The Role of Sea Ice in Global Biogeochemical Cycles

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IARC

Talk strategy - Implications of the changing sea ice cover on biogeochemical cycles

Background

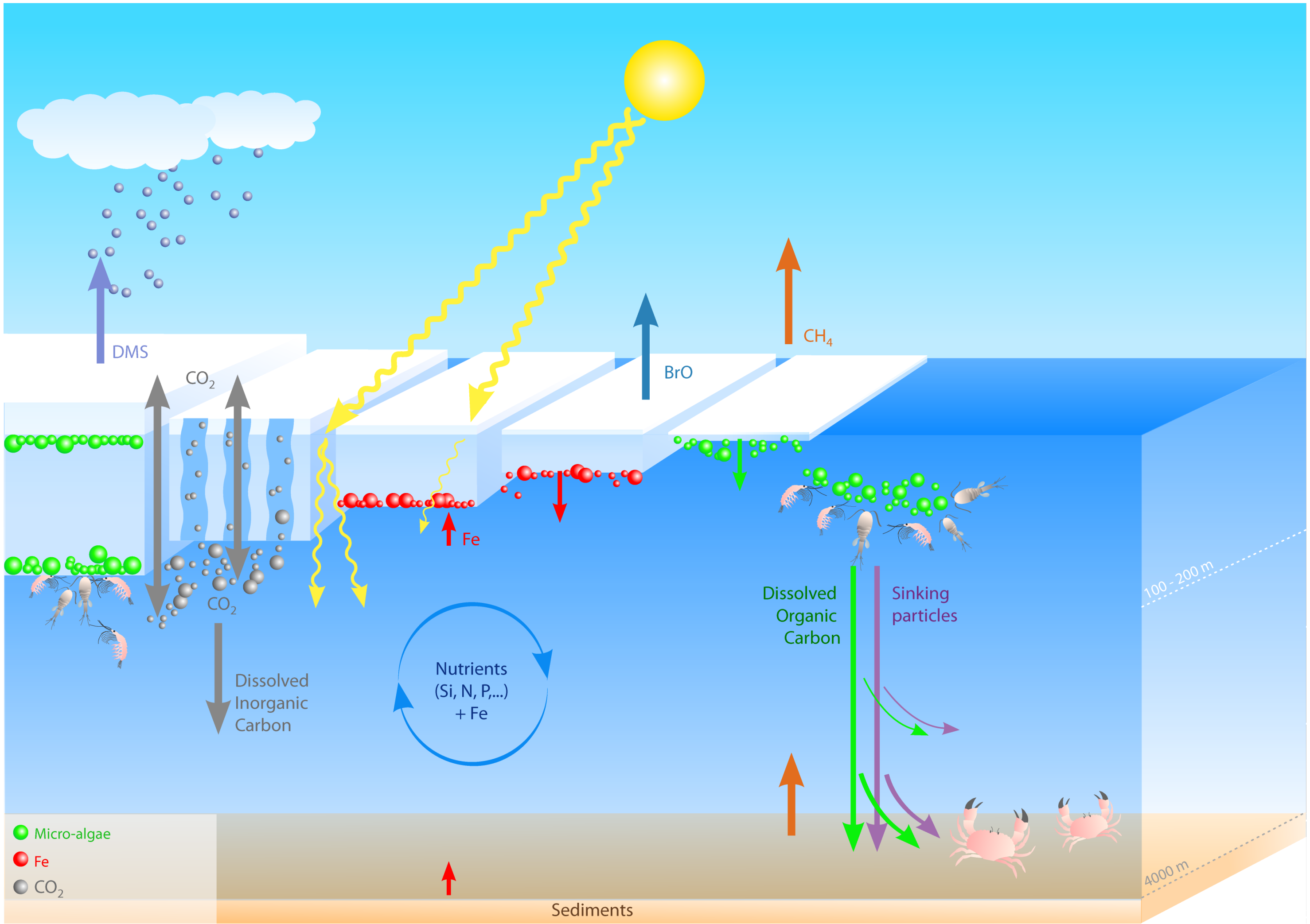
Marine biogeochemical cycling
Atmospheric chemistry
Terrestrial C cycling

What observations and models suggest

Challenges ahead

Big questions

Sea ice is both a reservoir and a substrate for biogeochemical compounds.



Simplified schematic of some of the biogeochemical processes occurring in the sea ice environment. Figure courtesy M. Vancoppenolle.

Reviews on sea ice and large-scale biogeochemical cycling:

Vancoppenolle M., et al.The role of sea ice in global biogeochemical cycles: Emerging views and challenges, *Quaternary Science Reviews*, 2013.

"The implications of sea ice retreat on the future oceanic capacity to absorb CO_2 *and emit DMS, as well as … , are poorly understood."*

Loose, B., et al., Sea ice biogeochemistry and material transport across the frozen interface, *Oceanography*, 2011.

"The future large-scale biogeochemical dynamics of the polar oceans … are difficult to predict."

Shepson, P. et al., Changing polar environments: Interdisciplinary challenges, *EOS*, 2012

"Currently, significant gaps remain in understanding biologically mediated processes in sea ice environment…"

Implications won't be uniform because of spatial variability and dynamic nature of Arctic.

The key processes and responses to change will likely vary within different Arctic sub-regions (Carmack et al. 2006).

How will patterns of biogeochemical sinks and sources change?

The dynamic nature of the Arctic affects responses to change.

- different shelf characteristics – riverine inputs
- stratification
- sea ice drift
- currents

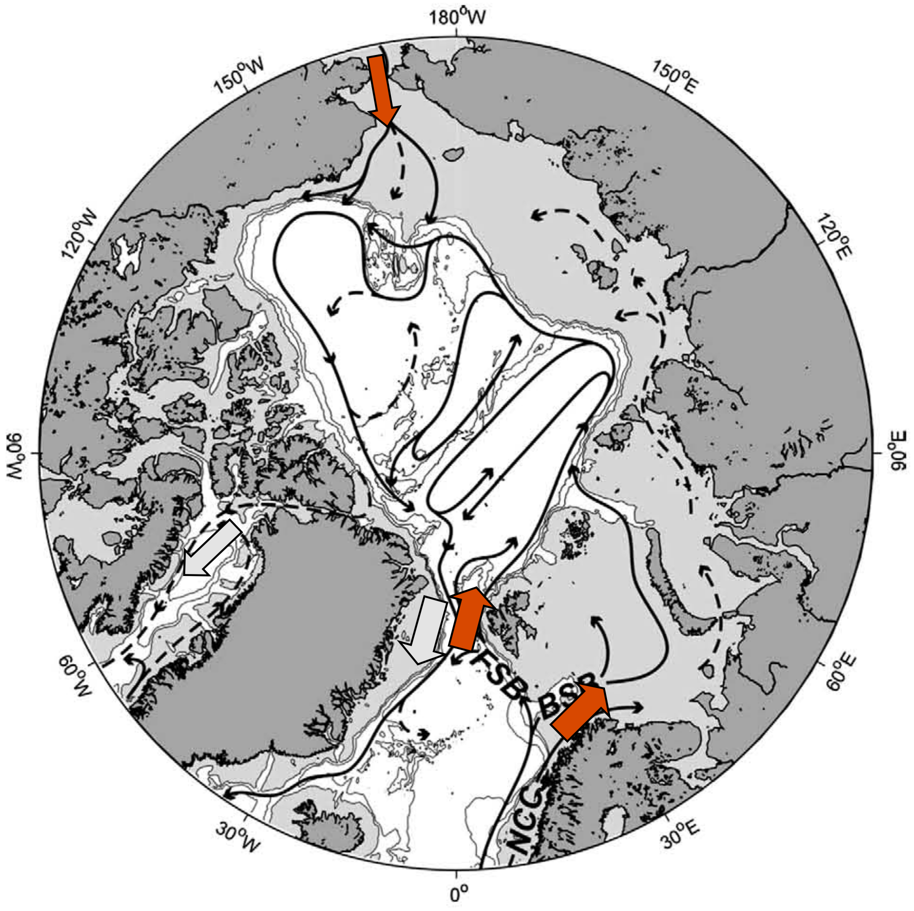
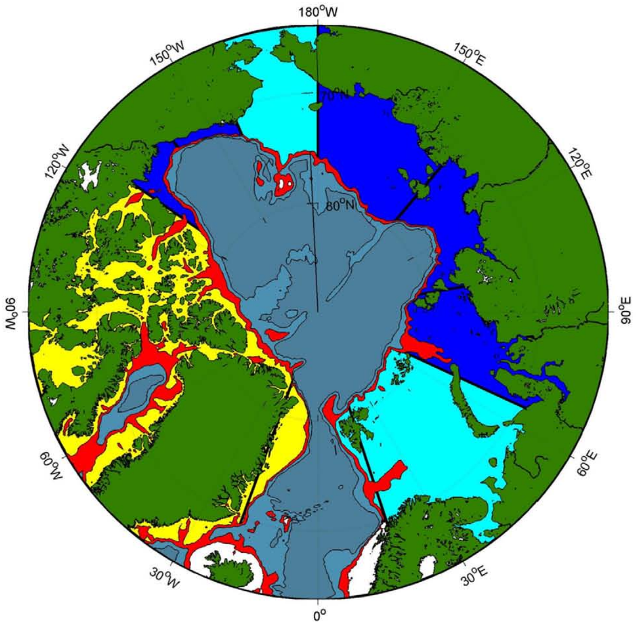


Figure modified from Carmack et al. 2006

Different responses may be attributed to the spatial heterogeneity of the physical environment.

E. Carmack, P. Wassmann / Progress in Oceanography 71 (2006) 446 477



"Food webs and physical-biological Coupling on pan-Arctic shelves: Unifying concepts and comprehensive perspectives"

E. Carmack and P. Wassman (2006)

Green: inflow shelves.
Blue: interior shelves.
Yellow: outflow shelves.
Red: shelf break.
Gray: the deep basins.

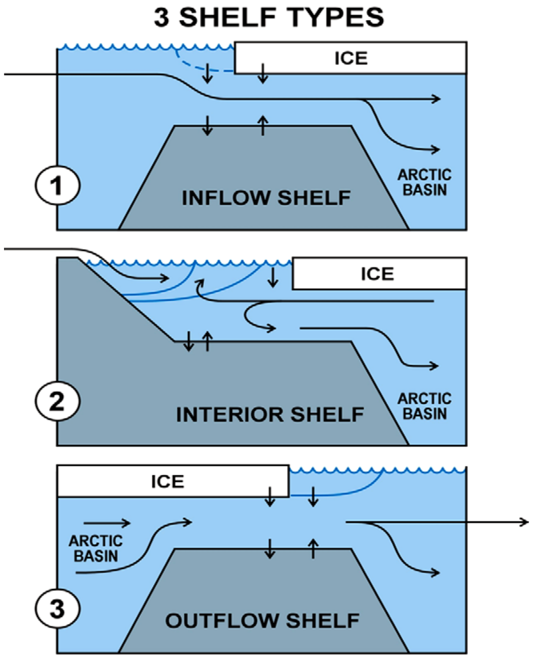


Table 1 in Vancoppenolle et al. (2013).

Different geographical, geophysical and geo-morphological settings drive differences between Arctic and Antarctic ice covers.

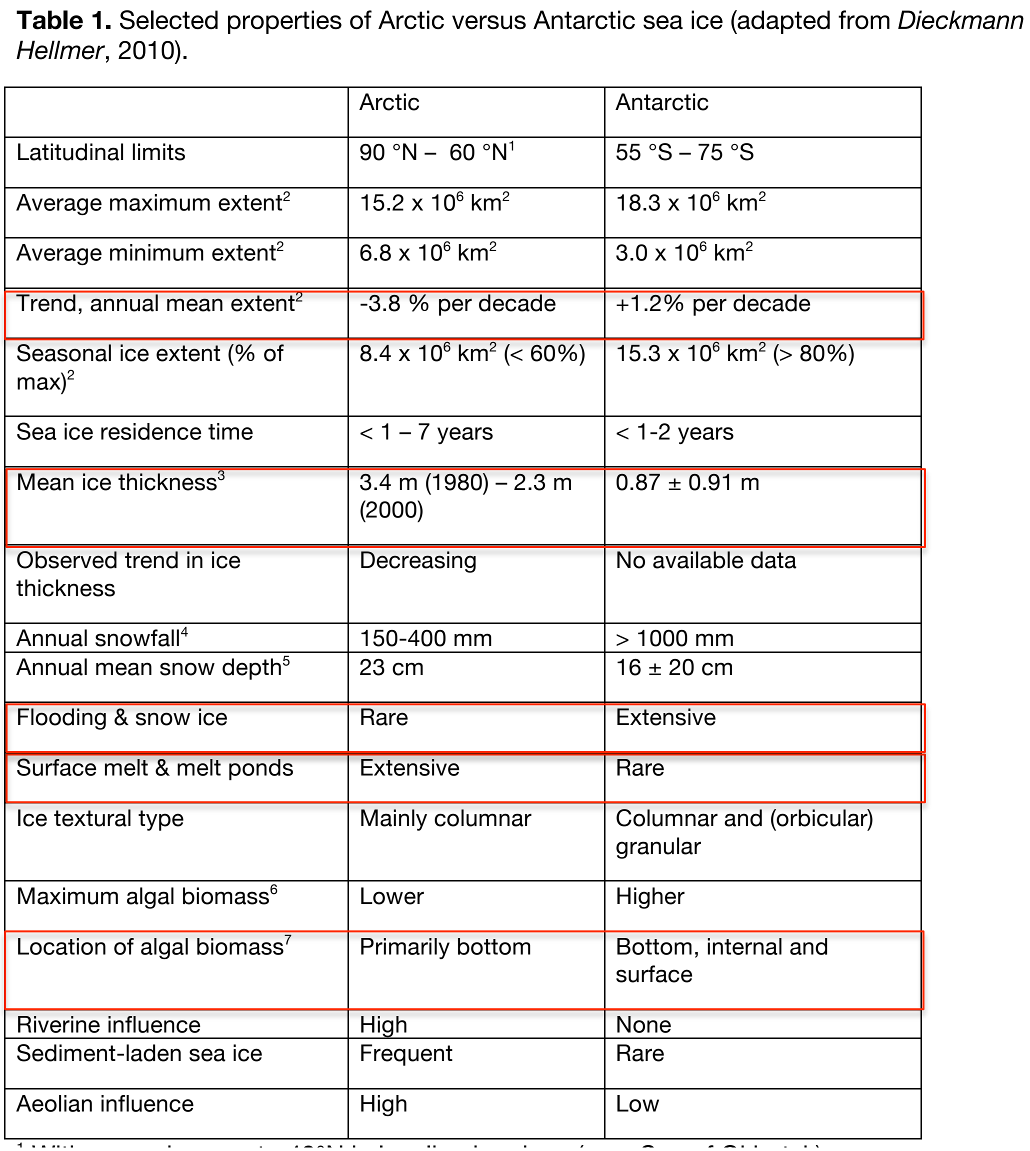


Table 1. Selected properties of Arctic versus Antarctic sea ice (adapted from *Dieckmann Hellmer*, 2010).

