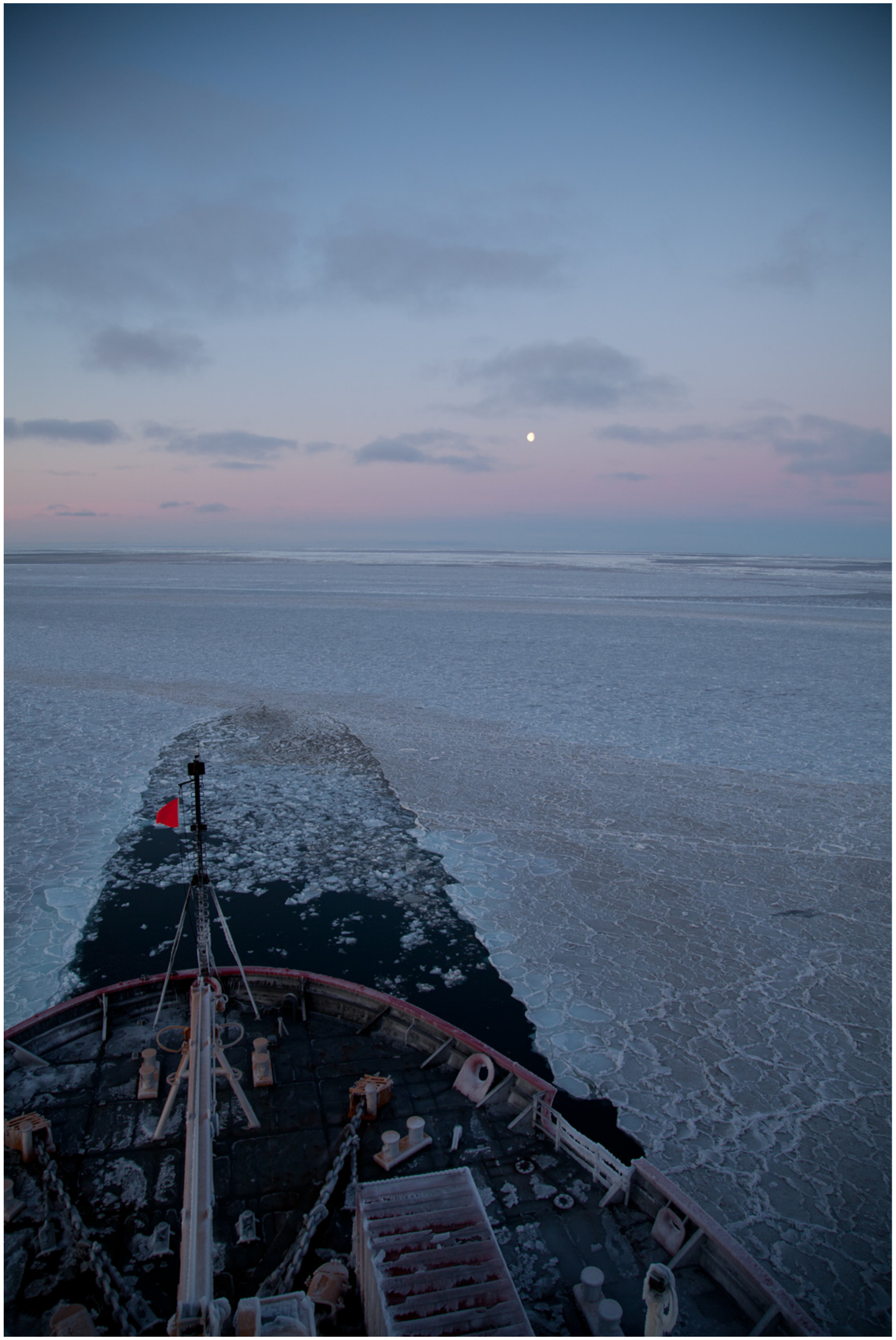


New observations from an Arctic Ocean in rapid transition

The Pacific Sector

ICESCAPE (2010 – 2011)

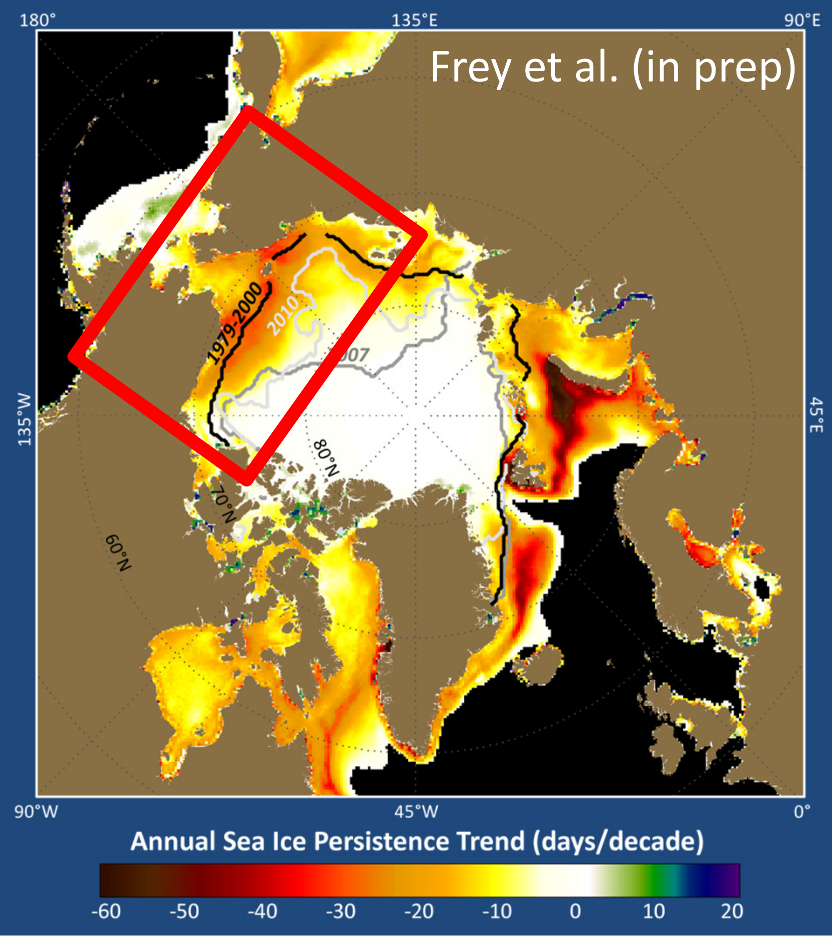
Western Arctic OA Study (2010 – 2011)

RUSALCA (2009 – 2011)

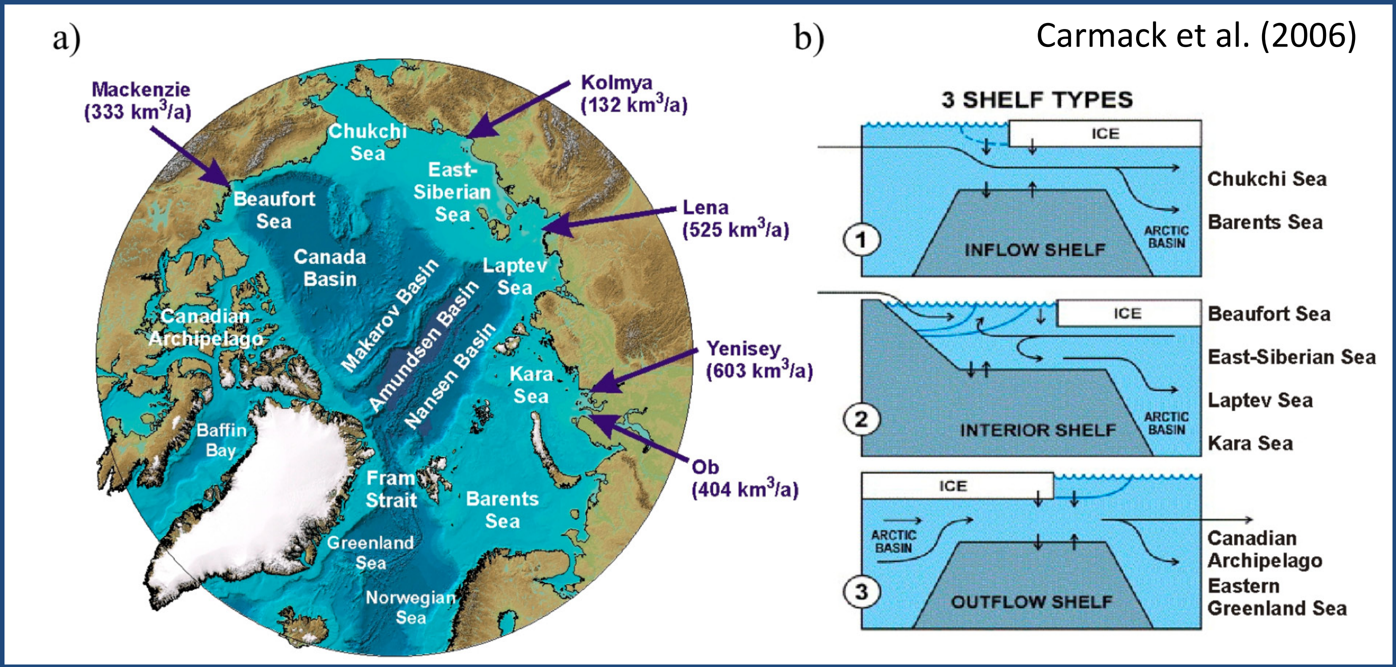
Kevin Arrigo
Donald Perovich
Bob Pickart
Zach Brown
Gert L. van Dijken
Kate Lowry
Matthew Mills
Molly Palmer
William Balch
Nick Bates
Claudia Benitez-Nelson
Karen Frey
Samuel Laney
Atsushi Matsuoka
B. Greg Mitchell
G. W. K. Moore
Bob Byrne
Craig McNeil
Laurie Juranek
Sherwood Liu
Jian Ma
Regina Easley
Jessica Cross
Stacey Reisdorph
Jim Morison
Trina Lichendorph
Dick Feely
Jackie Grebmeier
Sue Moore
Rick Reynolds
Heidi Sosik
Jim Swift

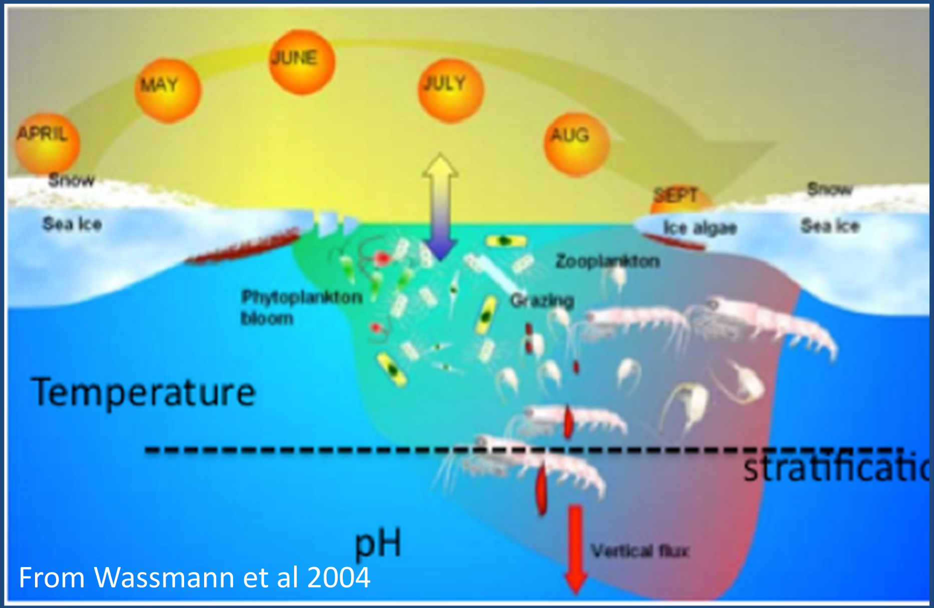
Outline

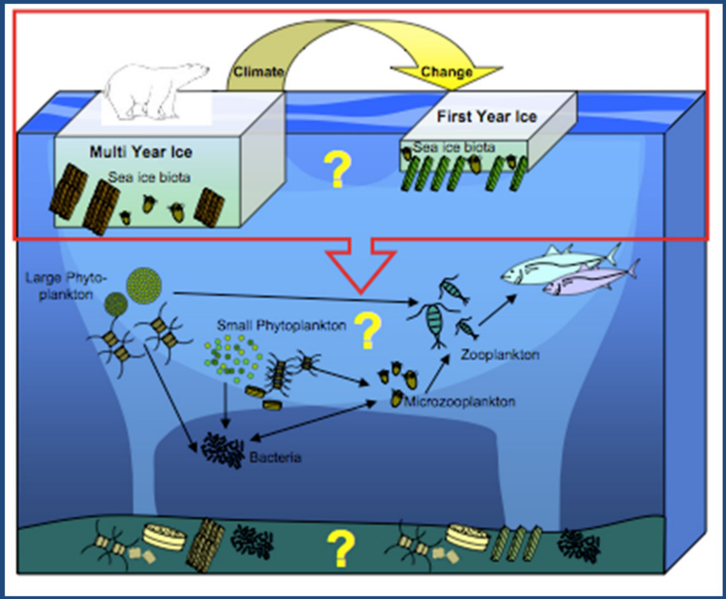
- Implications of Reduced Sea Ice
- A Massive Under Ice Bloom
- Reduced Ω and OA
- Wind Induced Coastal Upwelling



Introduction to the Western Arctic Region

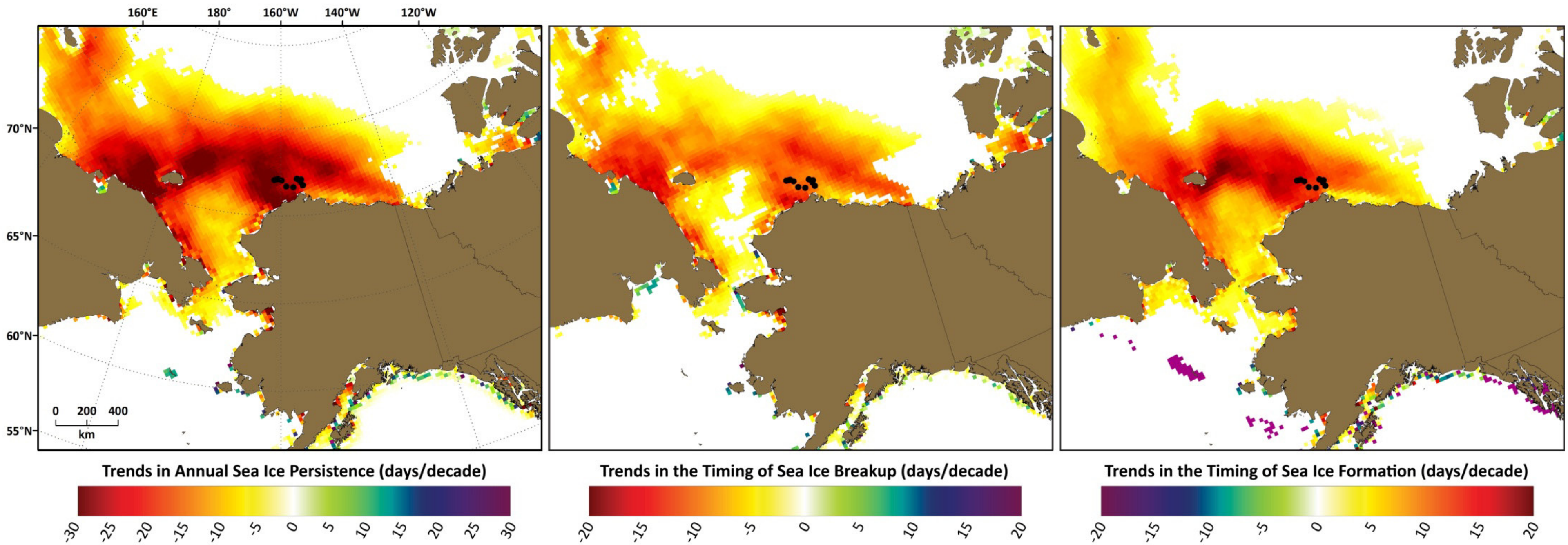






Trends in Sea Ice Cover

Trends in Annual Persistence	***Trends in Sea Ice Breakup***	***Trends in Sea Ice Formation***

