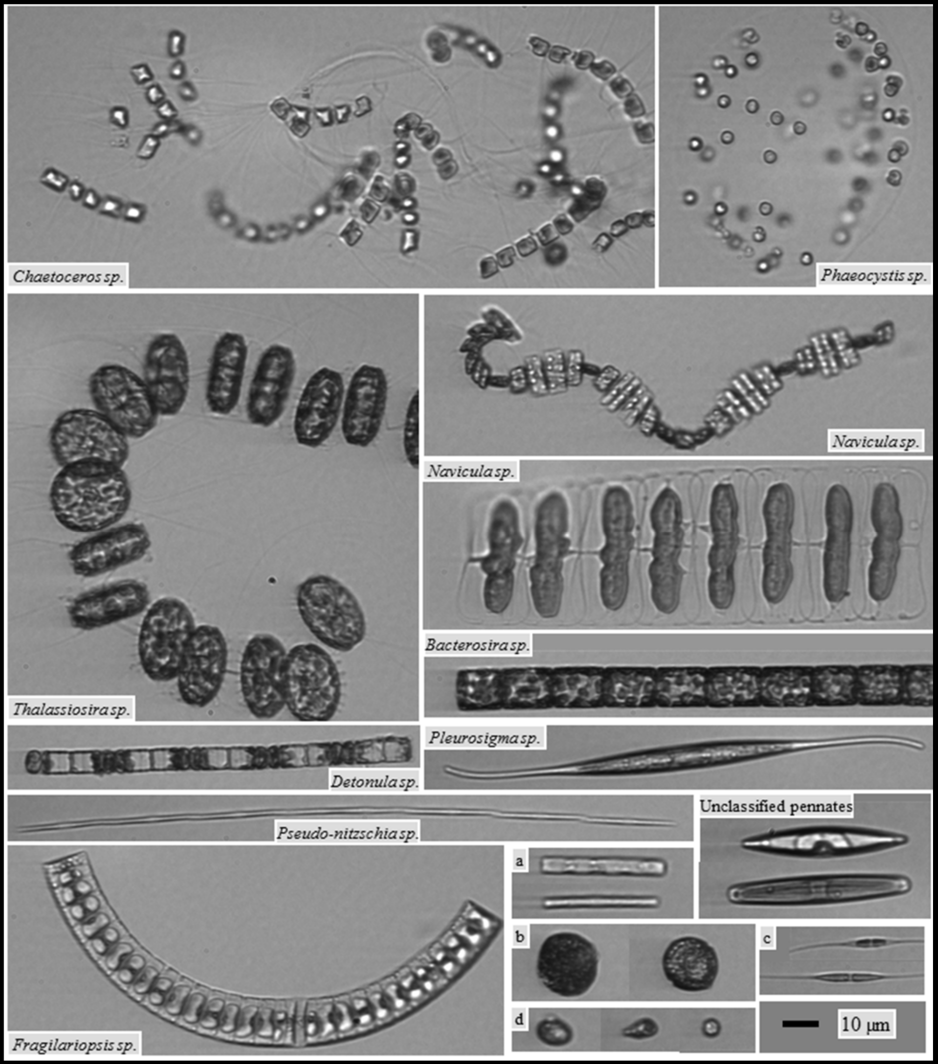


Laney & Sosik 2014

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



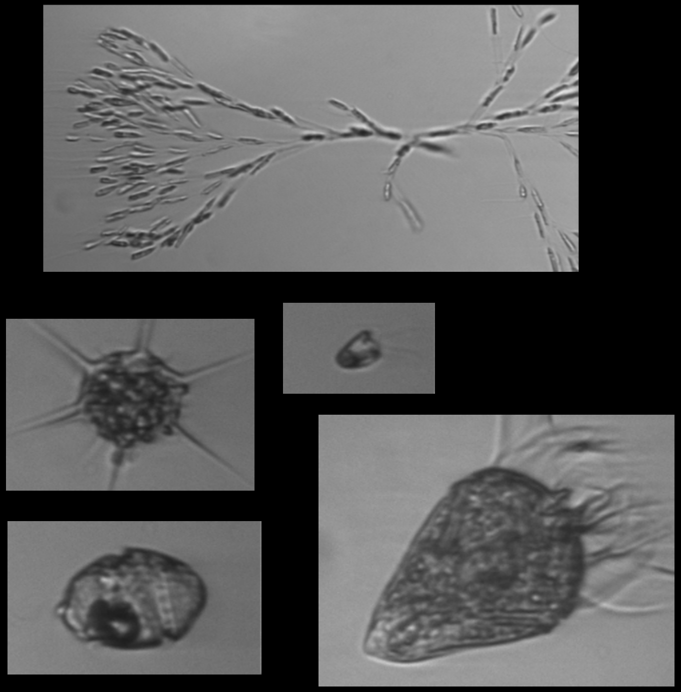
Details of 2011 under-ice bloom composition



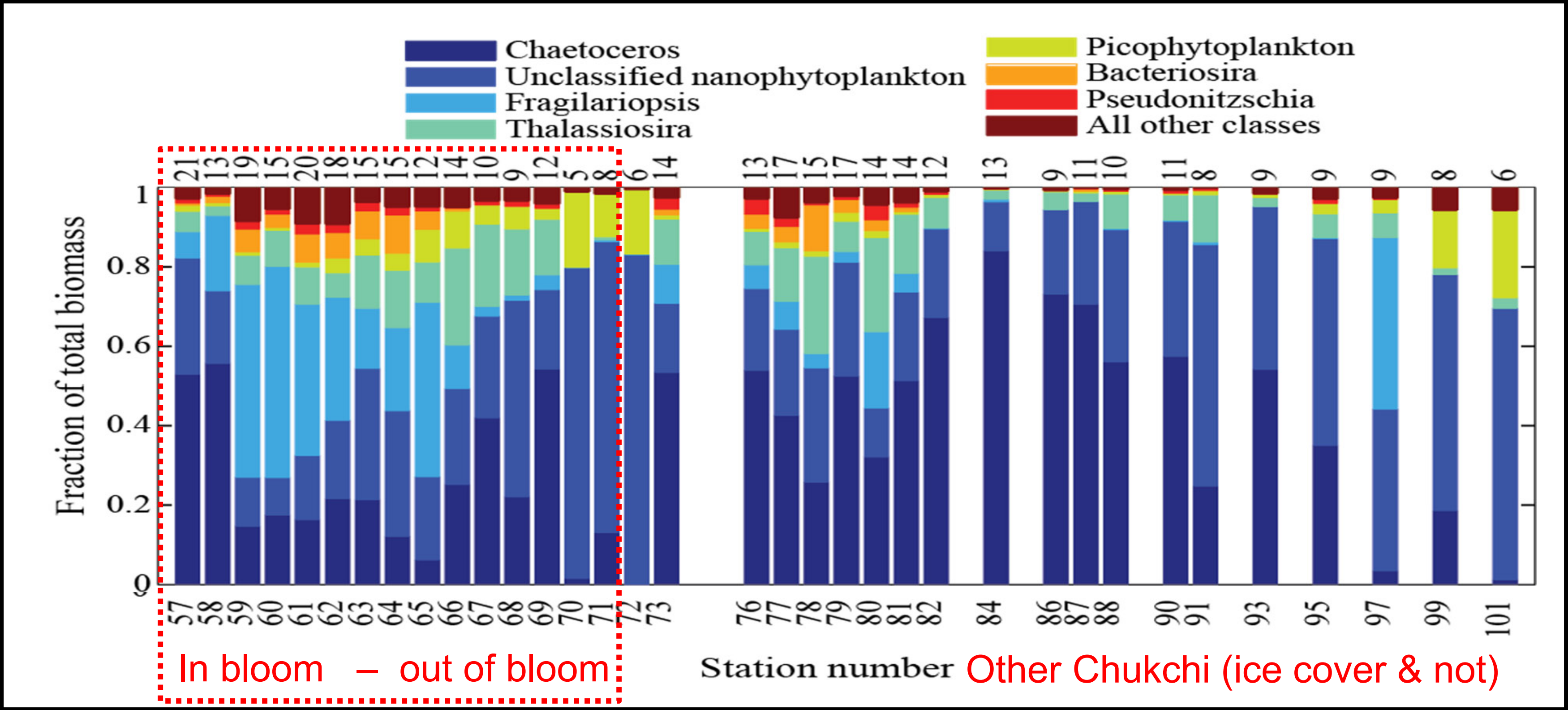
Laney & Sosik 2014

Imaging FlowCytobot

Bloom & non-bloom taxa



Under-ice bloom composition → complex distributions



Laney & Sosik 2014

Beginning to examine higher order taxonomic complexity in bloom beyond just ‘bloom’ and ‘diatom bloom’