	Arctic	Antarctic
Latitudinal limits	90 °N – 60 °N[1]	55 °S – 75 °S
Average maximum extent[2]	15.2×10^6 km^2	18.3×10^6 km^2
Average minimum extent[2]	6.8×10^6 km^2	3.0×10^6 km^2
Trend, annual mean extent[2]	-3.8 % per decade	+1.2% per decade
Seasonal ice extent (% of max)[2]	8.4×10^6 km^2 (< 60%)	15.3×10^6 km^2 (> 80%)
Sea ice residence time	< 1 – 7 years	< 1-2 years
Mean ice thickness[3]	3.4 m (1980) – 2.3 m (2000)	0.87 ± 0.91 m
Observed trend in ice thickness	Decreasing	No available data
Annual snowfall[4]	150-400 mm	> 1000 mm
Annual mean snow depth[5]	23 cm	16 ± 20 cm
Flooding & snow ice	Rare	Extensive
Surface melt & melt ponds	Extensive	Rare
Ice textural type	Mainly columnar	Columnar and (orbicular) granular
Maximum algal biomass[6]	Lower	Higher
Location of algal biomass[7]	Primarily bottom	Bottom, internal and surface
Riverine influence	High	None
Sediment-laden sea ice	Frequent	Rare
Aeolian influence	High	Low

Physical forces interact with chemical and biological processes within the ice in complex ways.

> “Perhaps the most important lesson from recent sea ice studies is that physical, chemical, and biological processes interact in distinctive and complex ways and should not be studied independently of one another.”
>
> Shepson et al. (*EOS*, 2012)

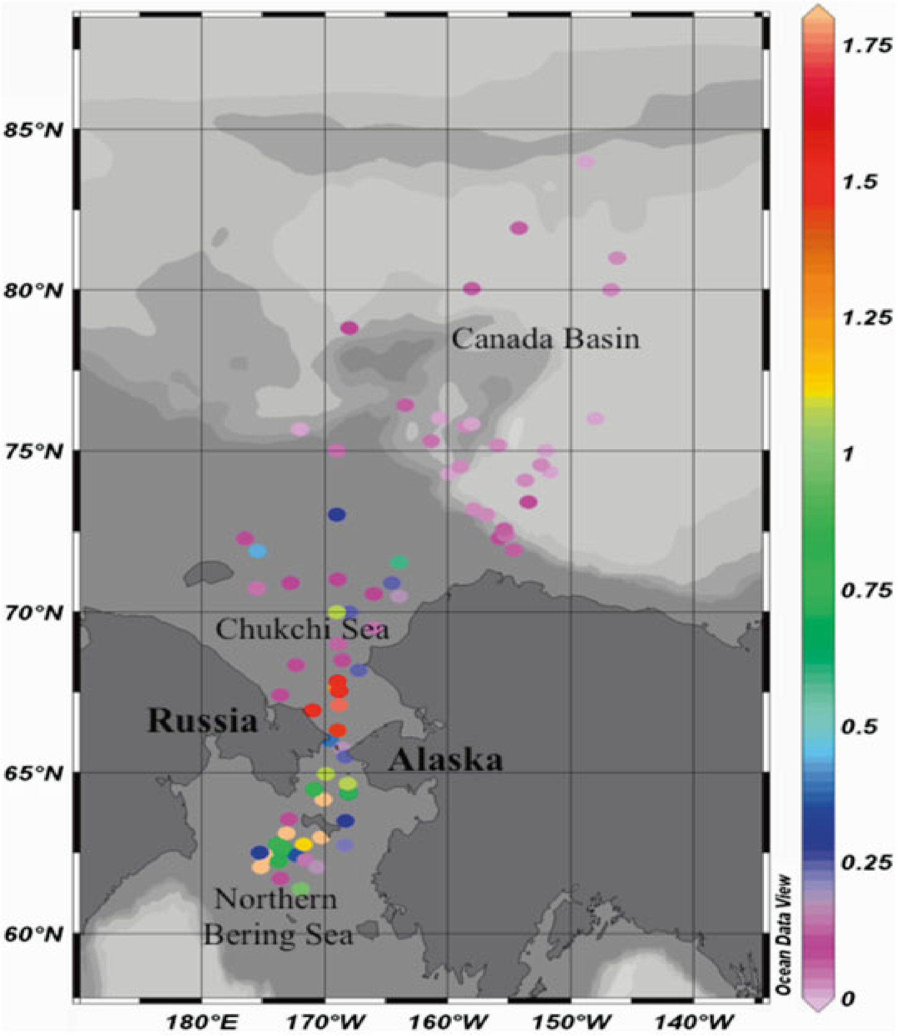
How does the changing sea ice cover impact pp?

Physical changes:

- increased open water area
- thinning at rapid rate
- increasing melt pond coverage
- more storm events
- changing seasonality
- sea ice transport

General consensus: Increased productivity

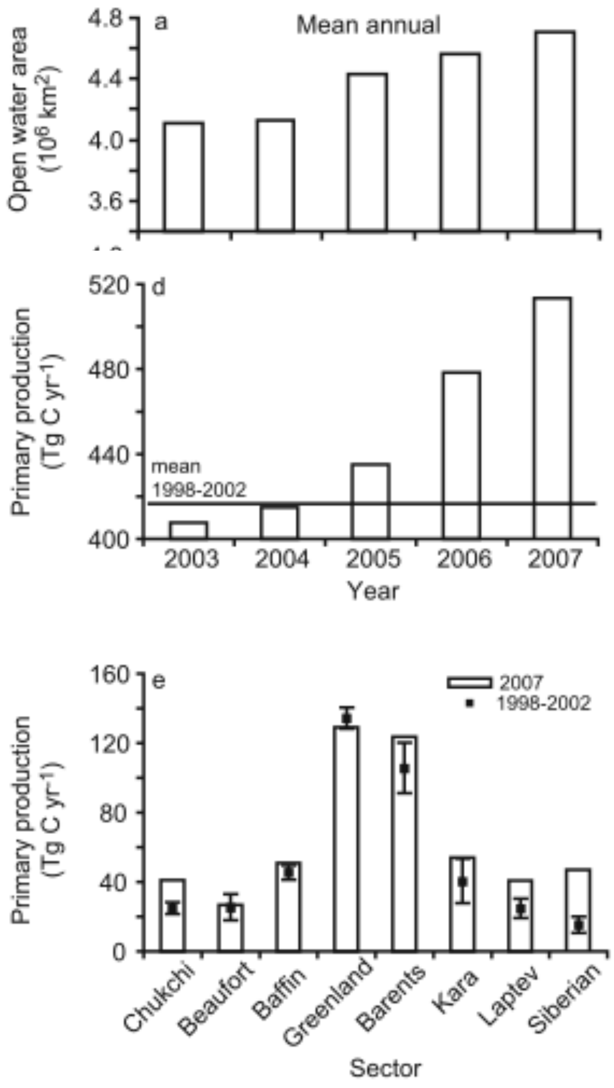
Field measurements suggest that primary productivity in the Bering Strait and Chukchi Sea has declined in recent years (Lee et al. 2012).



Carbon uptake rates (g C m^{-2} day^{-1}) integrated to the 1% light depth (Data from Lee and Whitledge 2005: Lee et al. 2007, 2010, 2011). Figure from Mathis et al. (2014).

- Recent Northern Bering Sea estimate of 120 g C m^{-2} vs. 250-480 g C m^{-2} more than decade ago
- Recent average annual production (55 mg C m^{-2}; Lee et al. 2007) in Chukchi Sea is 2 to 3 times lower than previous estimates
- may be the result of seasonal, annual, or geographic variations in PP

Remote sensing estimates of primary production display overall increase in Arctic Ocean PP resulting from sea ice loss (Arrigo et al. 2008).

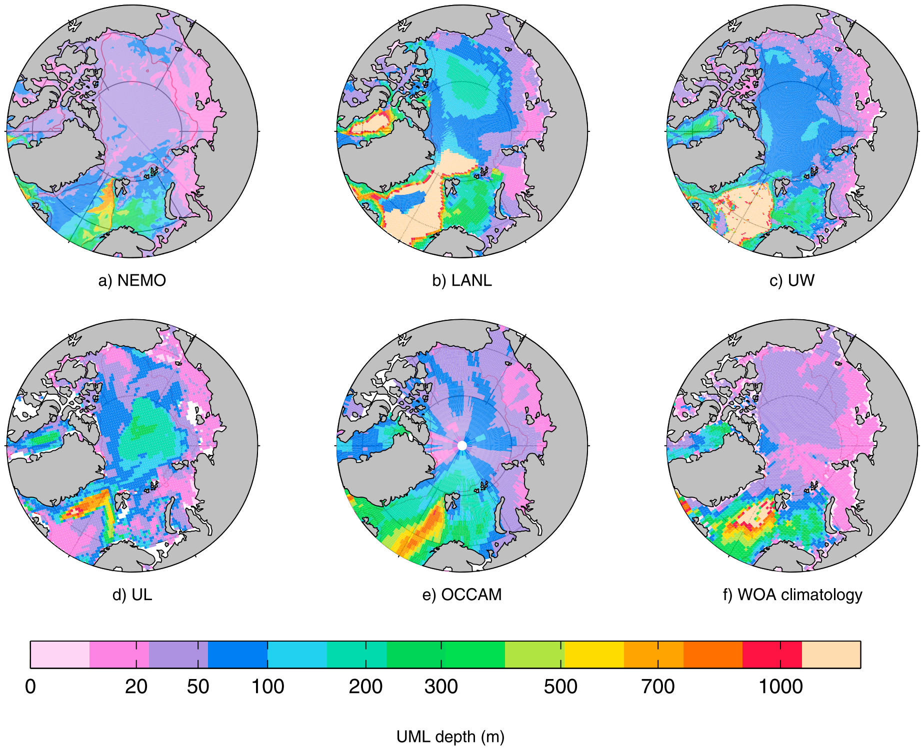


Yearly increases:

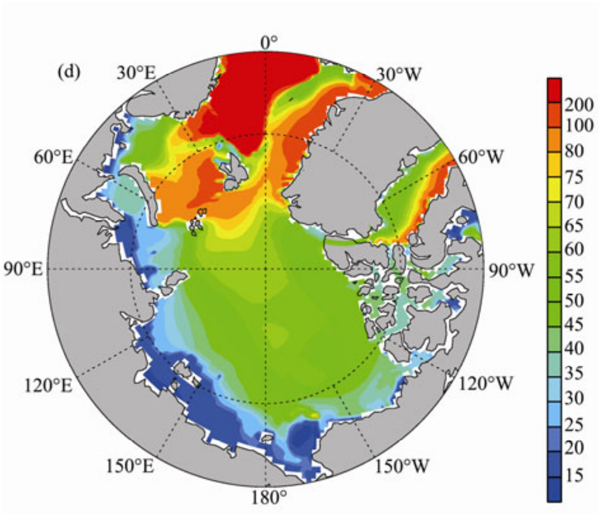
- 30% attributable to decreased minimum summer ice extent and
- 70% to a longer phytoplankton growing season

Figures from Arrigo et al. (2008).

In relation to increased open-water area, five GCM's with biogeochemistry disagree on whether nutrients or light control "present-day" AO productivity (Popova et al. 2012).

