Impacts of Climate on the Eco-Systems and Chemistry of the Arctic Pacific Environment (ICESCAPE)- Synthesis

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Arrigo, Bates, Benitez-Nelson, Chavez, Cooper, Frey, Freeman, Frouin, Hooker, Laney, Matrai, Mitchell, Ortega-Retuerta, Perovitch, Pickart, Reynolds, Sosik, Steel, Stramski, Swift, Werdell, Yvon, Zhang

Acknowledgements

- Investigators who sent me slides
- Paty Matrai for some of the early literature citations
- Captains and crew of the USCGC Healy
- Quincey Allison, Sue Tolley-NASA logistics for moving people and gear
- NASA for funding

Outline

- Introduction and perspective
- Physics
- Chemistry and Biogeochemistry
- Optics and Bio-optics
- Biology
- Modeling
- Summary

Introduction and perspective

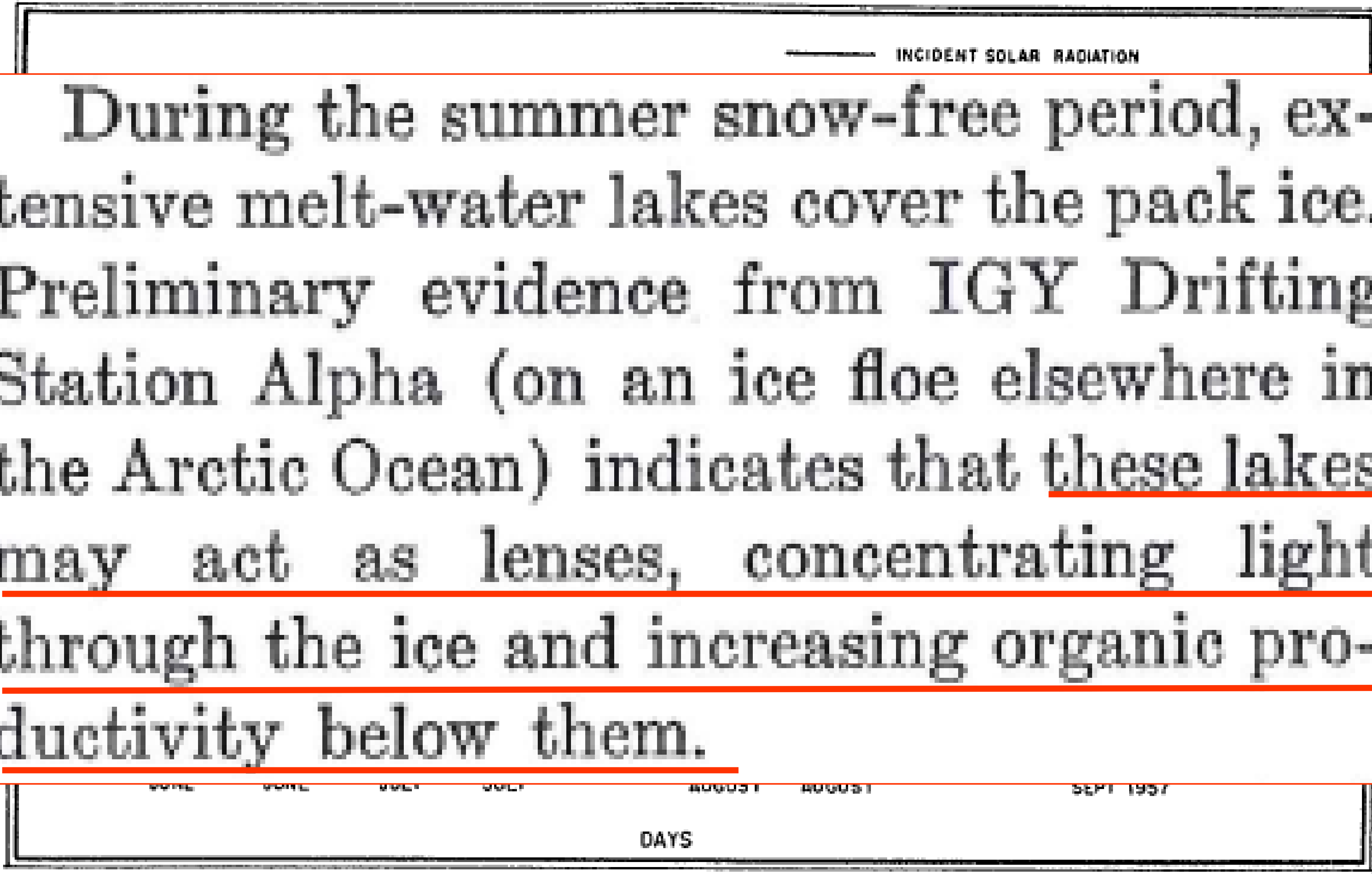
Spencer Apollonio, Yale Univ. Summer 1957; T-3 Ice Island.

Hydrobiological Measurements on IGY Drifting Station Bravo

The following report is based on material supplied by Spencer Apollonio, Yale University. The IGY work it describes was supported by the Air Force Cambridge Research Center and the Woods Hole Oceanographic Institution.

Environmental Conditions

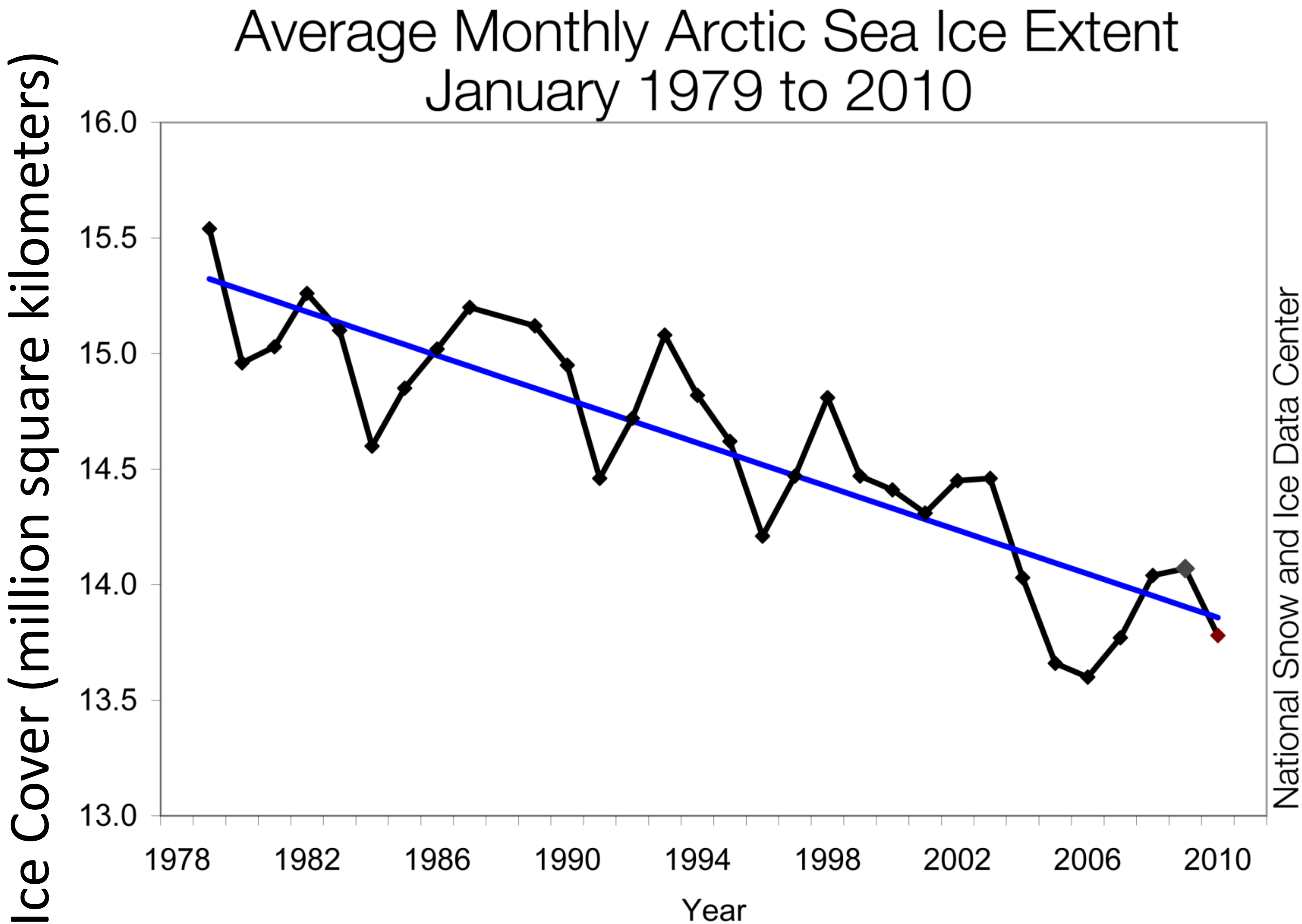
The drift of Station Bravo during this study was along the edge of the continental shelf, within 100 miles of the north coast of the Canadian Arctic Archipelago (see *Bulletin No. 24*). The ice island itself is es-



During the summer snow-free period, extensive melt-water lakes cover the pack ice. Preliminary evidence from IGY Drifting Station Alpha (on an ice floe elsewhere in the Arctic Ocean) indicates that these lakes may act as lenses, concentrating light through the ice and increasing organic productivity below them.

FIG. 12. *Average Thickness of Snow Cover and Average Amounts of Incident Solar Radiation, Photosynthesis, and Chlorophyll a, Summer 1957, at IGY Drifting.*

More justification for ICESCAPE…



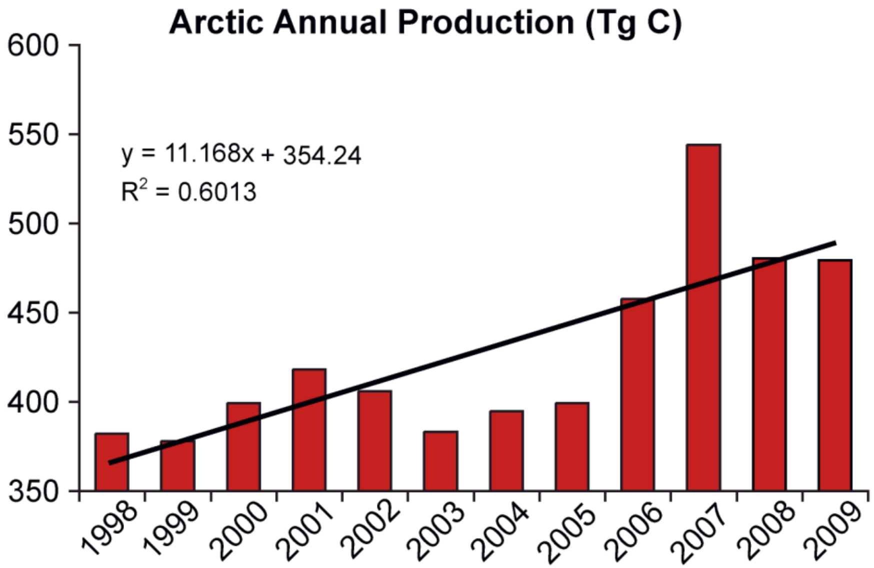
Given ongoing changes in the Arctic Ocean…

How has primary production changed in recent years?

Changes in Pan-Arctic Annual Productivity

-Suggested 38% increase

-What is responsible for this increase?



- Lower ice cover and longer growing seasons play a role

- Increased nutrient supply also must be important
  - Greater shelf-break upwelling as sea ice retreats?
  - Increased eddy activity?
  - Intensified advection of nutrients from Bering Strait?

ICESCAPE

***Central science question**:*

What is the impact of climate change (natural and anthropogenic) on the biogeochemistry and ecology of the Chukchi and Beaufort seas?

ICESCAPE

When?

June 15 - July 21, 2010
& September 2011

Where?

Start in Dutch Harbor, AK
Cruise to Bering Strait
Beaufort/Chukchi Sea
  - Continental shelf
  - Canada Basin
Sea ice sampling
Back through Bering Strait
End In Seward, AK

ICESCAPE- Investigators

***Physical Oceanography/modeling*:**

Bob Pickart – XBTs, ADCP, eddies

Jim Swift – CTD, O_2, salinity

Mike Steele– Bio-ARGO floats (hydrographic measurements)

Jinlun Zhang – 3D coupled physical-chemical-biological ice-ocean modeling

***Biological Oceanography/Biogeochemistry*:**

Kevin Arrigo, *Greg Mitchell*, *Barney Balch* – Carbon fixation, microalgal abundance (ice and water column), physiology

Sam Laney/Heidi Sosik – Phytoplankton community composition

Eva Ortega-Retuerta - Bacterial production

Claudia Benitez-Nelson- Export fluxes with thorium

Patricia Matrai- Bio-ARGO Floats (chlorophyll, optics, nitrate, O_2)

ICESCAPE-Investigators (cont.)