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

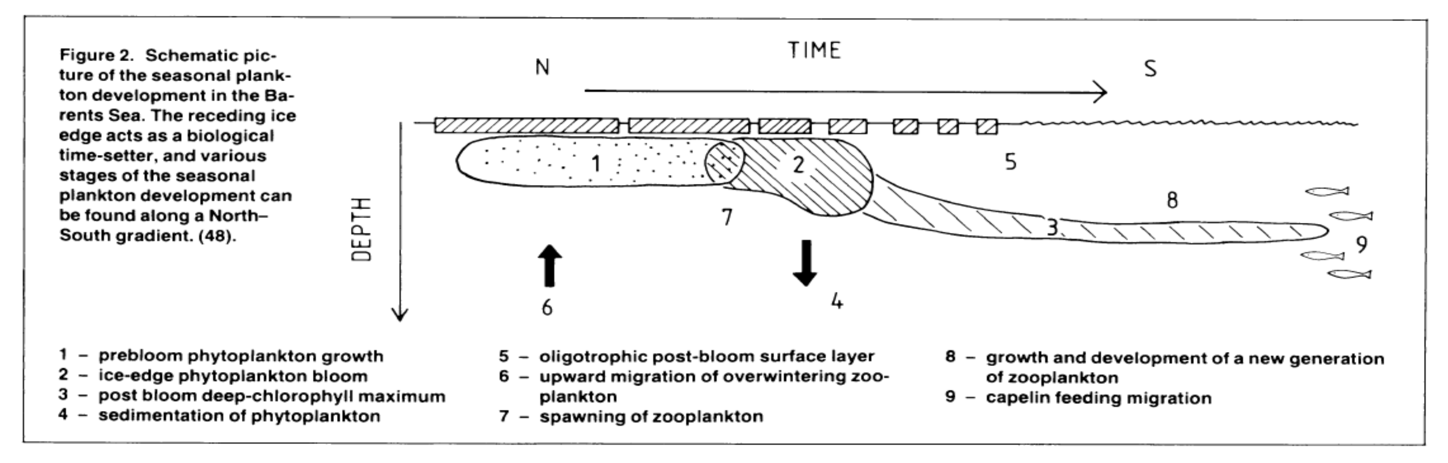
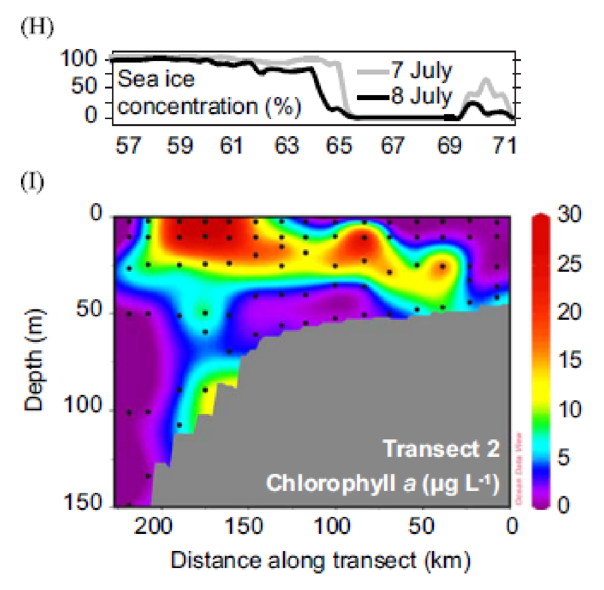


Figure 2. Schematic picture of the seasonal plankton development in the Barents Sea. The receding ice edge acts as a biological time-setter, and various stages of the seasonal plankton development can be found along a North–South gradient. (48).

1 – prebloom phytoplankton growth
2 – ice-edge phytoplankton bloom
3 – post bloom deep-chlorophyll maximum
4 – sedimentation of phytoplankton
5 – oligotrophic post-bloom surface layer
6 – upward migration of overwintering zooplankton
7 – spawning of zooplankton
8 – growth and development of a new generation of zooplankton
9 – capelin feeding migration



Arrigo et al. 2012

Possible explanations:

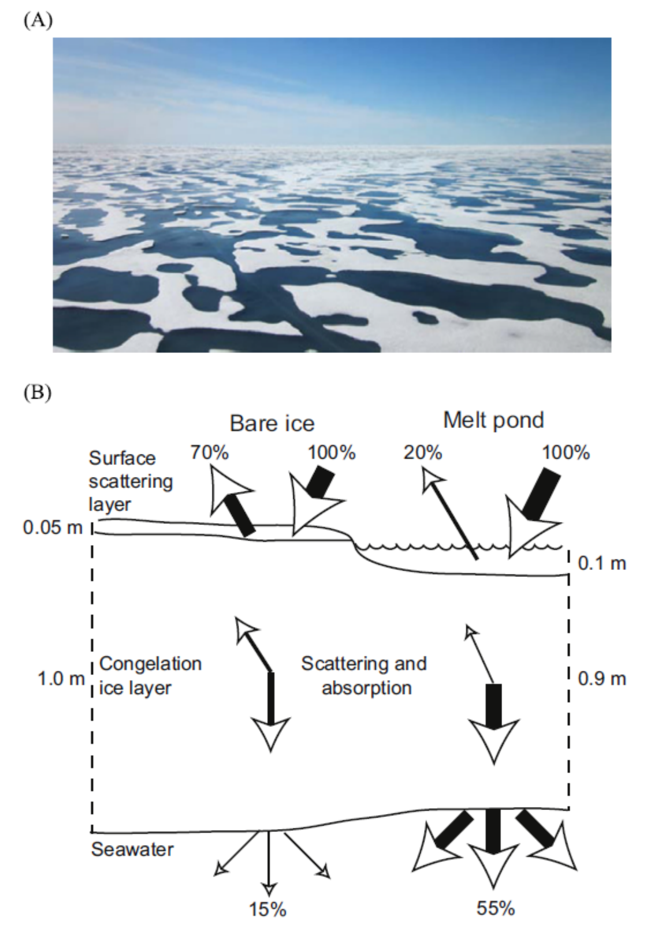
☒ Ice-edge bloom advecting back under ice?

☒ 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

Karen Frey, Clark Univ.

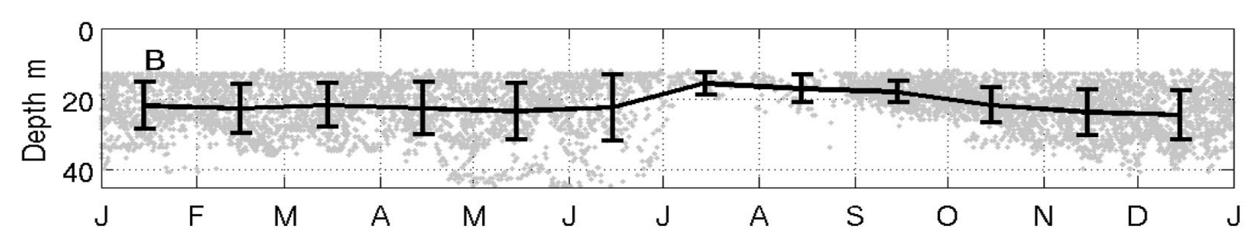
Phytoplankton trapped in winter water under-ice → suddenly released from light limitation → perfect conditions.