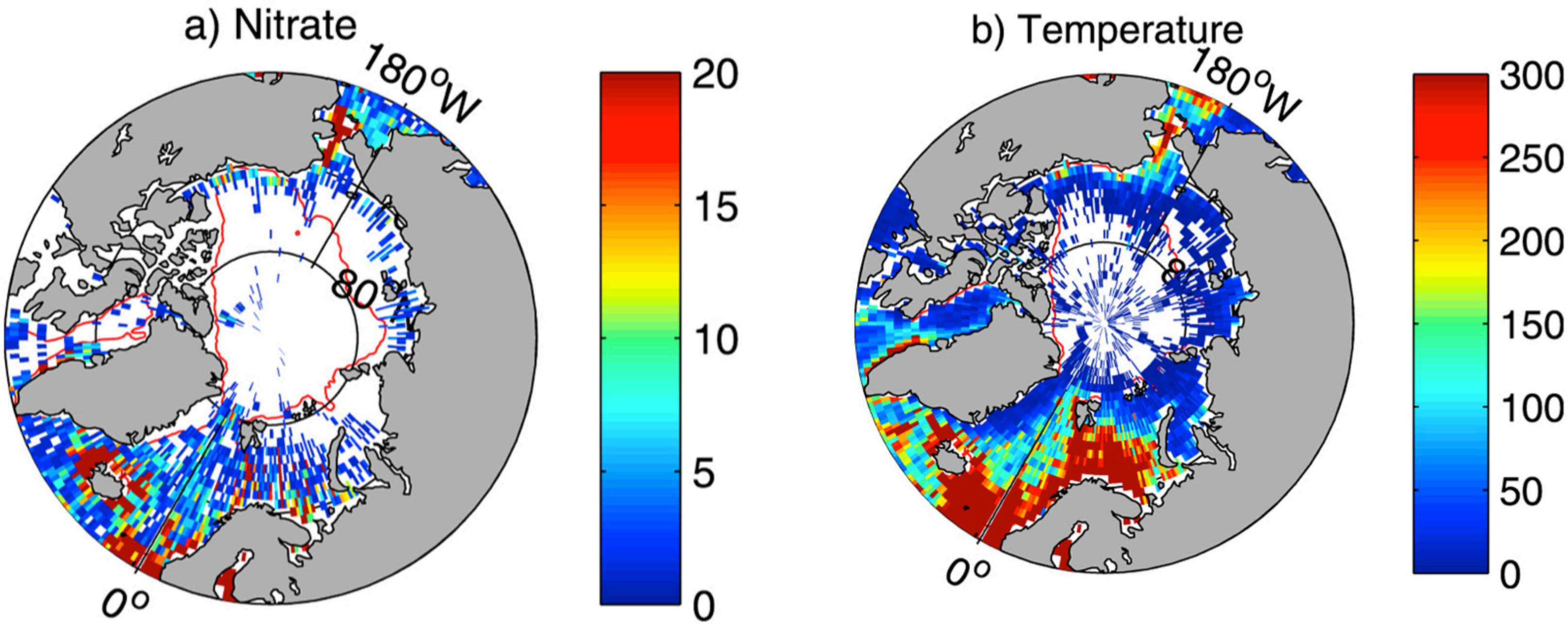


Maximum depth of UML during the year (Popova et al. 2012)



LANL model (Jin et al. 2013)

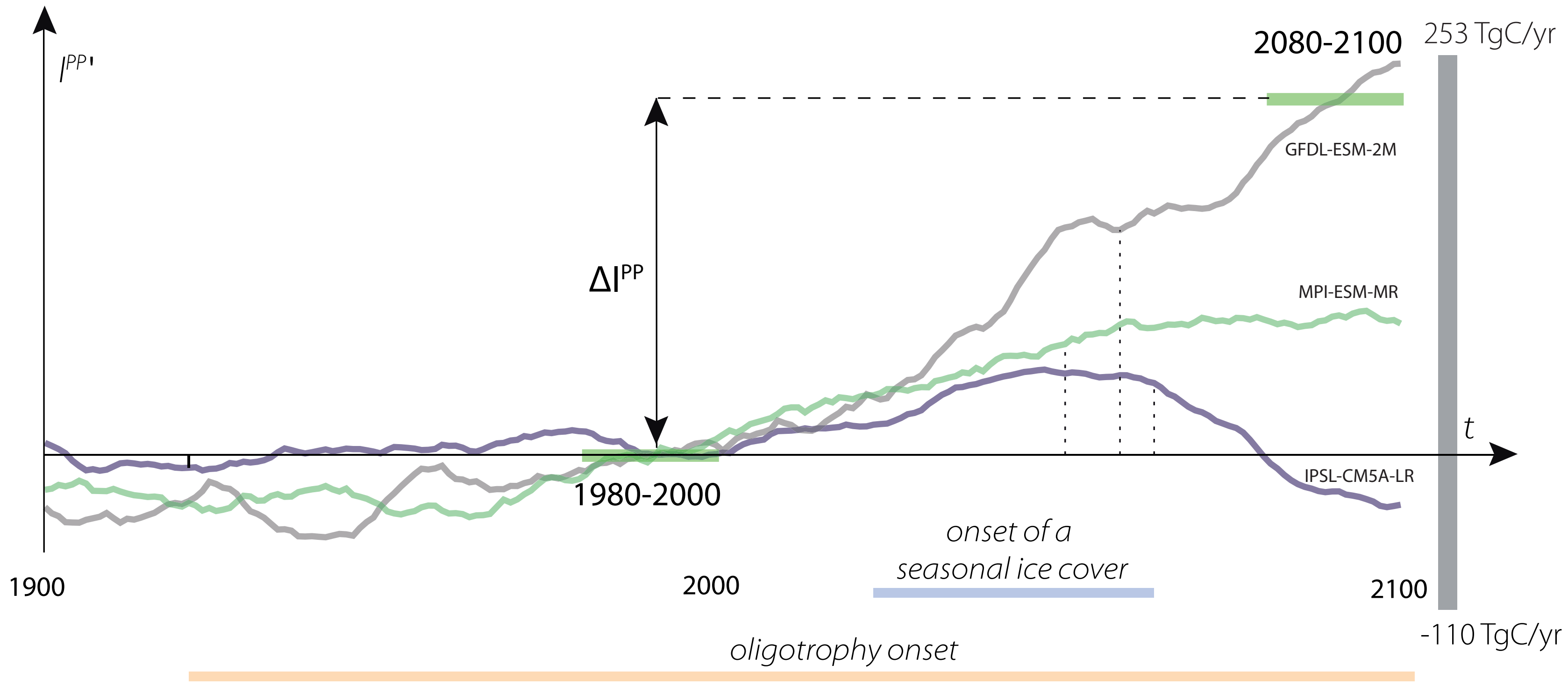
Disagreement among models is attributed to variations in the simulated vertical mixing that controls nutrient supply…



Total number of observations included into the annual WOA climatology per once degree grid area for (a) DIN and (b) temperature (Figures from Popova et al. 2012).

Three of the four global coupled carbon-cycle–climate models analyzed by Steinacher et al. (2010) project an increase in arctic marine net primary productivity over the 21st century.

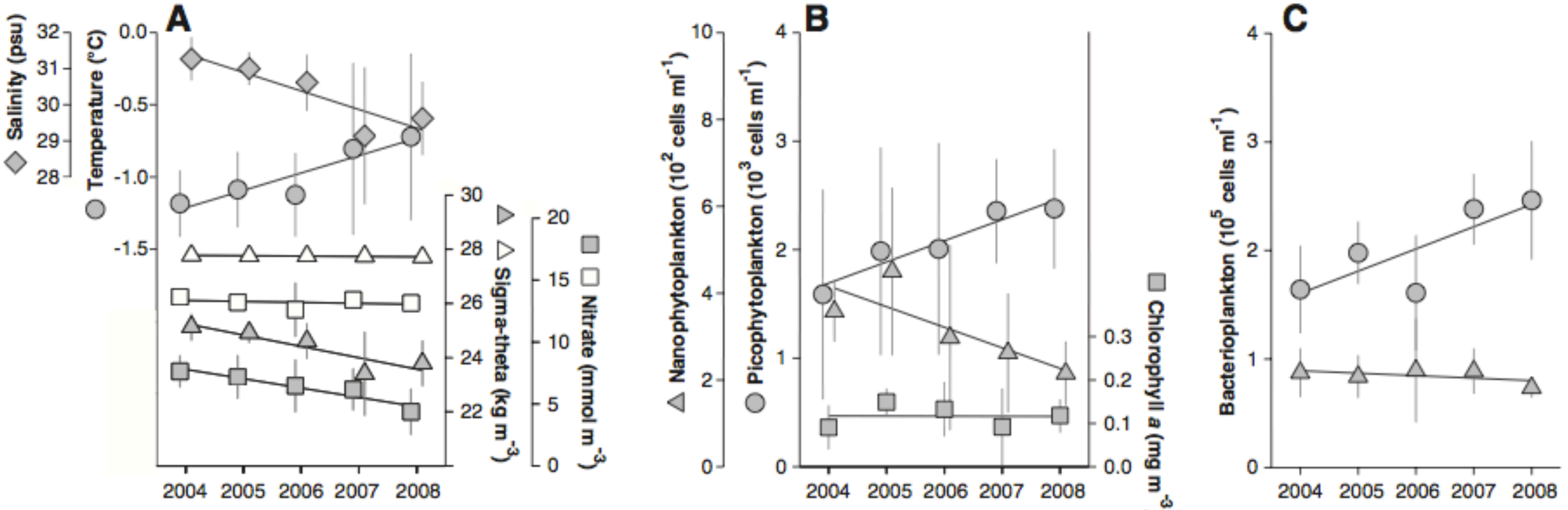
CMIP5 models do not agree on the sign of future AO PP change. Uncertainty due to inter-model spread of nitrate (Vancoppenolle et al. 2013).



Typical evolution of Arctic Ocean IPP anomalies (TgC/yr) over 1900–2100 (with respect to the 1980–2000 mean, 20 year running mean) from three selected CMIP5 models. Figure from Vancoppenolle et al. (2013).

Recent observations suggest that expected freshening/stratification and consequently changes that limit nutrient supply could benefit small picophytoplankton cells over large diatoms.

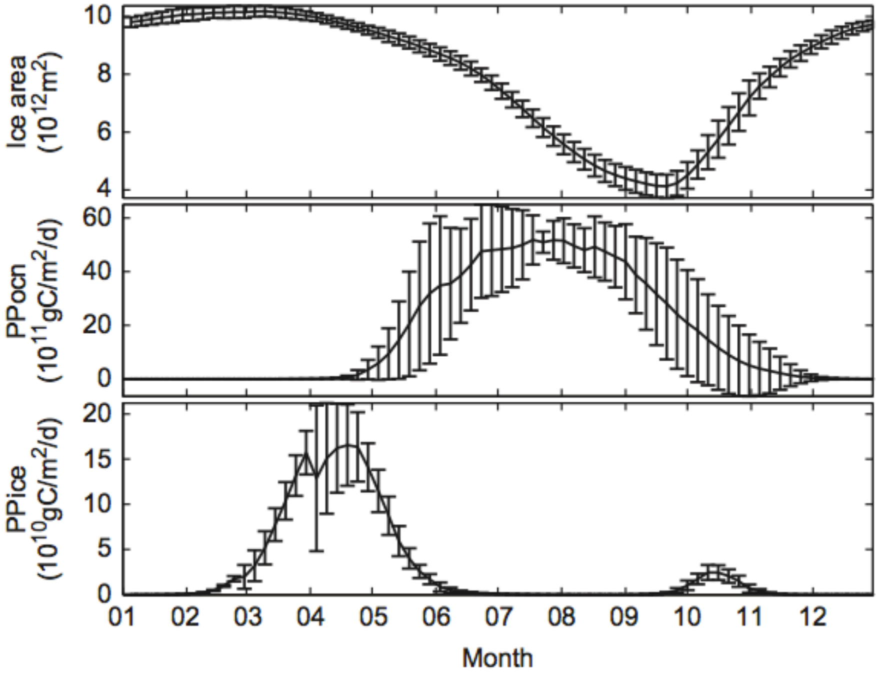
Repeated survey of 23 stations in the Canada Basin in summer. Figures from Li et al. (2009).

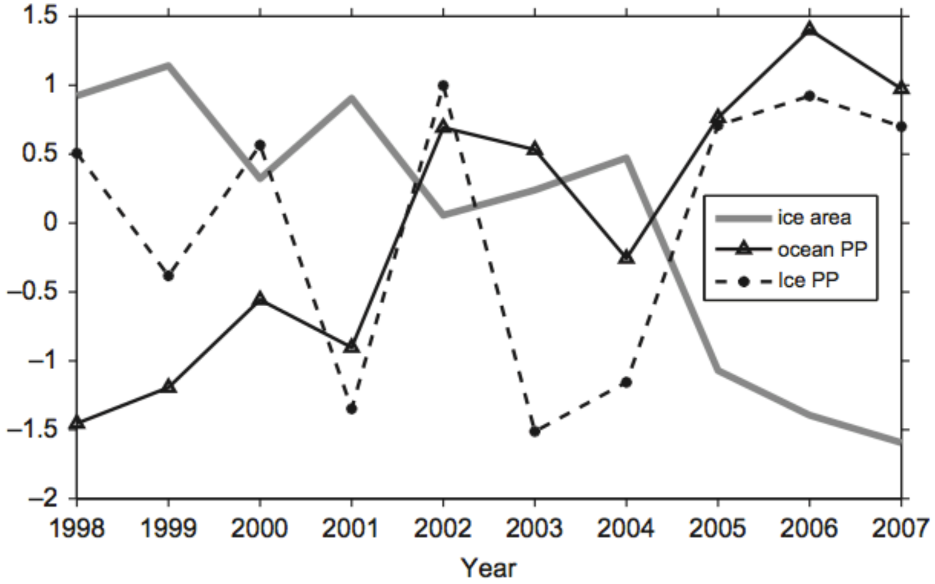


Gray symbols – upper ocean
Open symbols – deep ocean

Circles – upper ocean
Triangles – deep ocean

Coupled ice-ocean ecosystem modeling (LANL CICE-POP) results suggest that in the short term, ice algal production may increase.





- (Above right) Simulated annual sea ice primary production north of the Arctic Circle shows a lack of correlation with ice area (Jin et al. 2012). Not just result of thinner ice.

