Modeling the carbon cycle in the polar oceans :

Present and Future Challenges

Manfredi Manizza

Scripps Institution of Oceanography
University of California - San Diego

mmanizza@ucsd.edu

Outline

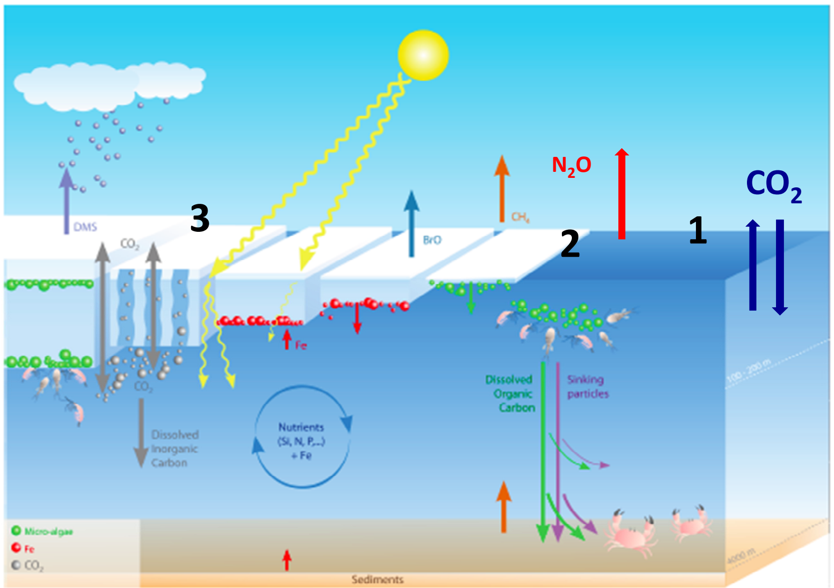
1) Carbon cycle in the polar oceans
   and the role of (changing) sea-ice

2) BGC key-processes involving Sea-Ice

3) Models : Status and Gaps to fill

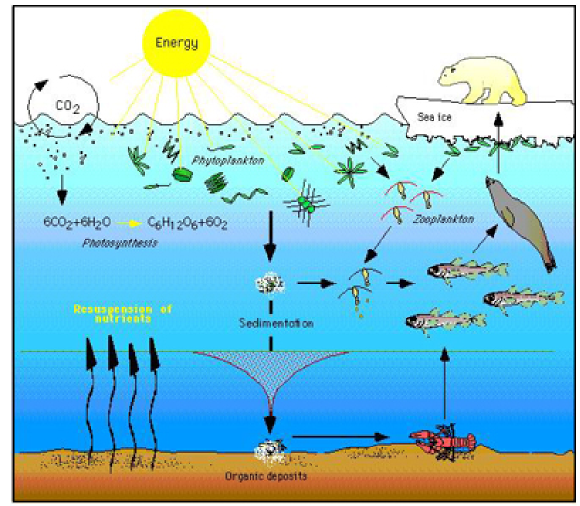
4) Conclusions

Life in a (fizzy) freezer



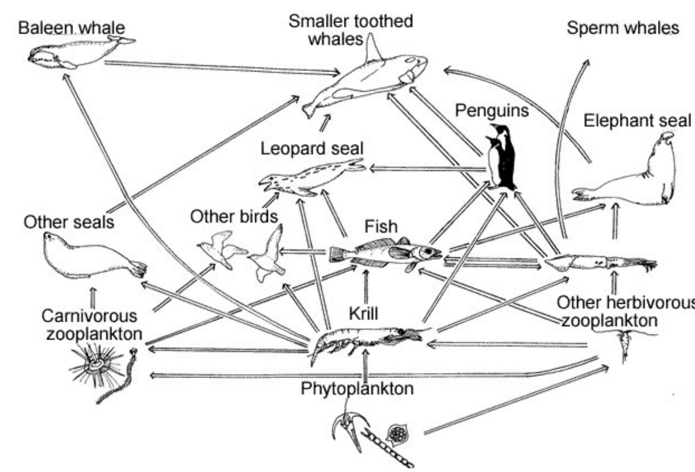
Modified from Vancoppenolle *et al*. (2013)