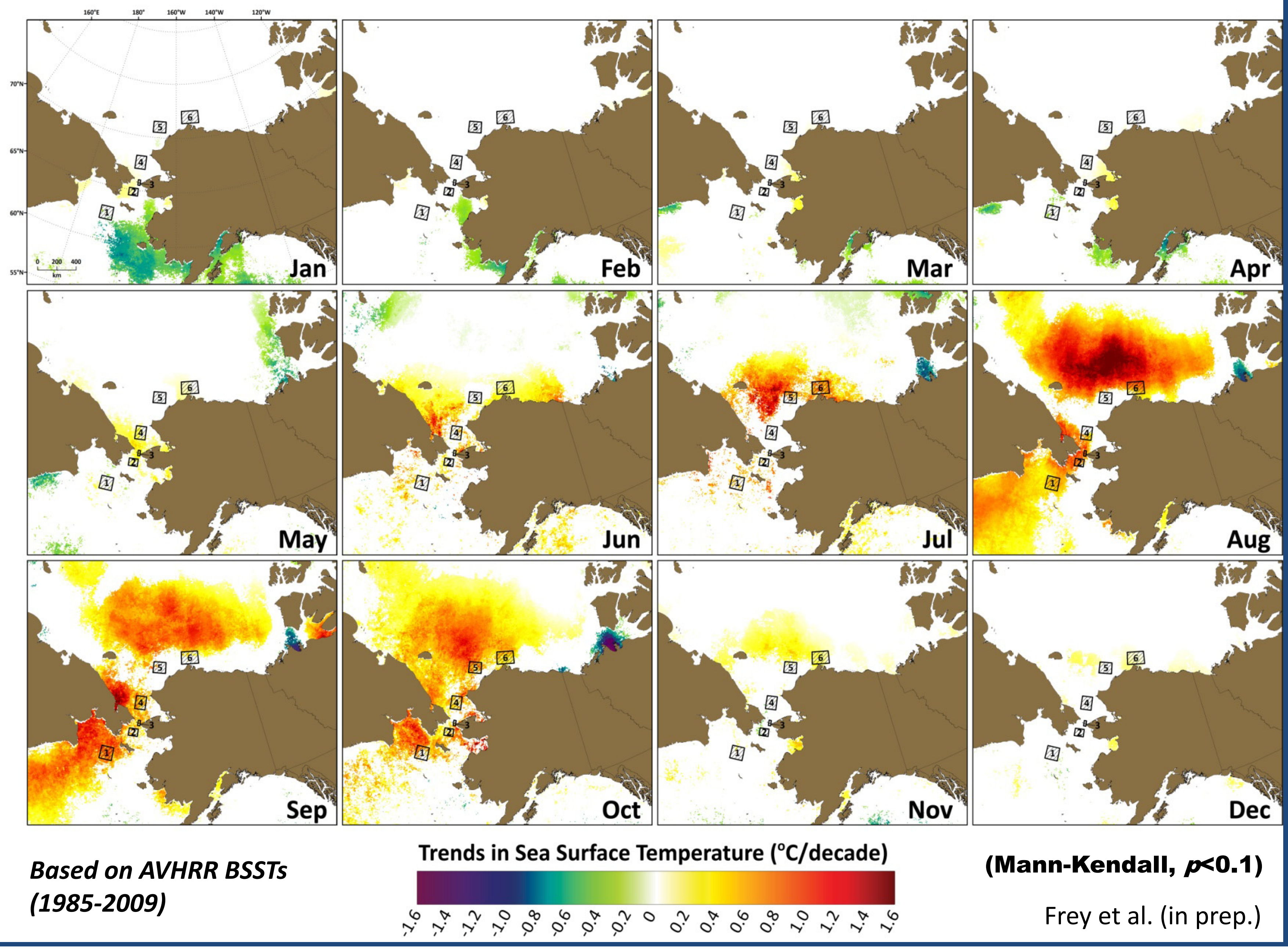


Annual Sea Ice Persistence	**Timing of Sea Ice Breakup**	**Timing of Sea Ice Formation**
-27.3 days/decade	**-10.9 days/decade**	**+14.2 days/decade**

Only those trends that are statistically significant at $p<0.10$ are mapped above
Based on SMMR and SSM/I Satellite-Derived Sea Ice Concentrations (1979-2008)

Frey et al. (in prep)

Trends in Sea Surface Temperatures

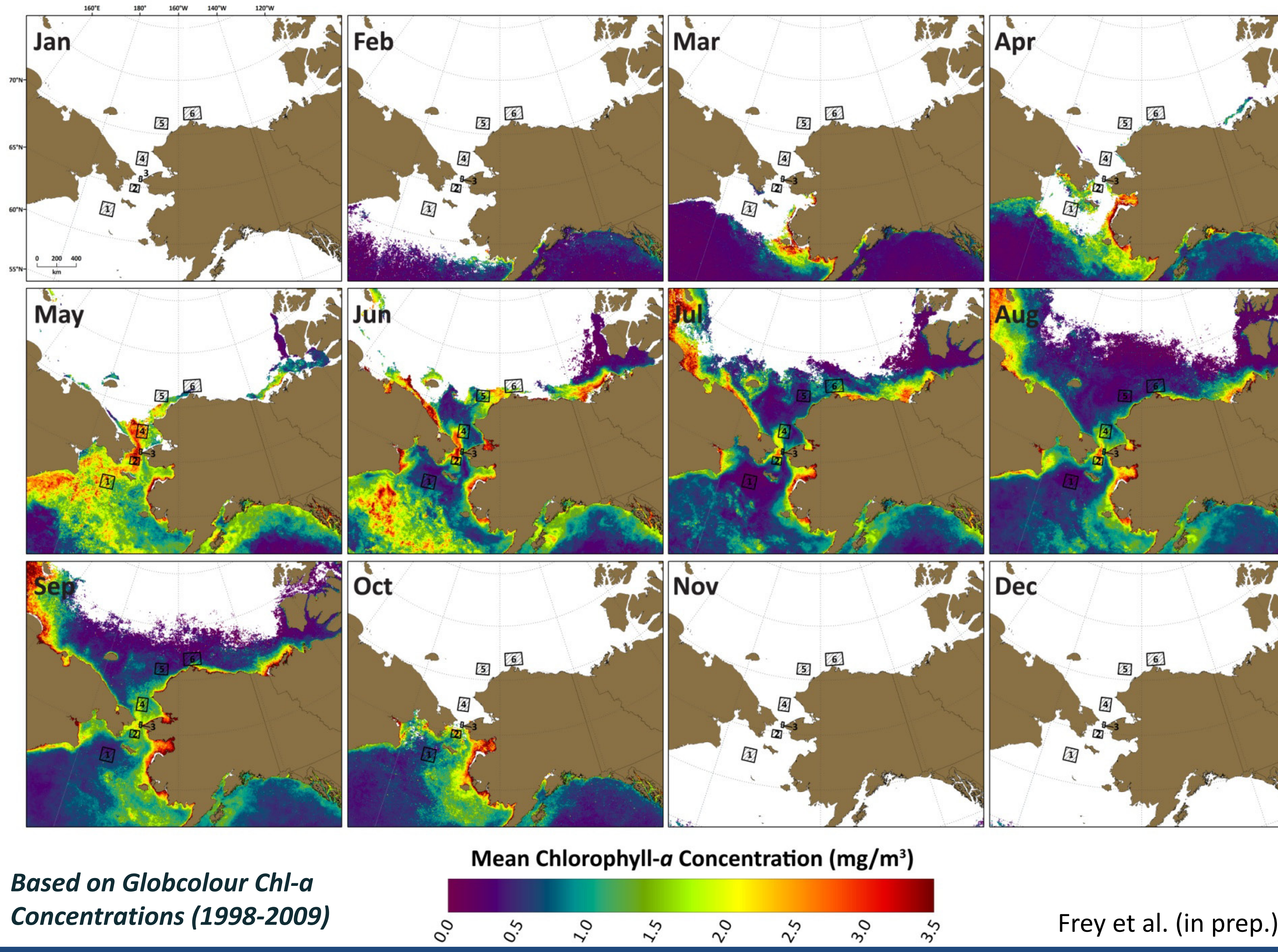


Based on AVHRR BSSTs (1985-2009)

(Mann-Kendall, *p*<0.1)

Frey et al. (in prep.)

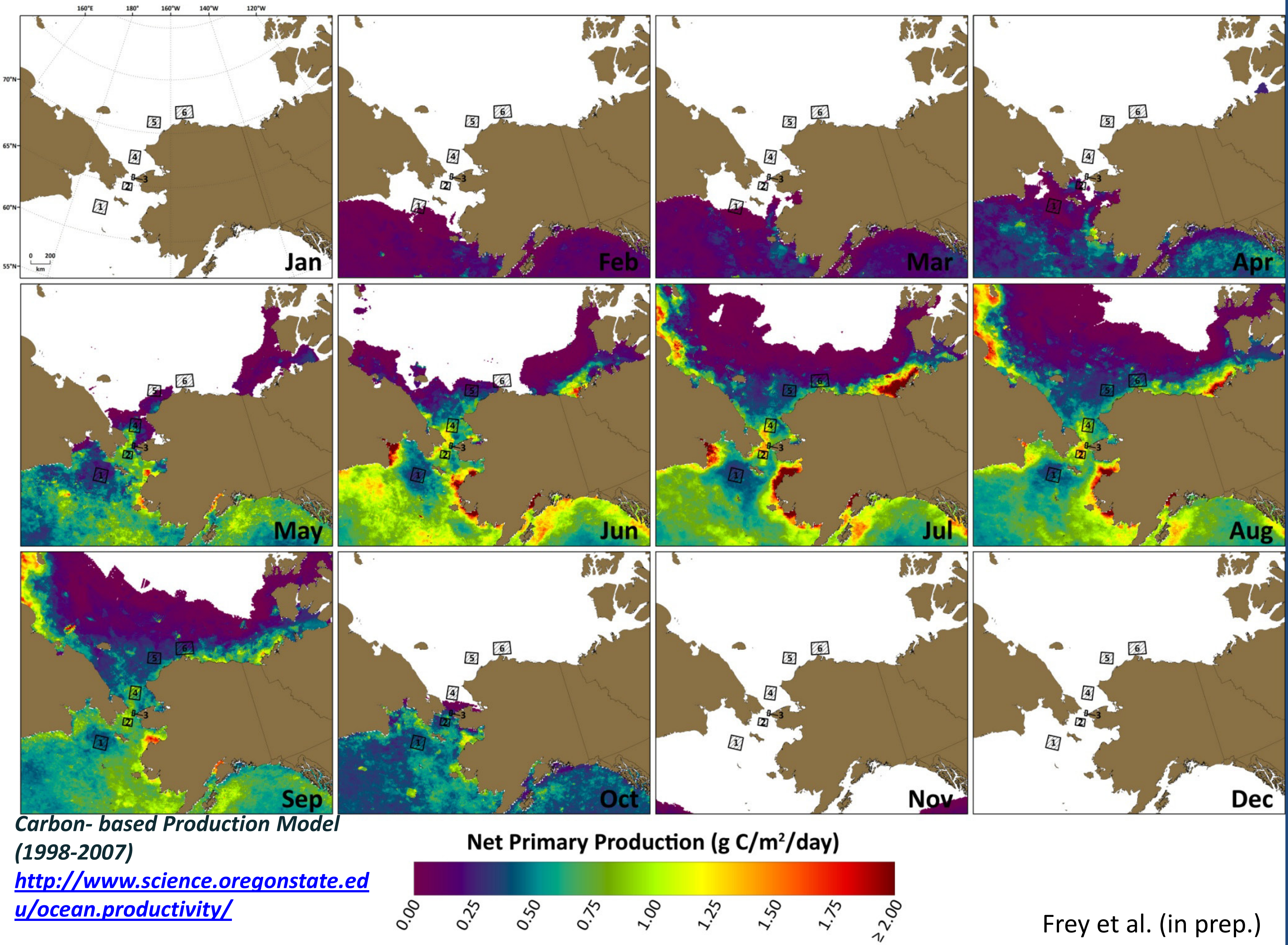
Mean Chlorophyll-*a* Concentrations



Based on Globcolour Chl-a Concentrations (1998-2009)

Frey et al. (in prep.)

Mean Net Primary Production Rates

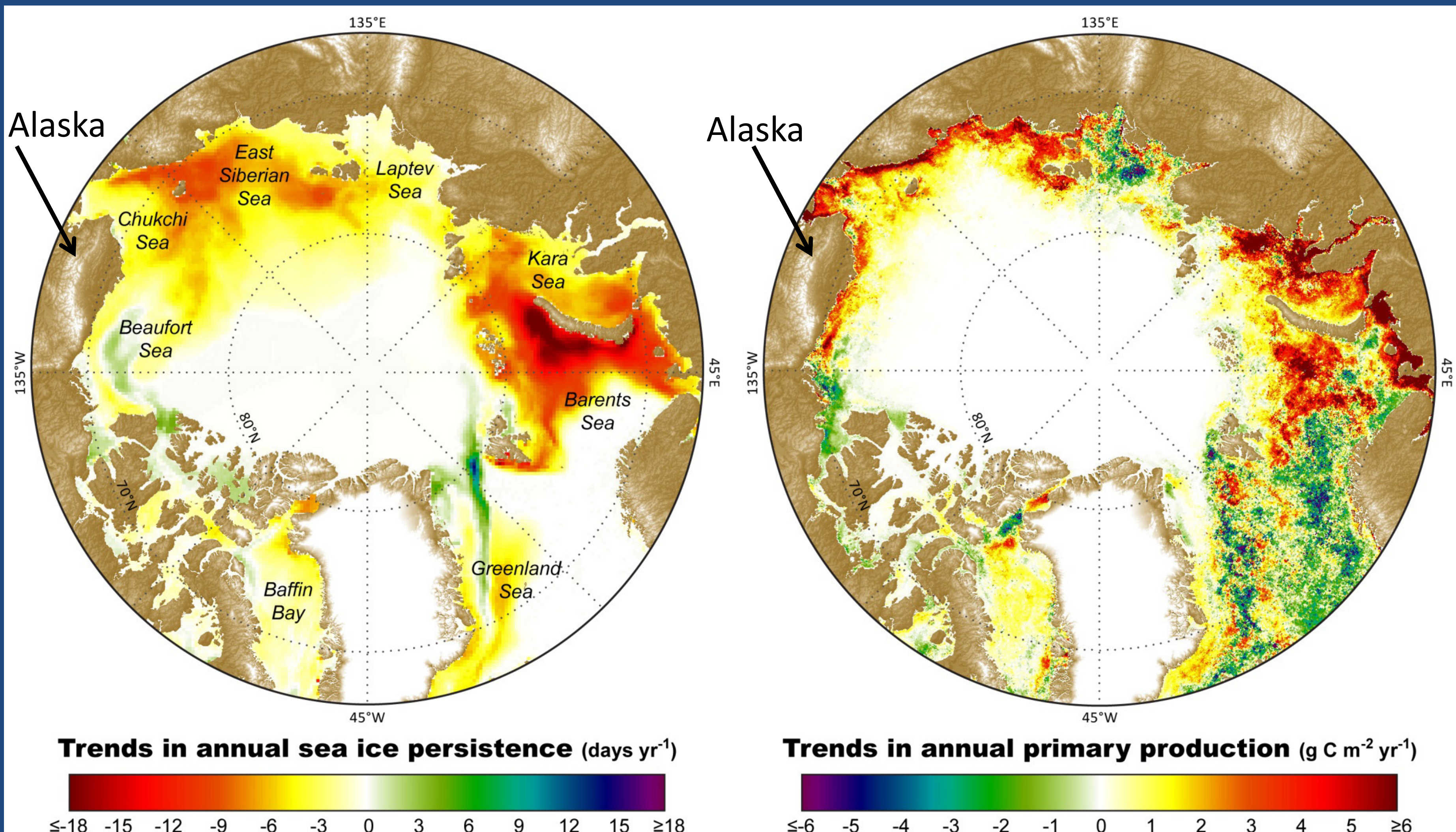


Carbon- based Production Model (1998-2007)
[***http://www.science.oregonstate.edu/ocean.productivity/***](http://www.science.oregonstate.edu/ocean.productivity/)

Frey et al. (in prep.)