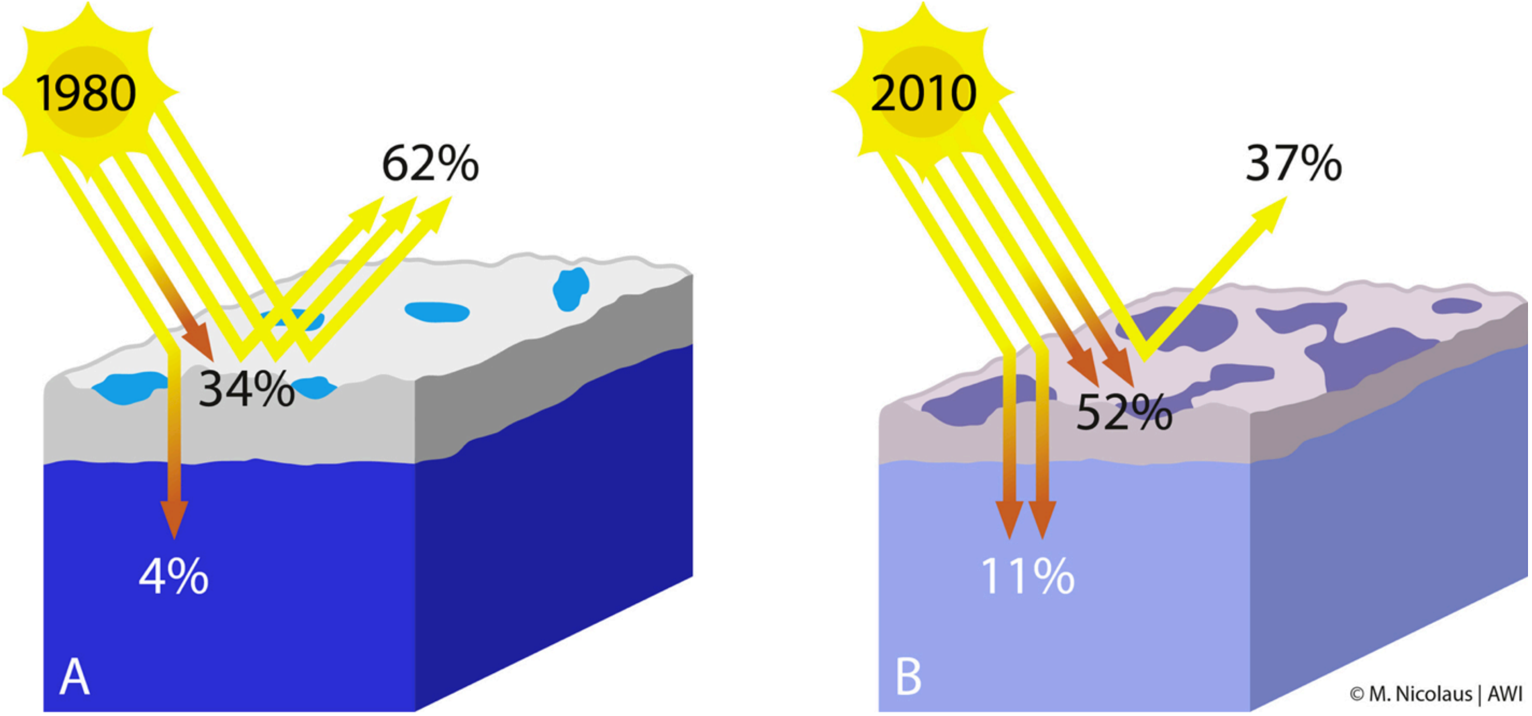
- Model results of Tedesco et al. (2012) suggest mild climate change may increase ice algal production at the expense of phytoplankton production “because the melt of sea ice will occur earlier in the season when light is less favorable to sustain the growth”.

Ice thickness

- vertical exchange of biogeochemical material

- light available for ice algae and phytoplankton under the ice

The growing coverage of the ice by darker melt ponds increases the share of sunlight, which is transmitted through the sea ice.



See Nicolaus et al. GRL, 2008.

Arrigo et al. (2012) observed a massive phytoplankton bloom that had developed beneath the 0.8- to 1.3-m-thick first-year sea ice on the Chukchi Sea continental shelf.

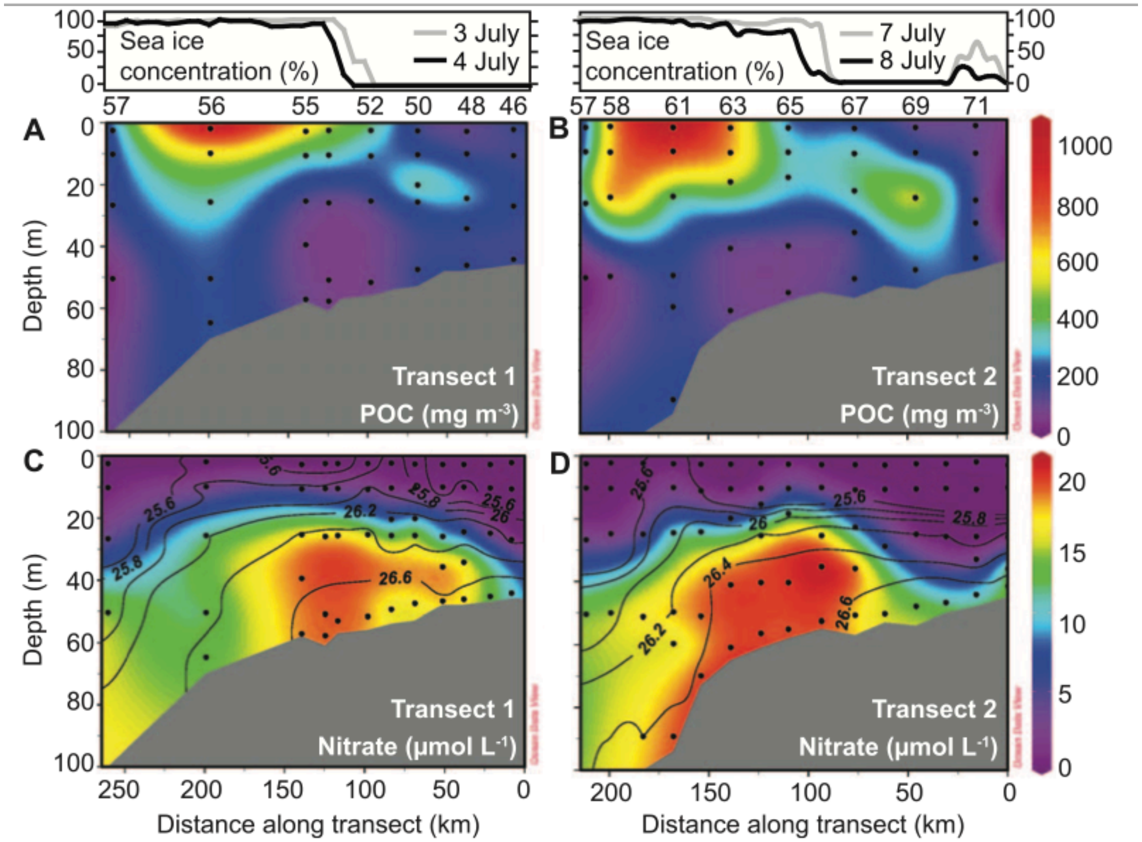
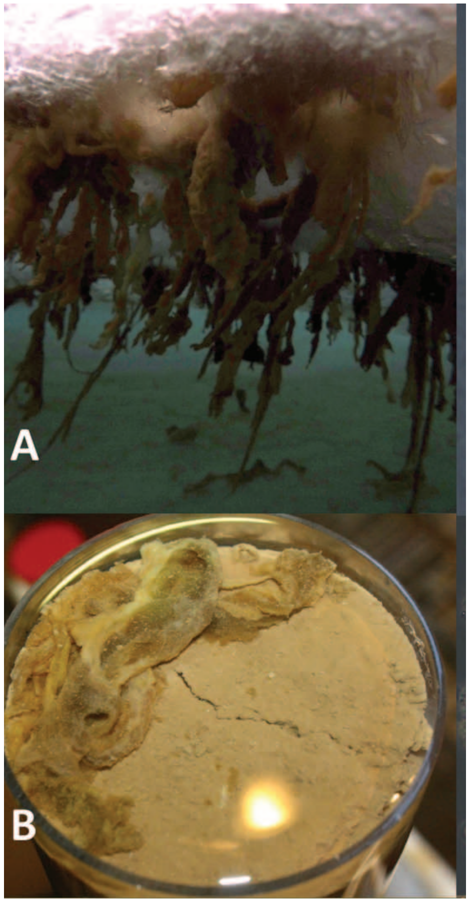


Fig. 1. Under-ice phytoplankton bloom observed during ICESCAPE 2011. (**A**) Particulate organic carbon (POC) and (**C**) nitrate from transect 1. (**B**) POC and (**D**) nitrate from transect 2. Sea ice concentrations and station numbers are shown above (A) and (B); black dots represent sampling depths; black lines denote potential density.

Figures from Arrigo et al. (2012).

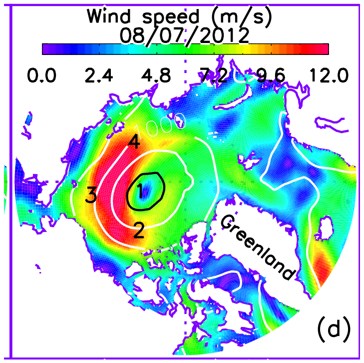
Boetius et al. (2013) observed deposition of significant ice algal biomass (ave = 9 g C m^{-2}) to the deep-sea floor of the Central Arctic basins.

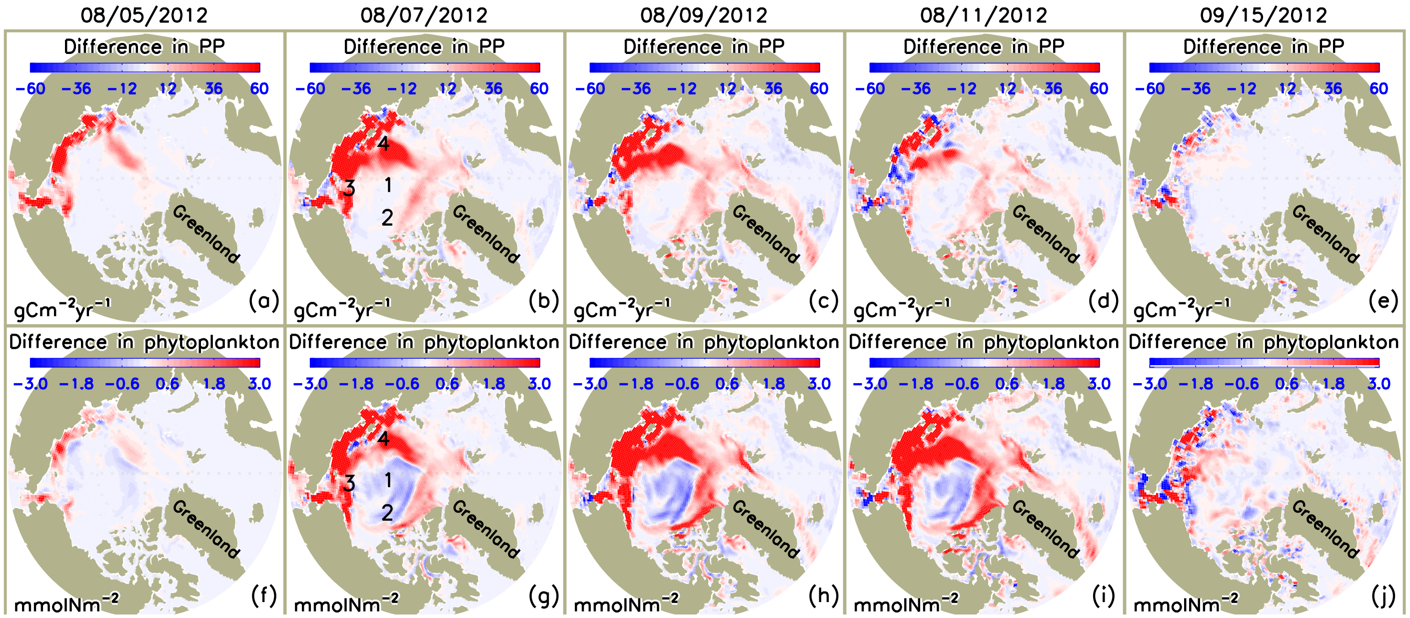
COVER Accumulation of algal biomass under thinning Arctic sea ice (image diameter ~25 meters). This photograph was taken on 17 September 2012 in the central Arctic basin at 85°30'47"N, 59°54'11"E, from the bridge of the research vessel Polarstern. Here, the central ice floe is surrounded by a green cloud of sub-ice diatoms.
Photo: Stefan Hendricks, Alfred Wegener Institute, Expedition IceArc (ARK27-3)



M. Arctica aggregations. Strands (~20cm) of *Melosira* (A) under Ice and (B) recovered from sea floor (Boetius et al. 2013).

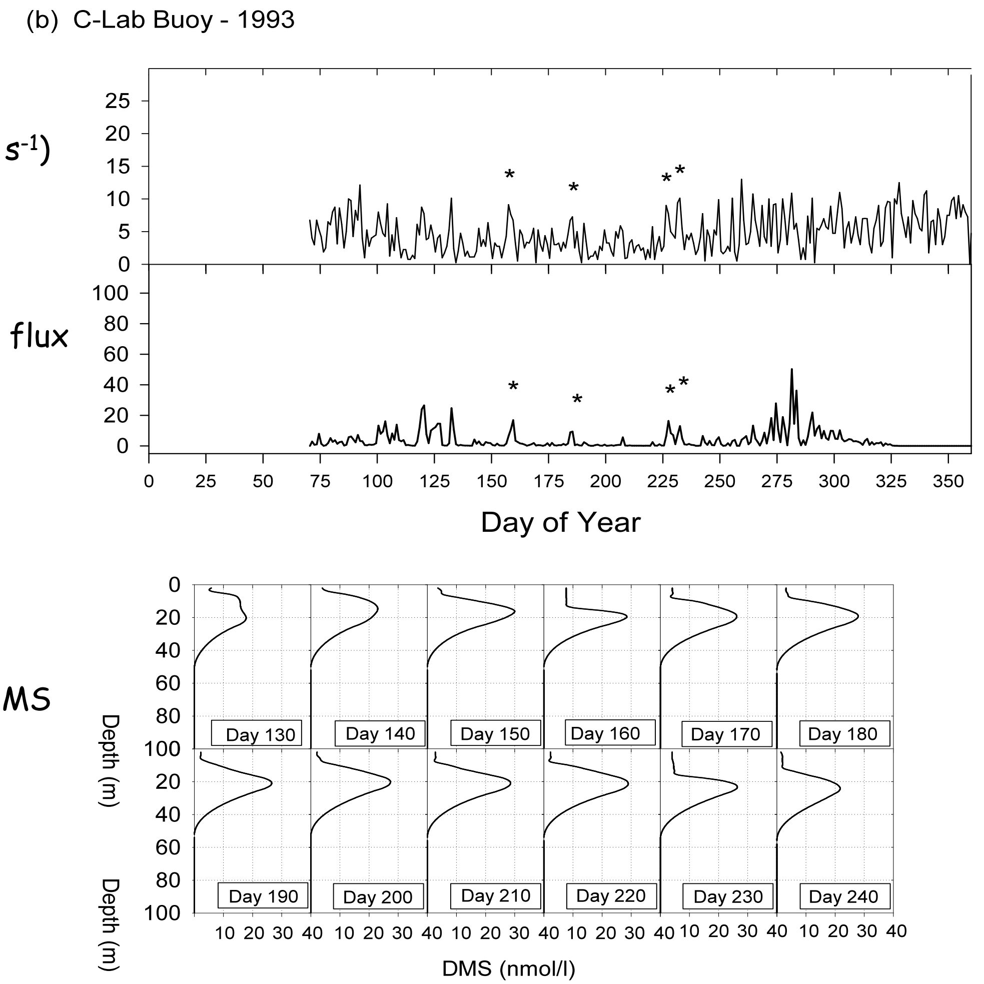
Using pan-Arctic coupled biophysical model (BIOMAS), Zhang et al. (2014) show "positive impact of cyclones on the marine ecosystem of the Arctic".