Chemical Oceanography:

Nick Bates – Carbon cycle measurements (e.g. DIC, alkalinity)

Jim Swift – Nutrients (e.g. NO3, NO2, NH4, PO4 , SiO3), O2, salinity

Optical Oceanography:

Greg Mitchell, *Barney Balch*, *Stan Hooker* – Spectral Lu, Ed, AOPs, IOPs, underway IOPs

Rick Reynolds and Dariusz Stramski – Particle size distribution, bb, volume scattering, SPM

Atsushi Matsuoka – absorption of CDOM

Robert Frouin – Atmospheric correction

Sea Ice:

Don Perovich, *Bonnie Light* – Concentration, thickness, salinity, snow cover, optical properties

Karen Frey – CDOM, DOC, O2 isotopes

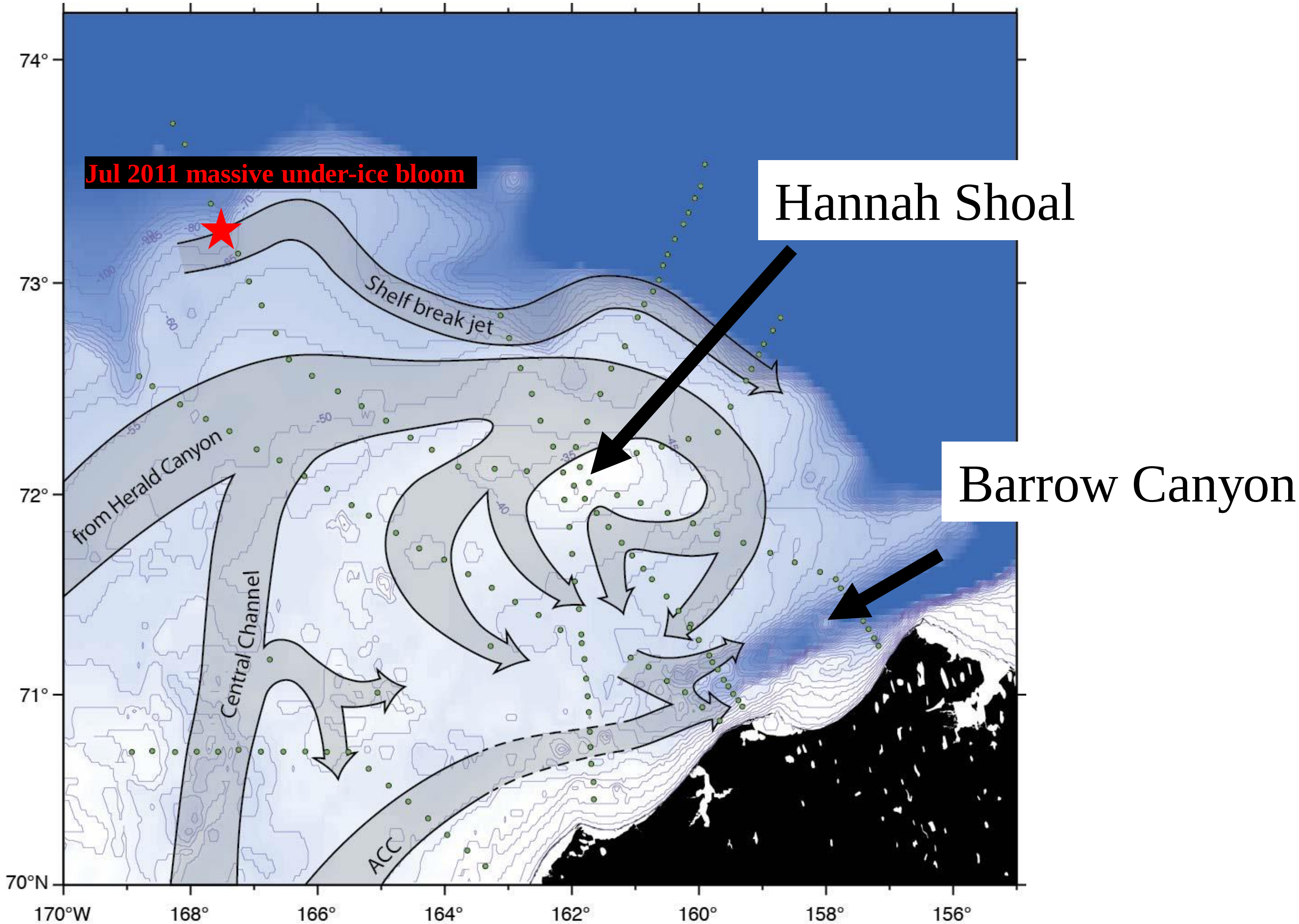
Modeling:

Jinlun Zhang- modeling bloom onset

Robert Frouin – Modeling primary productivity (PISCES model)

Physical observations

Revised circulation scheme of high-nutrient winter water



Based on the ICESCAPE hydrographic/velocity surveys

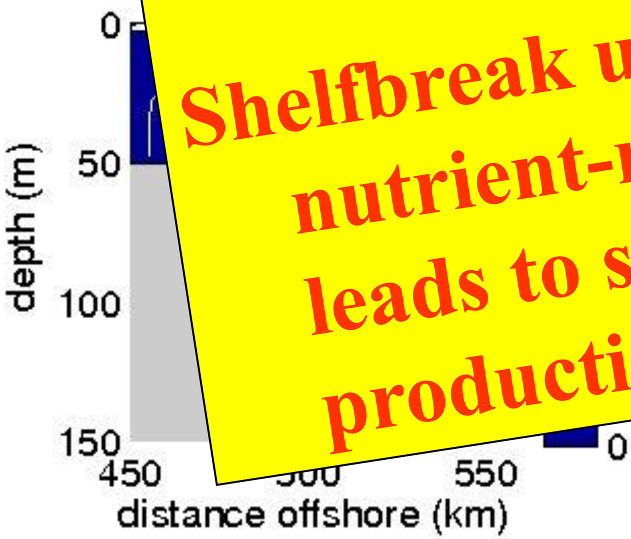
Pickard, WHOI

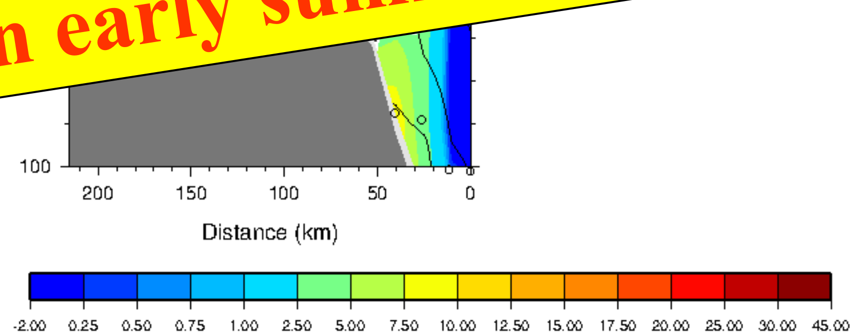
Schematic of upwelling at the shelfbreak due to easterly winds

The pathways of winter water across the Chukchi shelf have been clarified

Shelfbreak under-ice upwelling of nutrient-rich, halocline water leads to significant primary production in early summer

Ve... chlorop... E

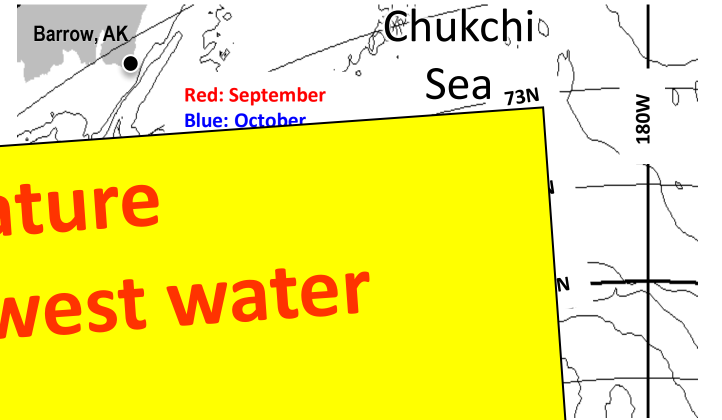




Chl a (color) overlain by density (contours)

Pickard, WHOI

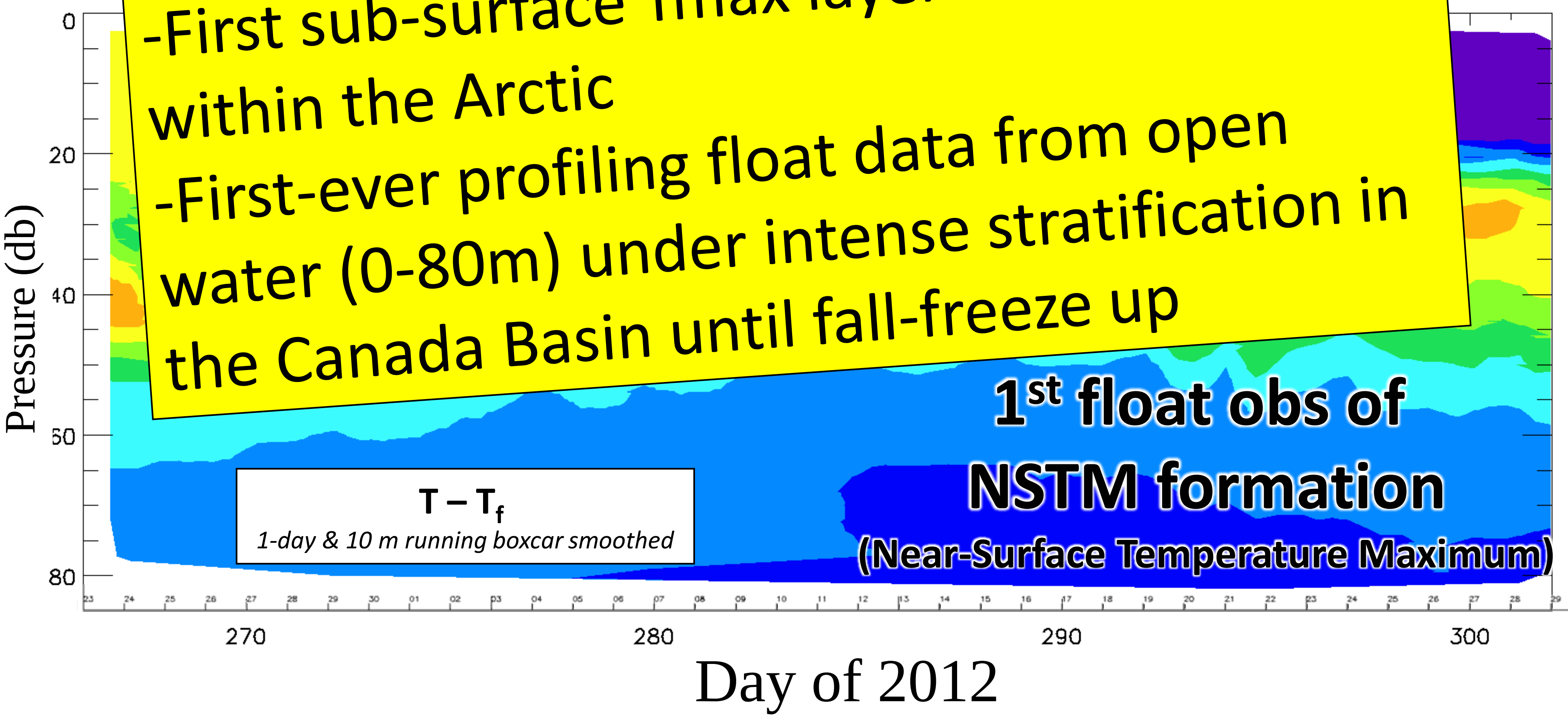
ICESCAPE float program:



-NSTM (Near Surface Temperature Maximum) is the "world's newest water mass."

-First sub-surface Tmax layer to form locally within the Arctic

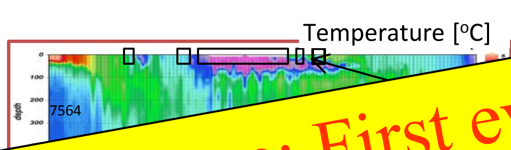
-First-ever profiling float data from open water (0-80m) under intense stratification in the Canada Basin until fall-freeze up

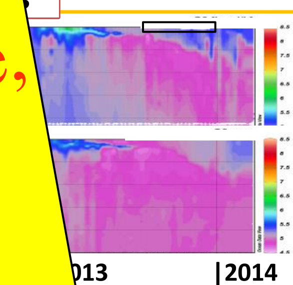


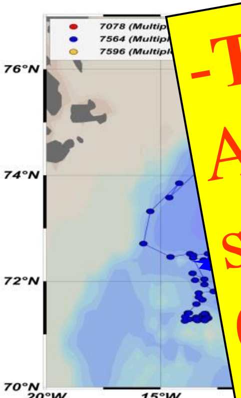
Chemistry/Biogeochemistry

Arctic Phytoplankton Productivity: Bio-float observations in ice-covered waters

P. Matrai[1], M. Steele[2], D.Swift[2], S. Riser[2], K. Johnson[3] and J. Nutt[1]
[1]Bigelow Laboratory for Ocean Sciences, [2]University of Washington, [3]MBARI

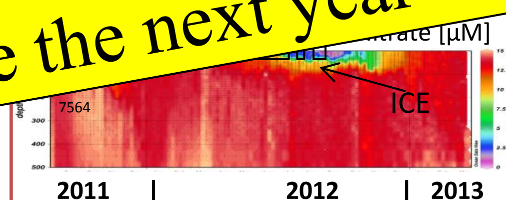


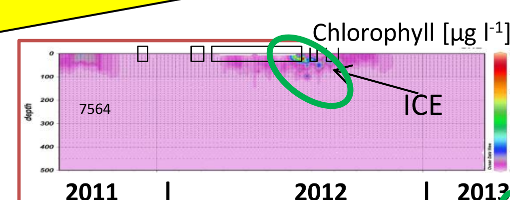




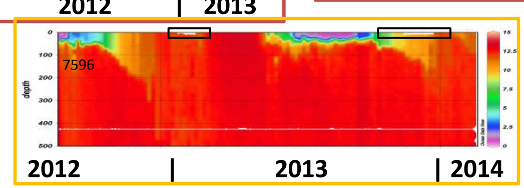
-Technological advance: First ever Arctic ARGO bio-floats with ice avoidance algorithm, survive stratification and function under sea ice, 0-1000m, 20+ months!