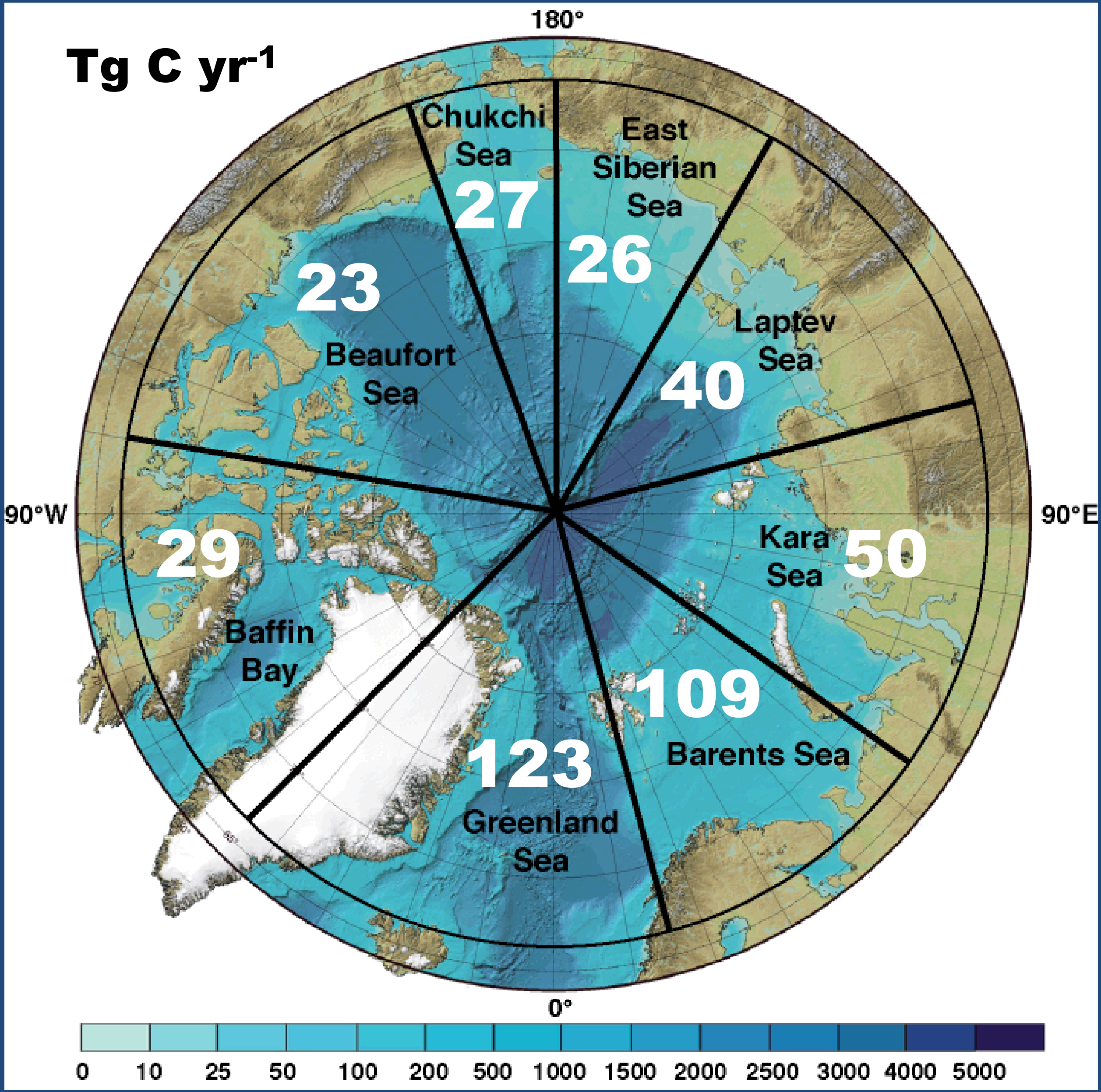
Recent Trends in Annual Sea Ice Persistence

Annual Primary Production (1998–2009)



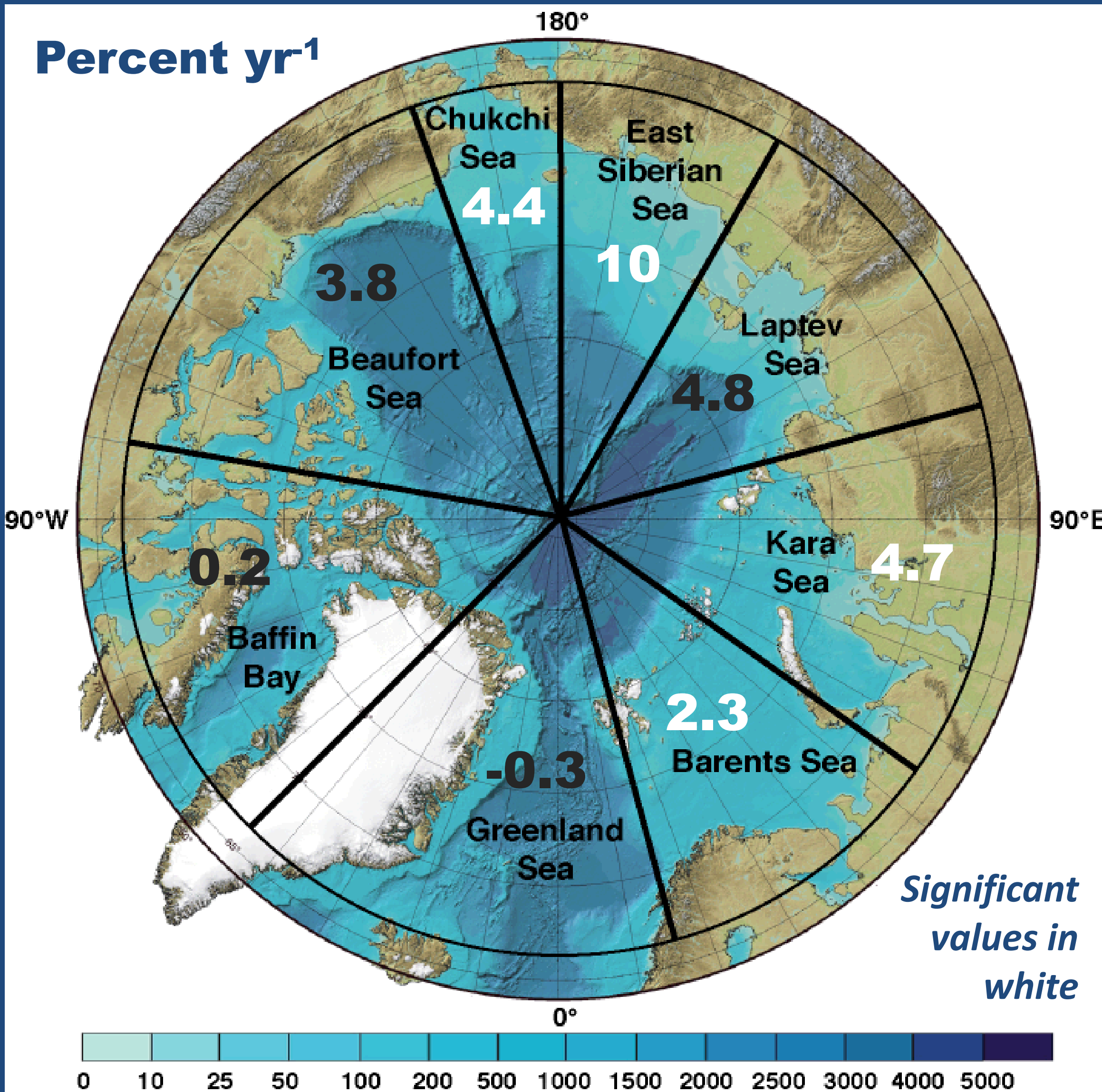
Frey et al. (2011), Arctic Report Card

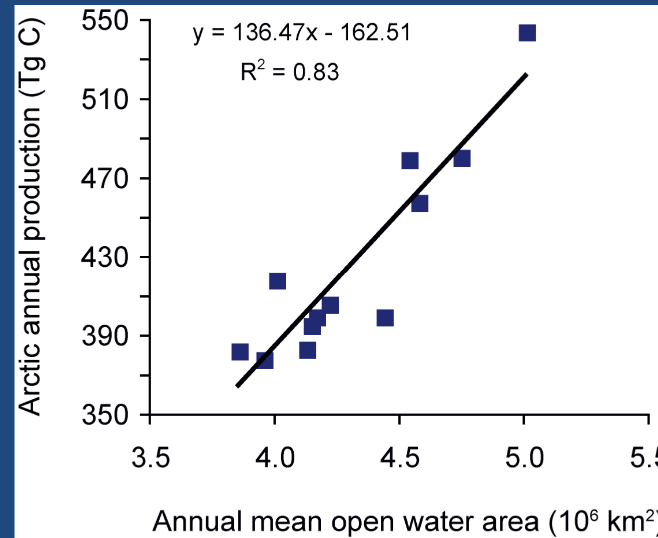
Annual Primary Productivity (1998–2009)

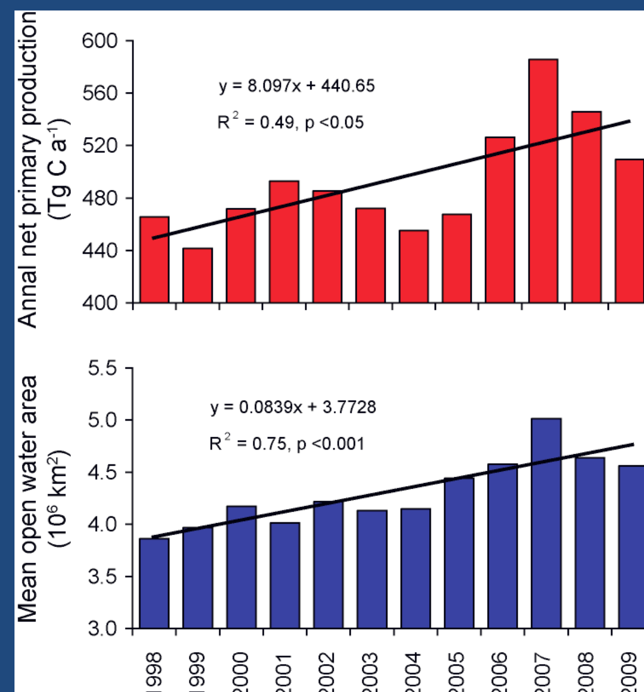


Arrigo and van Dijken (2011)

Changes in Annual Primary Productivity (1998–2009)



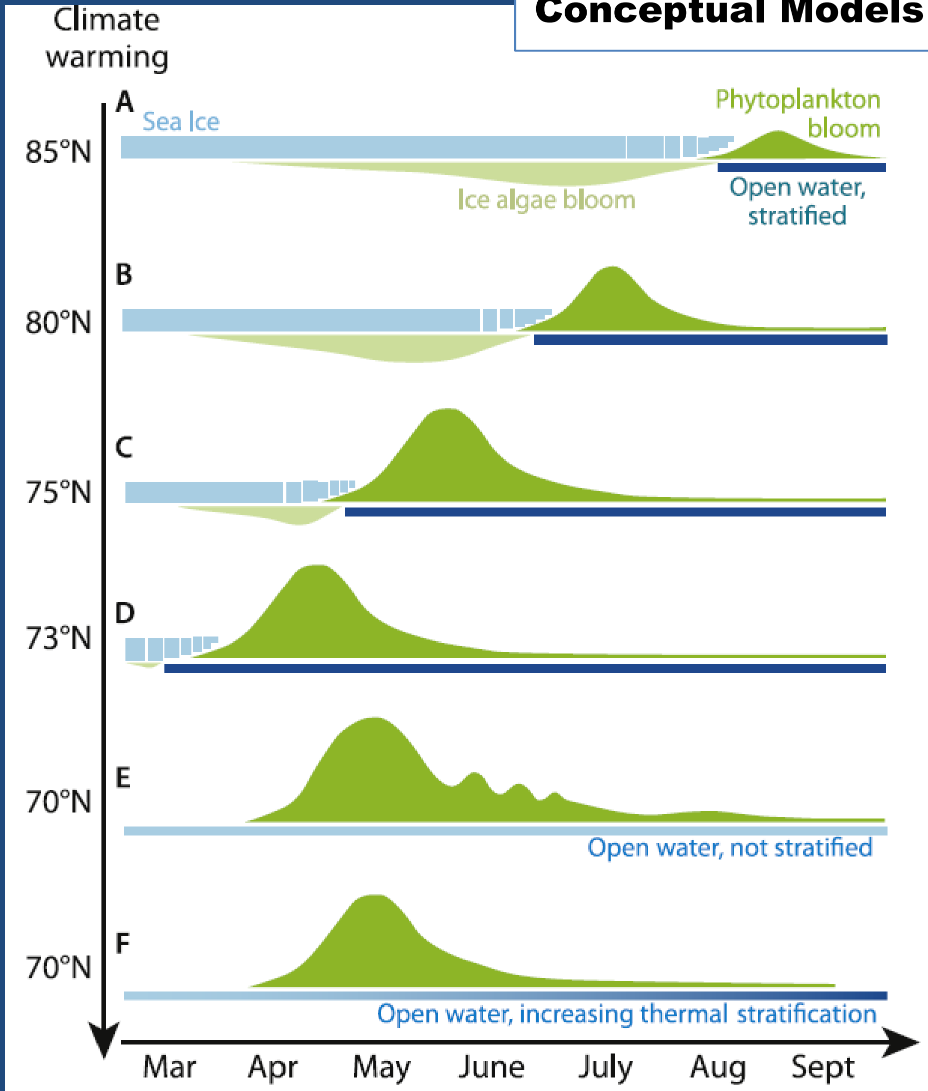




Arrigo and van Dijken (2011)