Difference between control run and run without cyclone influence (Zhang et al. 2014).

Model results suggest that short intervals between wind events may not allow sufficient time to recharge the DMS(P) pools near the surface resulting in DMS emissions smaller than expected.



Measured wind speed (m s^{-1})

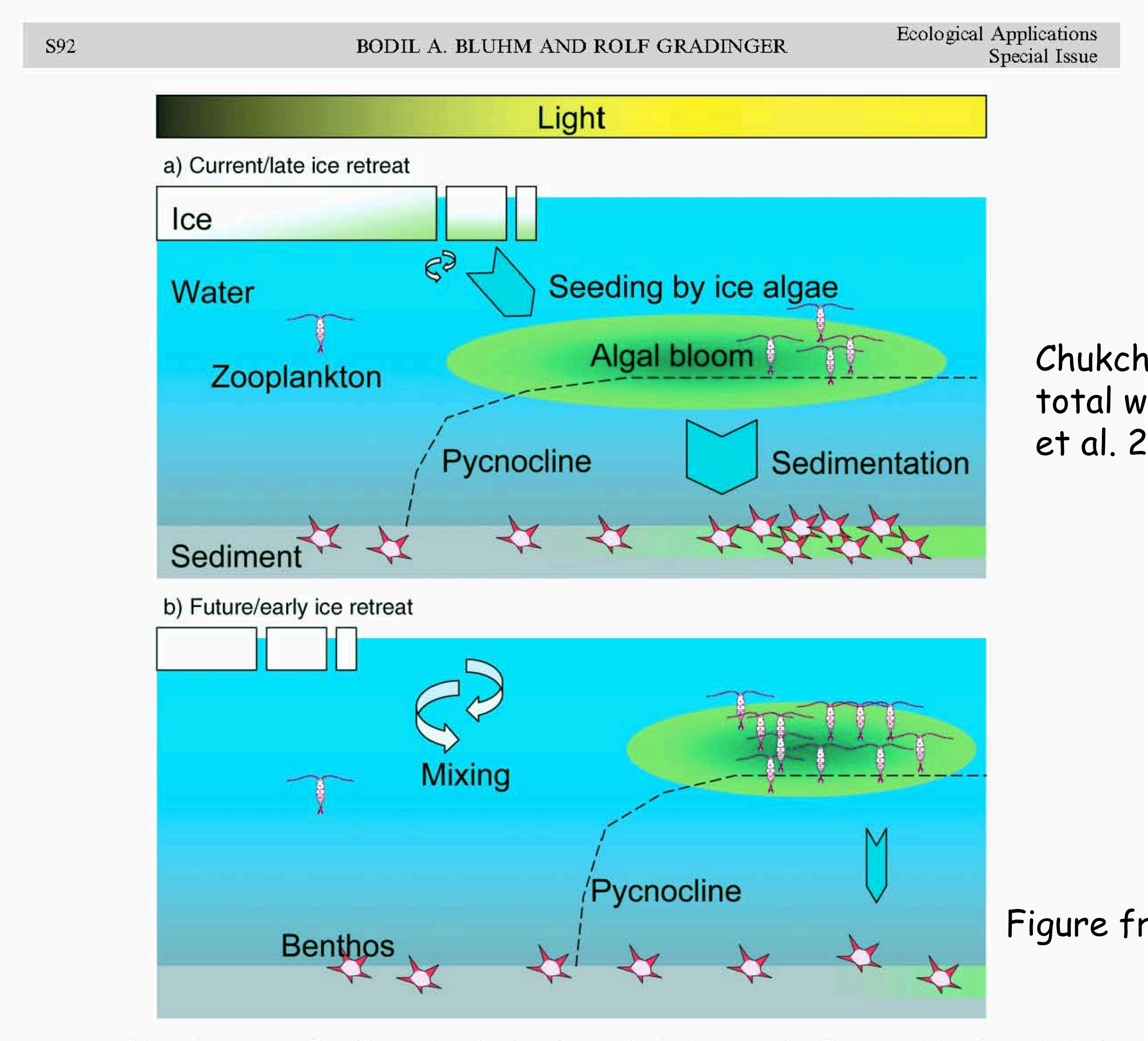
Simulated DMS sea-to-air flux (μmol m^{-2} d^{-1})

Simulated seawater DMS concentration (nM)

Jodwalis (Deal) et al. 2001

Manizza et al. (2013) suggest that the decrease in sea ice cover would cause a MLD deepening (via wind-driven mixing) that would "in theory promote the entrainment of DIC-rich water into the upper ocean and hence lower the potential CO_2 uptake".

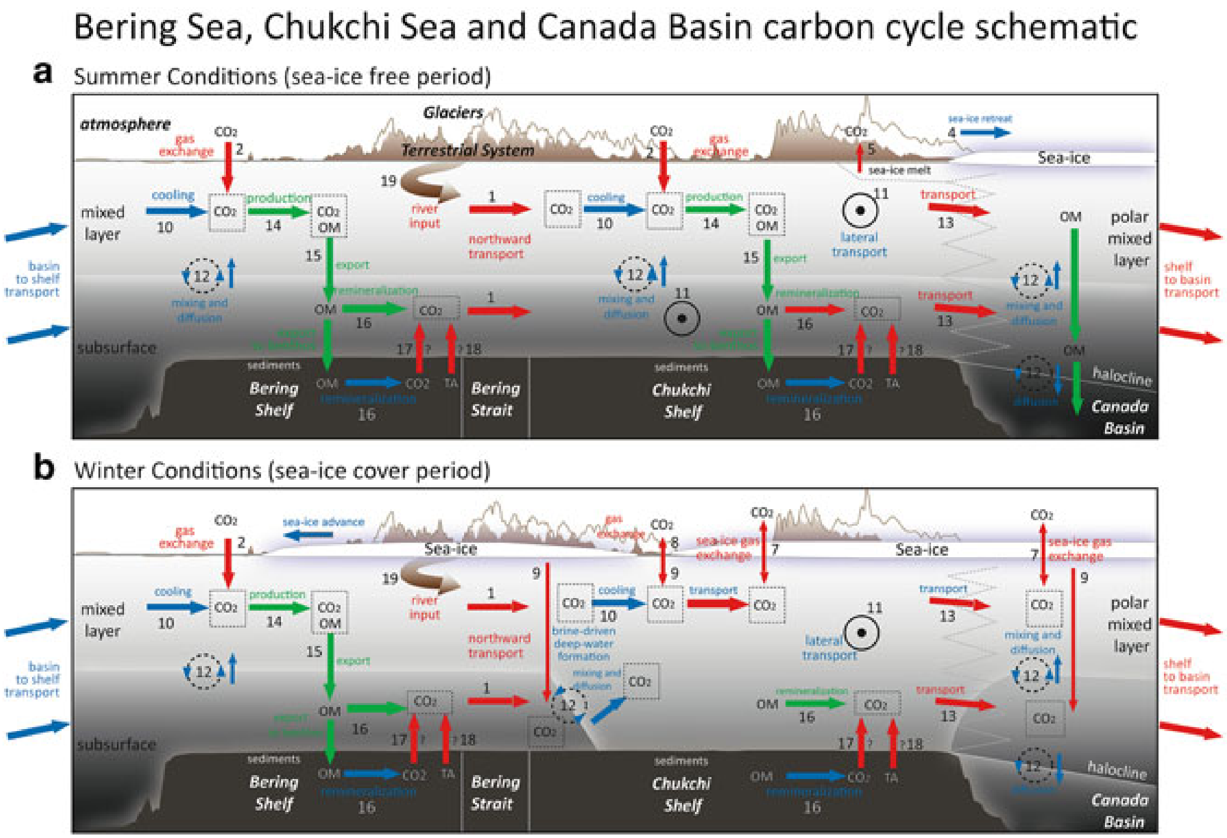
Timing of ice retreat impacts phytoplankton bloom timing and shapes the structure and function of food web.


S92 BODIL A. BLUHM AND ROLF GRADINGER Ecological Applications Special Issue

Chukchi Sea 2002-2004 only 44% of total water column PP grazed (Campbell et al. 2008).

Figure from Bluhm and Gradinger (2008)

Changes in freeze up will potentially impact the C cycle.



Bering Sea, Chukchi Sea and Canada Basin carbon cycle schematic

a Summer Conditions (sea-ice free period)

b Winter Conditions (sea-ice cover period)

Figure from Mathis et al. (2014).

4 exposure of surface water to the atmosphere due to sea-ice retreat and melting

5 localized air-sea gas exchange from surface water highly influenced by sea-ice melt

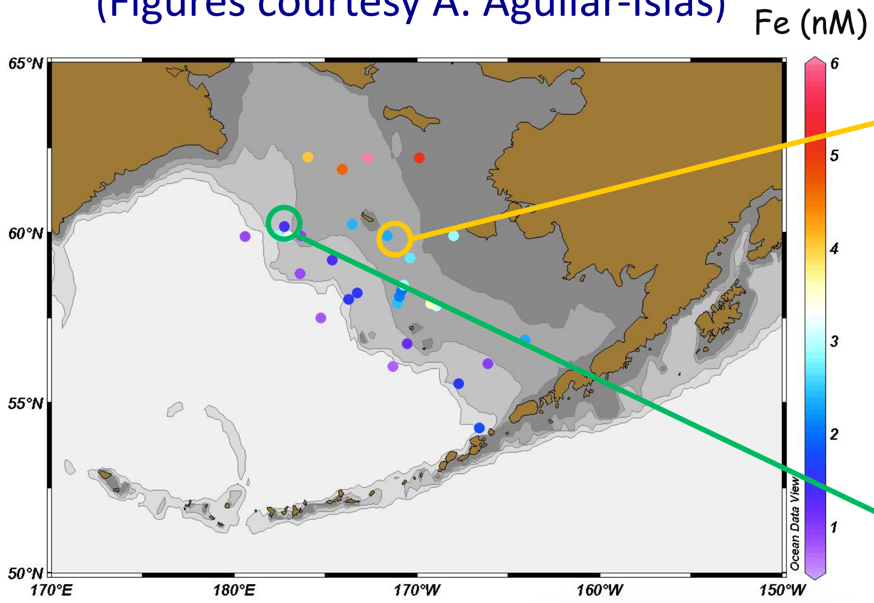
7 air-sea gas exchange through sea-ice

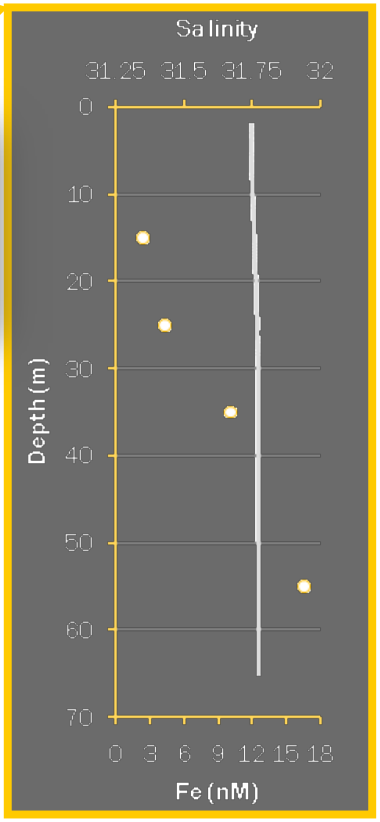
8 winter air-sea gas exchange in leads and polynyas

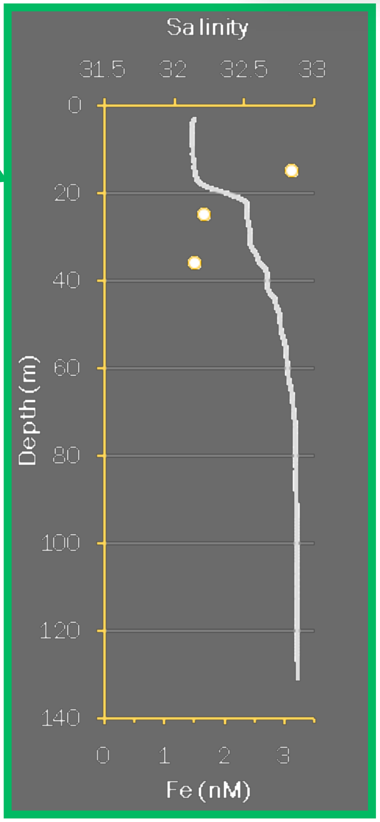
9 inorganic carbon flux due to brine-rejection during deep-water formation in fall and winter

Sea ice-derived dissolved iron influences the spring algal bloom in the outer shelf and shelf break of the Bering Sea.