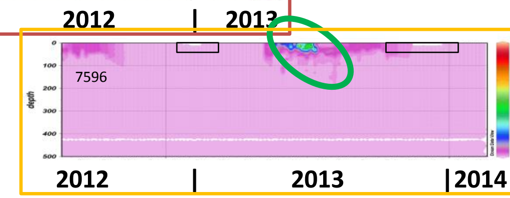
- Four independent sensors document phytoplankton bloom at ice edge one year and without ice the next year

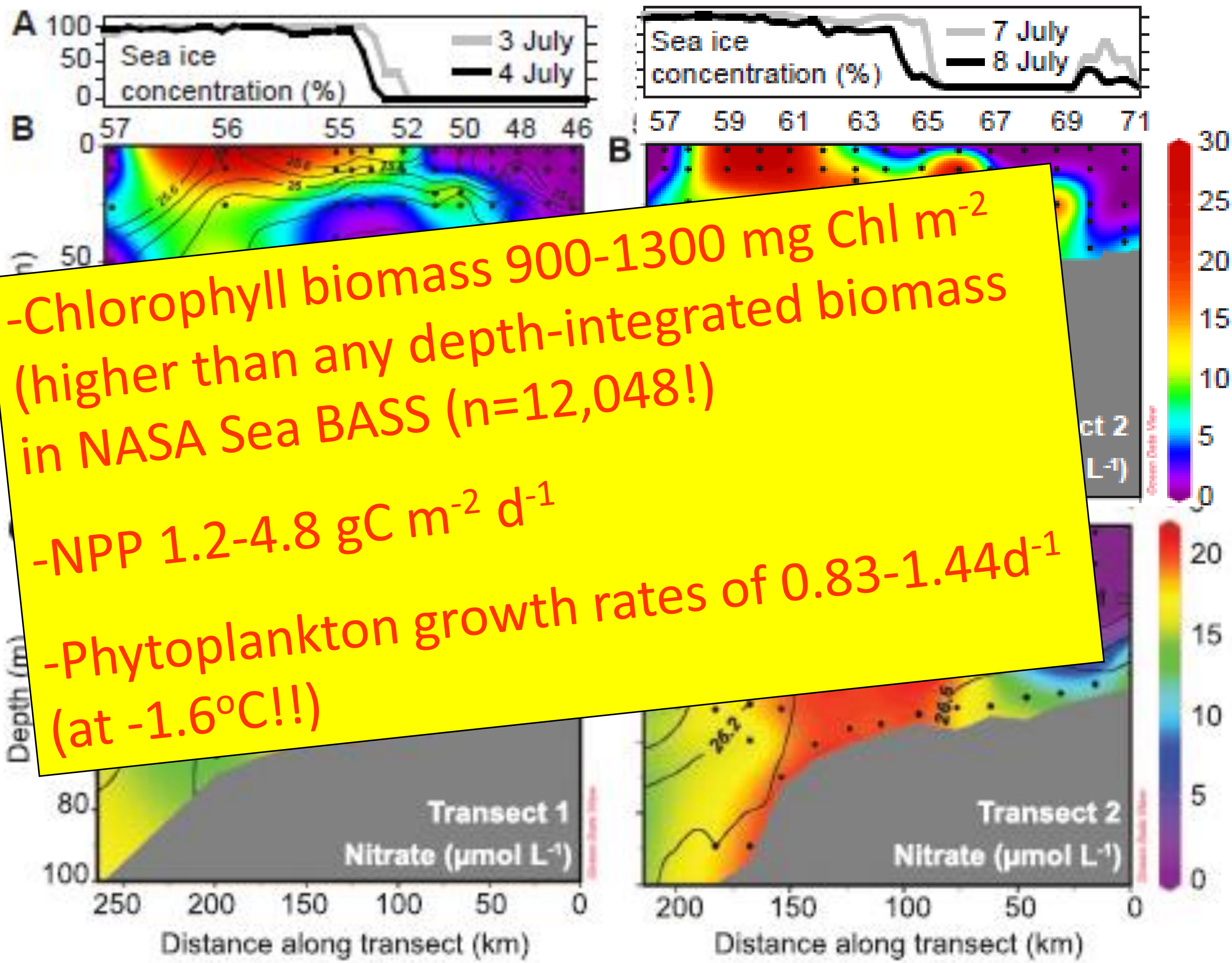




Spring bloom: Ice, no ice







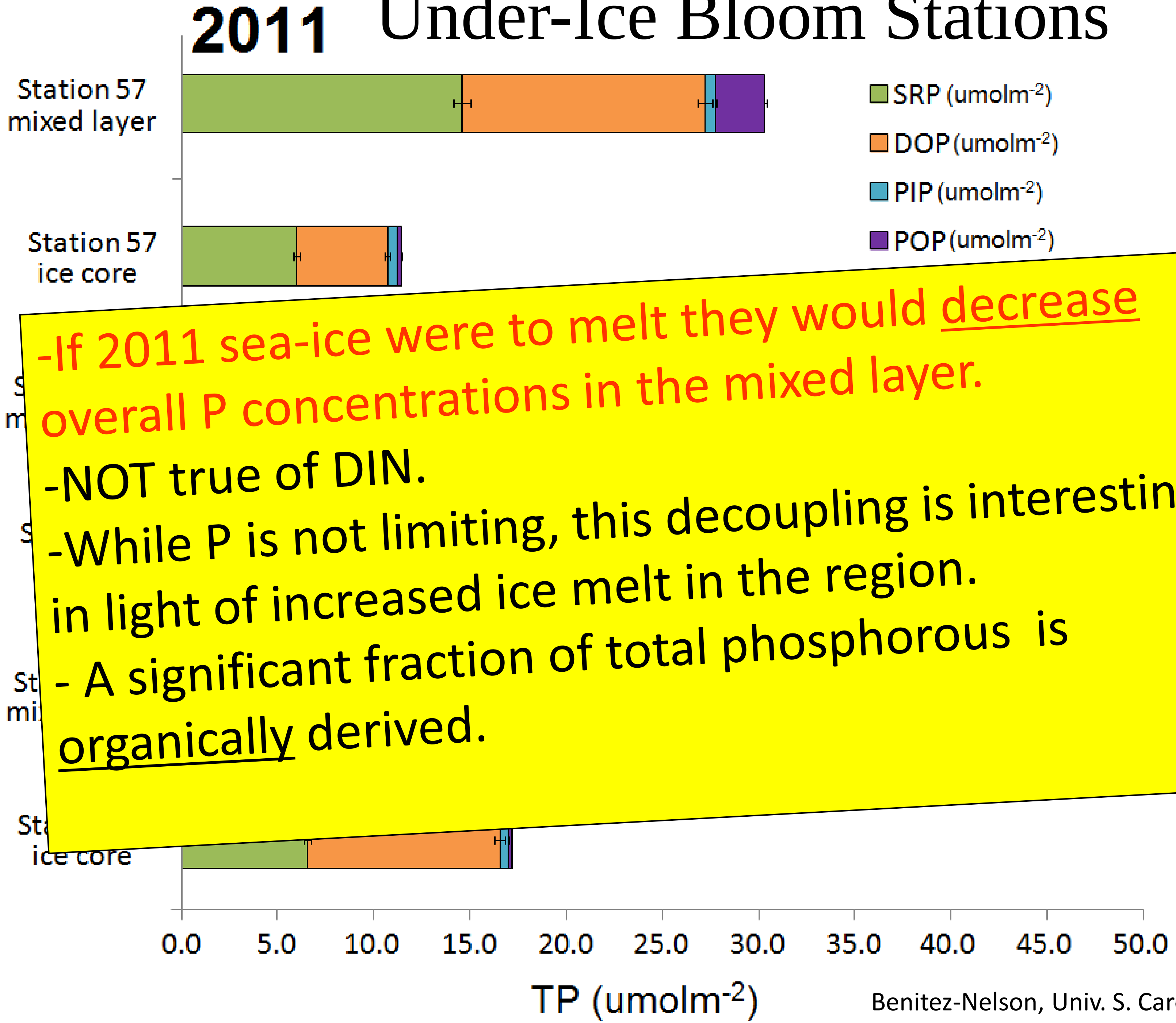
-Chlorophyll biomass 900-1300 mg Chl m^{-2} (higher than any depth-integrated biomass in NASA Sea BASS (n=12,048!)

-NPP 1.2-4.8 gC m^{-2} d^{-1}

-Phytoplankton growth rates of 0.83-1.44d^{-1} (at -1.6°C!!)

Arrigo et al. Stanford

Under-Ice Bloom Stations



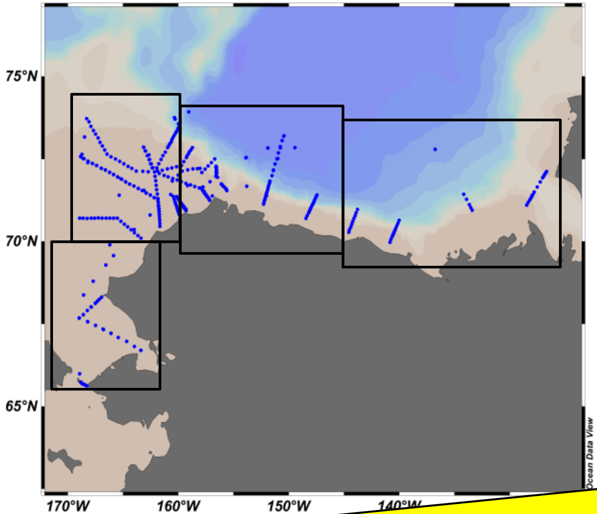
-If 2011 sea-ice were to melt they would <u>decrease</u> overall P concentrations in the mixed layer.

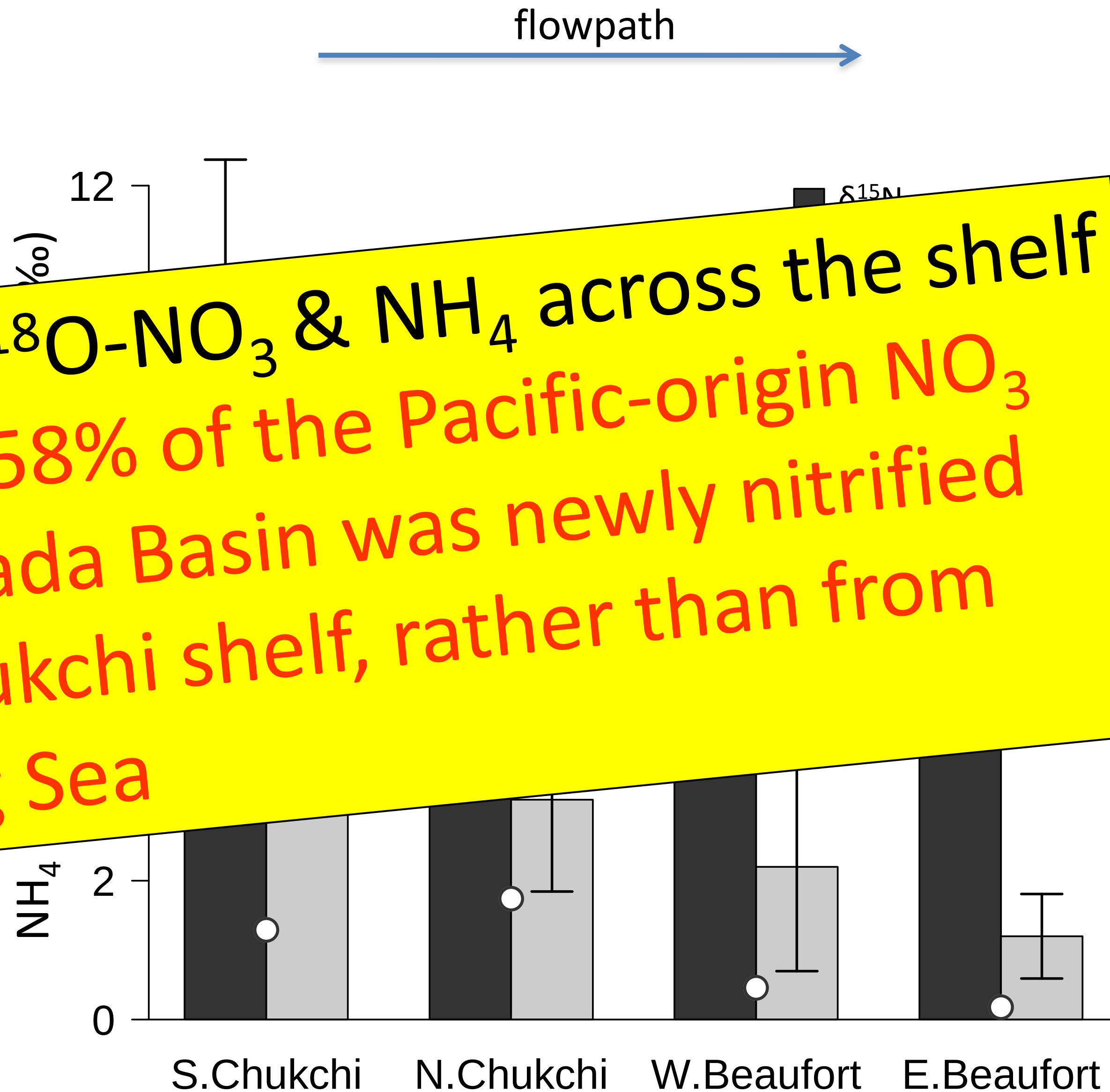
-NOT true of DIN.