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

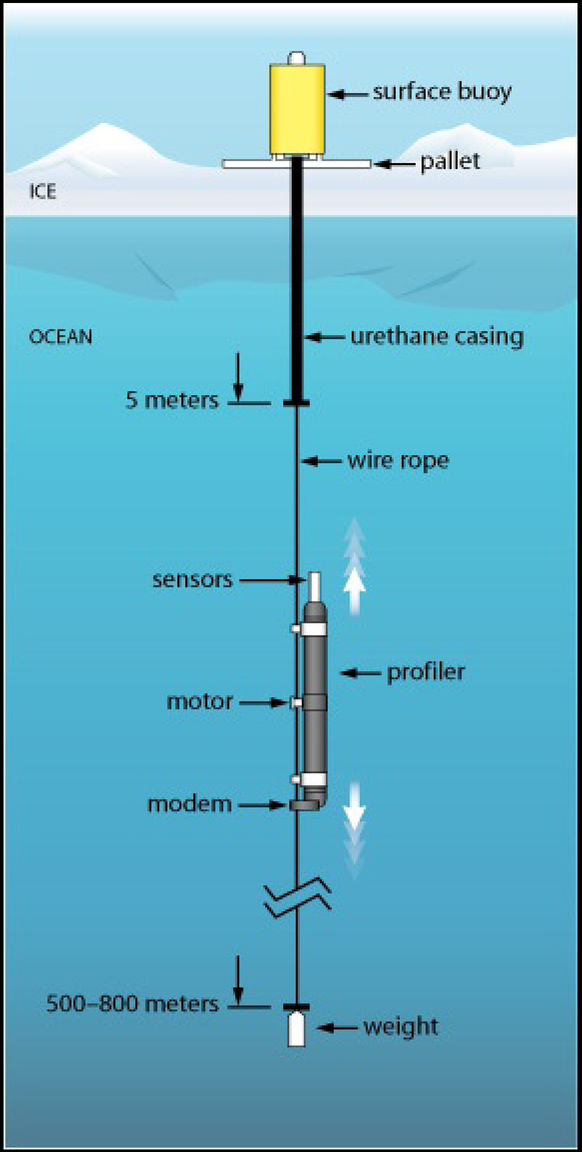
- Where sea ice only loses snow cover & thins, but does not melt away
- Growth season very short: ~ 6 weeks
- Mixed-layer depths typically very shallow (10-20 m), shoaling in Jul-Aug:



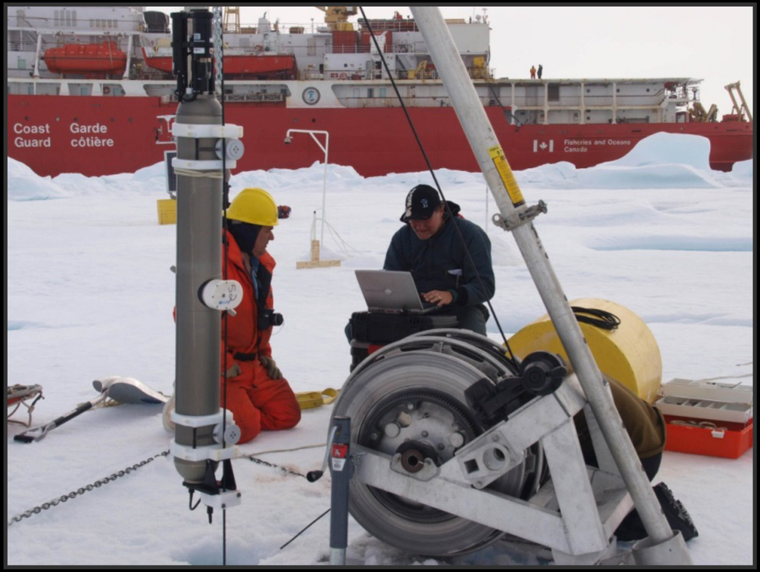
Composite of ~5600 ITP profiles in Canada Basin (Toole et al. 2010)

- 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)

Ice-Tethered Profilers



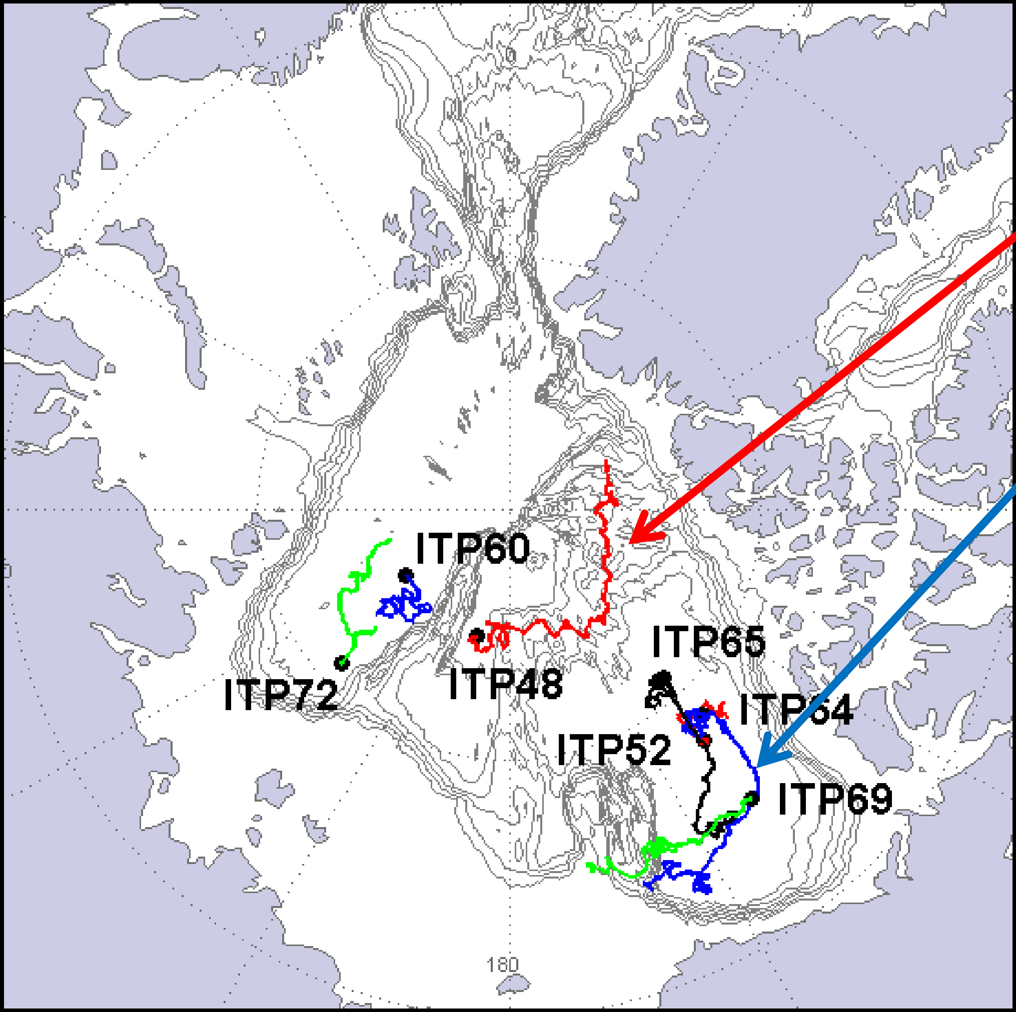
Automated instrument system to obtain & transmit upper ocean water property profiles under perennial sea ice in the polar oceans, multiple times daily over months to years.