(Figures courtesy A. Aguilar-Islas)





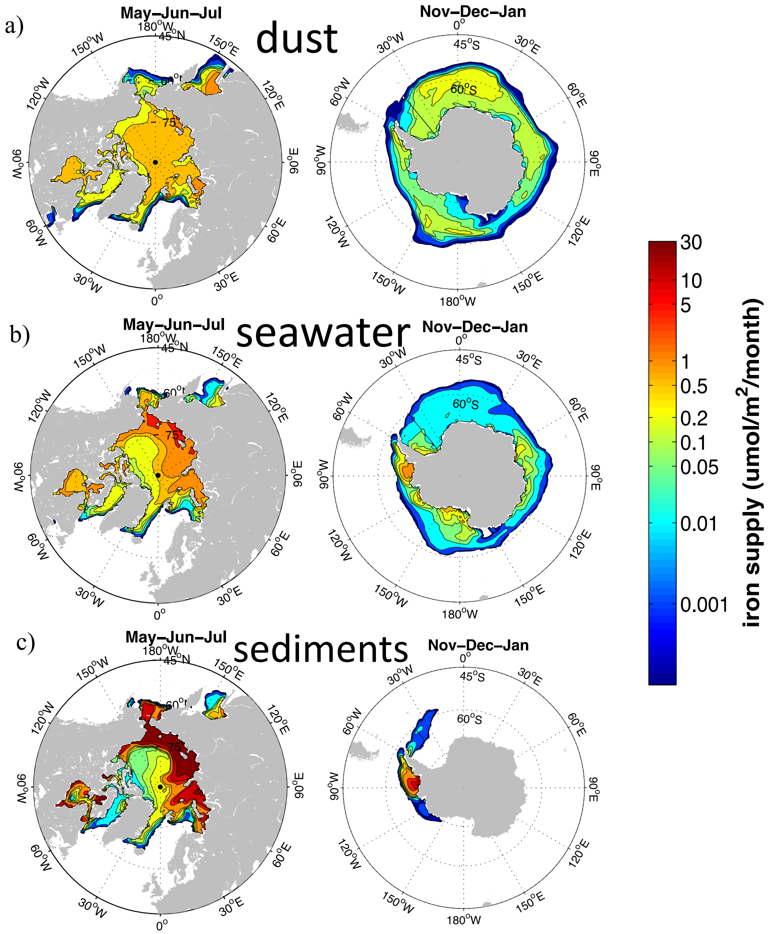


- In the outer shelf and shelf break melting sea ice provides additional iron for the complete assimilation of available nitrate by large cells (Aguilar-Islas et al. 2008).

- In the mid and inner shelf sedimentary iron inputs can reach surface waters during spring (Aguilar-Islas et al. 2008).

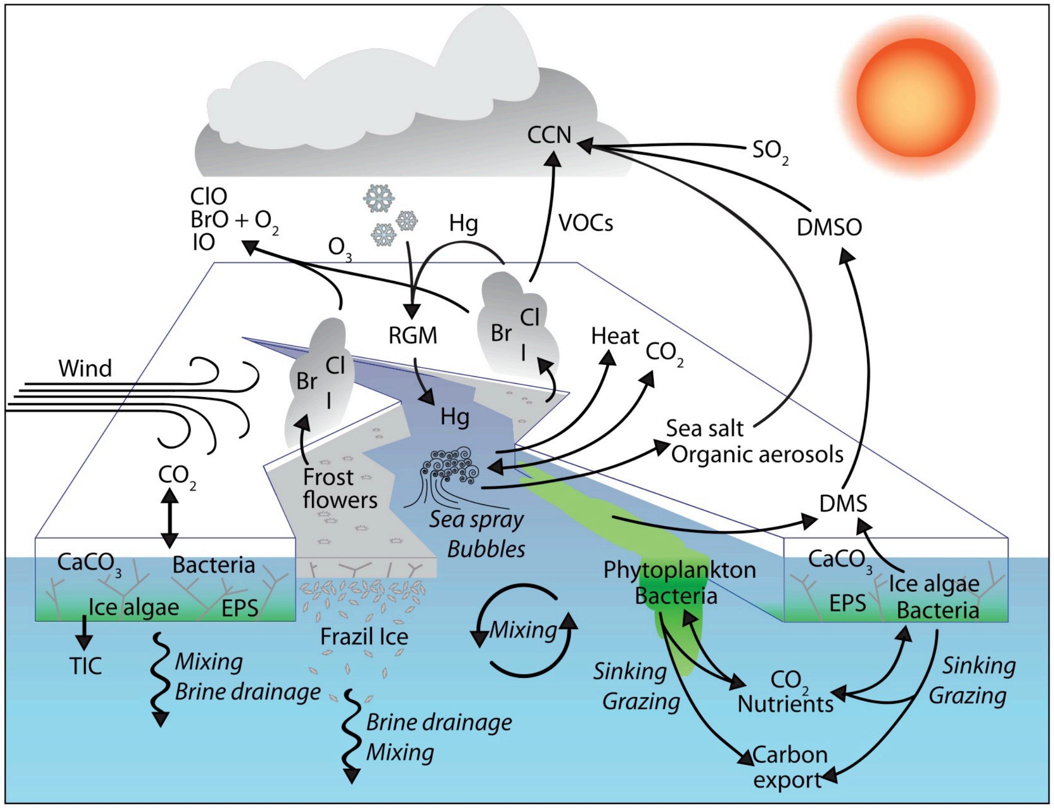
Coupled ice-ocean modeling studies provide insights into the role of sea ice in Fe cycling and its importance to phytoplankton growth.

- Sea ice is important for transporting iron from coastal to open ocean regions in Southern Ocean and Central Arctic (Wang et al. Biogeosciences Discussions, 2014)
- Storage and release of Fe in sea ice may initiate phytoplankton blooms in the marginal ice zones of the Southern Ocean (Lancelot et al., *Biogeosciences*, 2009)



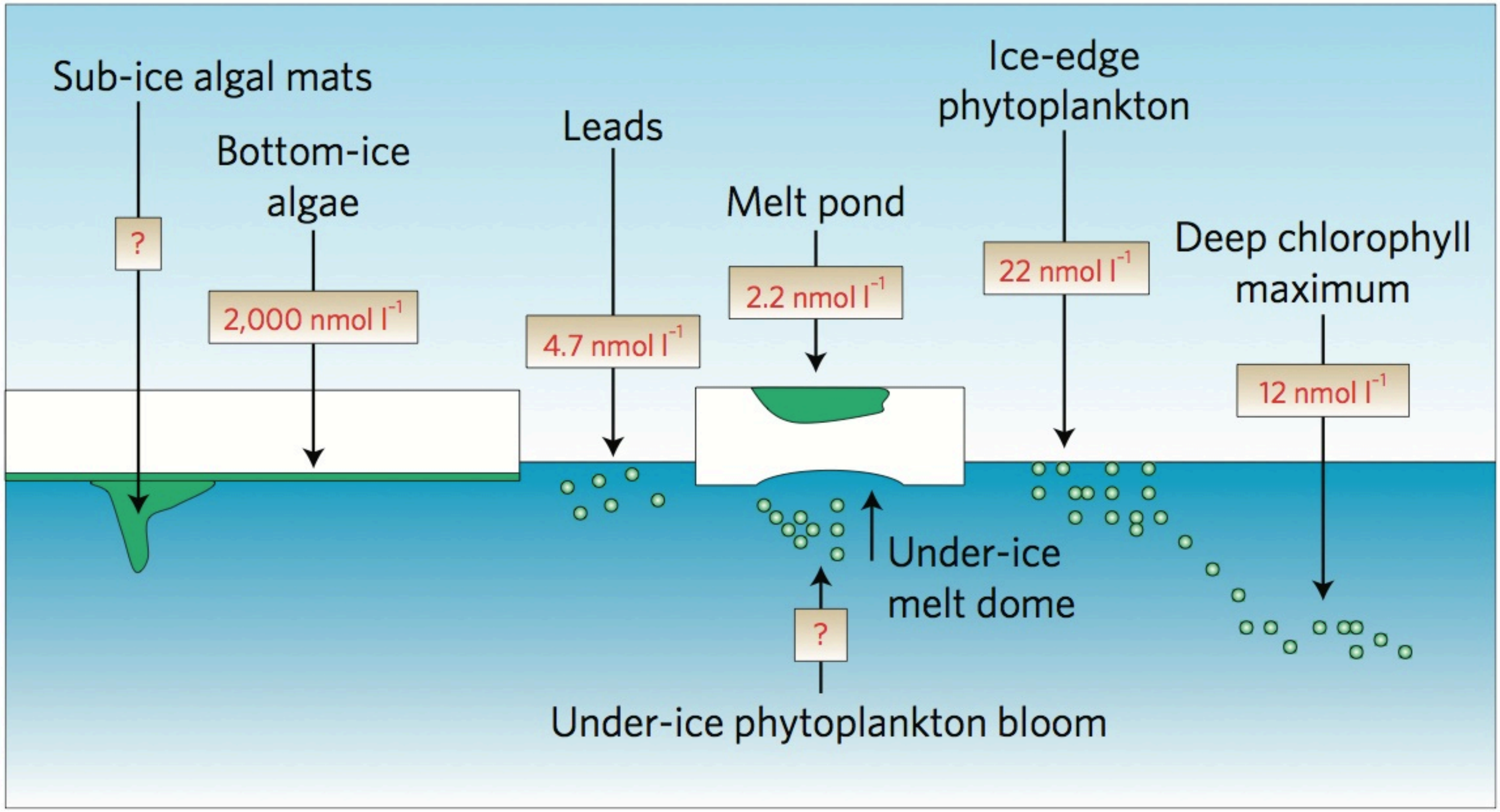
Iron supply from sea ice contributed by different iron sources in summer (Wang et al. 2014).

Tight physical, chemical, and biological interactions between ocean, sea ice, and atmosphere drive large scale biogeochemical cycling.



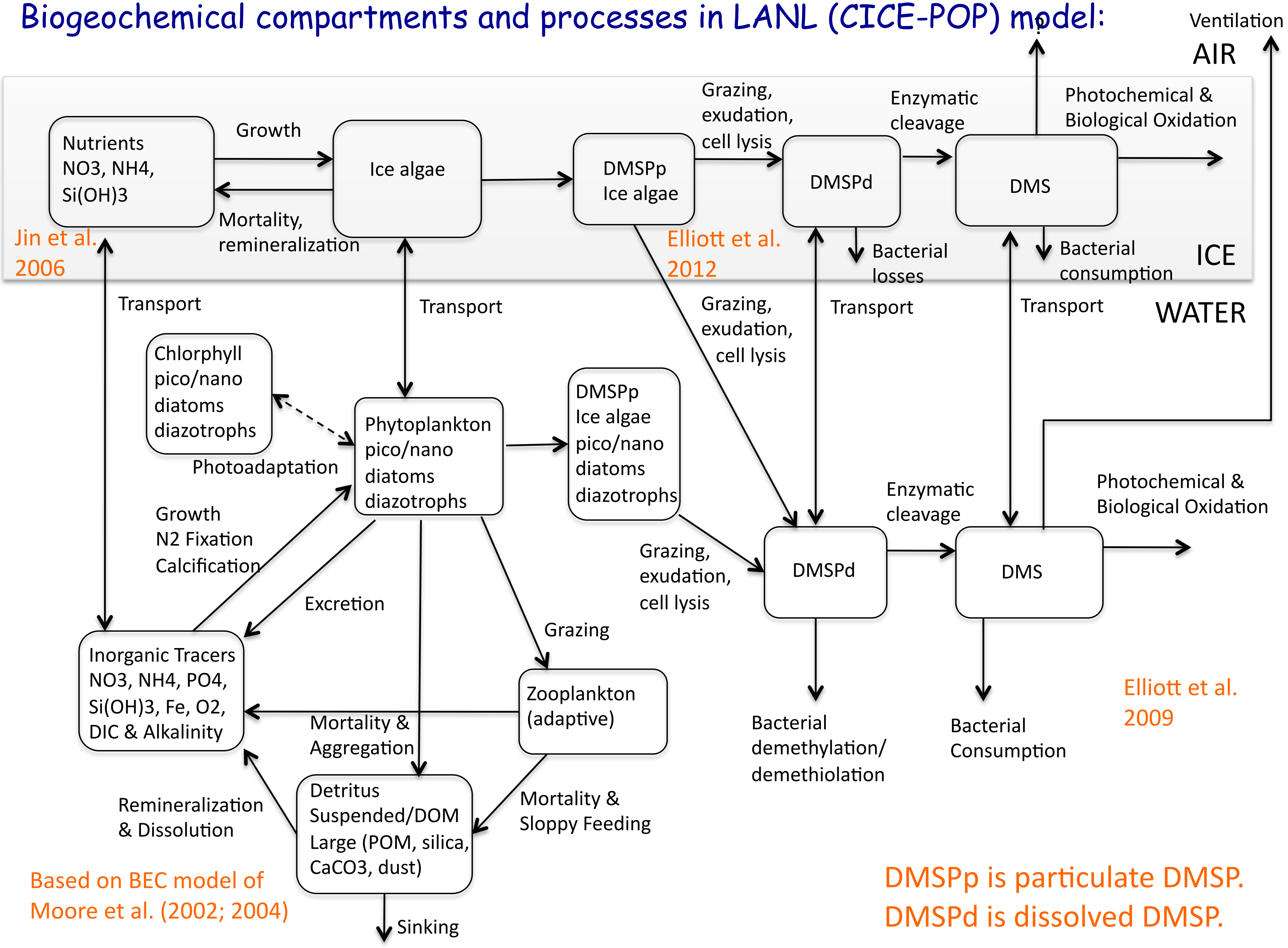
Simplified schematic of some biogeochemical exchange processes in sea ice regions. Figure from Shepson et al. (2012).

During spring and summer, high levels of DMS can accumulate at the bottom of the ice, in leads, and in the water column at the ice edge.



Values in boxes represent the maximum concentrations of DMS reported in each of these habitats. Figure from Levasseur (*Nature Geoscience*, 2013).