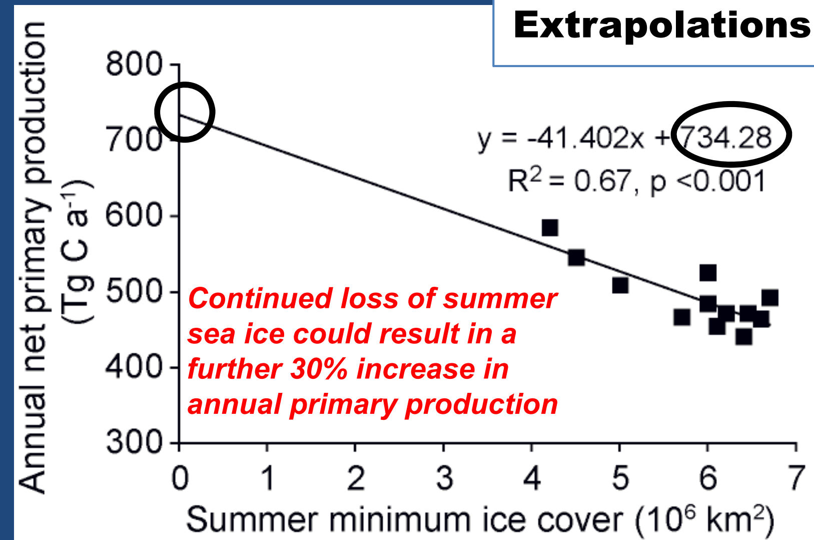
Future Predictions of Change

Conceptual Models

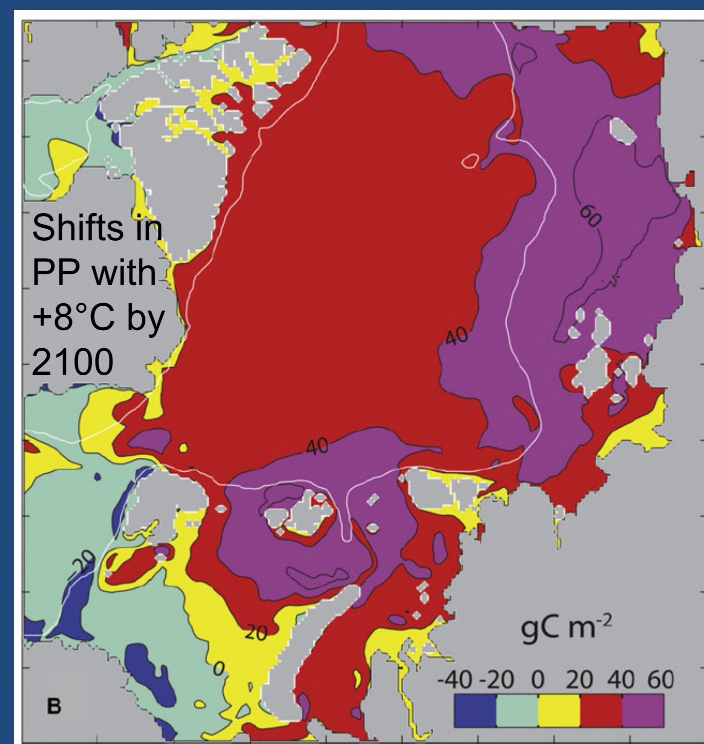


Wassman (2011)

Extrapolations

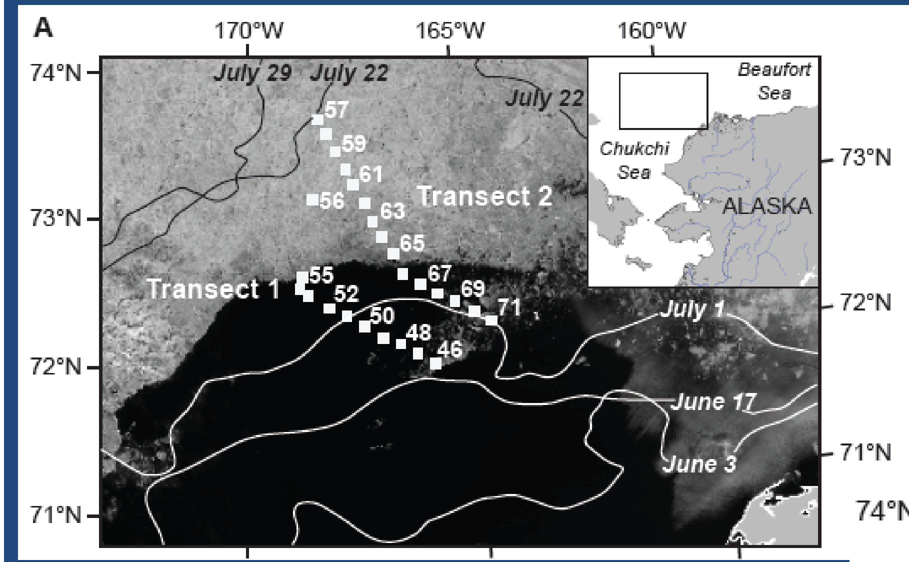


Arrigo and van Dijken (2011)



Slagstad et al. (2011)

A Game Changer in Chukchi Sea?

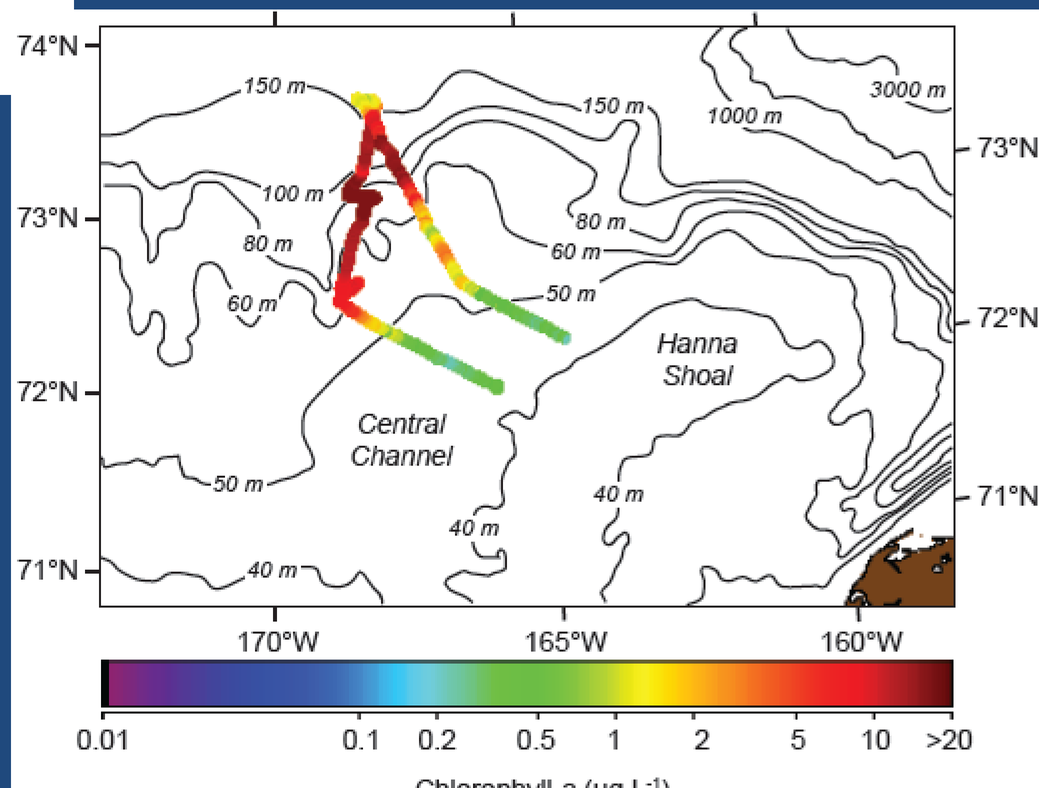


NASA ICESCAPE (2011)

- USCGC *Healy* from 25 June to 29 July
  - 188 CTD casts at 173 stations

- Very high concentrations of Chl-*a* were observed under the ice and were not associated with sea ice production.

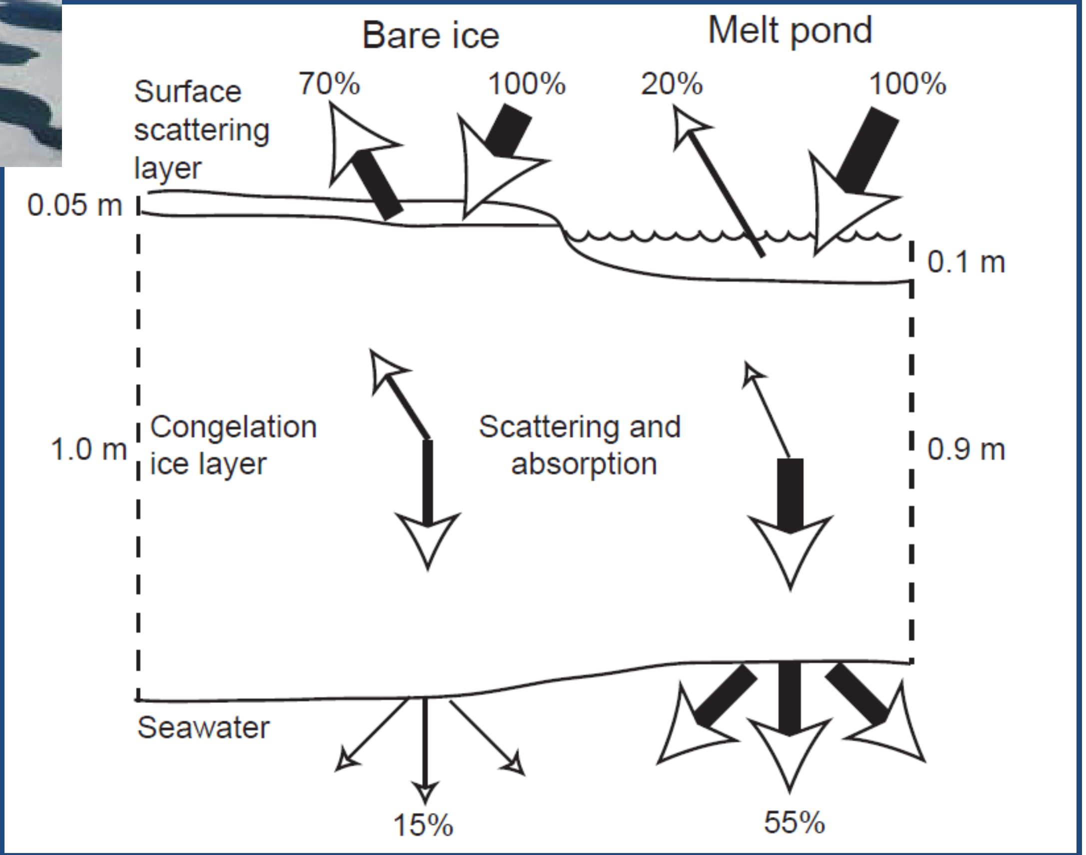
- How is this possible?



Arrigo et al., 2012

A Game Changer in Chukchi Sea?

Ice was thick but melt pond fraction was high (~50%)