8 ‘bio-optical’ ITPs deployed in Aug / Sept 2011-2013

NSF AON

7 of these ITPs collected profiles for at least 100 days



ITP	days	km	# profs	ECO data	PAR data
48	433	3085	1370	✓	✗
52	99	925	377	✓	✓
60	105	1200	260	✓	✗
64	360	3324	1124	✓	✓
65	405	2671	904	½	✗
68	☠	☠	☠	✗	✗
69	182	2067	414	✓	✓
72	107	1196	242	¾	✓

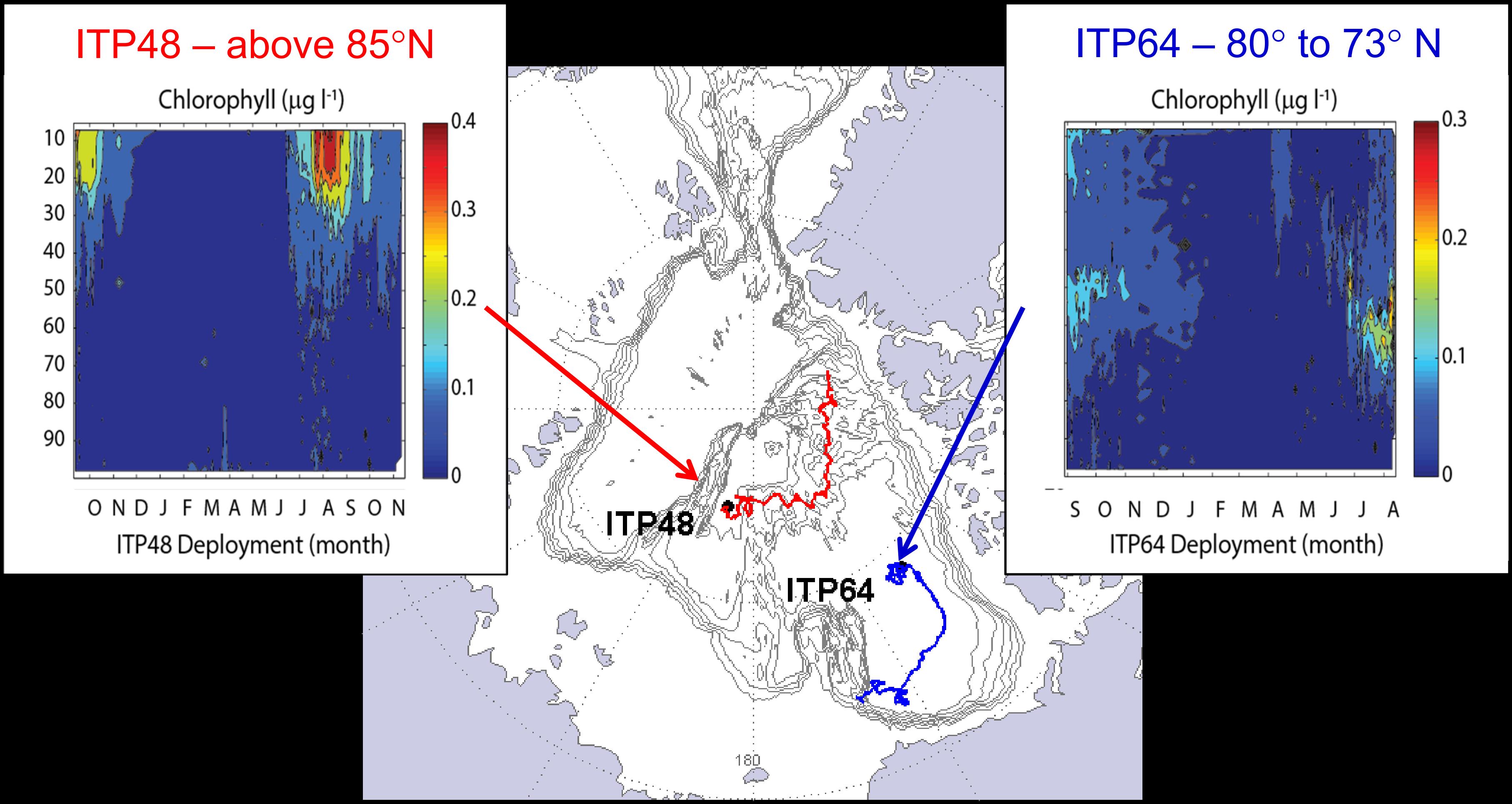
Two systems: 1 year *chl* data

One also: 1 year light data

Seasonal trends in depths & timing of blooms

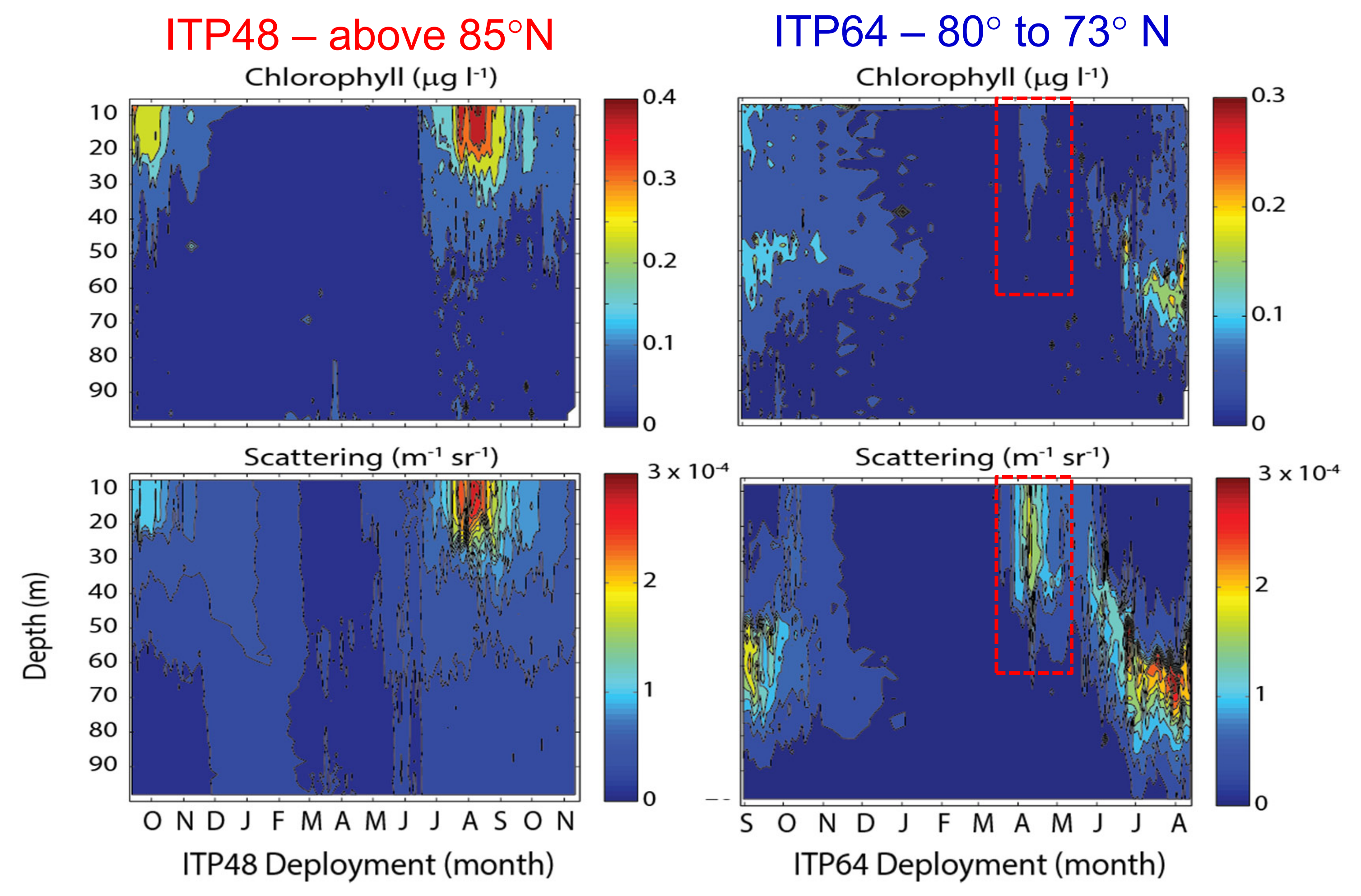
2011-2015: 8 ITPs outfitted with *chl* fluorometers (NSF AON)

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



Laney et al. 2014

Late spring event: Start of bloom? Release of sea ice algae?