-While P is not limiting, this decoupling is interesting in light of increased ice melt in the region.

- A significant fraction of total phosphorous is <u>organically</u> derived.

Benitez-Nelson, Univ. S. Carolina





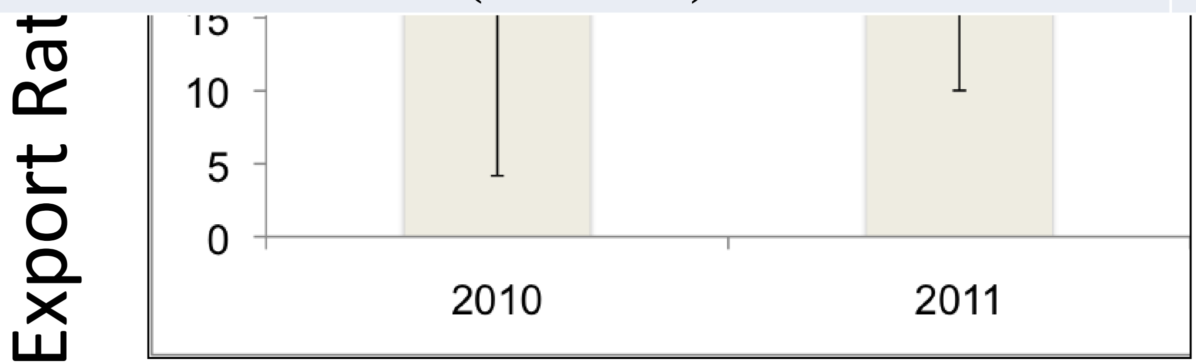
Decrease in $\delta^{18}O-NO_3$ & NH_4 across the shelf indicates ~58% of the Pacific-origin NO_3 in the Canada Basin was newly nitrified on the Chukchi shelf, rather than from the Bering Sea

Brown et al. , Stanford Univ.

Quantify C Export Rate

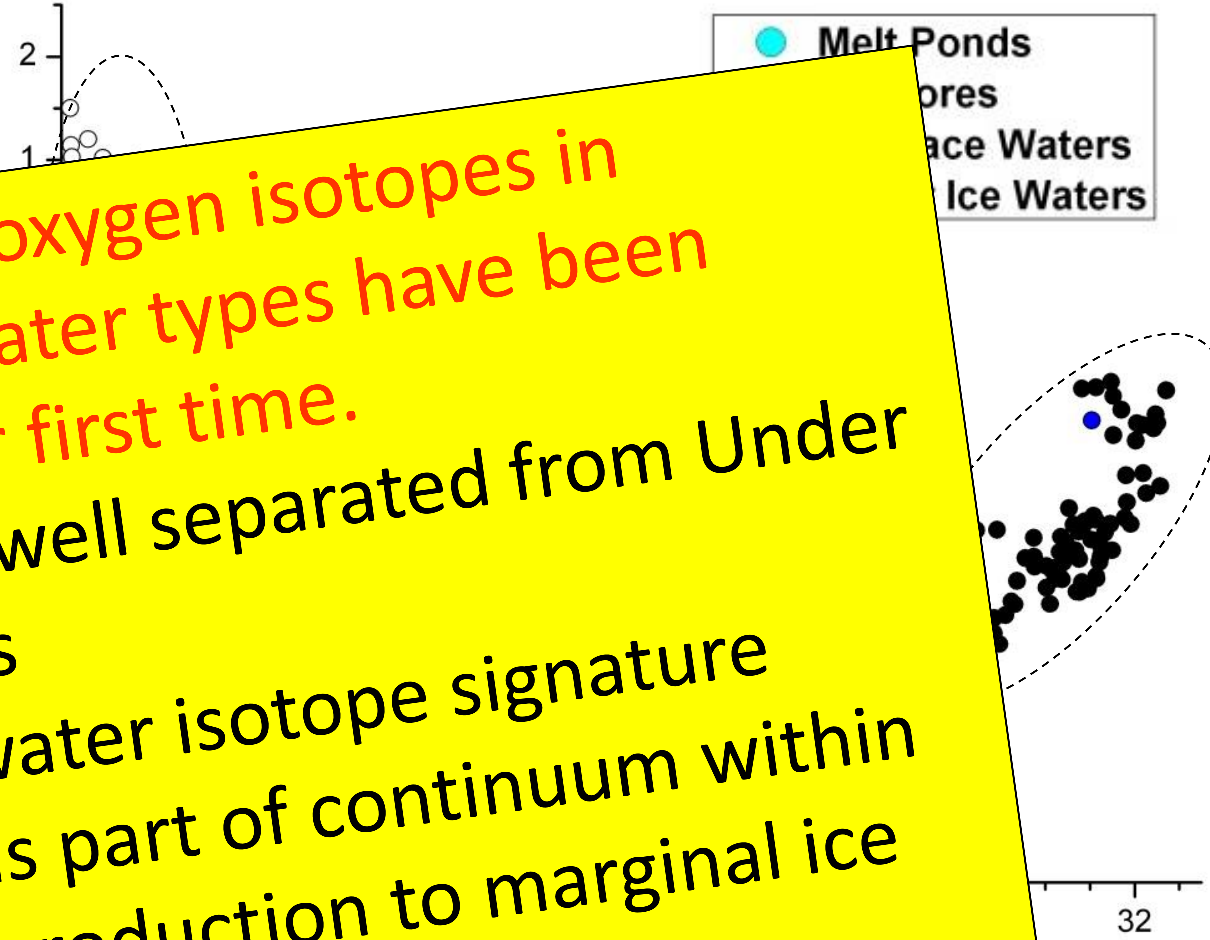
- C "export" averages ~ 50% of DIC deficit
- At sampling, 15 - 17 Tg C lost from Chukchi shelf water column (with active blooms still ongoing)

[illegible] (non-ACC)	45±15%
2011 ICESCAPE Whole Chukchi Shelf (non-ACC)	55%±19%



Strong, Arrigo and Bates

$\delta^{18}O$ in sea ice and s… fro… coll…



-Values for oxygen isotopes in different water types have been defined for first time.

-Ice cores well separated from Under Ice Waters

- Bloom water isotope signature shows it is part of continuum within ice algal production to marginal ice edge bloom

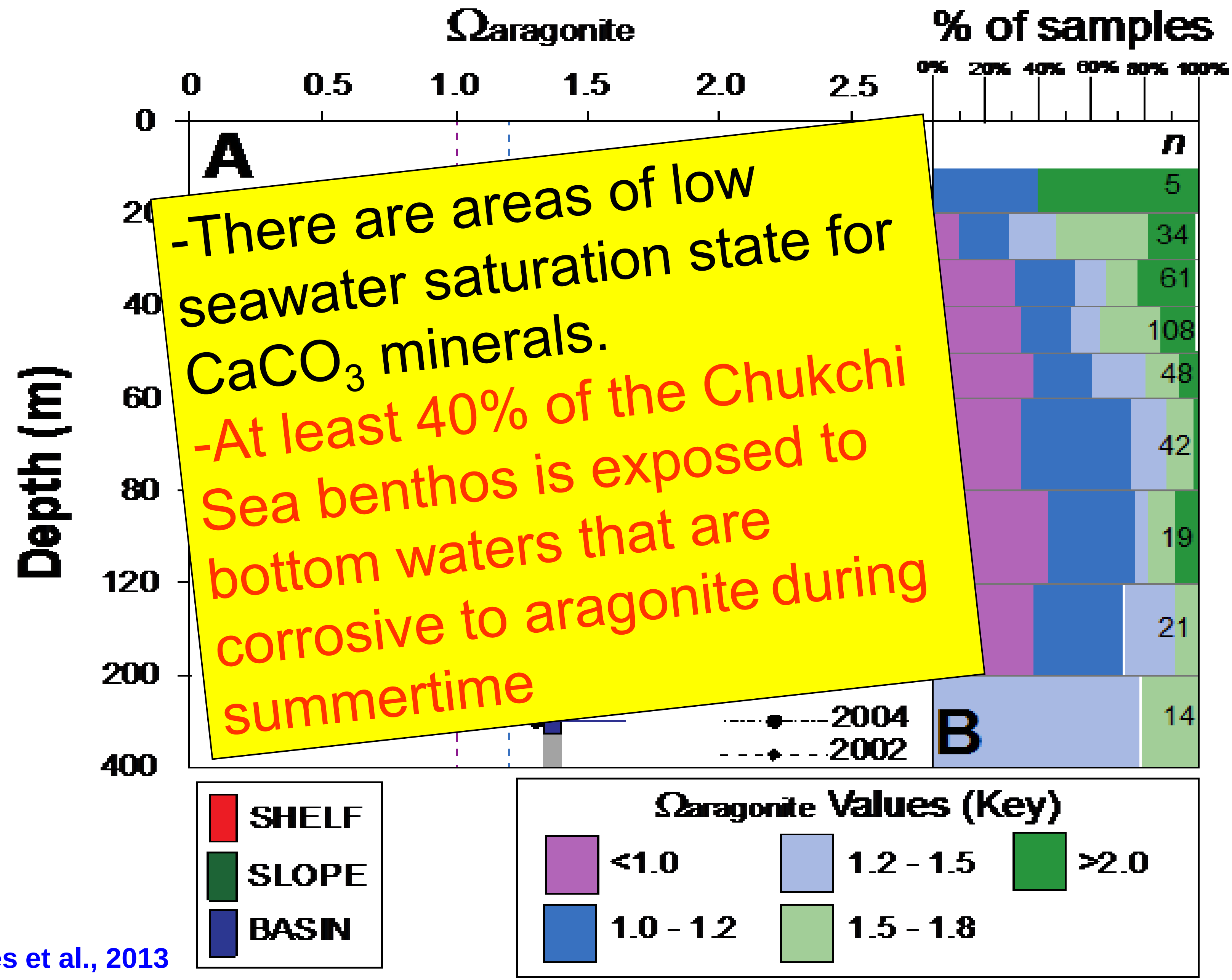
Averag…

Ice Cores -0.97 ± 0.9

Under Ice Waters -2.8 ± 0.8

Lee Cooper, UMCES

Western Arctic OA Impacts



-There are areas of low seawater saturation state for $CaCO_3$ minerals.

-At least 40% of the Chukchi Sea benthos is exposed to bottom waters that are corrosive to aragonite during summertime