Arctic Marine Food Web



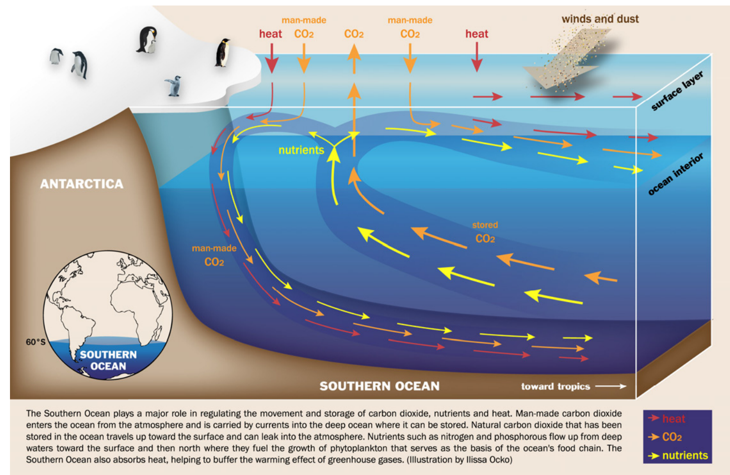
NOAA / Drawn by Chrostopher Krembs

1) **Open Water**
2) **Marginal Ice Zone**
3) **Ice-covered zone**

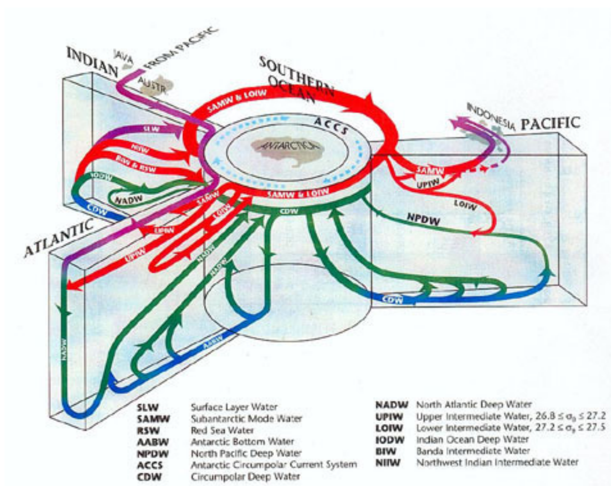