Biogeochemical compartments and processes in LANL (CICE-POP) model:



Ventilation

AIR

ICE

WATER

Nutrients
NO3, NH4,
Si(OH)3

Growth

Ice algae

Mortality,
remineralization

DMSPp
Ice algae

Grazing,
exudation,
cell lysis

DMSPd

Enzymatic
cleavage

DMS

Photochemical &
Biological Oxidation

Bacterial
losses

Bacterial
consumption

Jin et al.
2006

Elliott et al.
2012

Transport

Transport

Grazing,
exudation,
cell lysis

Transport

Transport

Chlorphyll
pico/nano
diatoms
diazotrophs

Photoadaptation

Phytoplankton
pico/nano
diatoms
diazotrophs

DMSPp
Ice algae
pico/nano
diatoms
diazotrophs

Enzymatic
cleavage

Photochemical &
Biological Oxidation

Growth
N2 Fixation
Calcification

Excretion

Grazing,
exudation,
cell lysis

DMSPd

DMS

Grazing

Inorganic Tracers
NO3, NH4, PO4,
Si(OH)3, Fe, O2,
DIC & Alkalinity

Mortality &
Aggregation

Zooplankton
(adaptive)

Bacterial
demethylation/
demethiolation

Bacterial
Consumption

Elliott et al.
2009

Remineralization
& Dissolution

Detritus
Suspended/DOM
Large (POM, silica,
CaCO3, dust)

Mortality &
Sloppy Feeding

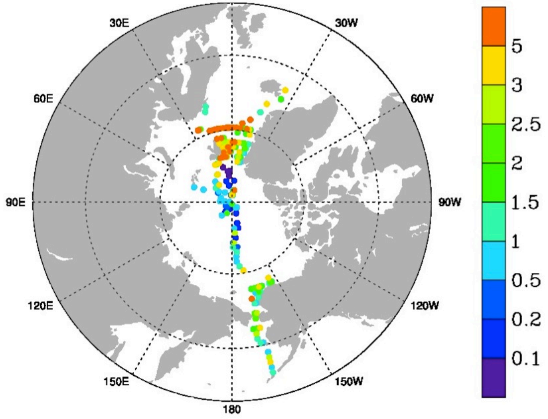
Sinking

Based on BEC model of
Moore et al. (2002; 2004)

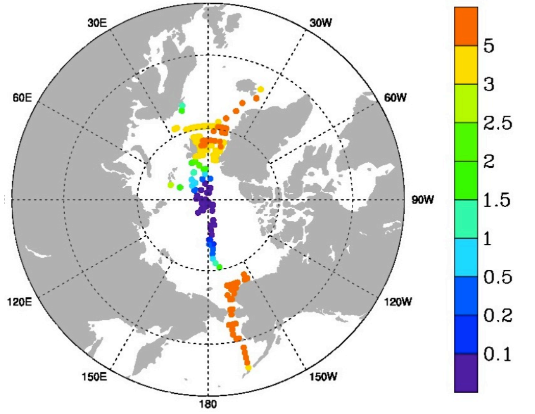
DMSPp is particulate DMSP.
DMSPd is dissolved DMSP.

Sea surface DMS concentrations in summer (June-July-Aug) for years 1958-2009

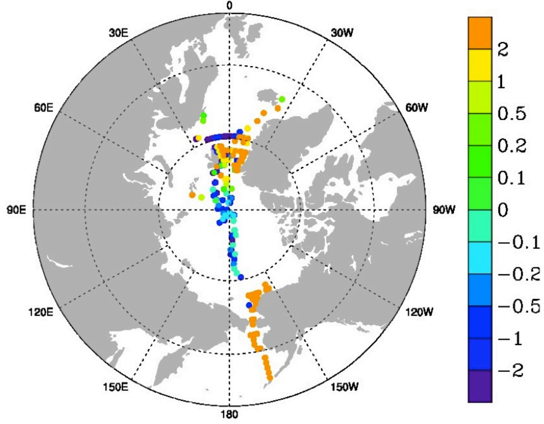
Gridded Observations (Lana et al. 2011)



Modeled Values



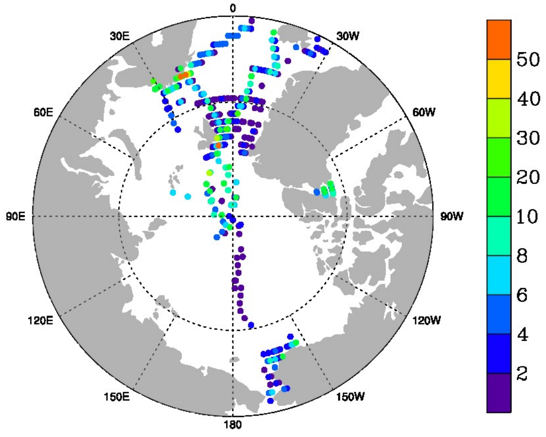
Modeled – Gridded Observations



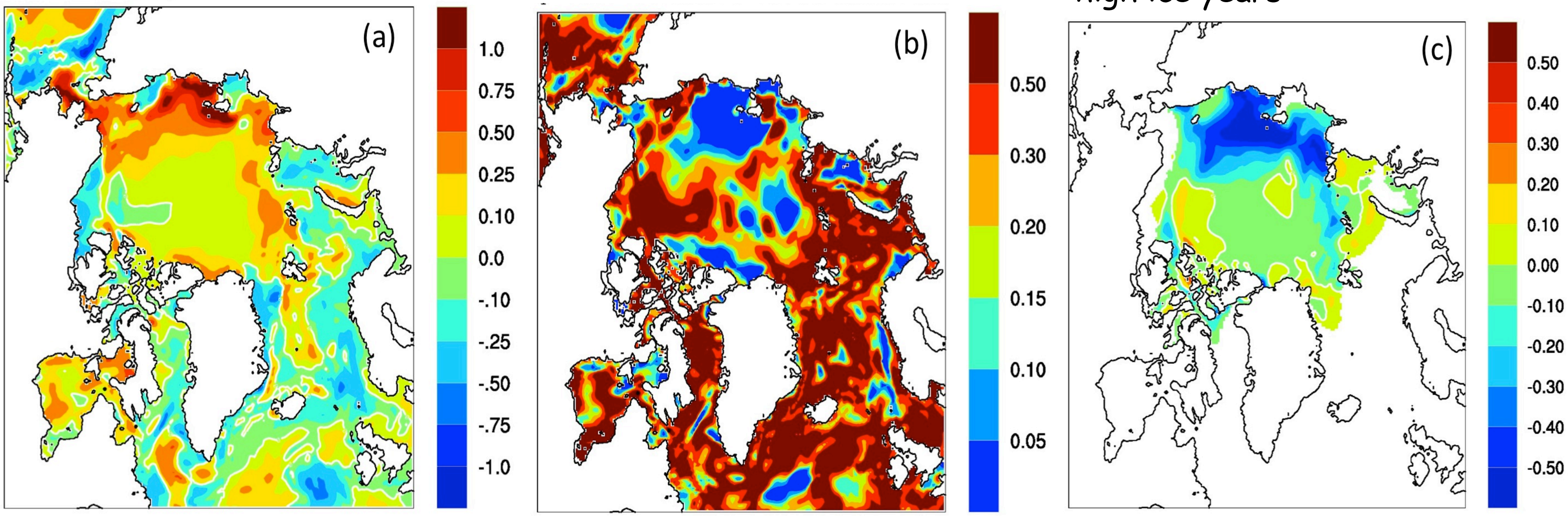
Distribution of seawater DMS concentration data from NOAA PMEL DMS database.

http://saga.pmel.noaa.gov/dms/

DMS data density (number)



Model results show significant surface seawater DMS increases correspond to areas of substantial sea ice loss.



DMS (nM) for mean of low ice years minus mean of high ice years

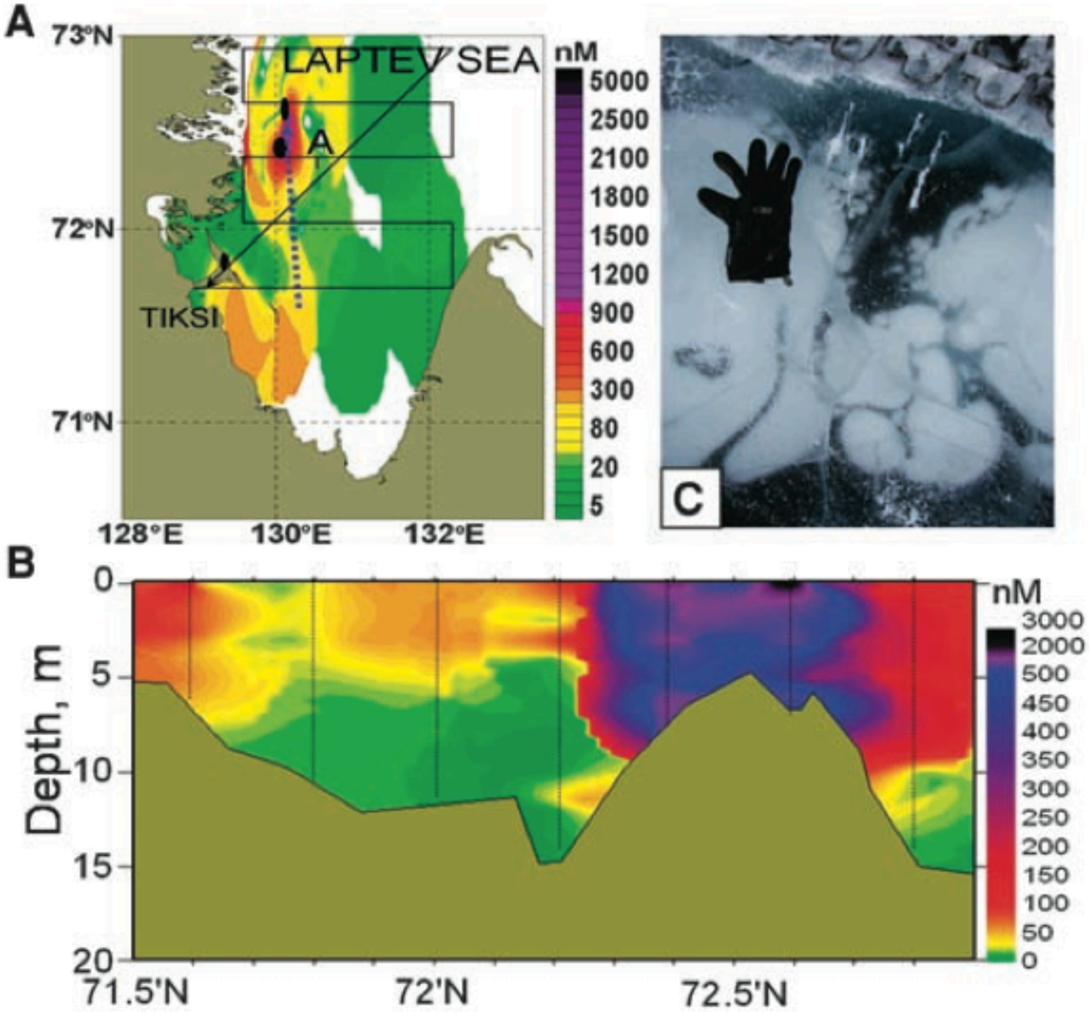
P-value of student t-test for DMS

Ice concentration difference for mean of low minus mean of high ice years

low (2002, 2003, 2005-2007)
high (1998-2001, 2004)

Figures from Deal et al. (in preparation).

Methane stored in the Siberian shelf is being vented to the winter atmosphere through polynyas and then at ice break-up. Bubbles of gas entrapped within the sea ice were "ubiquitously observed" (Shakhova et al. 2009).



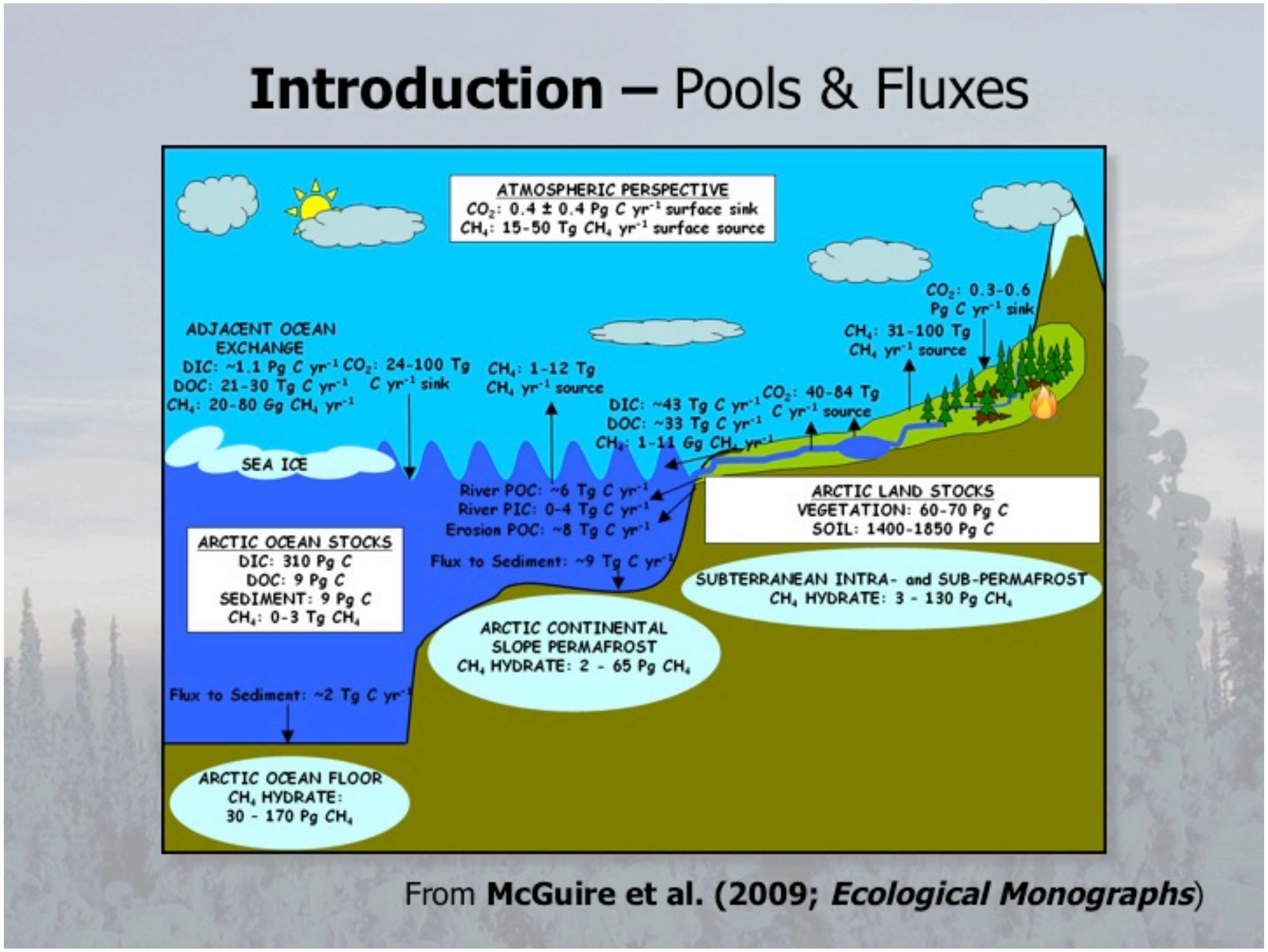
Wintertime observations of dissolved CH_4 (A) Beneath the ice, (B) Vertical distributions along transect, and (C) bubbles trapped in ice (Shakhova et al. 2009)

Complicating factors…

Ocean acidification further complicates the effects of warming and reduced sea ice on marine ecosystems.