Bates et al., 2013

Optical observations

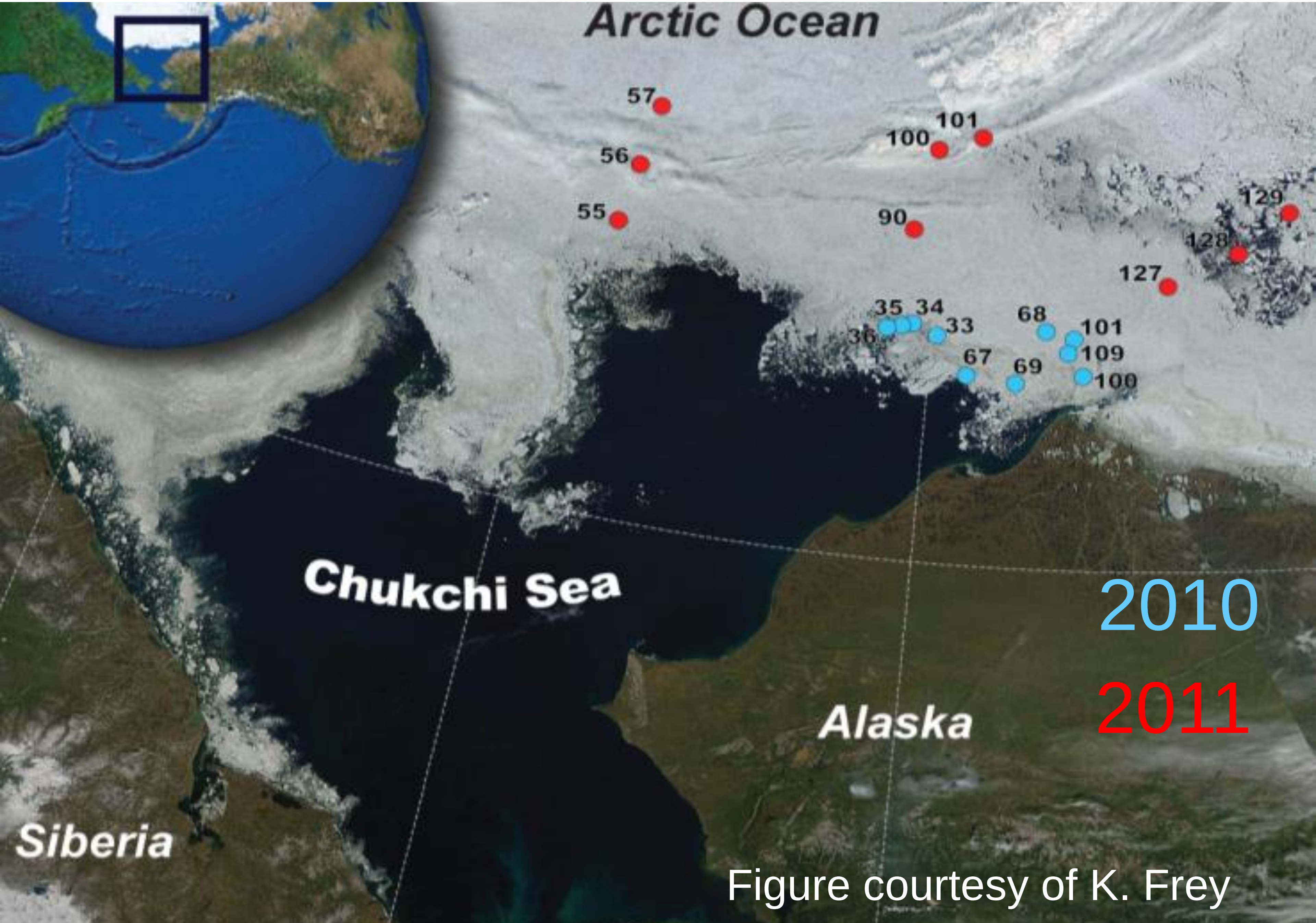
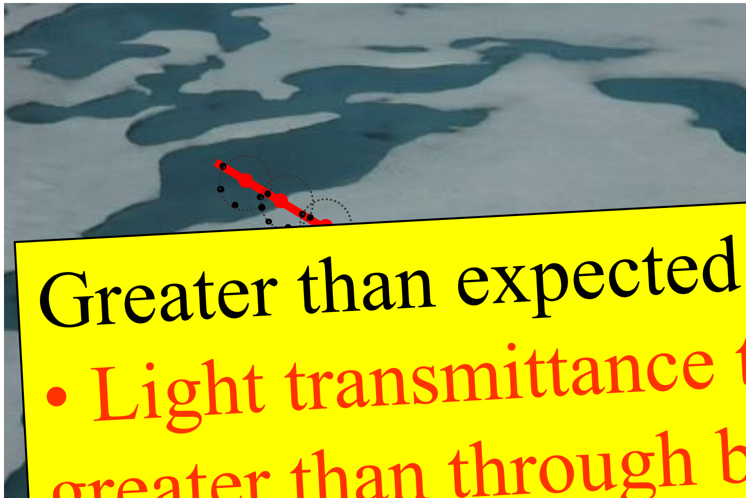
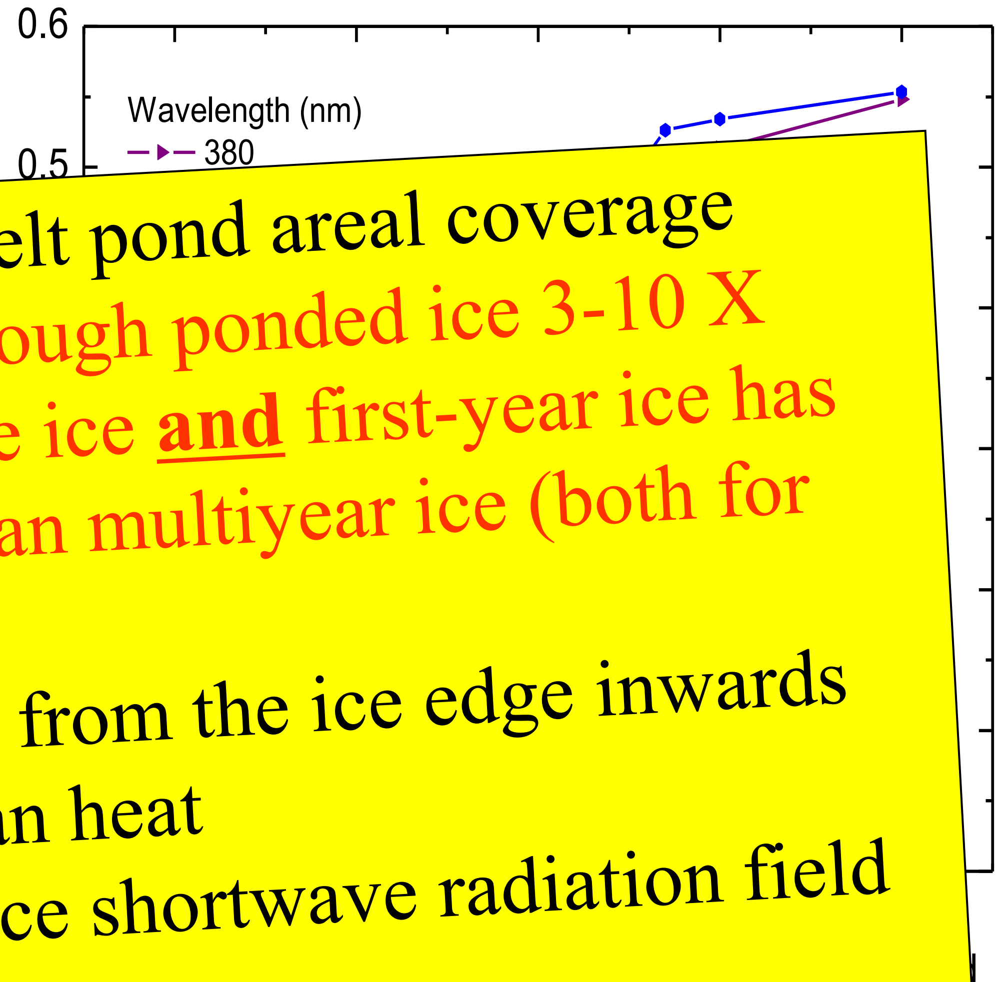


Figure courtesy of K. Frey

ICESCAPE – Sea ice studies





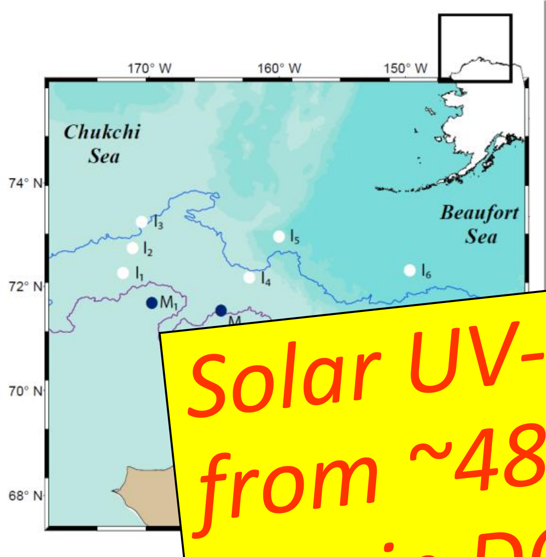
Greater than expected melt pond areal coverage

- Light transmittance through ponded ice 3-10 X greater than through bare ice **and** first-year ice has lower light extinction than multiyear ice (both for bare and ponded)
- Ice thickness increased from the ice edge inwards due to reduction of ocean heat
- Description of under-ice shortwave radiation field and spatial variability

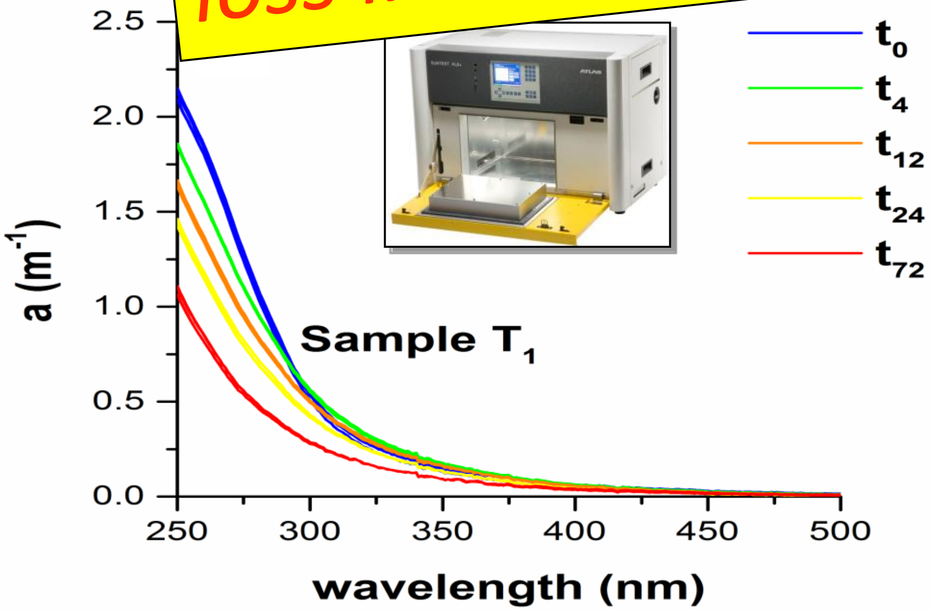
Light field is spatially complex – ponds are skylights to the ocean

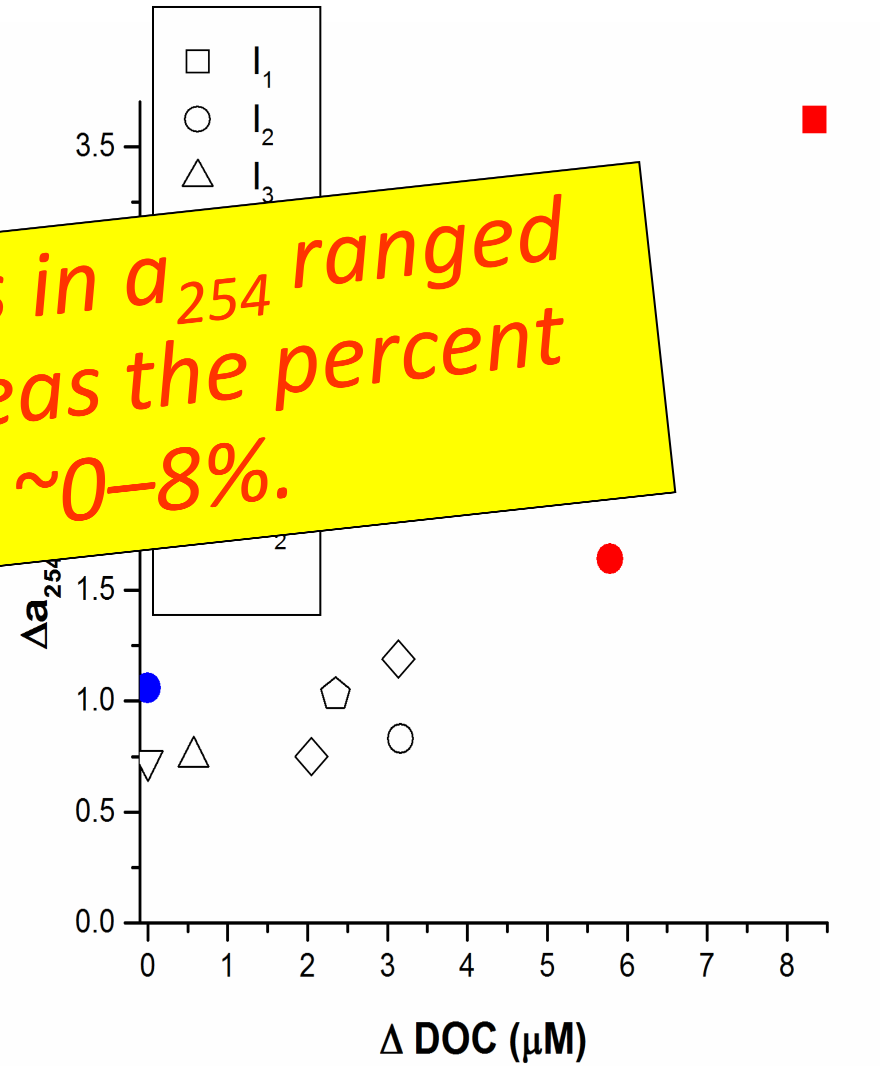
Perovich, Light; CRREL

Impacts of a declining Arctic sea ice cover on the photodegradation of dissolved organic matter



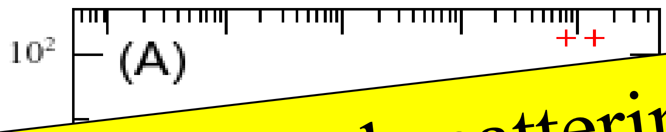
Solar UV-induced loss in a_{254} ranged from ~48–62% whereas the percent loss in DOC was only ~0–8%.