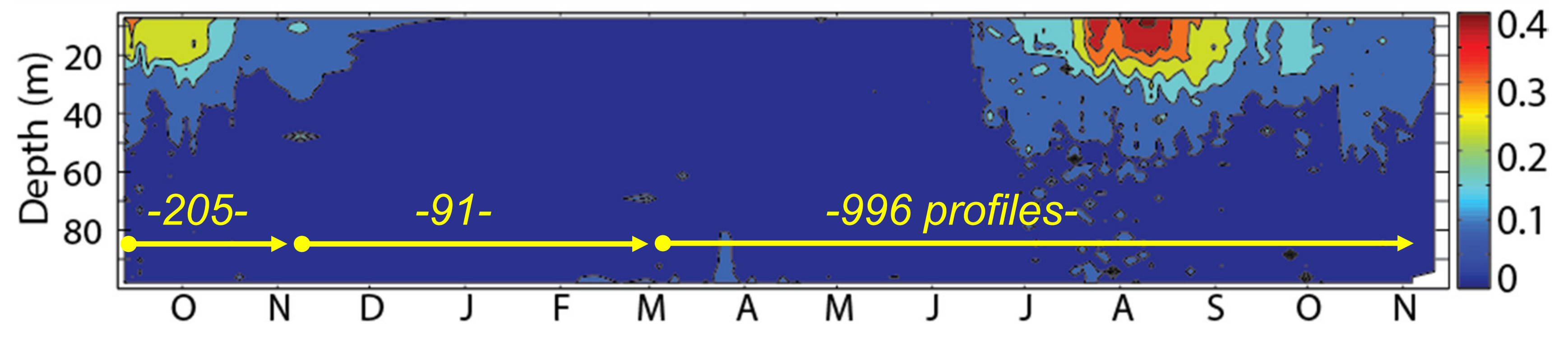


Laney et al. 2014

Frequent profiling → insight into a bloom's rapid dynamics

ITP48 – Central Arctic

- 4 profiles day^{-1} Mar-Oct
- 1.5 profiles day^{-1} Nov-Feb
- All profiles: 25 cm vertical resolution



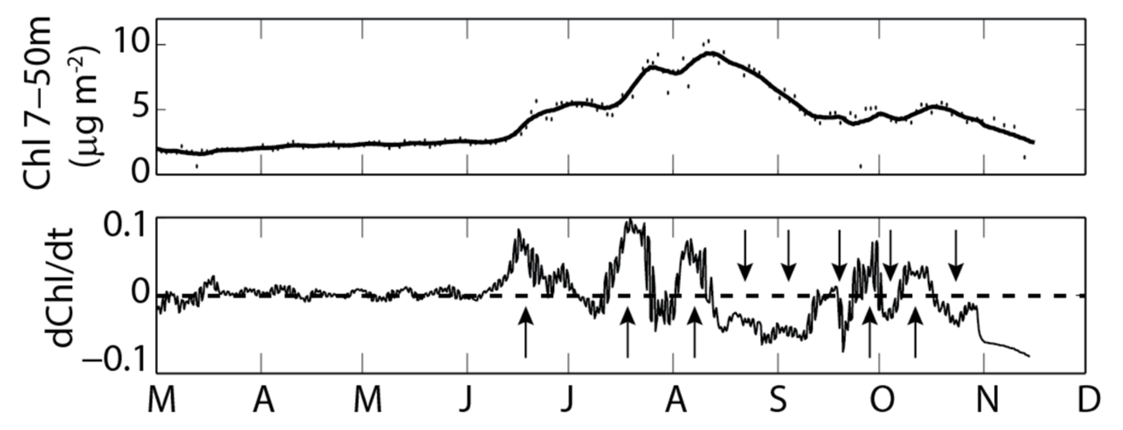
Laney et al. 2014

Day-to-day trends in *chl*

1-2 week changes in the time derivative of *chl* →

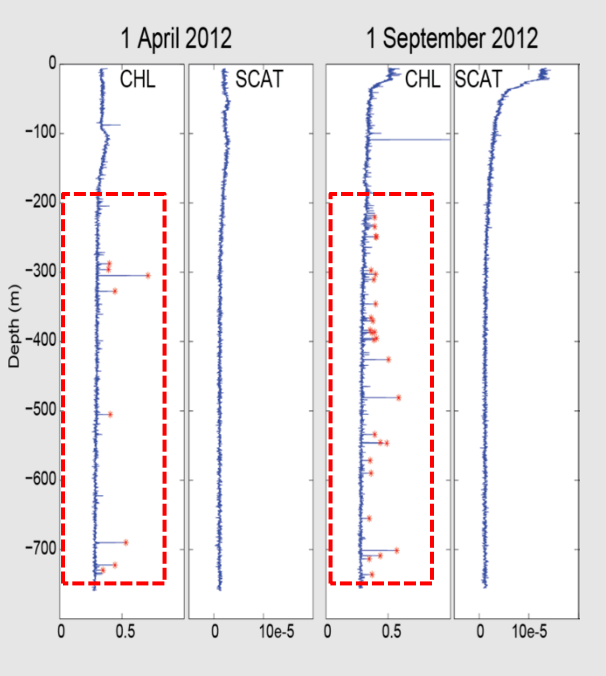
Bloom? Local growth or loss within euphotic zone?

Vertical fluxes through it?