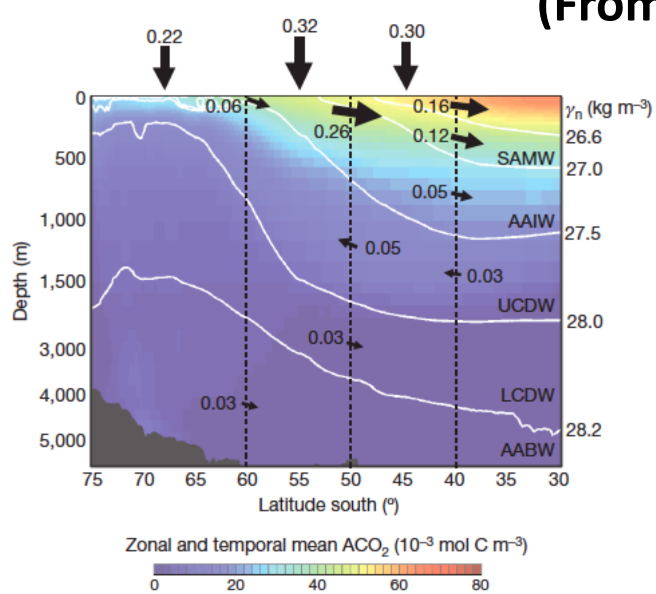
Southern Ocean Food Web

Southern Ocean Carbon Cycle



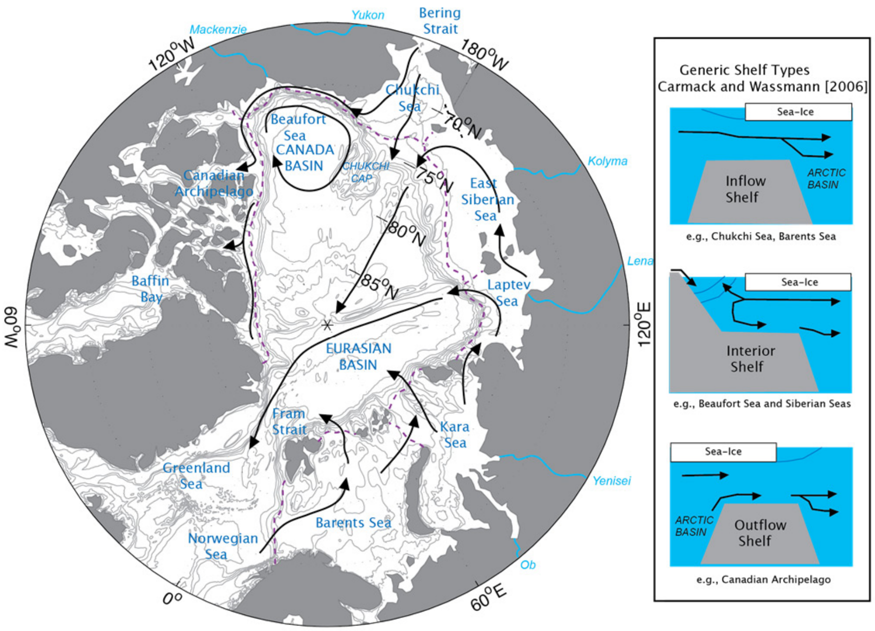
(From Princeton U.)





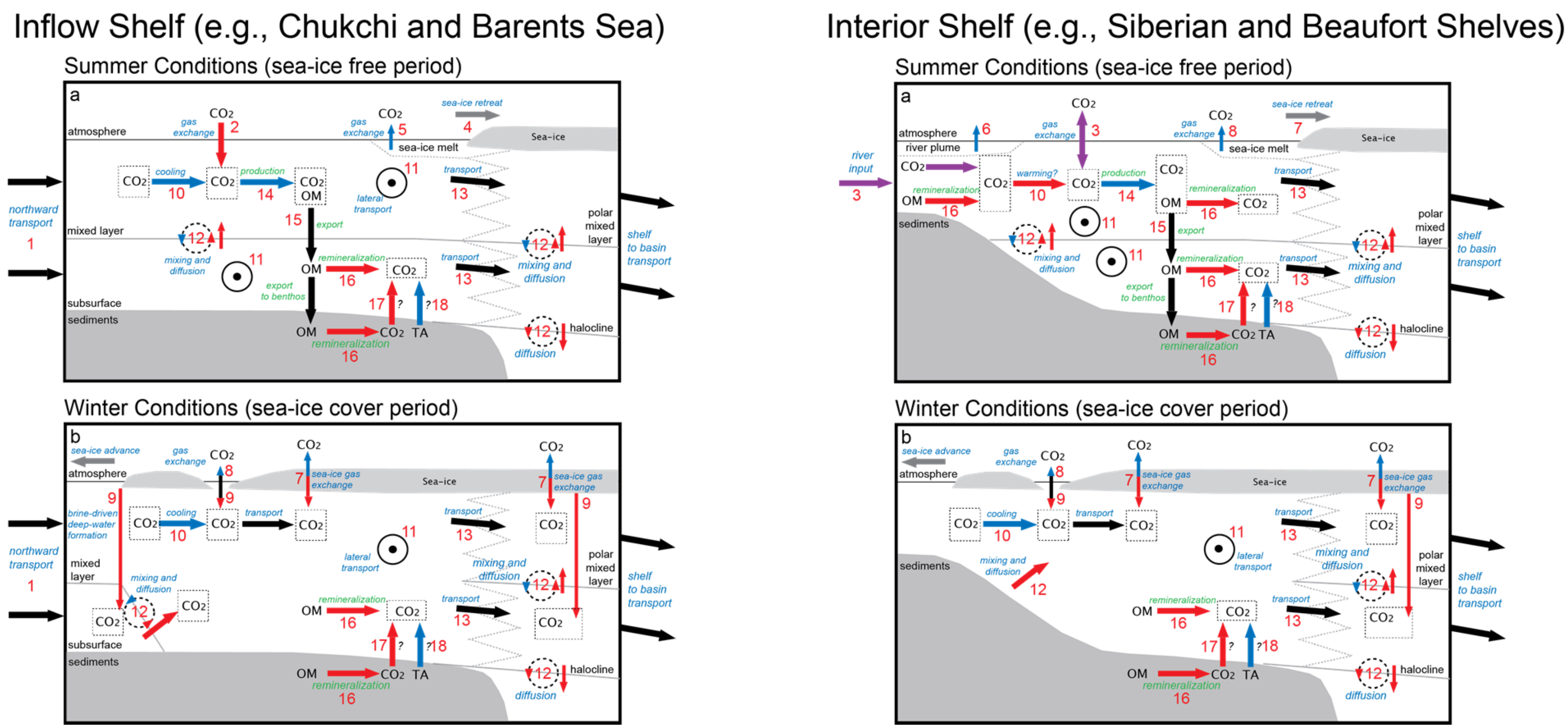
Ito *et al*. (2010)
(PgC yr^{-1})