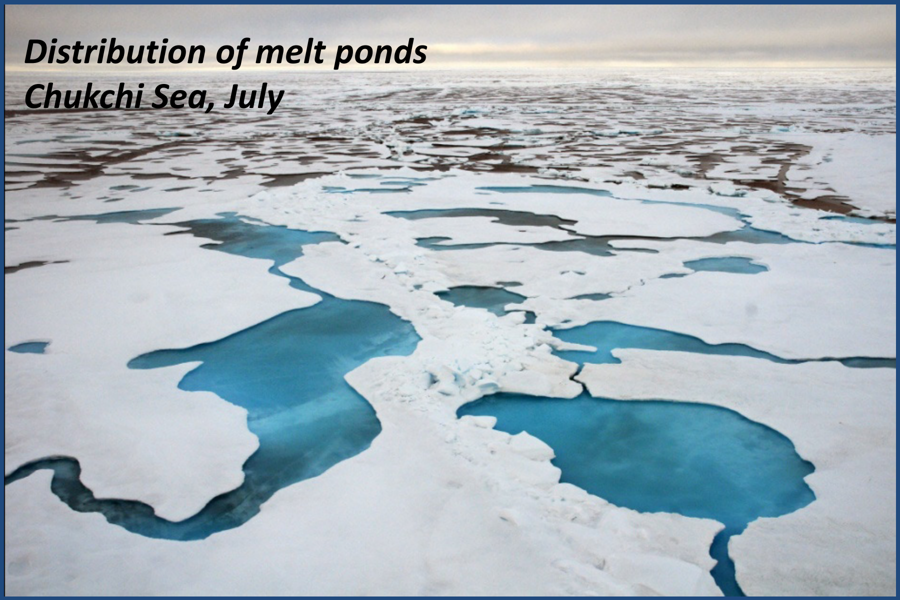


Melt ponds transmit >50% of incident surface irradiance

~4 times more than bare ice

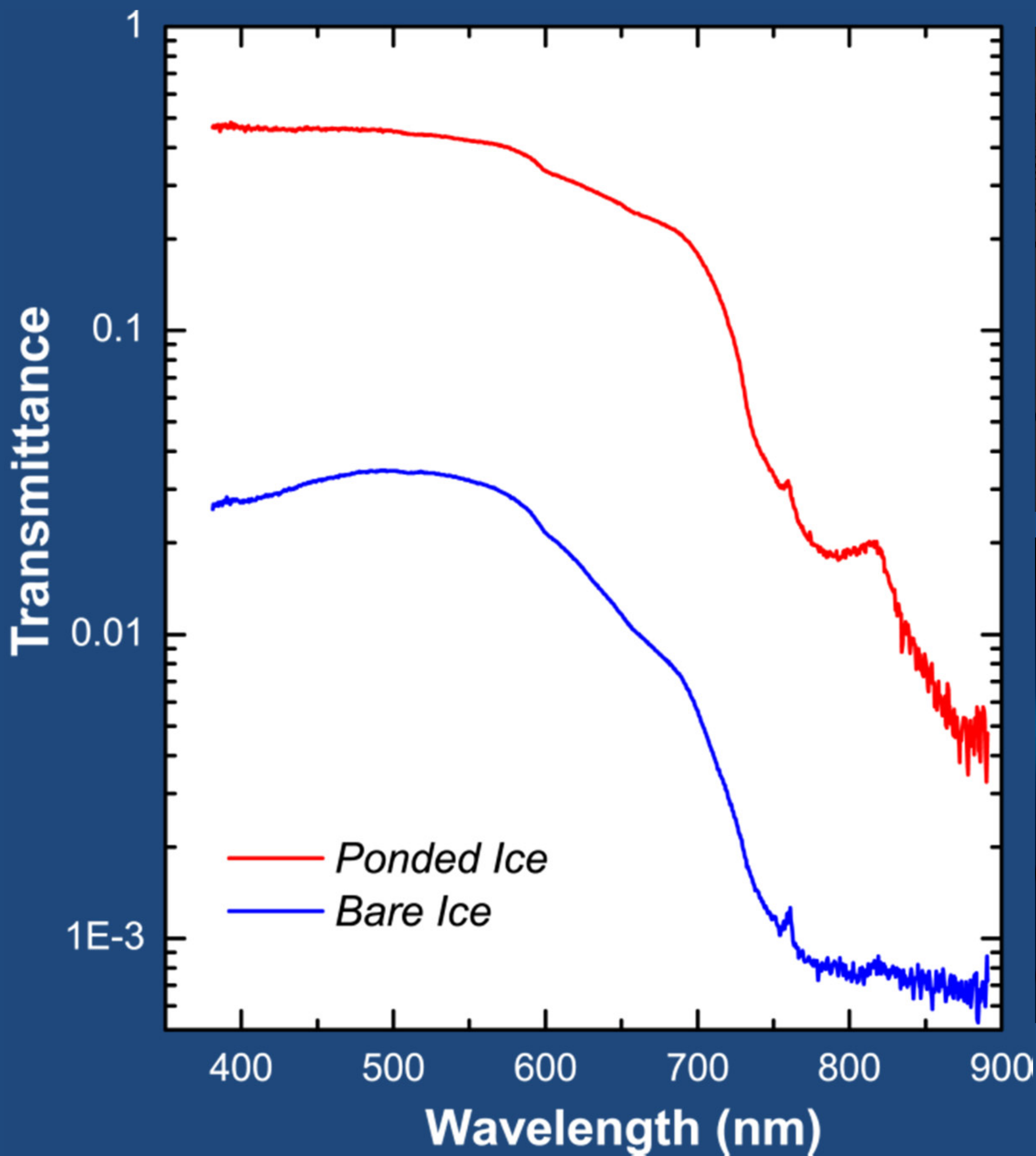
Arrigo et al., 2012

Melt-Season Sea Ice in the Chukchi Sea



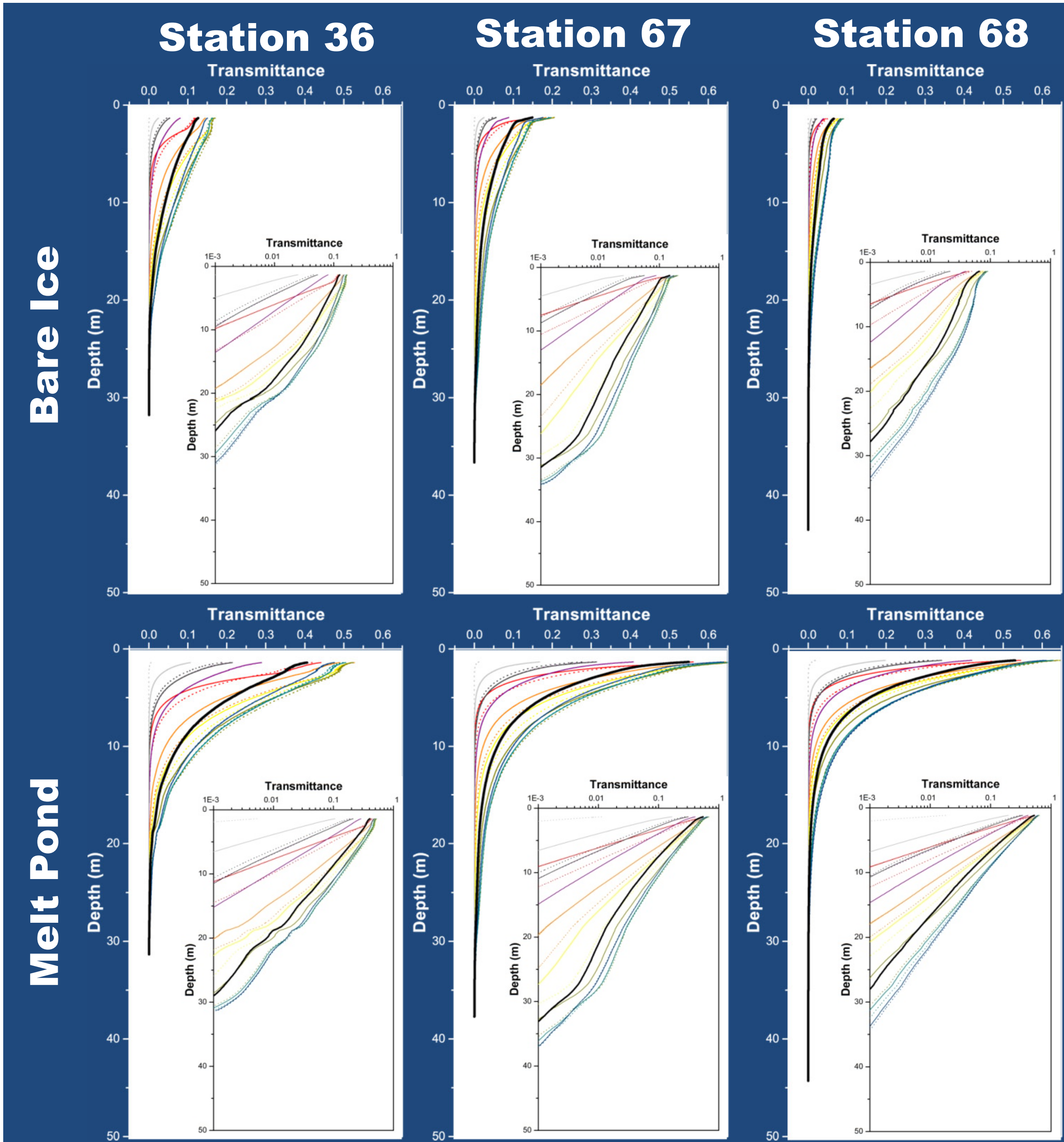
Frey et al. (2011),
Geophysical Research Letters

Light Transmittance Directly Beneath The Ice



Frey et al. (2011),
Geophysical Research Letters

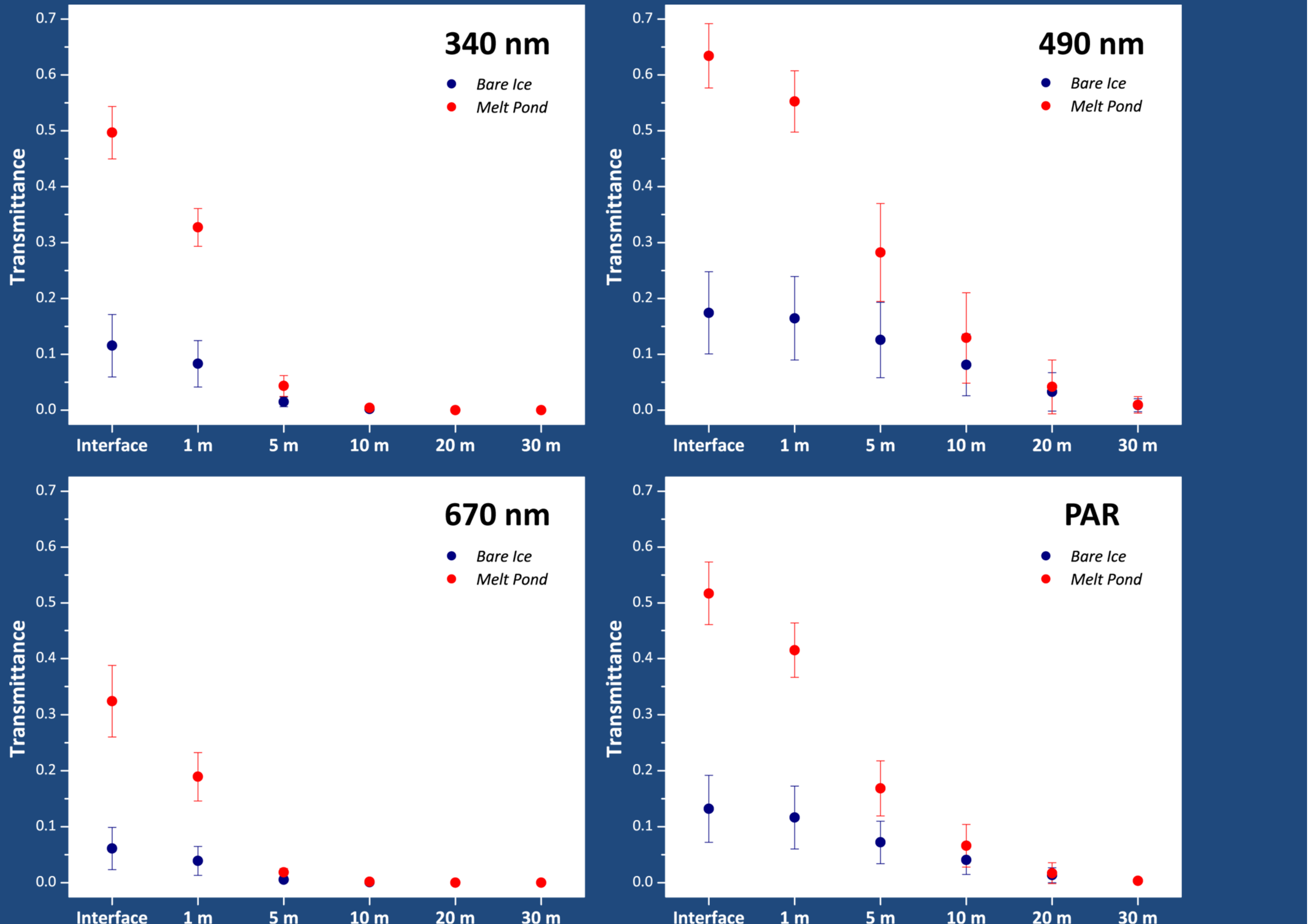
Under-Ice Optical Profiles



320 340 380 395 412 443
465 490 510 532 555 560
625 665 670 683 710 780
PAR

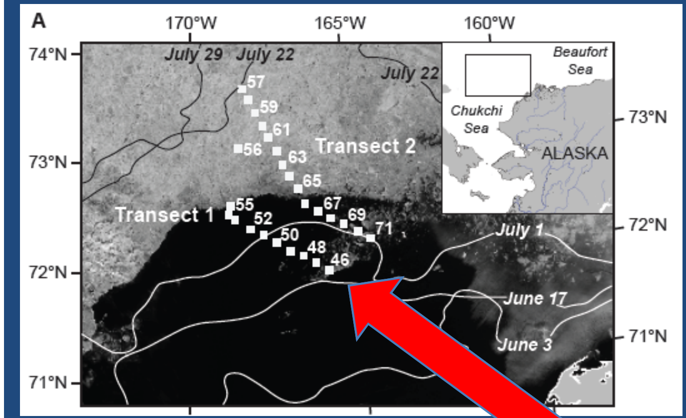
Frey et al. (in prep)

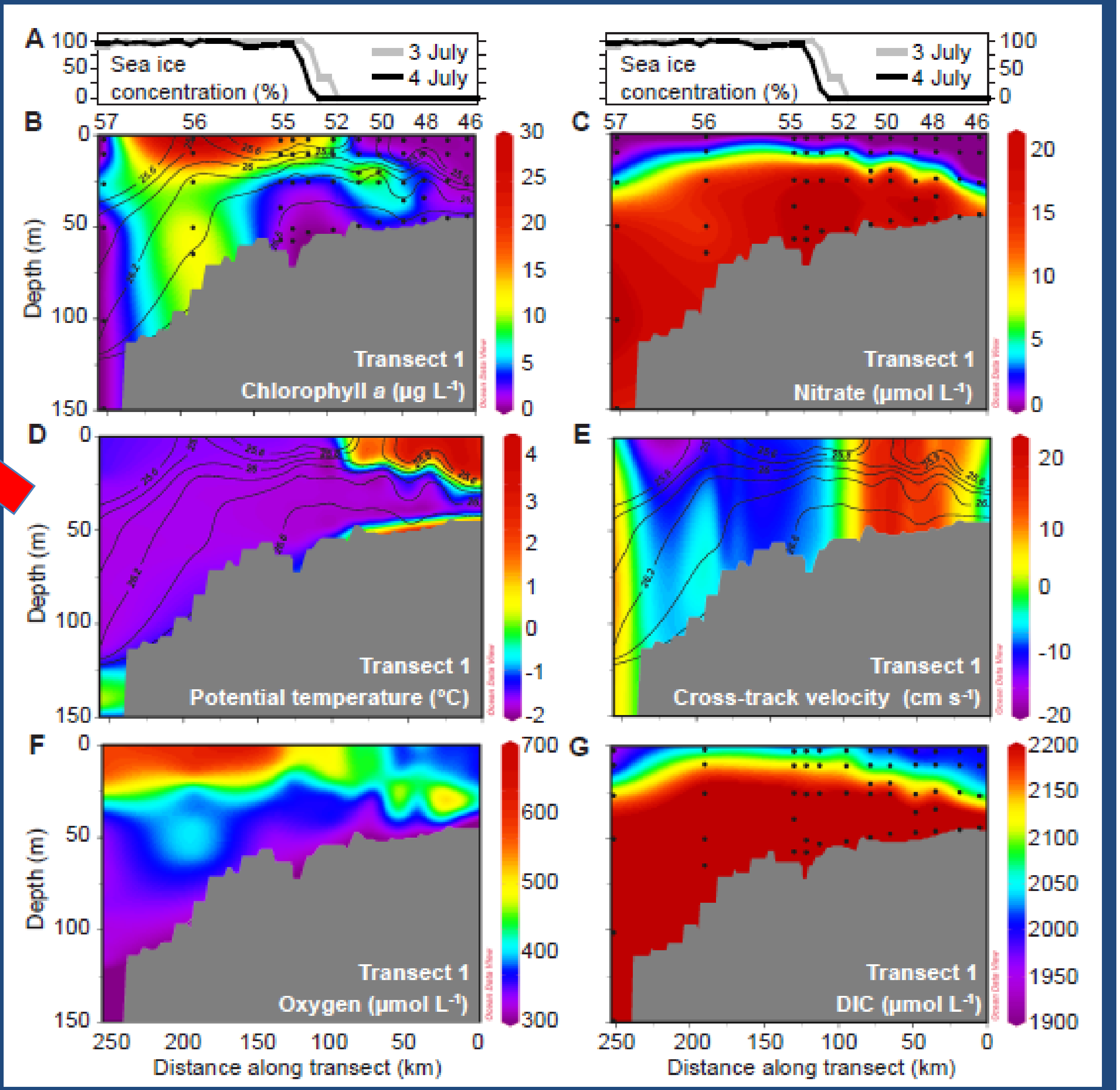
Convergence of Light at Depth



Frey et al. (in prep)