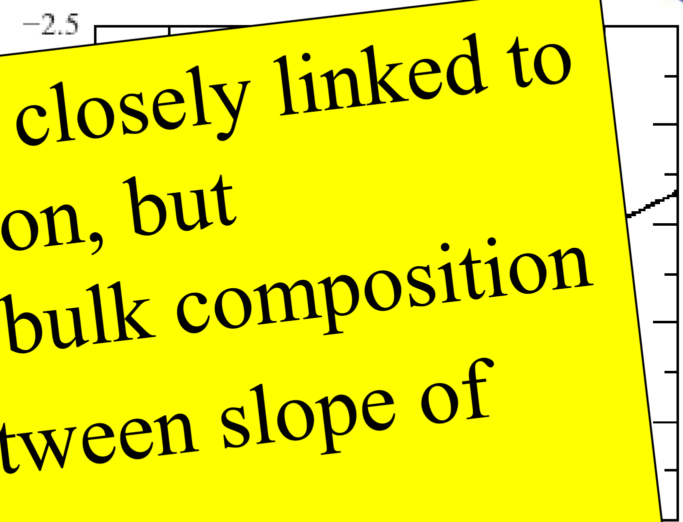




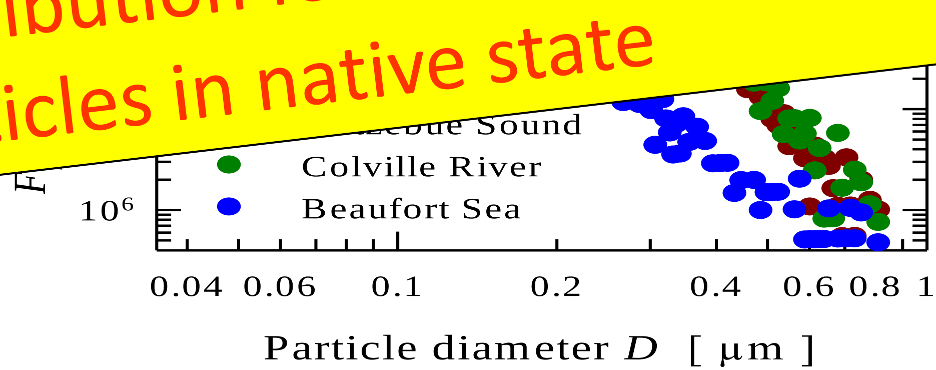
Frey, Christie Logvinova, *et al.*,*Clark Univ.*

Optical detection of particle concentration, composition, and size within Arctic waters





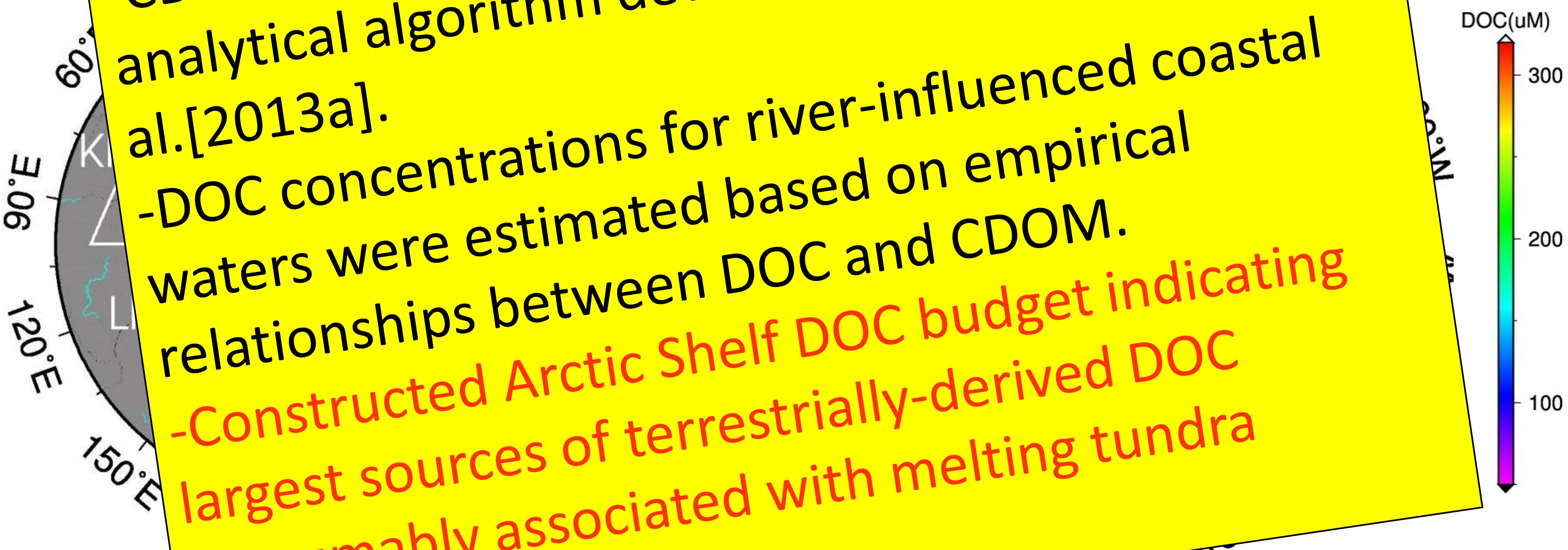
- Particle backscattering is closely linked to particle mass concentration, but relationship differs with bulk composition
- No clear relationship between slope of PSD and slope of $b_{bp}(\lambda)$
- First measurements of particle size distribution for oceanic submicron particles in native state



surface waters at three locations during the 2011 ICESCAPE cruise.

Rick A. Reynolds and Dariusz Stramski, SIO, UCSD

CDOM and DOC estimates using semi-analytical algorithm



-CDOM was estimated remotely using a semi-analytical algorithm developed by Matsuoka et al.[2013a].

-DOC concentrations for river-influenced coastal waters were estimated based on empirical relationships between DOC and CDOM.

-Constructed Arctic Shelf DOC budget indicating largest sources of terrestrially-derived DOC presumably associated with melting tundra

[Matsuoka et al., 2013b]

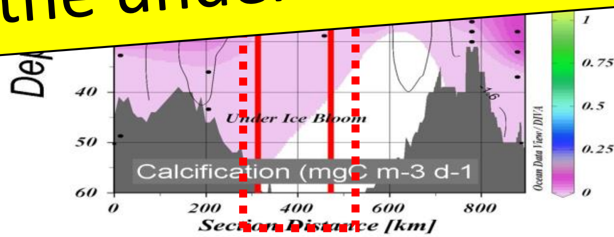
ICESCAPE: Bio-optics and coccolithophore observations in Arcti

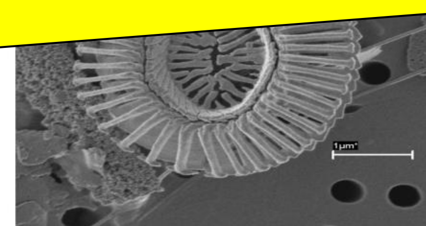
- Minimum diameter of under-Ice bloom ~150km

-PIC standing stock, coccolith b_{bp} and coccolithophore calcification clearly measurable but low

-Independent est of NPP using microdiffusion technique; max **2.86 g C m^{-2} d^{-1}** in under-ice bloom

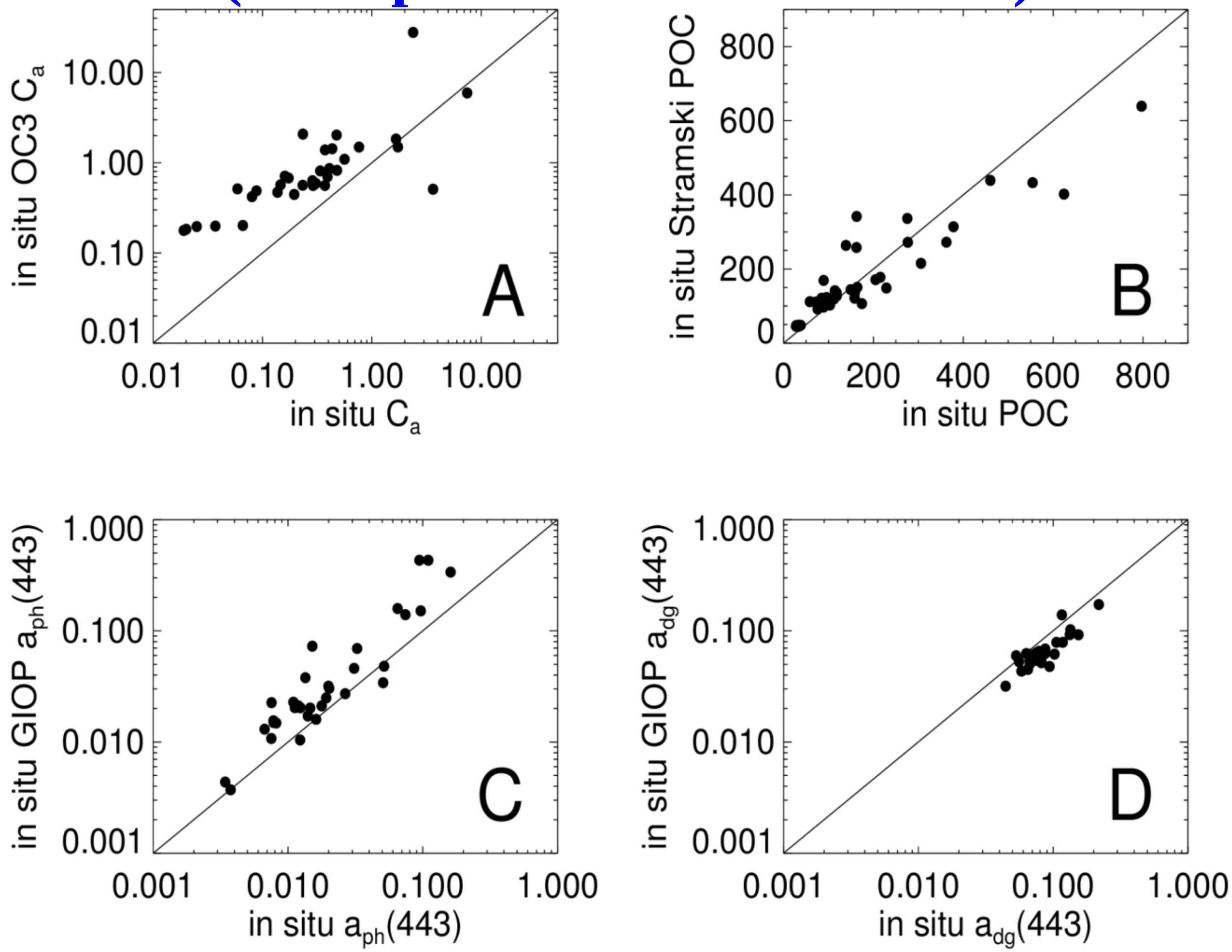
-Scanning electron microscopy provides unequivocal evidence of coccolithophores in the under-ice bloom!





Balch; Bigelow Laboratory

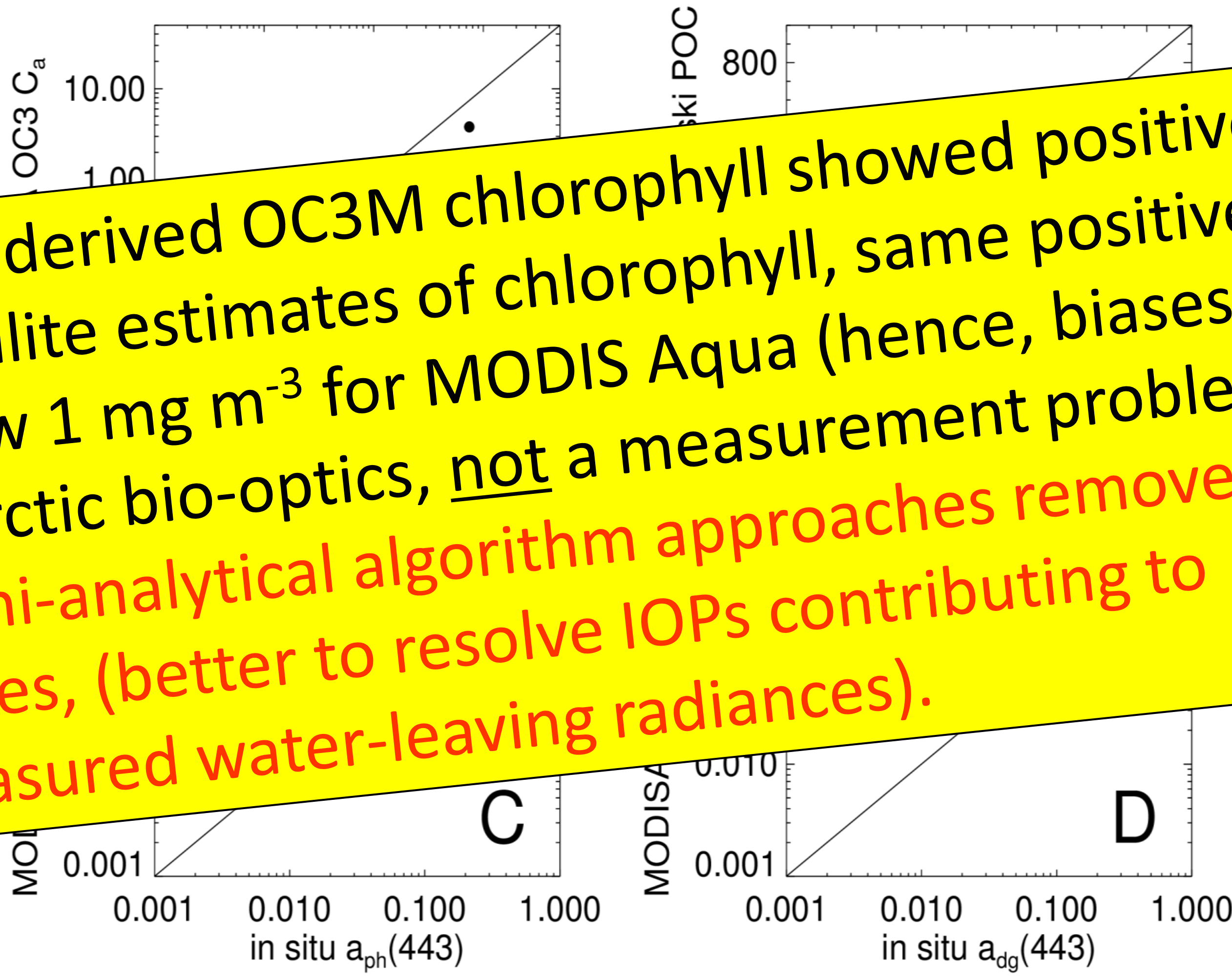
in situ ICESCAPE match-ups measured with in situ radiometry (not a problem with a satellite)



OC3M C_a (A), Stramski POC (B), GIOP $a_{ph}(443)$ (C), and GIOP $a_{dg}(443)$ (D) using ***in situ* R_{rs}** versus *in situ* measured values.