Arctic Ocean Carbon Cycle – I



Bates & Mathis (2009)

Arctic Ocean Carbon Cycle – II



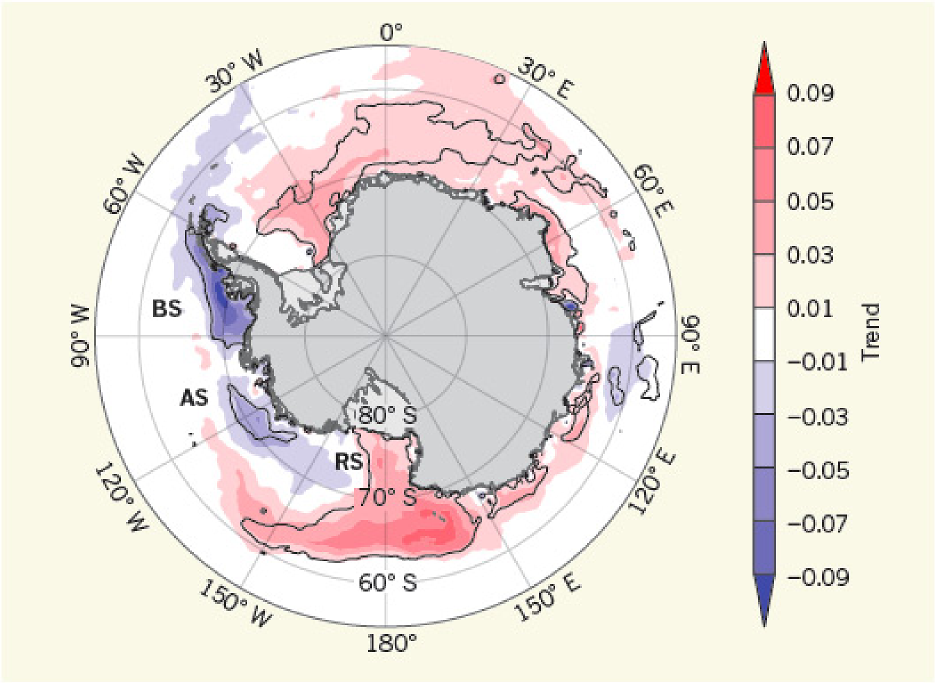
Bates & Mathis (2009)

Polar Oceans Carbon Cycle

Arctic Ocean	Southern Ocean
Smaller Area	Bigger Area
CO_2 Uptake : **0.12 - 0.06 PgC yr^{-1}** Schuster *et al*. (2013)	CO_2 Uptake : **0.4 – 0.27 PgC yr^{-1}** Lenton *et al*. (2013)
Strong River Influence	No River Influence
Land Surrounded	Land Centered
Thicker Sea-Ice	Thinner Sea-Ice