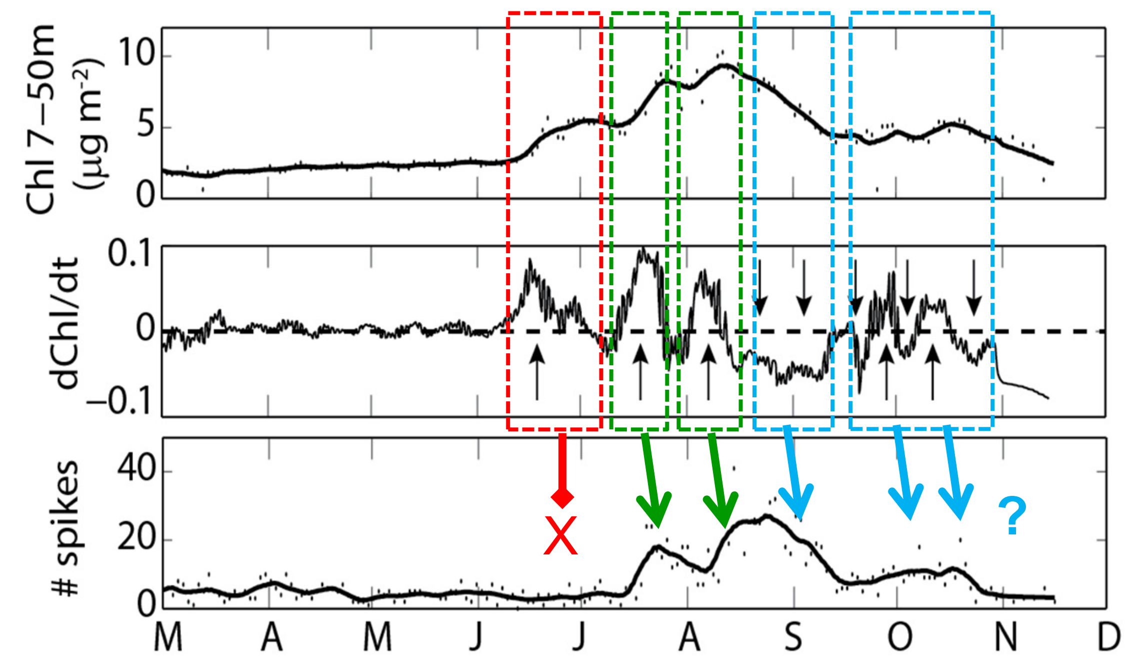


Controls on dChl/dt in the euphotic zone

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



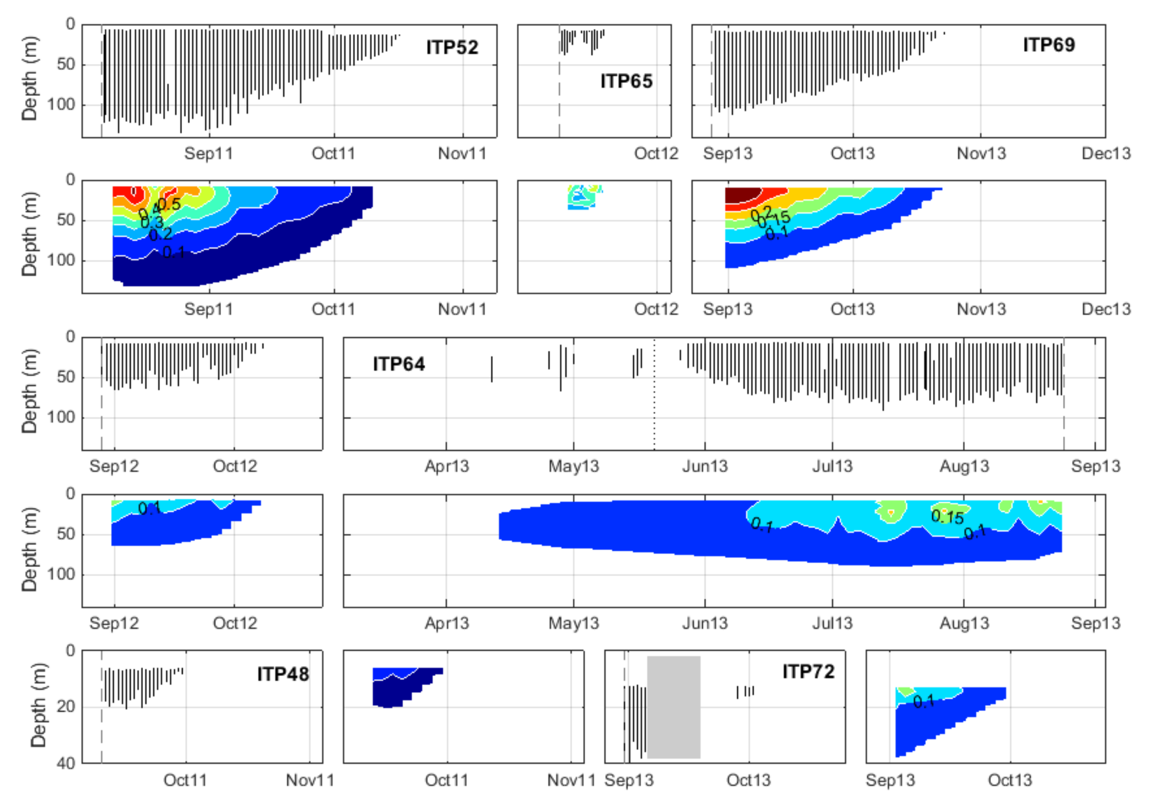
sensu Briggs et al.. 2013



Laney et al. 2014

- ❖ 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

III. High-latitude ecophysiology worth more study

Many high-latitude phytoplankton have overwintering strategies whose ecological role in bloom genesis & dynamics remain largely unexamined.

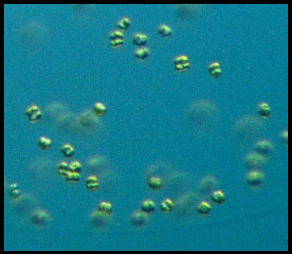
Healy 2011 'Winter' cruise: Chukchi Sea, Nov-Dec (NSF-OPP)

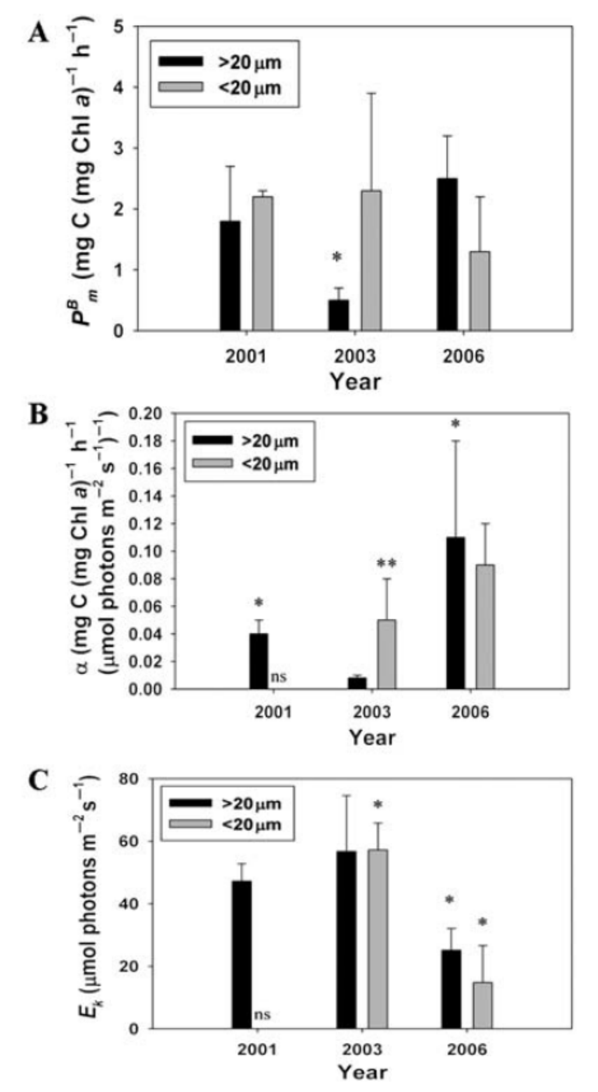
Chaetoceros resting stages (spores)

Laney *unpubl.*

III. High-latitude ecophysiology worth more study

Phaeocystis also has a complex life cycle, involving colony formation





Shields & Smith (2009)

A case where 1 + 1 ≠ 2 !!

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

Cells & colonies differ α, P_{max}

Solitary cells & colonies likely play different roles during bloom

Phenotype-level modeling:

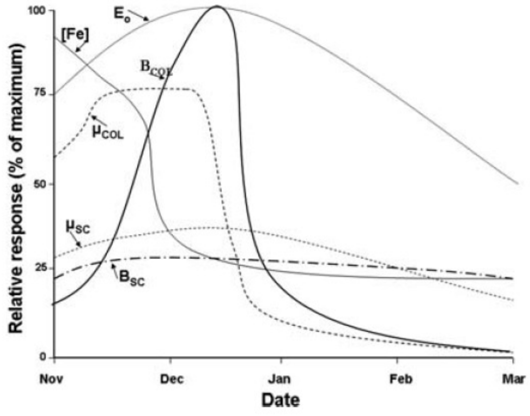


Fig. 7. Conceptual diagram of the temporal sequence of *Phaeocystis antarctica* growth rates, environmental variables (iron and irradiance) and biomass for both colonial and solitary forms. E_o, surface irradiance; [Fe], iron concentrations; B_{col}, biomass of colonies; μ_{col}, growth rate of colonies; B_{SC}, biomass of solitary cells; μ_{SC}, growth rate of solitary cells.

Where we stand after 70 years (Marshall 1957)

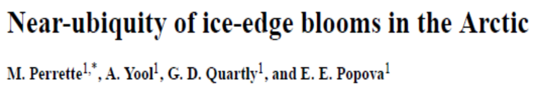
- Many basic aspects of high-latitude blooms remain unclear:
  - How long is the growing season? When does it start, end?
  - Where do blooms occur (vertically, spatially) & when?
  - Esp. in the Arctic: ice algae - phytoplankton interactions?