Expanded exploration and development.

The contemporary state of the carbon budget of the northern cryosphere regions.



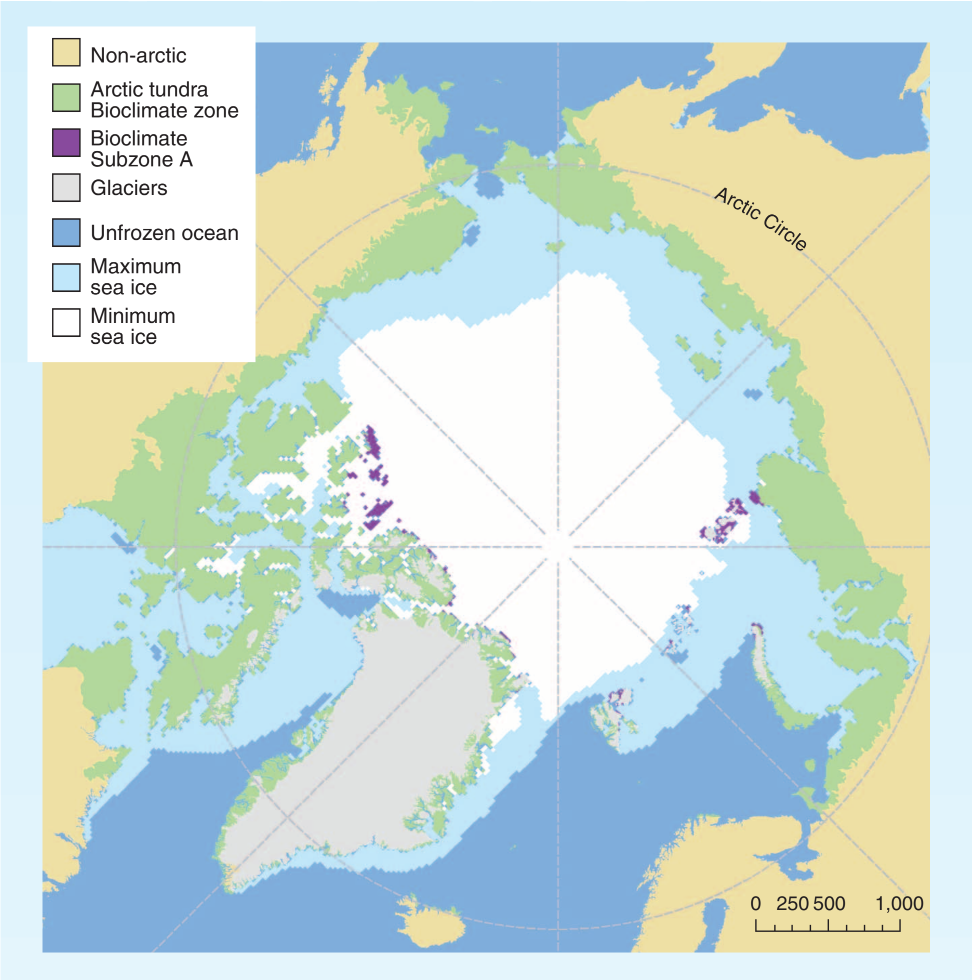
Introduction – Pools & Fluxes

From **McGuire et al. (2009; *Ecological Monographs*)**

Current estimates of ocean sink of atmospheric CO_2:

66–199 Tg C/yr
(Bates and Mathis, 2009)

The extent and location of Arctic tundra bioclimate zone are closely related to maximum and minimum of sea ice (Post et al. 2013, Science).



The mean (1982 to 2010) maximum ice boundary (50% ice cover) is shown for week 22 (1 June), and the minimum ice boundary (50% ice cover) is shown for week 35 (1 September).

Sea ice decline is associated with increases in terrestrial productivity across the Arctic (Post et al., 2013).

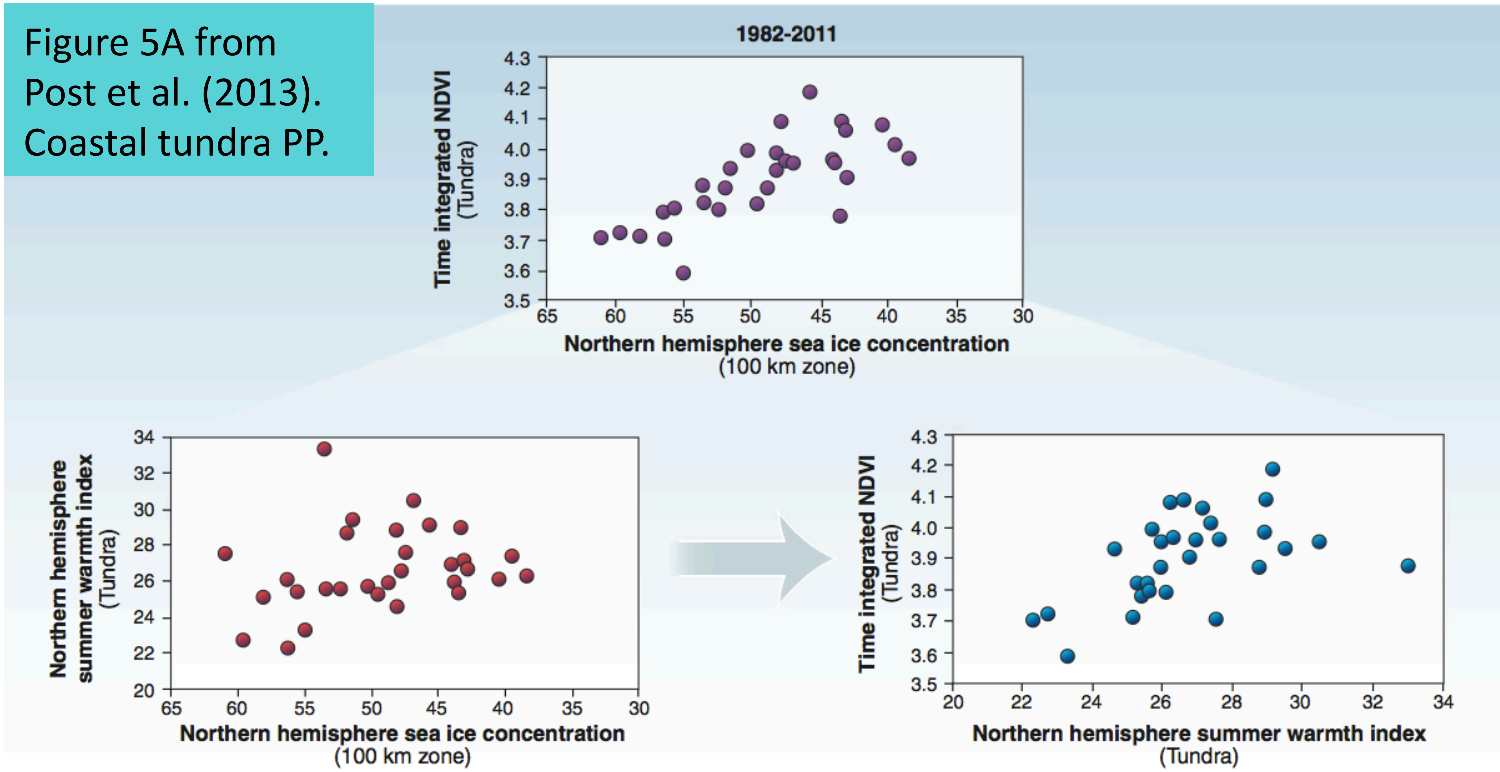


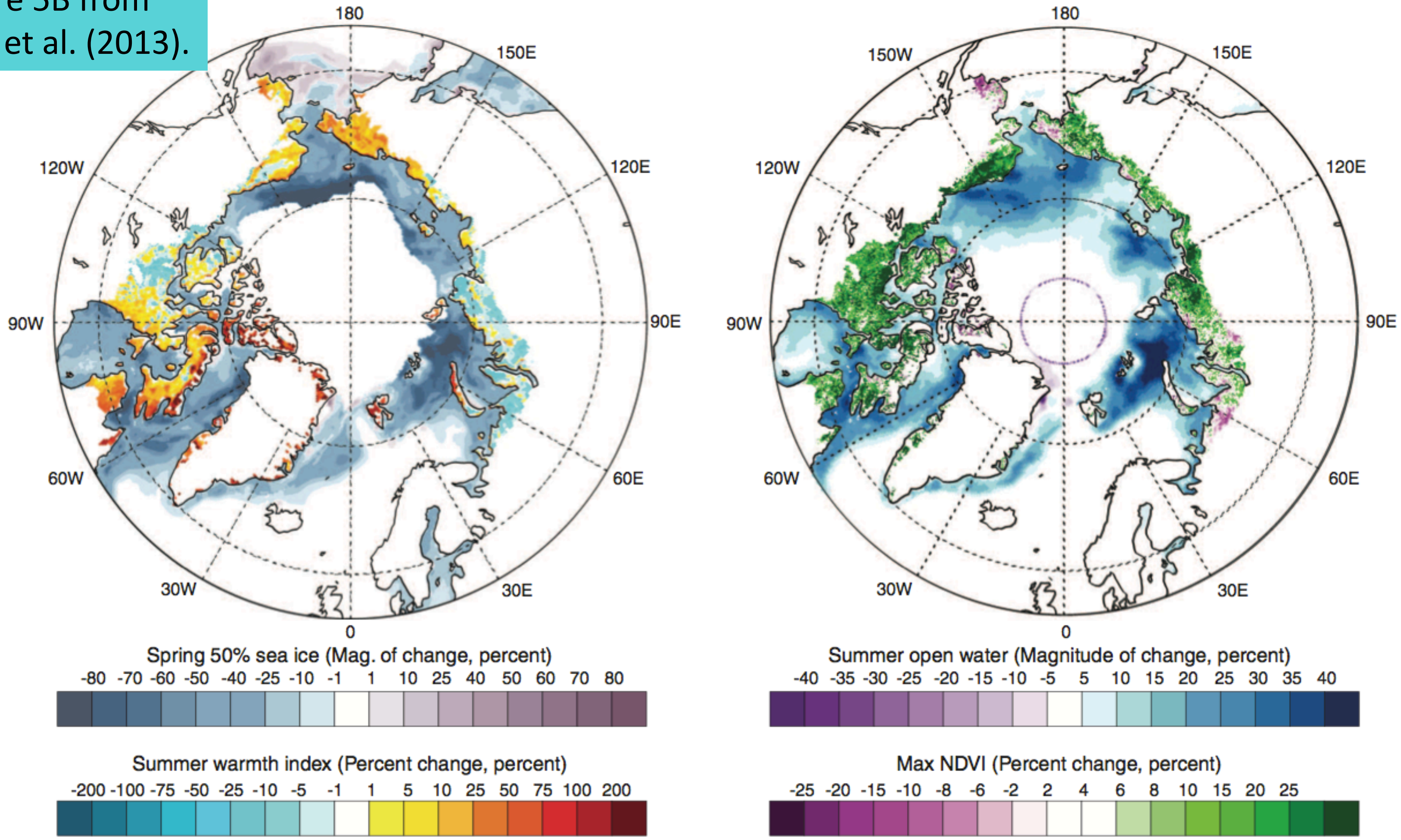
Figure 5A from Post et al. (2013). Coastal tundra PP.

SWI – Summer Warmth Index

NDVI - Difference between reflection of the near infrared light and absorption visible light gives the density of green vegetation.

“Pan-Arctic trends in SWI and NDVI very spatially across the Arctic, but almost all locations experienced an increase in maximum NDVI and an increase in summer open water”, Post et al. (2013).

Figure 5B from Post et al. (2013).



Modeling and measurements have found terrestrial C uptake and release linked to sea ice decline with the potential to alter carbon ecosystem flux (Post et al. 2013)

“Doubling of carbon uptake concordant with shrub increases in West Greenland between 2003 and 2010 (Cahoon et al. 2012).”

“Increases in arctic tundra methane emissions matching sea-ice fluctuations and trend for the period from 1979 to 2006 (Parmentier et al. 2012).”

“Link between sea-ice decline and the annual extent of tundra fires in Alaska (Hu et al. 2010).”

Challenges and Opportunities

Polar Oceans are poorly covered with observations, both physical and biogeochemical.

ESM's should prove essential to understanding and quantifying large-scale polar marine biogeochemical processes and feedbacks.

Future development and application of complex ocean ecosystem-biogeochemical models embedded in high-resolution ocean circulation models.

Paleoclimate studies are also relevant.

Big questions

How will patterns of biogeochemical sinks and sources change?

Will the Arctic Ocean remain a CO_2 sink?

Will Arctic Ocean PP increase or decrease in the future?

Will new (even unexpected) plankton types or ecosystems dominate?

What new and key feedbacks will emerge?