Antarctic Sea-ice : Current State

1979 - 2012



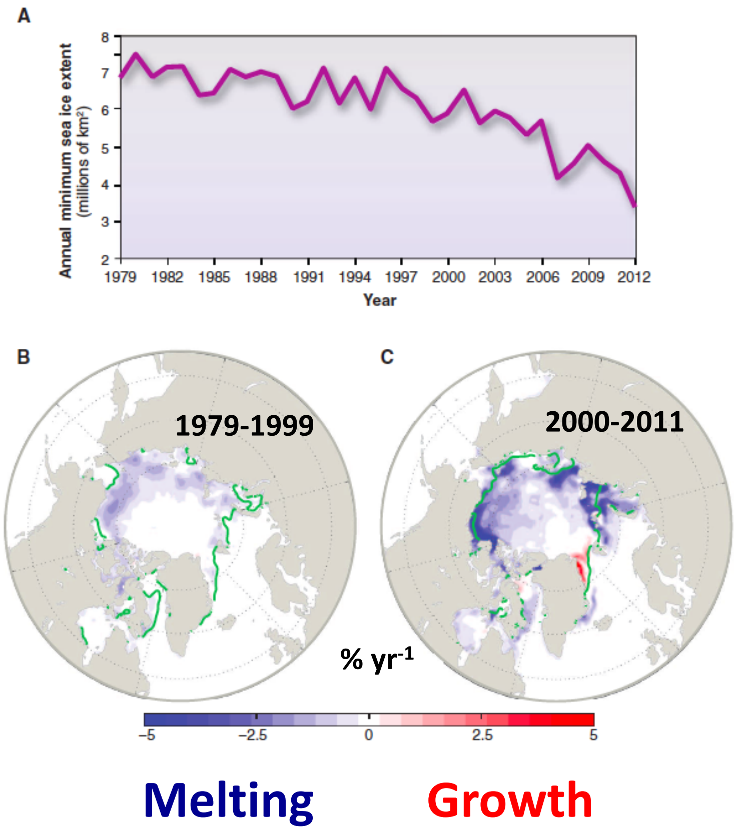
More Sea-Ice

Fractional Ice cover decade^{-1}

Less Sea-Ice

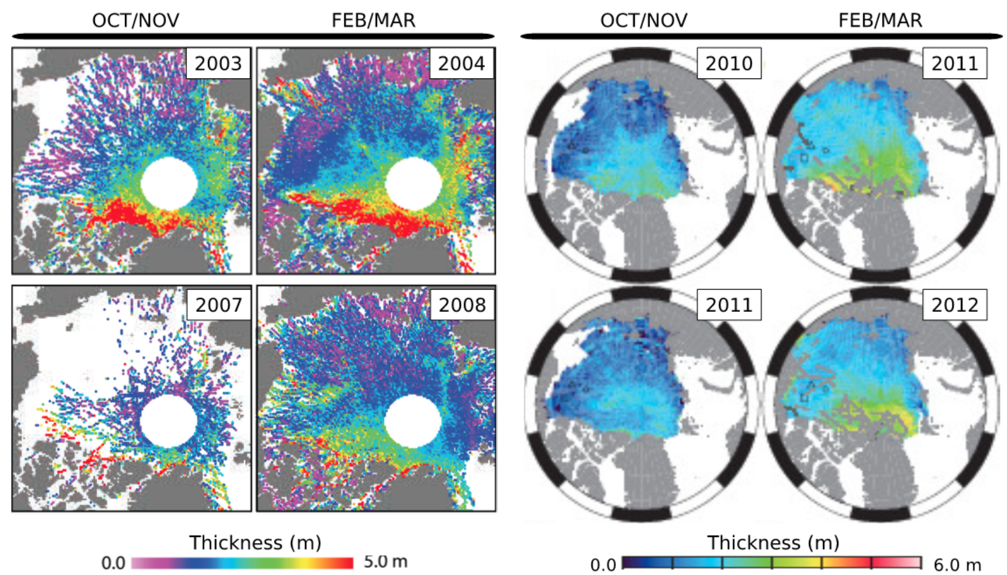
King (2014)