  → 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

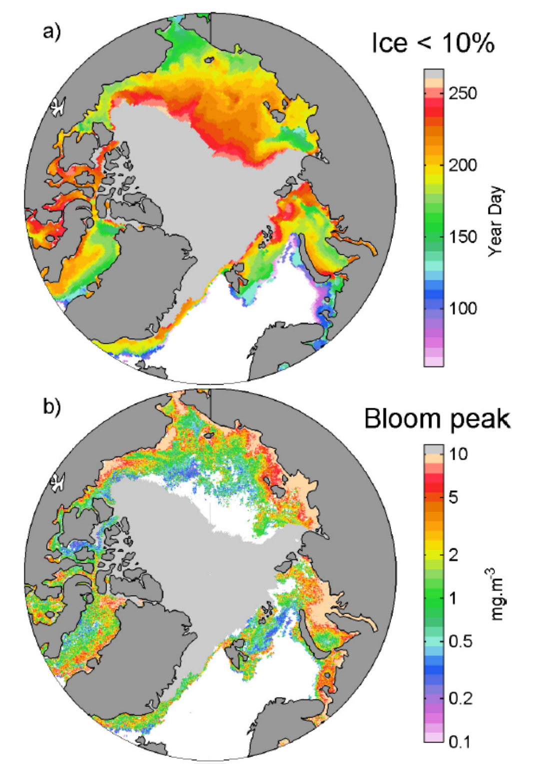
Last decade: new insight through satellite remote sensing

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



Near-ubiquity of ice-edge blooms in the Arctic

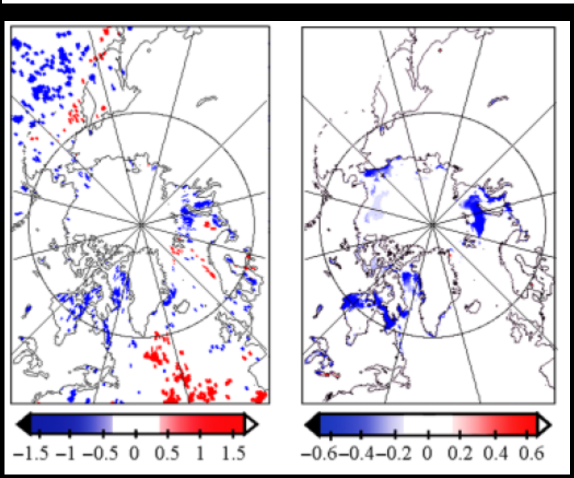
M. Perrette[1,*], A. Yool[1], G. D. Quartly[1], and E. E. Popova[1]



Perrette et al. 2011

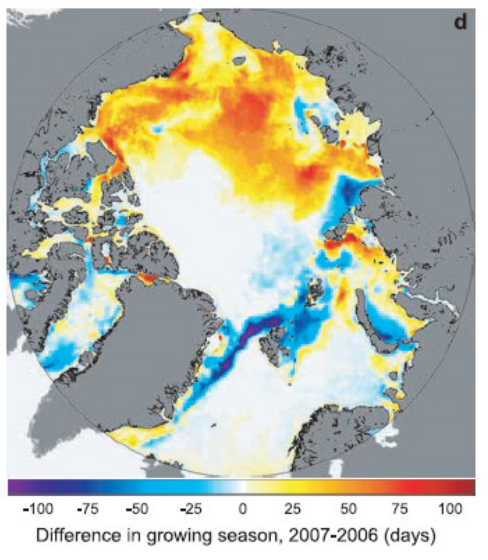
Are phytoplankton blooms occurring earlier in the Arctic?

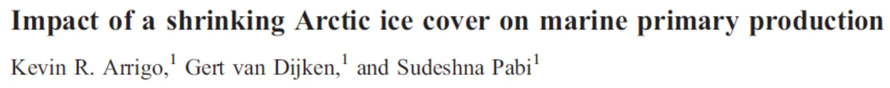
M. KAHRU*, V. BROTAS†, M. MANZANO-SARABIA‡ and B. G. MITCHELL*



Kahru et al. 2010

Arrigo et al. 2008





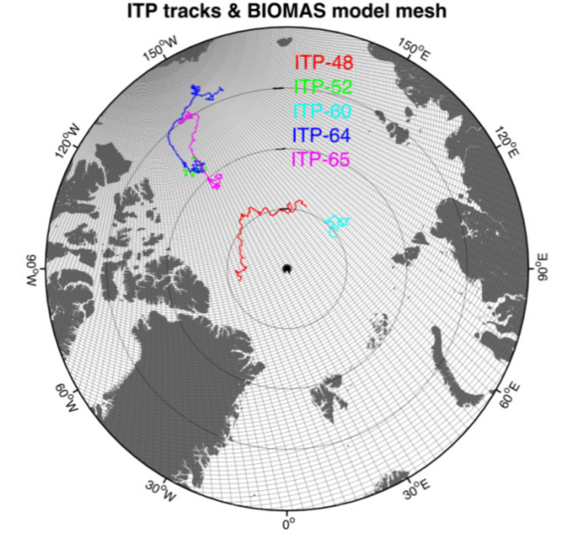
Impact of a shrinking Arctic ice cover on marine primary production

Kevin R. Arrigo,[1] Gert van Dijken,[1] and Sudeshna Pabi[1]

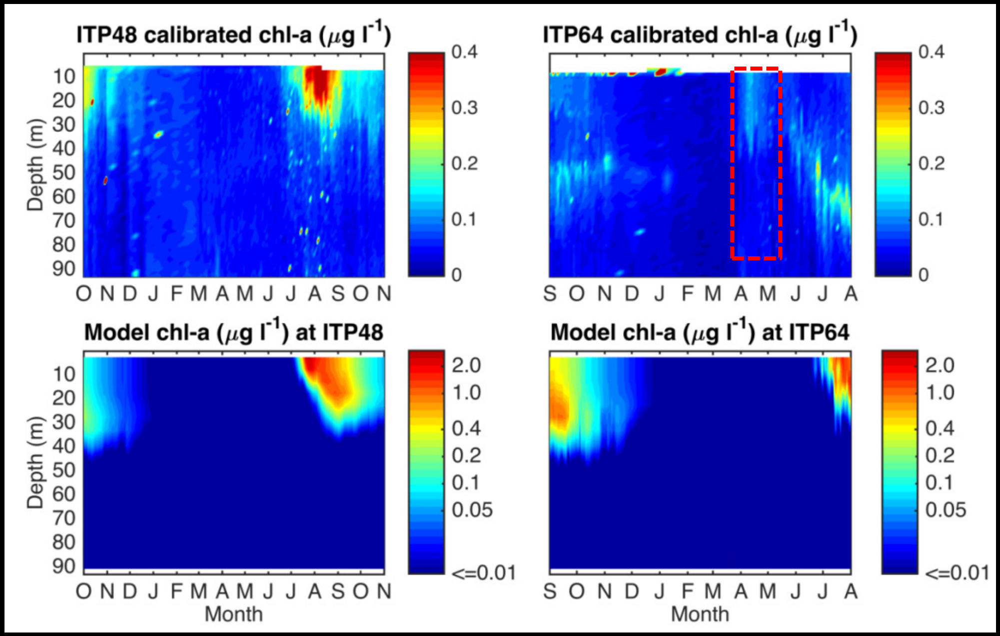
New insight using high-latitude ecosystem models

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

BIOMAS model


ITP tracks & BIOMAS model mesh

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


ITP48 calibrated chl-a (μg l^{-1})

ITP64 calibrated chl-a (μg l^{-1})

Model chl-a (μg l^{-1}) at ITP48

Model chl-a (μg l^{-1}) at ITP64

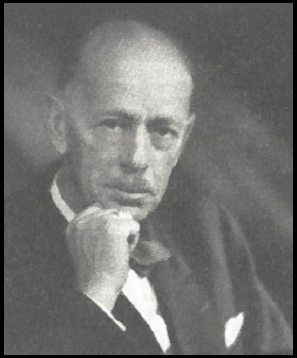
Zhixuan Feng (WHOI)

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

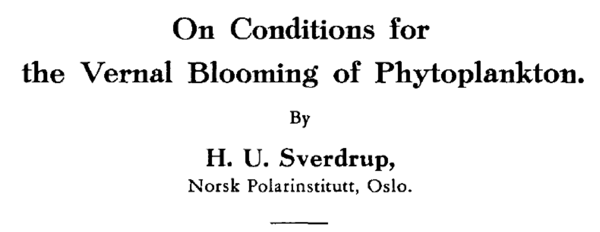
Funded by NSF Office of Polar Programs

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)