Werdell, Chavez, Freeman, Neely, Mannino

MODIS-Aqua ICESCAPE match-ups



-Ship-derived OC3M chlorophyll showed positive bias

-Satellite estimates of chlorophyll, same positive bias below 1 mg m^{-3} for MODIS Aqua (hence, biases due to Arctic bio-optics, <u>not</u> a measurement problem).

-Semi-analytical algorithm approaches removed biases, (better to resolve IOPs contributing to measured water-leaving radiances).

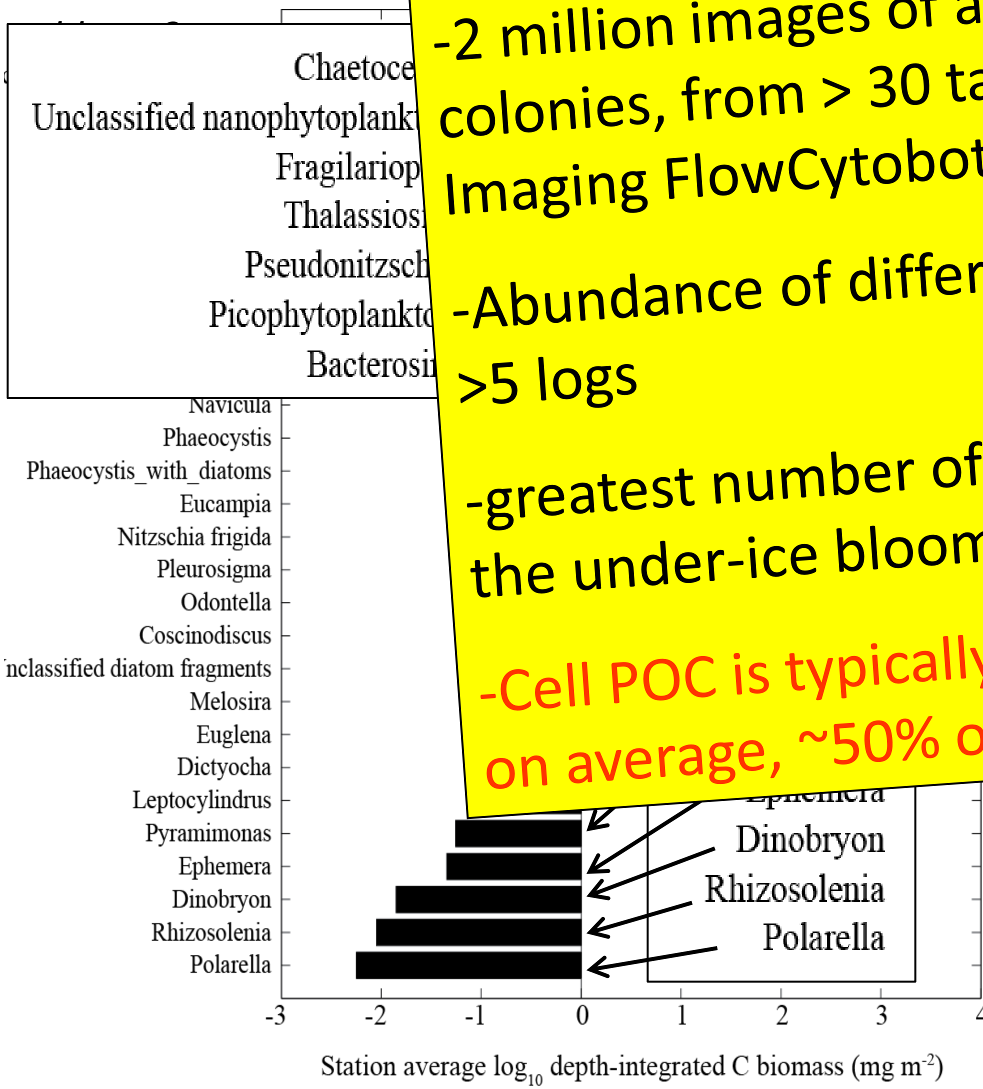
OC3M C_a (A), Stramski POC (B); GIOP $a_{ph}(443)$ (C) and $a_{dg}(443)$ (D) using **MODIS-Aqua $R_{rs}(\lambda)$** versus *in situ* measured values.

Werdell, Chavez, Freeman, Neely, Mannino

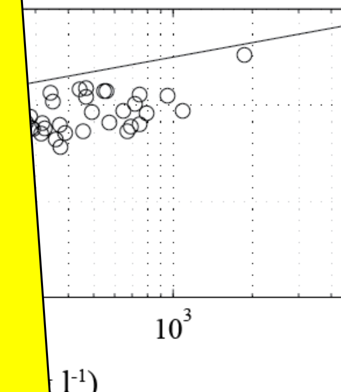
Biological Observations

Merge IFCB-derived and FCM C cell carbon estimates

E.g., which taxa contribute most to algal C biomass in the Chukchi overall



How much of th... be attributed to ...nder-ice bloom?



-2 million images of algal cells, chains, & colonies, from > 30 taxonomic classes by Imaging FlowCytobot (IFCB)

-Abundance of different species spanned >5 logs

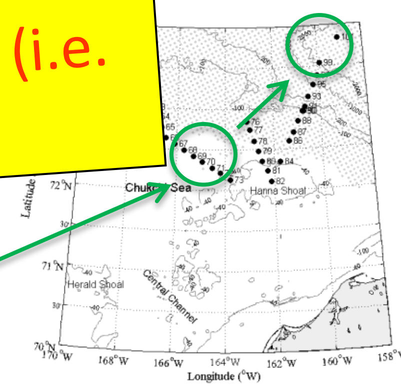
-greatest number of identifiable taxa in the under-ice bloom

-Cell POC is typically ~½ of bottle POC (i.e. on average, ~50% of POC is detritus)

...in the

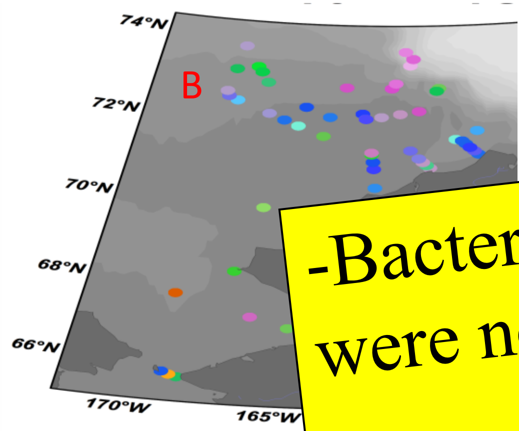
classes (~19-20)

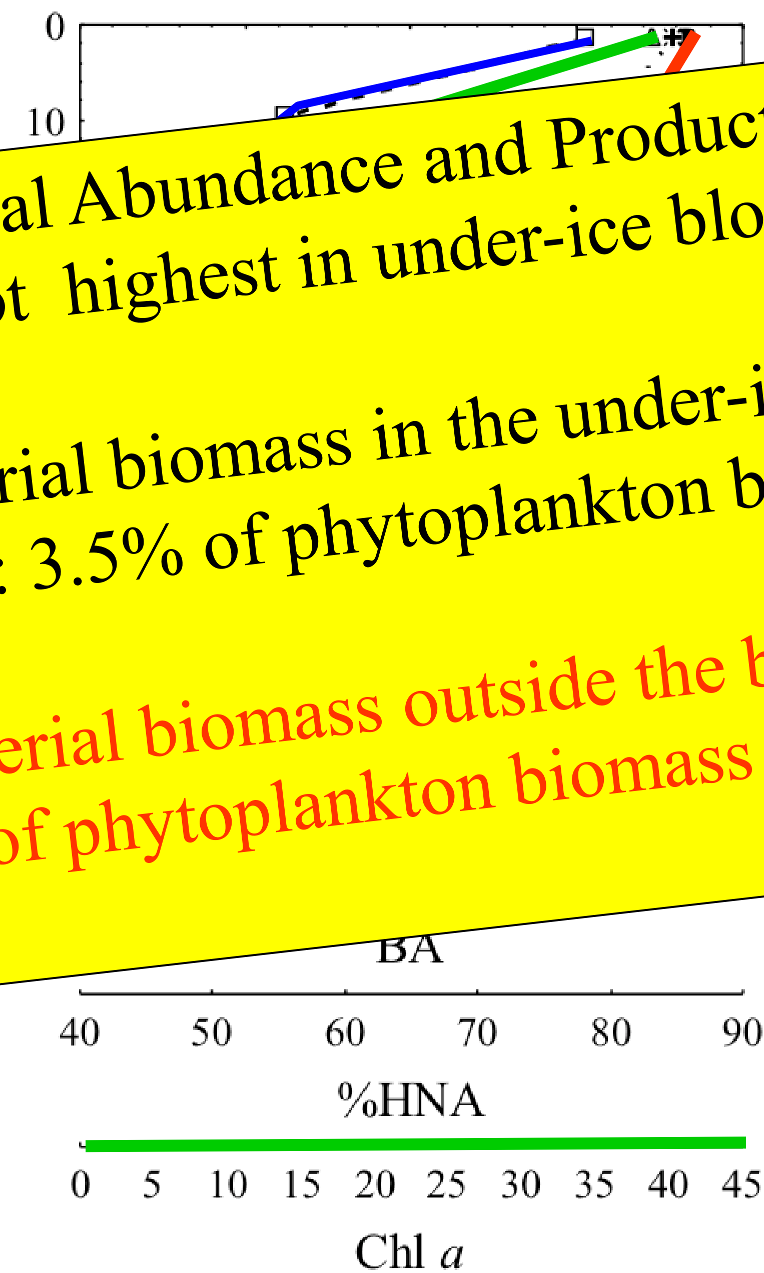
Fewest identifiable classes (~6-8)



Laney & Sosik 2014

Icescape 2011. Phytoplankton-bacteria coupling in the under-ice





-Bacterial Abundance and Production were not highest in under-ice bloom

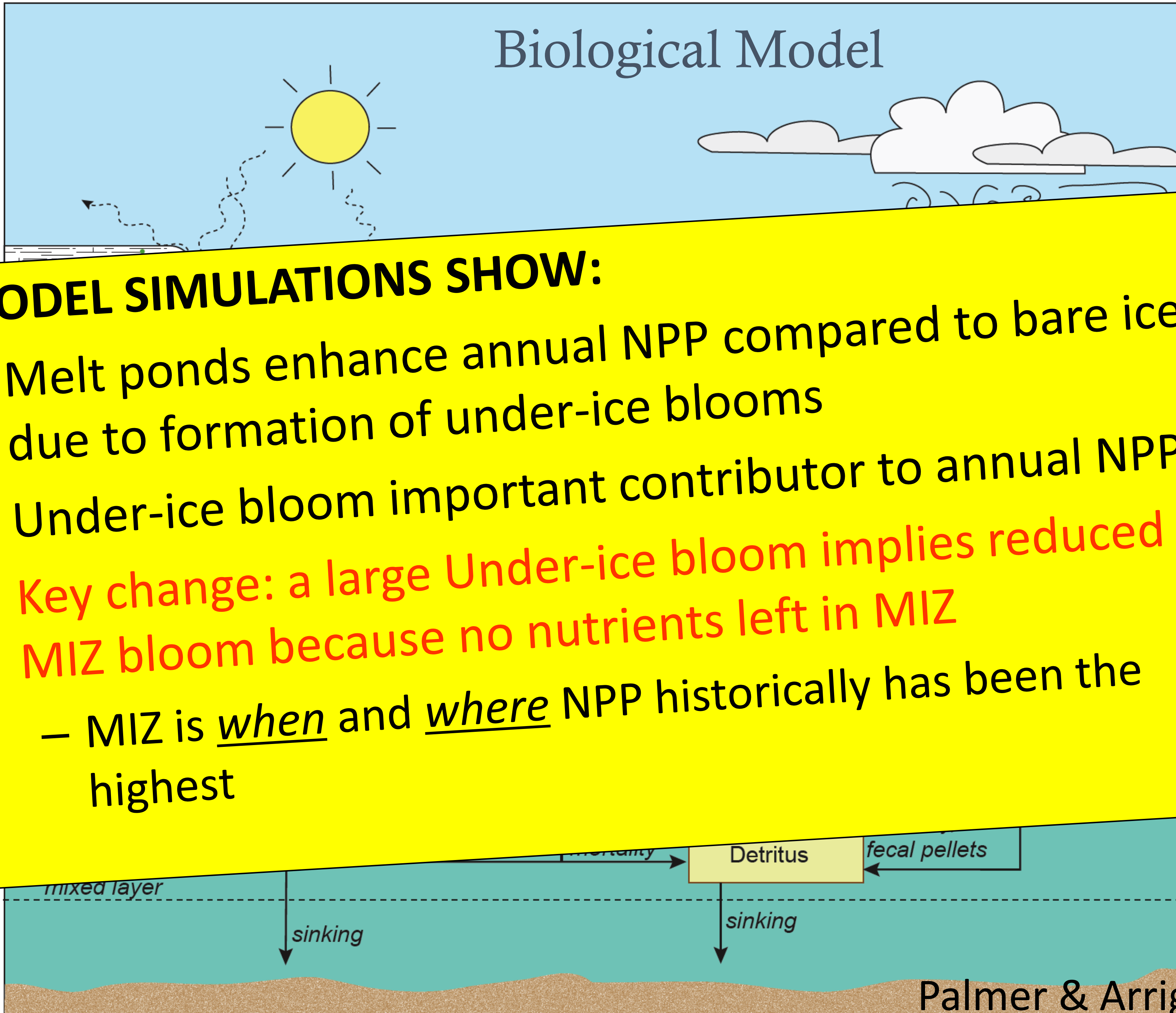
▪Bacterial biomass in the under-ice bloom: 3.5% of phytoplankton biomass