An Under-Ice Phytoplankton Bloom



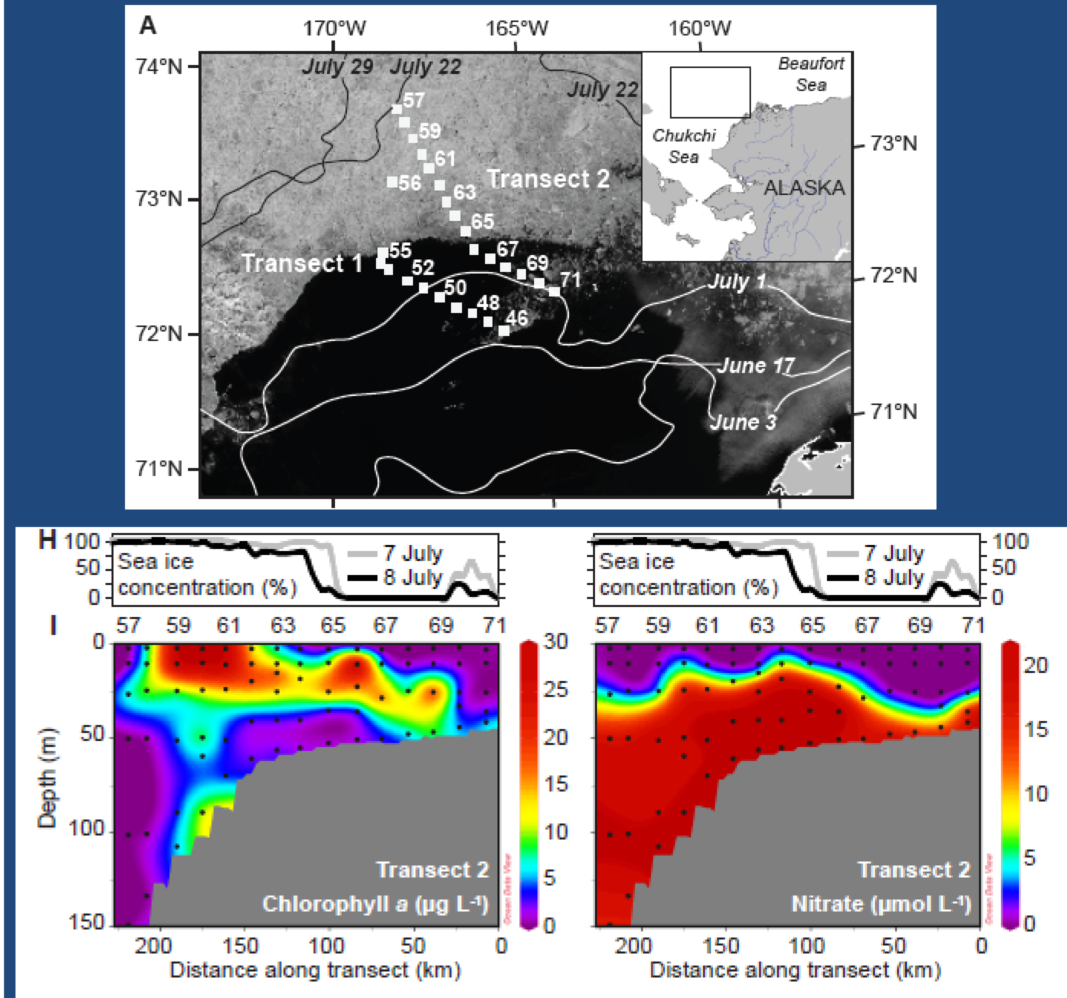


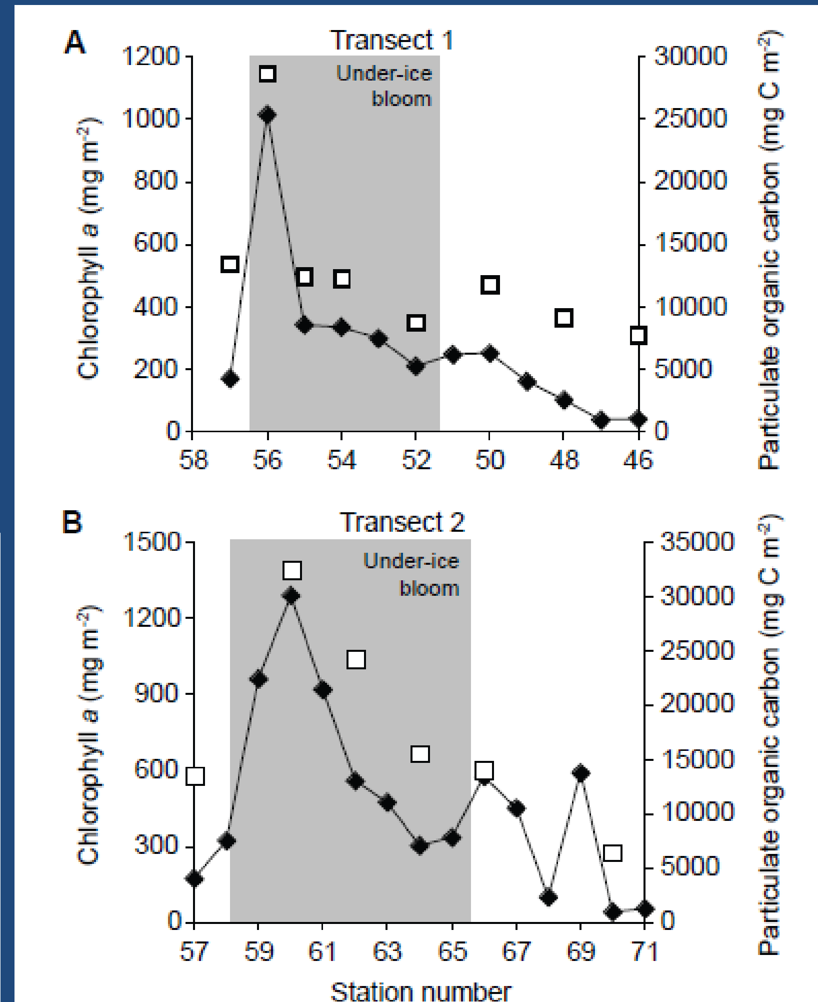
Ice-Edge Bloom

- Chl-*a* >25 μg L^{-1}
- Nitrate/DIC depleted
- DO >600 μmol L^{-1}
- Temp. <-1°C

Arrigo et al., 2012

An Under-Ice Phytoplankton Bloom

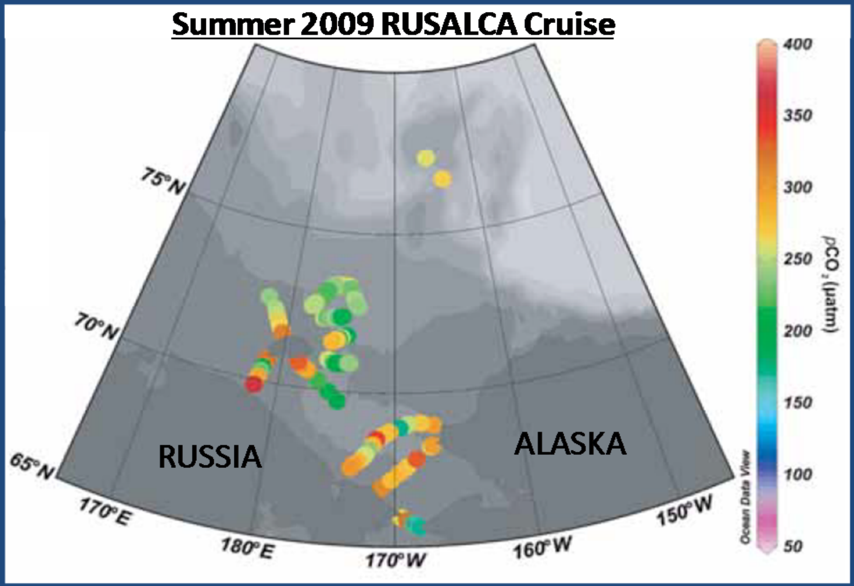


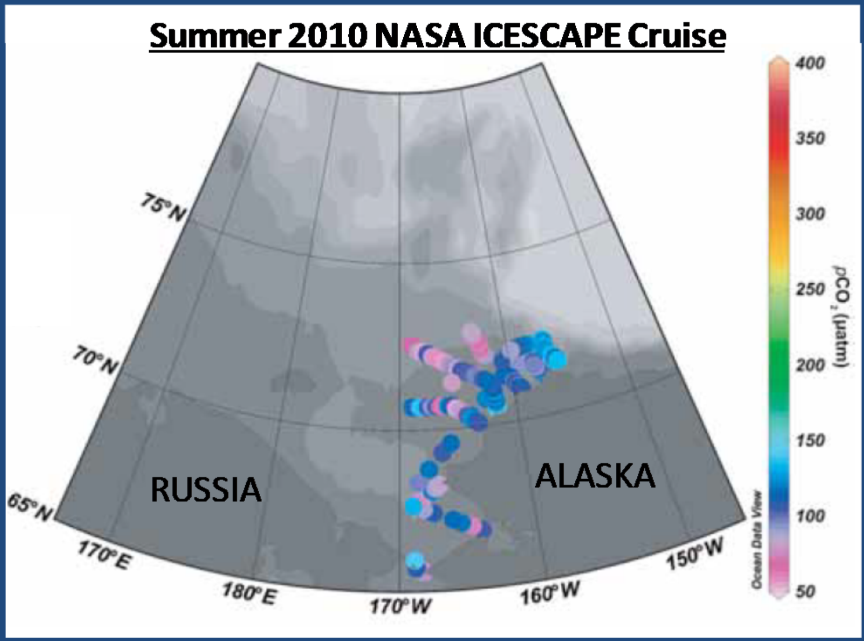


- Chl-*a* was >25 µg L^{-1}, but much farther from the ice edge
- pCO$_2$ < 100 µatm and nitrate was exhausted.
- Temp. <-1°C

Arrigo et al., 2012

Implications for CO_2 Fluxes in the Chukchi Sea



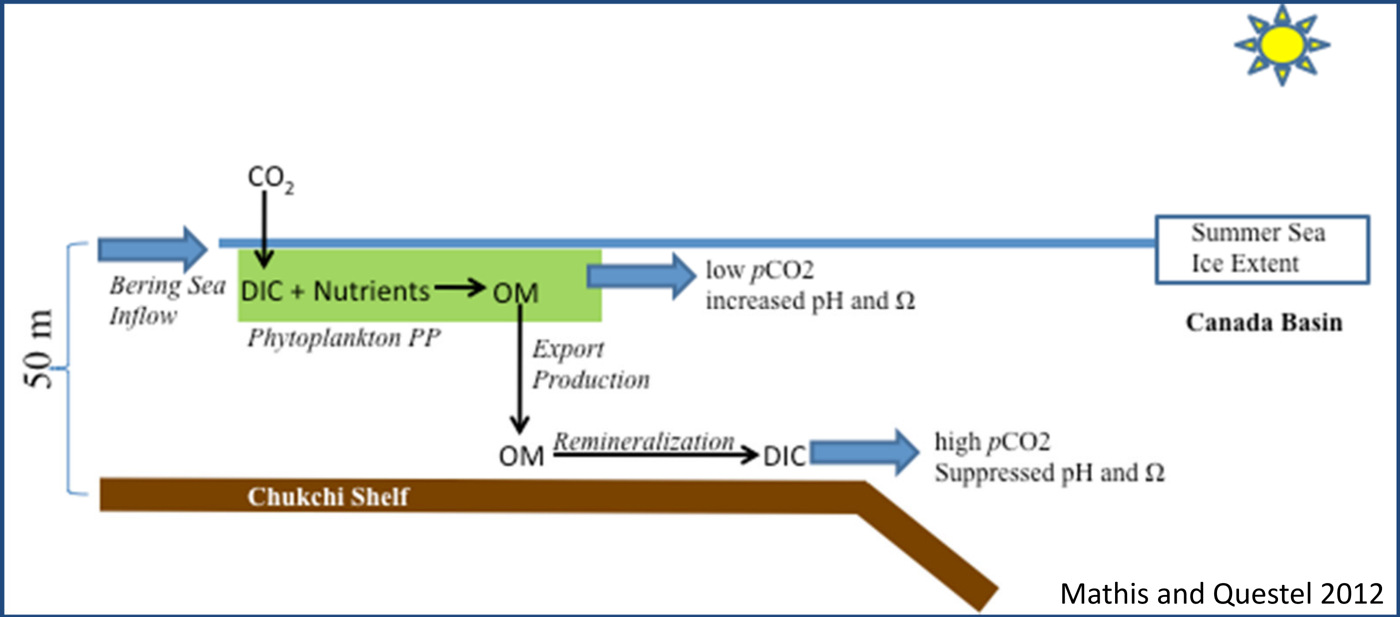


- The Chukchi Sea shelf dominates air-sea CO_2 fluxes in the western Arctic region, with the strong Chukchi Sea CO_2 sink heavily outweighing potential minor sources of CO_2 in the East Siberian Sea.

- Because of very high rates of primary production the Chukchi Sea has the potential to take up 11 – 53 Tg-C yr^{-1}

Bates, Cai, Mathis, 2011 (Oceanography Vol. 24, No.3)

Implications of Under-Ice Phytoplankton Blooms

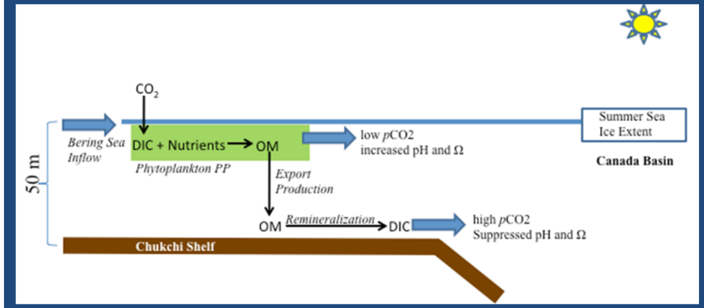


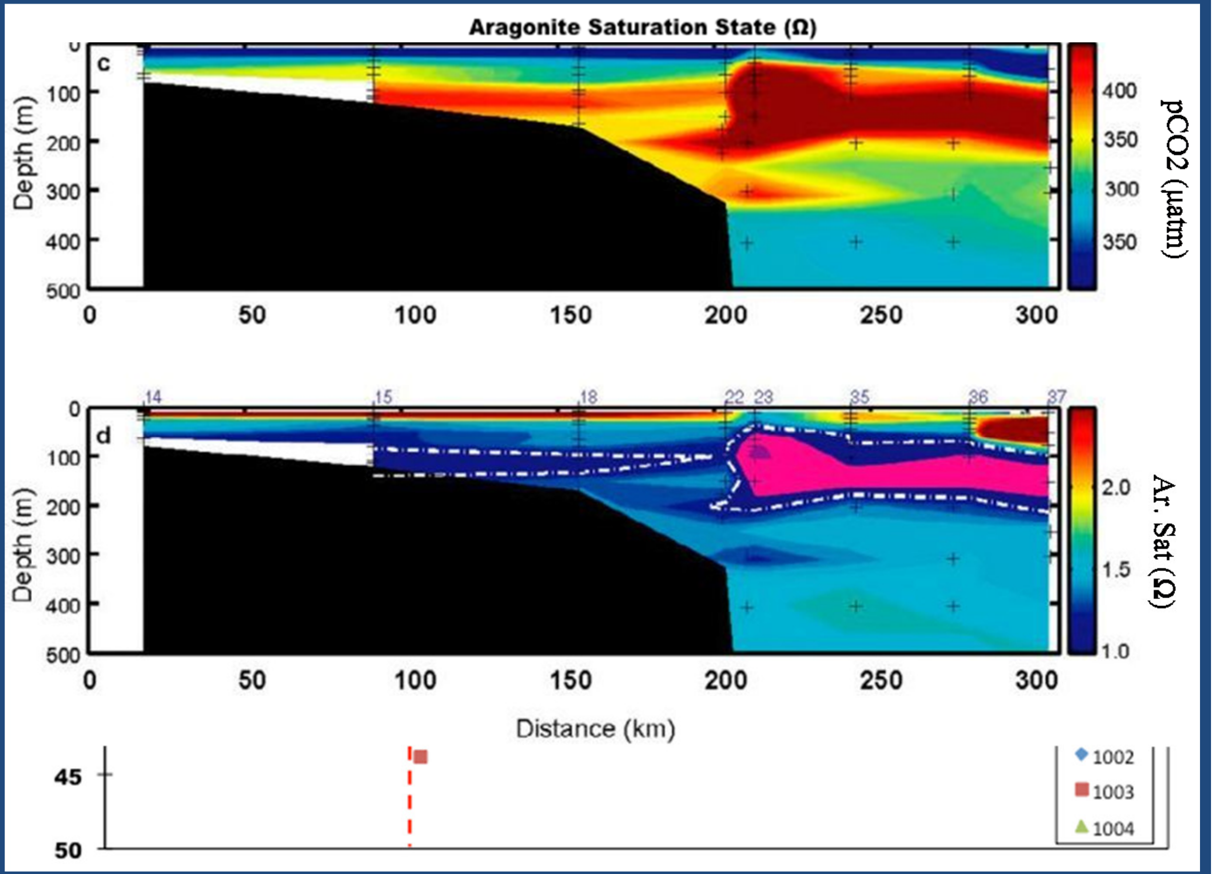
- There is already significant uncoupling between PP and zooplankton grazing in the Chukchi Sea causing ~75%* of PP to be exported to the bottom.

- However, if phytoplankton blooms under the ice become more prevalent that could lead to even higher export rates due to thermal limitations for grazers.