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

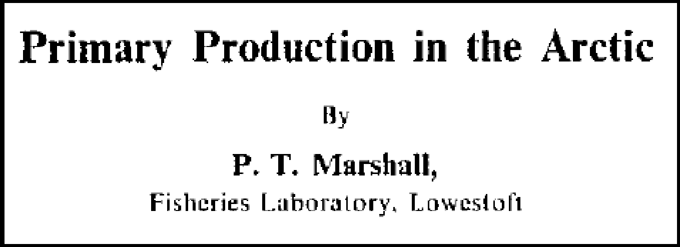


J. Cons. Int. Explor. Mer (1953)

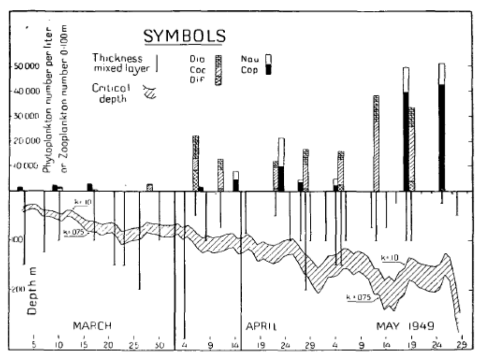


On Conditions for
the Vernal Blooming of Phytoplankton.
By
H. U. Sverdrup,
Norsk Polarinstitutt, Oslo.

J. Cons. Int. Explor. Mer (1957)



Primary Production in the Arctic
By
P. T. Marshall,
Fisheries Laboratory, Lowestoft



176 P. T. Marshall

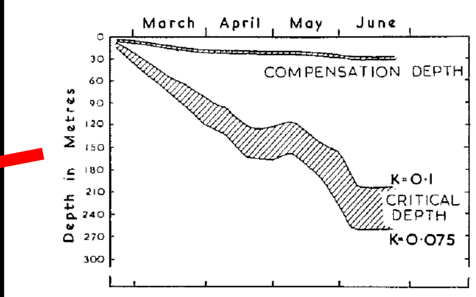
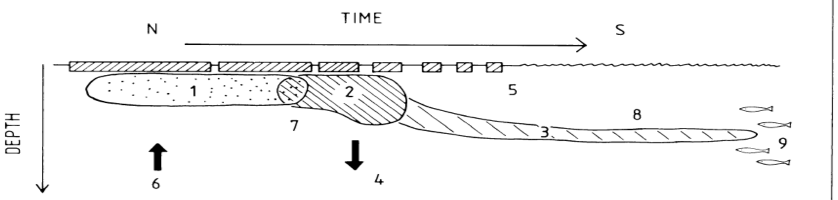


Figure 2. Critical depth and compensation depth near Bear Island in spring and early summer.

Figure 2. Schematic picture of the seasonal plankton development in the Barents Sea. The receding ice edge acts as a biological time-setter, and various stages of the seasonal plankton development can be found along a North–South gradient. (48).



1 – prebloom phytoplankton growth
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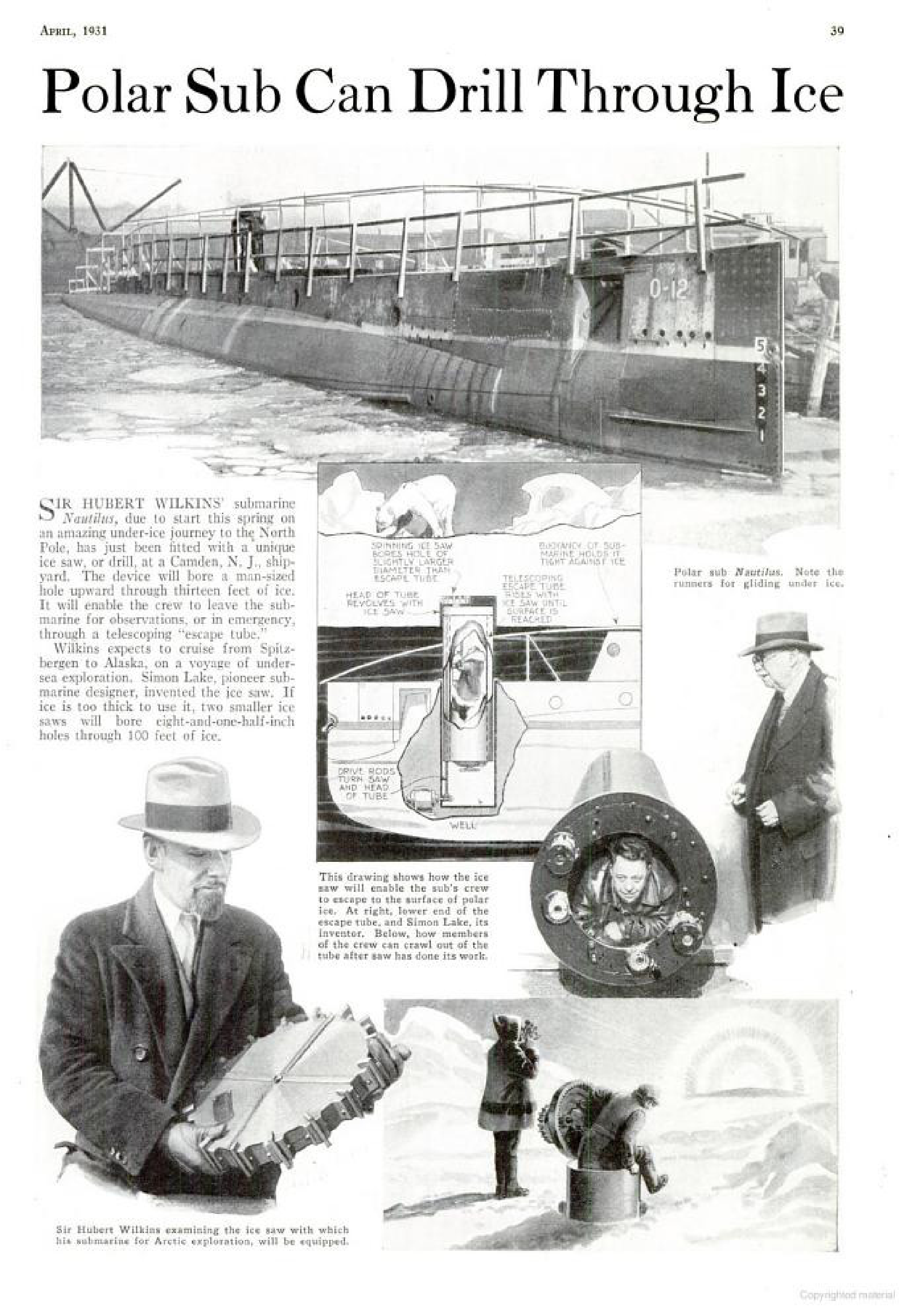

Polar Sub Can Drill Through Ice

SIR HUBERT WILKINS' submarine *Nautilus*, due to start this spring on an amazing under-ice journey to the North Pole, has just been fitted with a unique ice saw, or drill, at a Camden, N. J., shipyard. The device will bore a man-sized hole upward through thirteen feet of ice. It will enable the crew to leave the submarine for observations, or in emergency, through a telescoping "escape tube."

Wilkins expects to cruise from Spitzbergen to Alaska, on a voyage of undersea exploration. Simon Lake, pioneer submarine designer, invented the ice saw. If ice is too thick to use it, two smaller ice saws will bore eight-and-one-half-inch holes through 100 feet of ice.

Polar sub *Nautilus*. Note the runners for gliding under ice.

This drawing shows how the ice saw will enable the sub's crew to escape to the surface of polar ice. At right, lower end of the escape tube, and Simon Lake, its inventor. Below, how members of the crew can crawl out of the tube after saw has done its work.

Sir Hubert Wilkins examining the ice saw with which his submarine for Arctic exploration, will be equipped.