▪Bacterial biomass outside the bloom: 11% of phytoplankton biomass

Ortega-Retuerta et. al. 2014 DSRII

Modeling

Biological Model



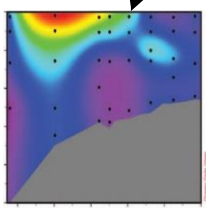
MODEL SIMULATIONS SHOW:

- Melt ponds enhance annual NPP compared to bare ice due to formation of under-ice blooms
- Under-ice bloom important contributor to annual NPP
- Key change: a large Under-ice bloom implies reduced MIZ bloom because no nutrients left in MIZ
  - MIZ is *when* and *where* NPP historically has been the highest

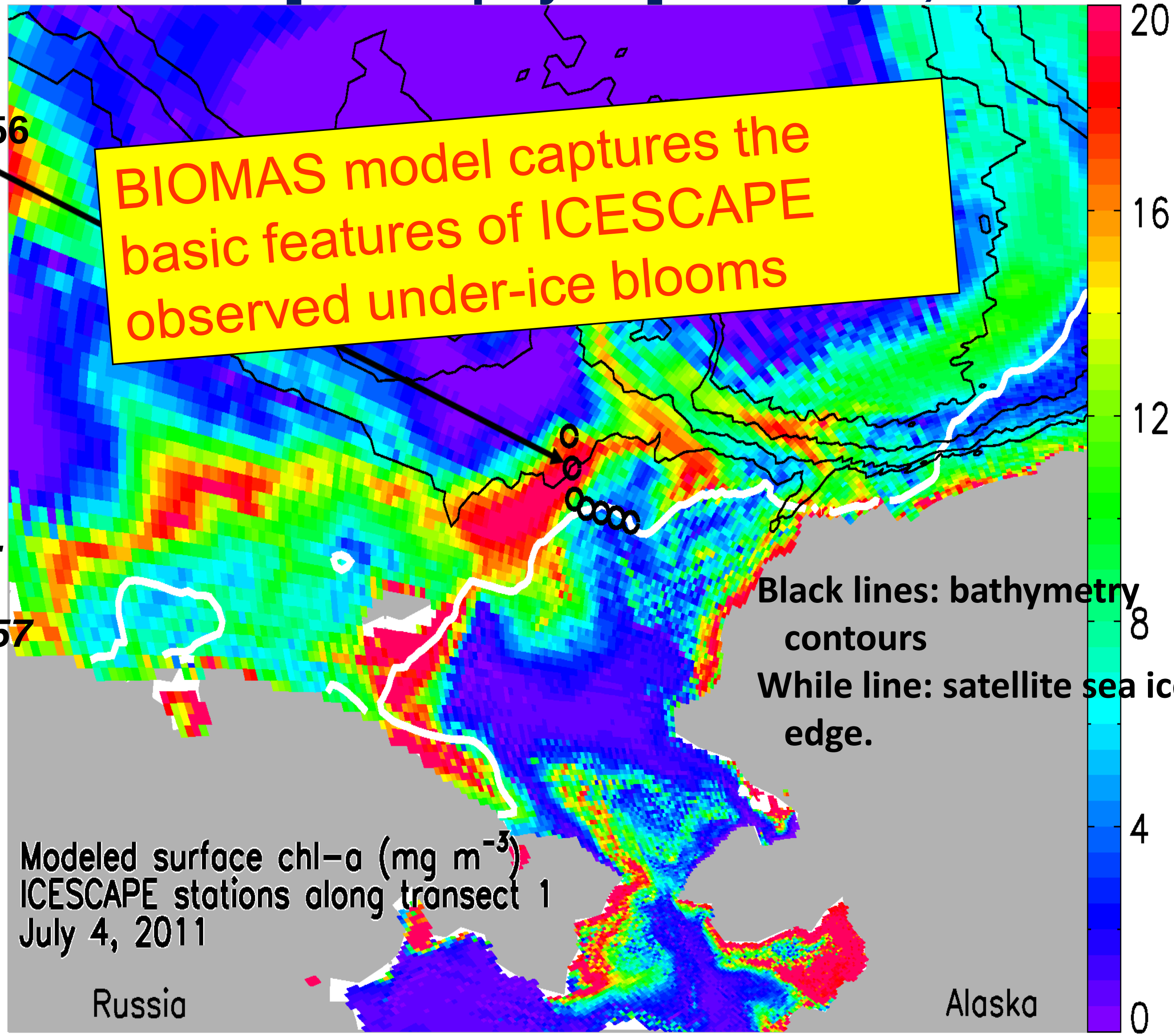
Palmer & Arrigo

BIOMAS surface [chlorophyll-*a*] on July 4, 2011

Station 56

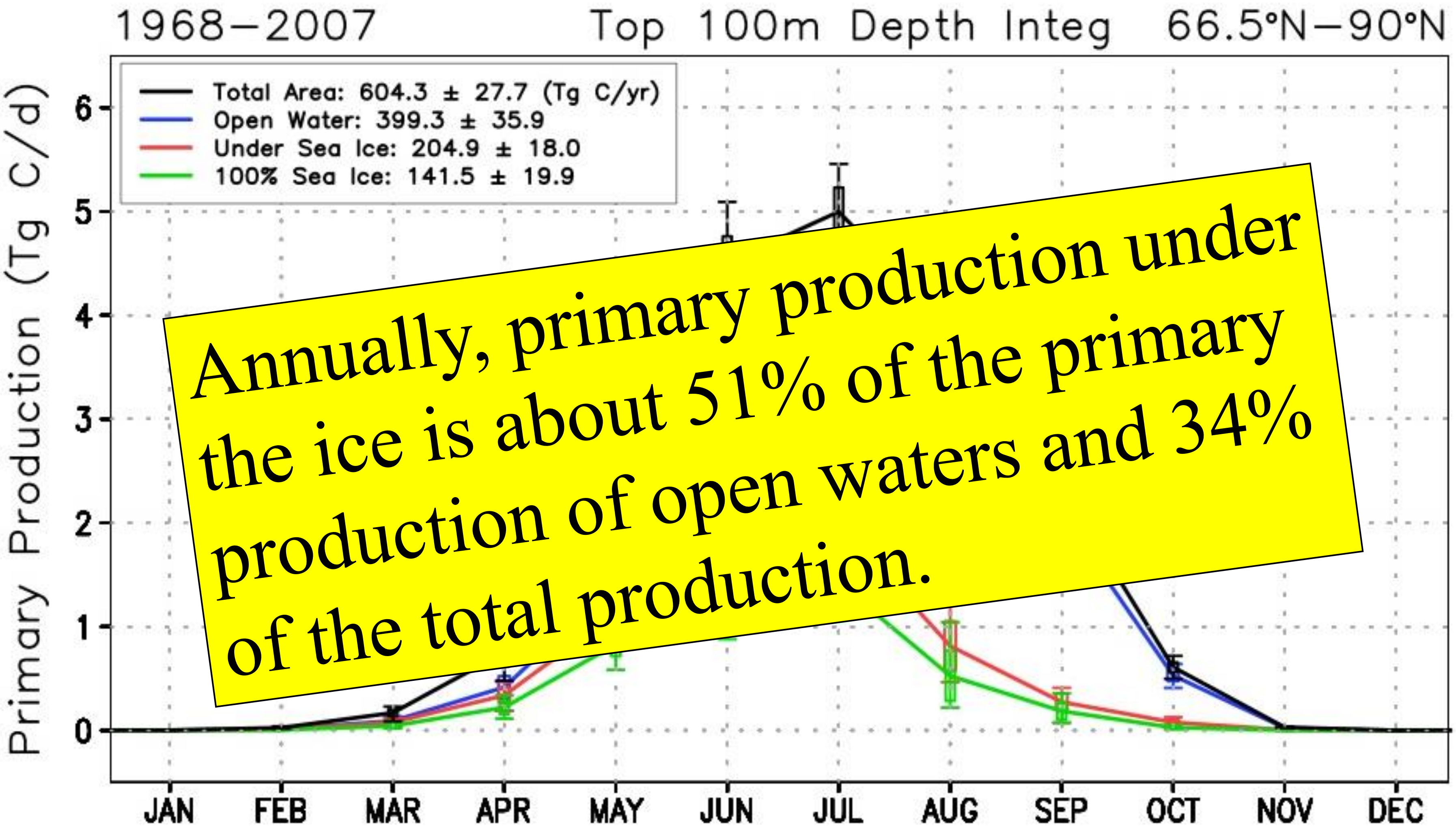


From Arrigo et al. 2012; transect 1 with stations 46-57



Jinlun Zhang, APL, Univ. Washington

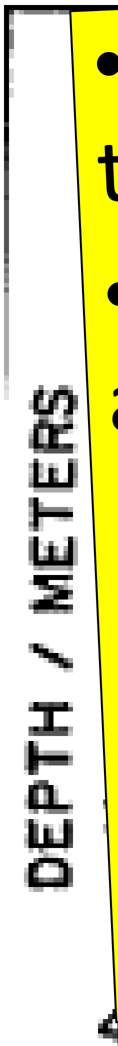
Modeled Primary production under ice in the Arctic
(*ORCA2/LIM2/PISCES configuration of the NEMO GCM***)**



Annually, primary production under the ice is about 51% of the primary production of open waters and 34% of the total production.

Frouin, SIO

Nitrate deficit- Apollonio, 1959



- Apollonio didn't see the chlorophyll that we did, nor the productivity
- However, the nitrate drawdown was a smoking gun to potentially high production
- He didn't have enough data to judge the legitimacy of such a wildly high production value!

2.86 g C m^{-2} d^{-1} with ^{14}C microdiffusion

So from "ICESKATE" to "ICESCAPE", science has come full circle…ICESCAPE unequivocally demonstrated presence of massive under-ice algal blooms only hinted at 57 years earlier!

Mar Biol
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ORIGINAL PAPER

New estimates of microalgae production based upon nitrate reductions under sea ice in Canadian shelf seas and the Canada Basin of the Arctic Ocean

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Thank you!
?

Summary-Main points

- **Physics**
- The pathways of winter water across the Chukchi shelf have been clarified
- Shelfbreak upwelling leads to significant primary production
- NSTM (Near Surface Temperature Maximum) is the “world’s newest water mass.”
- First ever Arctic ARGO bio-floats with ice avoidance algorithm, survive stratification and function under sea ice, 0-1000m, 20+ months!

Summary-Main points

- **Biogeochemistry/Chemistry**
- If 2011 ice sheets were to melt they would decrease overall Phosphorous concentrations in the Arctic mixed layer.
- ~50% of primary productivity is exported vertically
- ~58% of the Pacific-origin NO_3 in the Canada Basin was newly nitrified on the Chukchi shelf, rather than from the Bering Sea
- Values for oxygen isotopes in Arctic sea ice, interface waters, melt ponds and under-ice waters have been identified for first time.
- Ocean Acidification- At least 40% of the Chukchi Sea benthos is exposed to bottom waters that are corrosive to CaCO3 during summertime

Summary-Main points

- **Optics and Bio-optics**
- Light transmittance through ponded ice is 3-10 X greater than through bare ice and first-year ice has lower light extinction than multiyear ice (both for bare and ponded ice)
- Solar UV-induced photooxidation of CDOM (a_{p254}) ranged from ~48–62% whereas the percent loss in DOC was only ~0–8%.
- First measurements of particle size distribution for oceanic submicron particles in native state
- Arctic Shelf DOC budget now indicates largest sources of terrestrially-derived DOC to Arctic (presumably associated with melting tundra)
- Semi-analytical algorithm approaches remove biases in chlorophyll and IOPs

Summary-Main points

- **Biology**
- Chlorophyll biomass up to ~1300 mg Chl m^{-2} in under-ice bloom (higher than any depth-integrated biomass in NASA Sea BASS (n=12,048!)
- NPP 1.2-4.8 gC m^{-2} d^{-1}
- Phytoplankton growth rates of 0.83-1.44 d^{-1} (at -1.6^{o}C!!)
- Coccolithophore calcification, <1% of photosynthesis and combined evidence shows unequivocal proof of coccolithophores in and under the Arctic ice cap
- Imaging Flow Cytobot and Flow Cytometry summed cell C is typically ~½ of bottle POC (i.e. on average, ~50% of POC is detritus)
- Bacterial biomass typically 11% of phytoplankton biomass, only 3.5% inside under-ice bloom

Summary-Main points

- **Modeling**
- Key change: a large Under-ice bloom = reduced marginal ice zone bloom because no nutrients left after such an under-ice bloom
- BIOMAS model captures the basic features of ICESCAPE observed under-ice blooms