*Mathis et al., 2007

Carbonate Mineral Saturation States

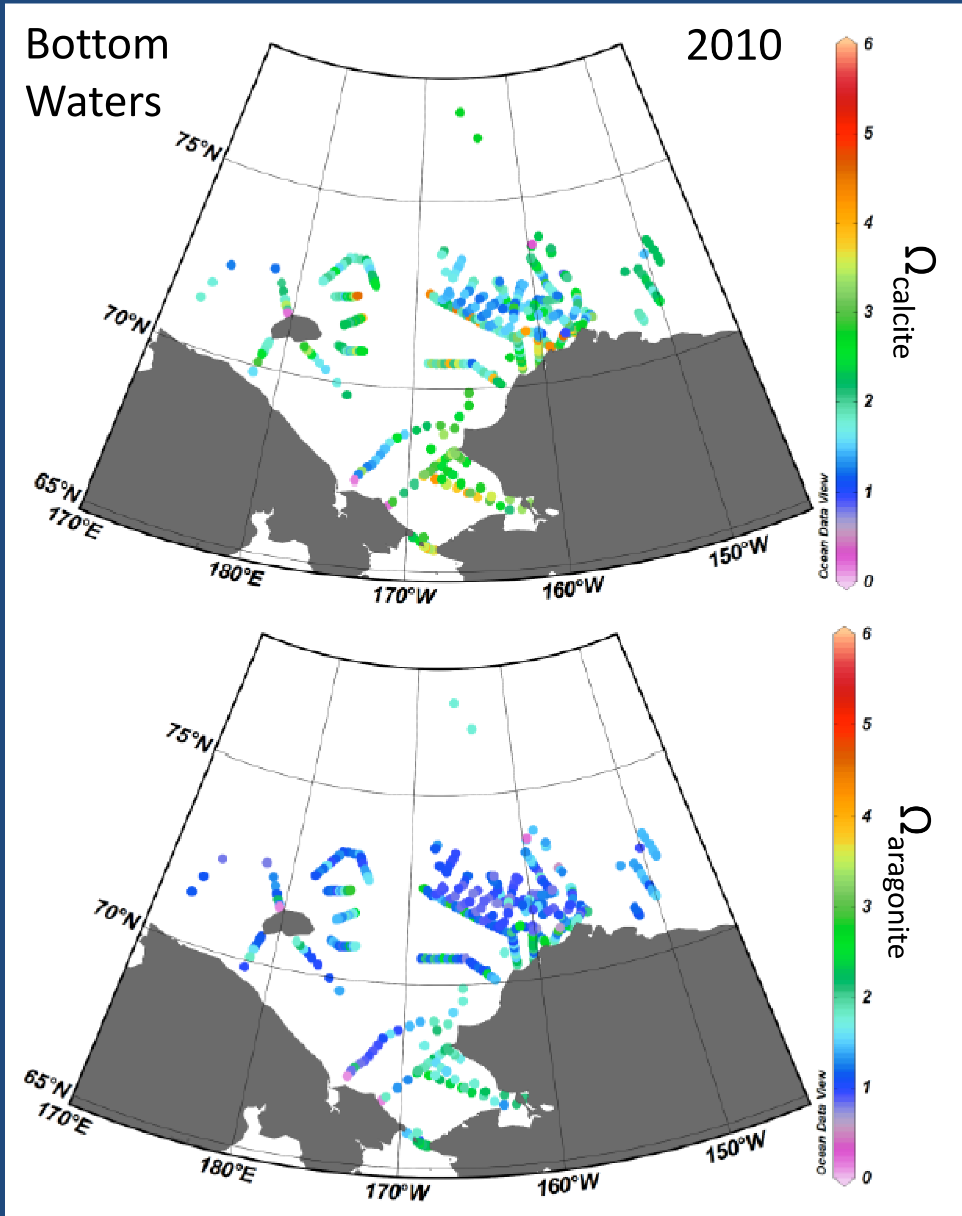




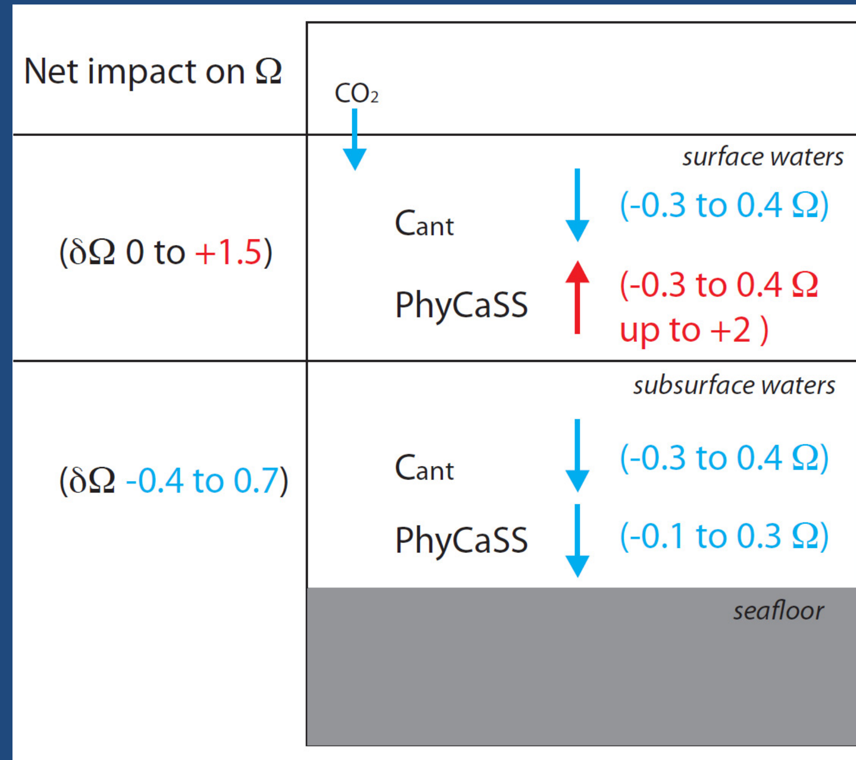
- Seasonal drawdown of DIC from PP lowers $p\mathrm{CO}_2$ and increases Ω at the surface
  - Remineralization of OM at depth causes suppression of Ω and aragonite undersaturations (PhyCaSS)

Mathis and Questel, 2012
Bates et al., 2008

Carbonate Mineral Saturation States



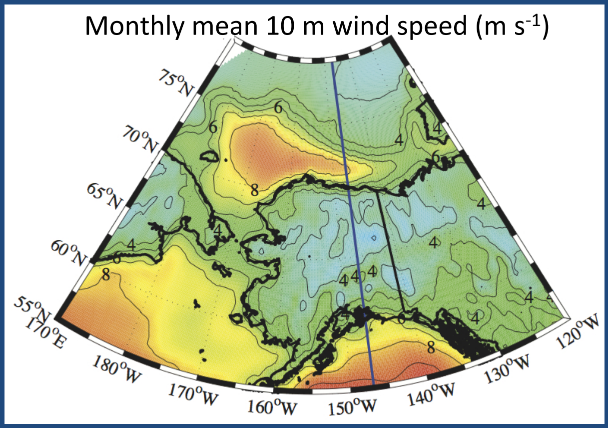
Orchowska et al., In Prep.

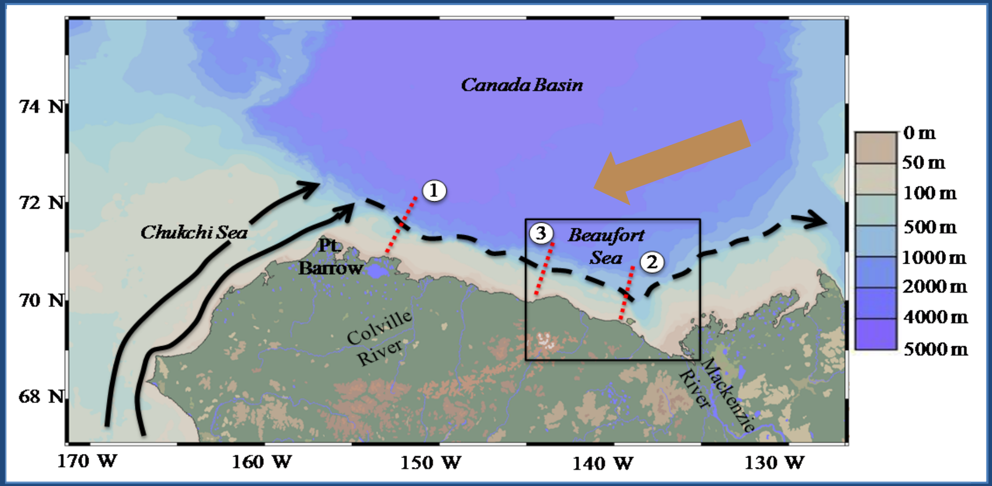


Broad areas of aragonite undersaturation have been observed across the western Arctic in summer and fall.

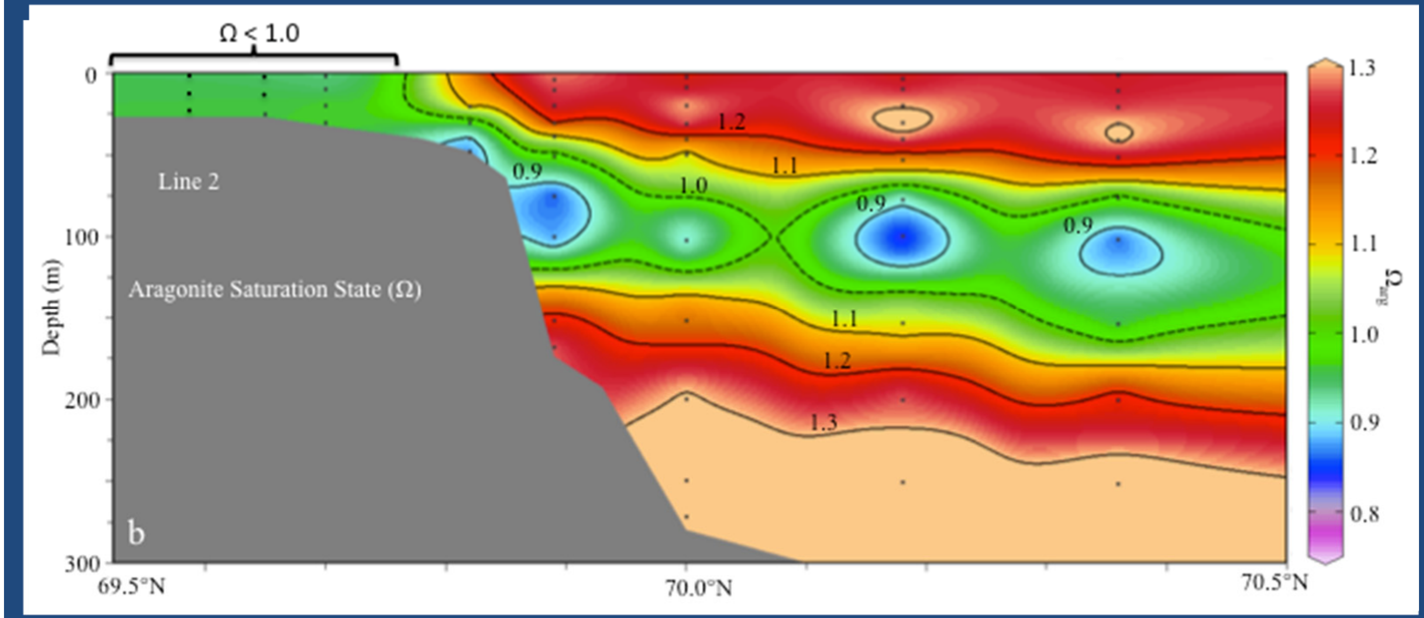
Enhanced Upwelling in the Beaufort Sea

During a cruise in October of 2011, a wind-driven upwelling event was observed along the Beaufort Shelf in open water.





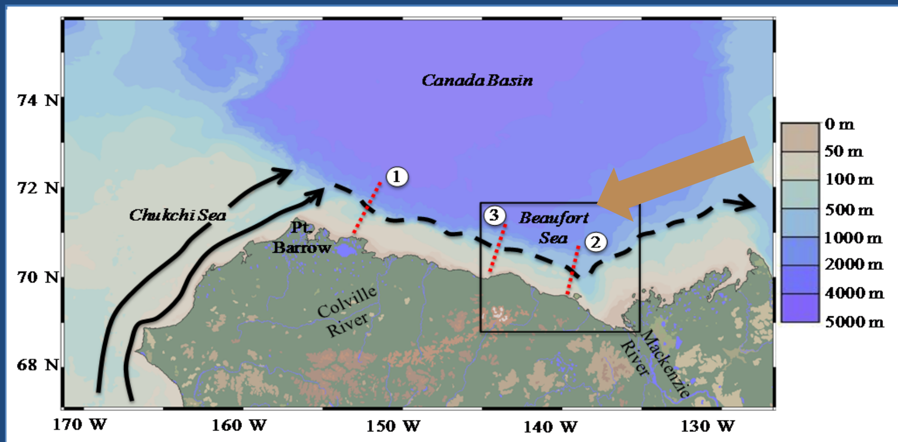
• During this time, cold (<-1.2°C), salty (>32.4) halocline water—supersaturated with respect to atmospheric CO_2 (pCO_2 > 500 µatm) was transported to the inner shelf.

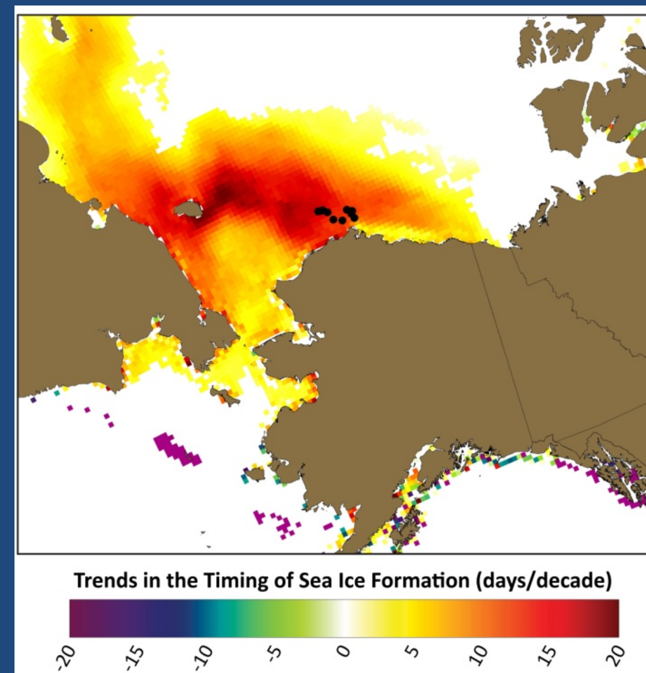


• Upwelling of halocline water caused an outcropping of water undersaturated in aragonite.

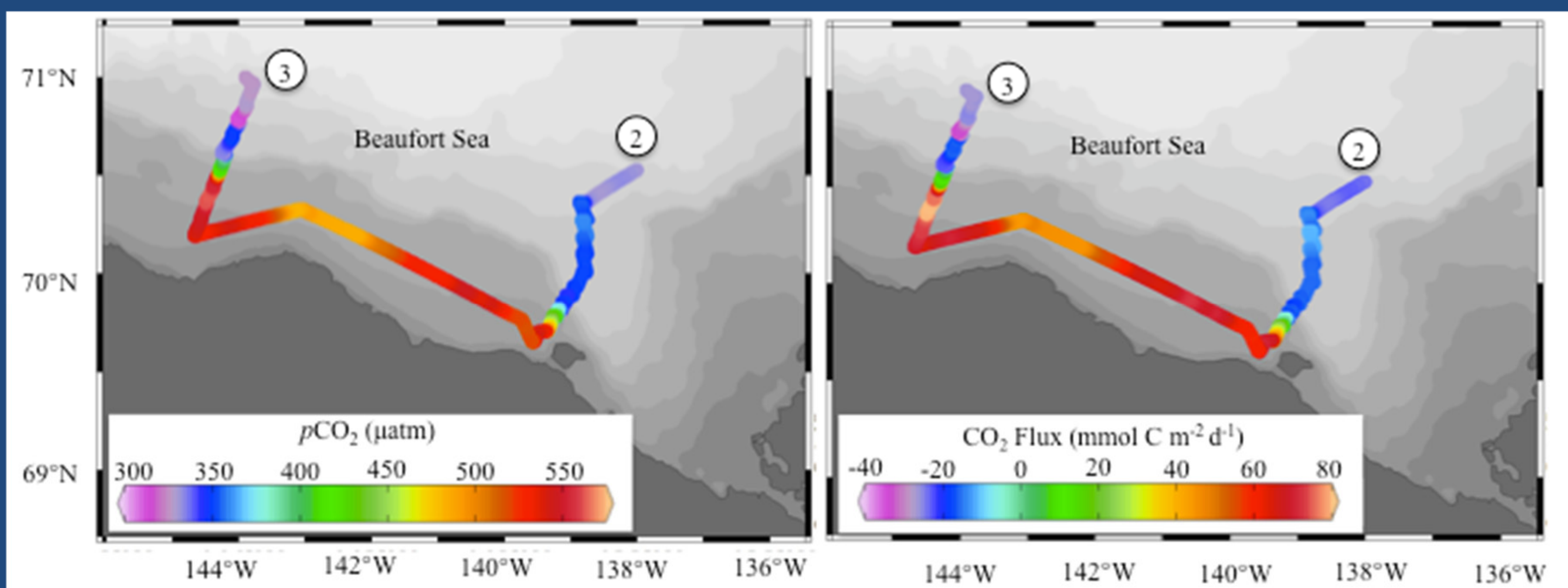
Mathis *et al.*, 2012- GRL

Enhanced CO_2 Fluxes in the Beaufort Sea

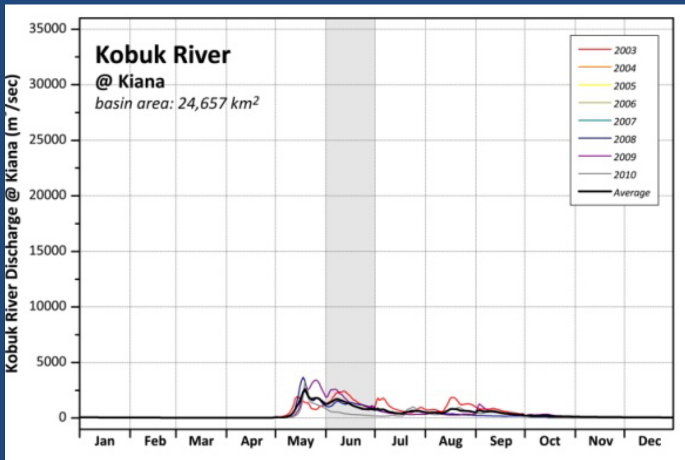


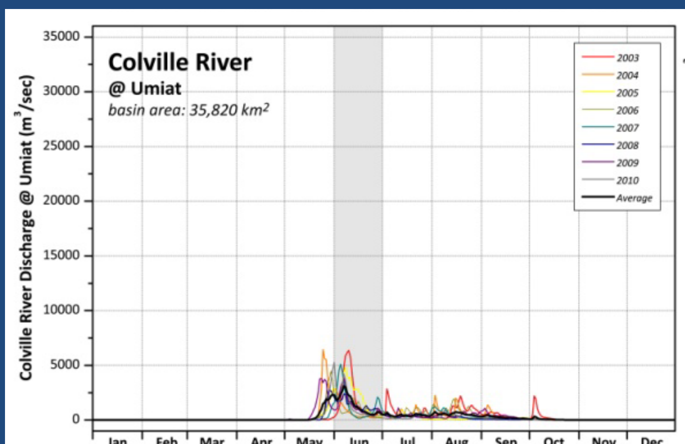


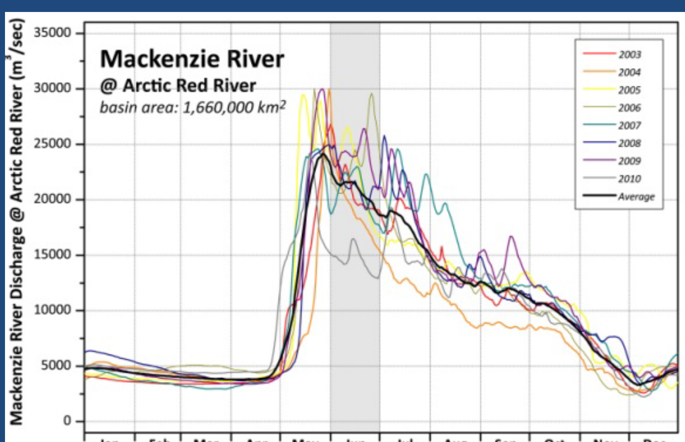
• A single week-long event led to the outgassing of ~1.8Tg C, which was equal to the total annual sink of CO_2 in the Beaufort Sea from PP and indicates that this region could be a moderate source of CO_2 to the atmosphere.



Mathis *et al.*, 2012 GRL







Major River Inputs to the Western Arctic

Kobuk River:

Basin Size: *24,657 km^2*

Annual Discharge: *13.4 km^3/year*

Colville River:

Basin Size: *35,820 km^2*

Annual Discharge: *10.8 km^3/year*

Mackenzie River:

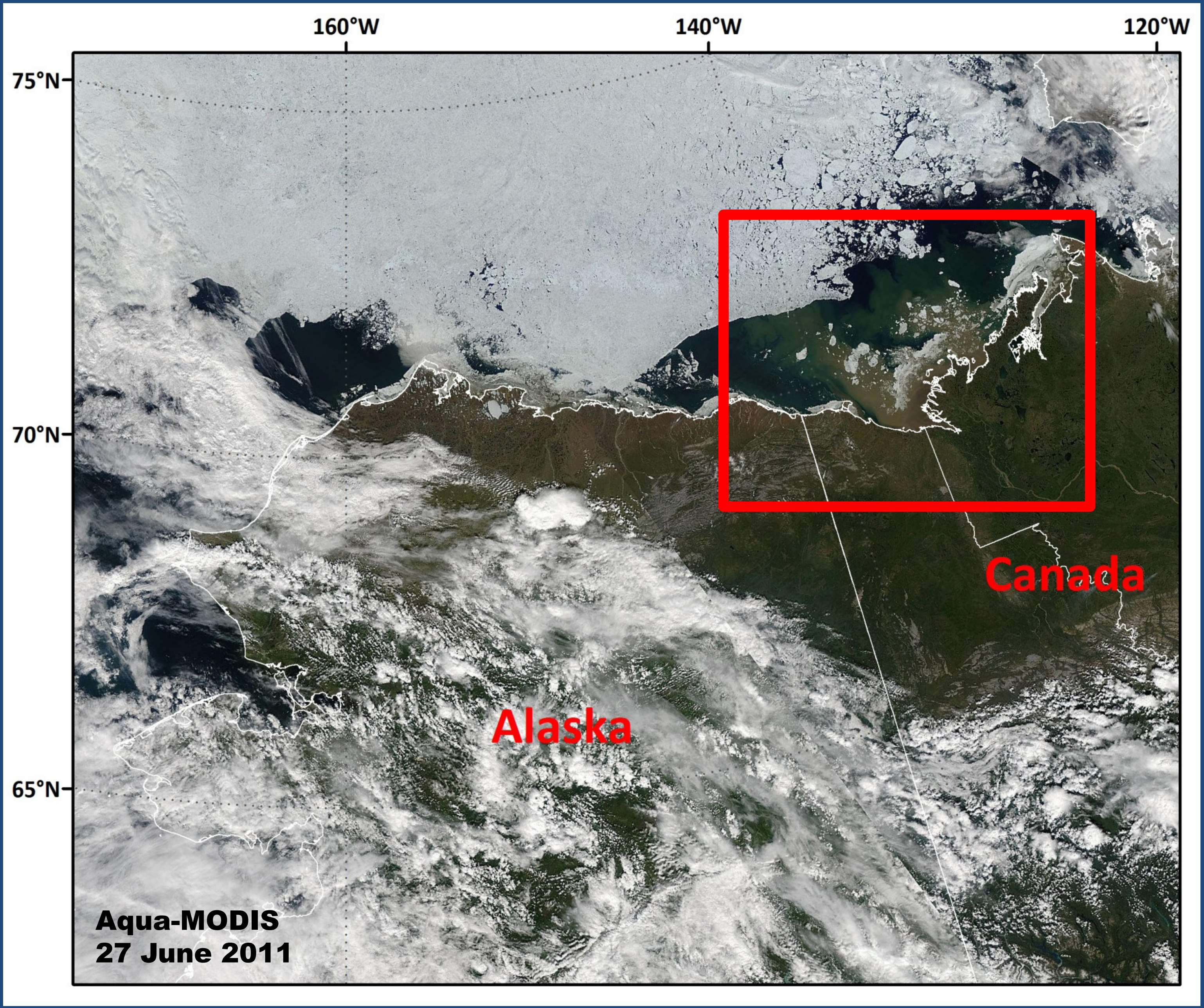
Basin Size: *1,660,000 km^2*

Annual Discharge: *249 km^3/year*

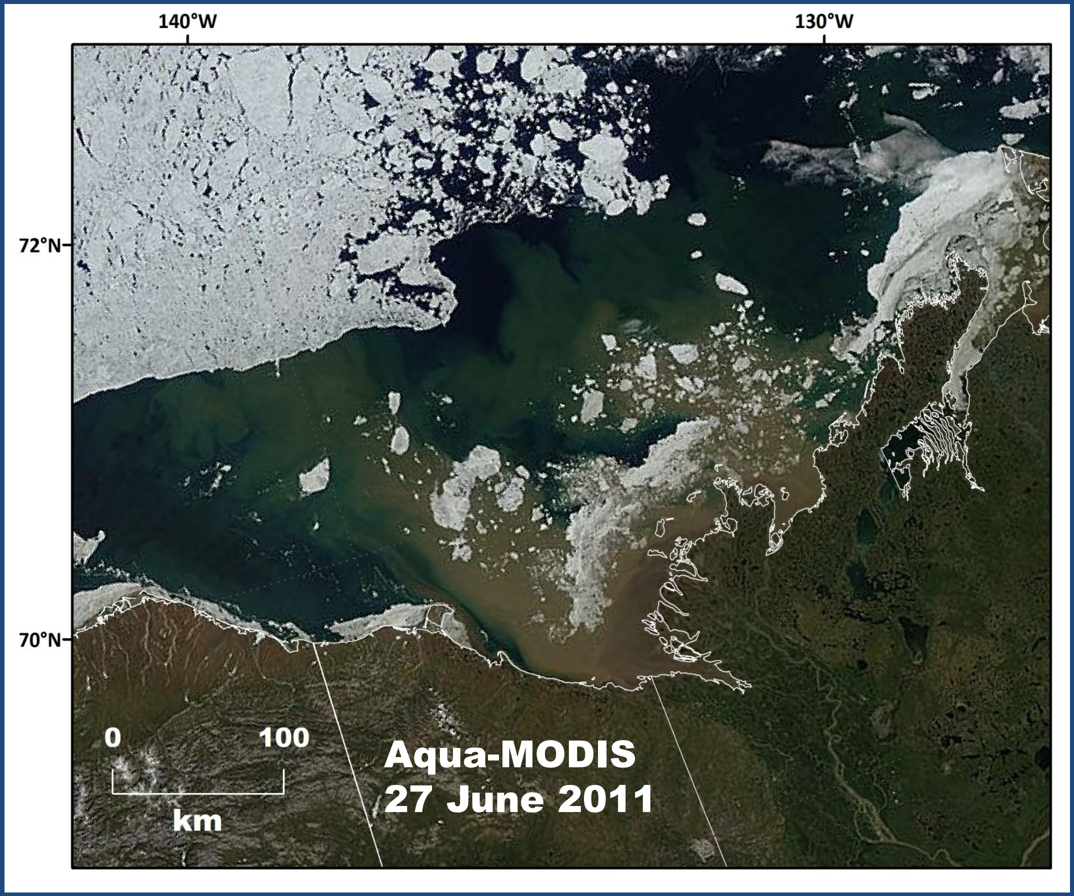
- In a warmer, wetter Arctic river discharge will almost certainly increase. Freshet usually occurs prior to the spring bloom
- Increase in particle delivery will reduce light transmission and increase $p\mathrm{CO_2}$
- Drainage basins are carbonate poor

Frey et al. (in prep.)

Coastal Impacts of River Discharge and Erosion



Coastal Impacts of River Discharge and Erosion



- Increased river discharge will bring high concentrations of POC, but is limited in nutrients.
- These plumes will increase pCO_2 at the surface and reduce light penetration.

- Large fluxes of organic carbon from coastal erosion.
- Will accelerate under warming conditions, reduced sea ice and increased storm intensity.

Future Predictions of Change

Confounding Variables

• Although general increases in primary production for the Arctic Ocean are predicted, trends are expected to be spatially heterogeneous and dependent upon several confounding factors.

• While some Arctic shelf seas may see significant increases in primary production with further sea ice declines, the central Arctic Ocean may see smaller increases in production:

- *owing to low nutrient concentrations*

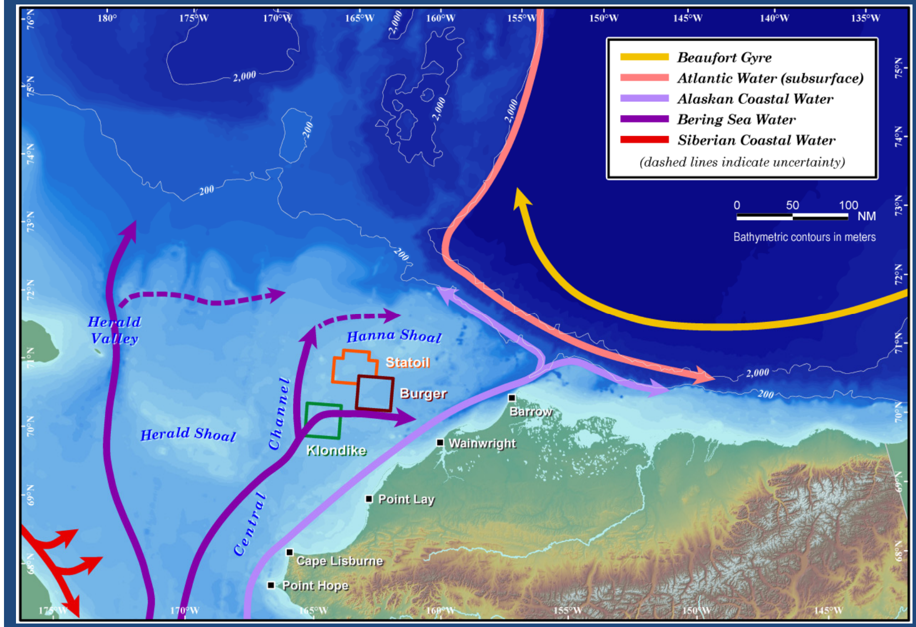
• Areas newly outside the seasonal ice zone may see decreases in production:

- *owing to increased stratification with overall warming*

• Inner coastal shelves may see little increases in production

- *owing to the enhanced delivery of light inhibiting river-derived material to this region*

What's Next in the Western Arctic?



- Shell, ConocoPhillips and Statoil are all developing lease sites in the region. Shell will begin drilling this month.
- In response to energy development BOEM is committing resources to studying the region.
- ONR is making a major commitment (mainly PO and sea ice) in the next few years.
- NOAA, NSF (Arctic Geo-traces), and NASA (ABOVE) are all planning new programs in the region.
- There are new international science and implementation plans (ART) to coordinate and share resources particularly post-IPY.

Conclusions

- Clear and definitive trends in sea ice reduction have been observed in the Western Arctic and are causing distinct transitions in biogeochemical processes.

- The increased prevalence of melt ponds in response to warming temperatures may induce broad under ice phytoplankton blooms, which may lead to greater uncoupling between primary produces and grazers.

- The remineralization of organic matter coupled with the intrusion of ant. CO_2 has lead to broad areas of carbonate mineral suppression across the Chukchi Shelf and this may be exacerbated if under ice phytoplankton blooms become routine.

- The Chukchi Sea is the strongest sink for atmospheric CO_2 in the region taking up as much as 53 Tg-C yr^{-1}. On the other hand, new observations have shown that the Beaufort Sea may be a moderate source of CO_2 (1.8 Tg C yr^{-1}) to the atmosphere due to upwelling that has been enhanced through the loss of sea ice and increased storm occurrence and intensity.

- Upwelling along the Beaufort Shelf causes broad areas of aragonite under saturation throughout the water column. Upwelling will likely increase as sea ice continues to diminish and storm frequency and intensity increase.


Thanks