Arctic Sea-ice : Current State



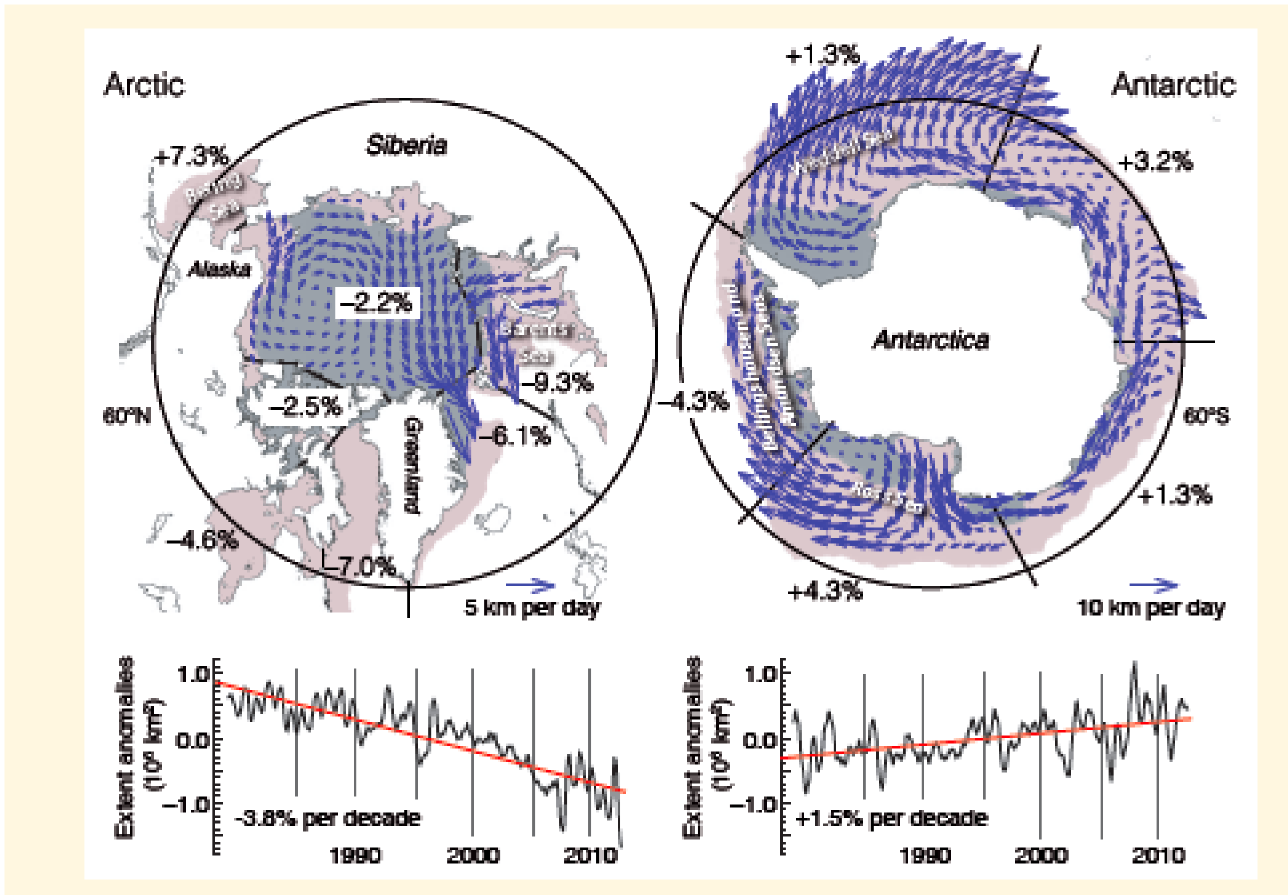
Post *et al.*, 2013

Arctic sea-ice becoming more "Antarctic" ??



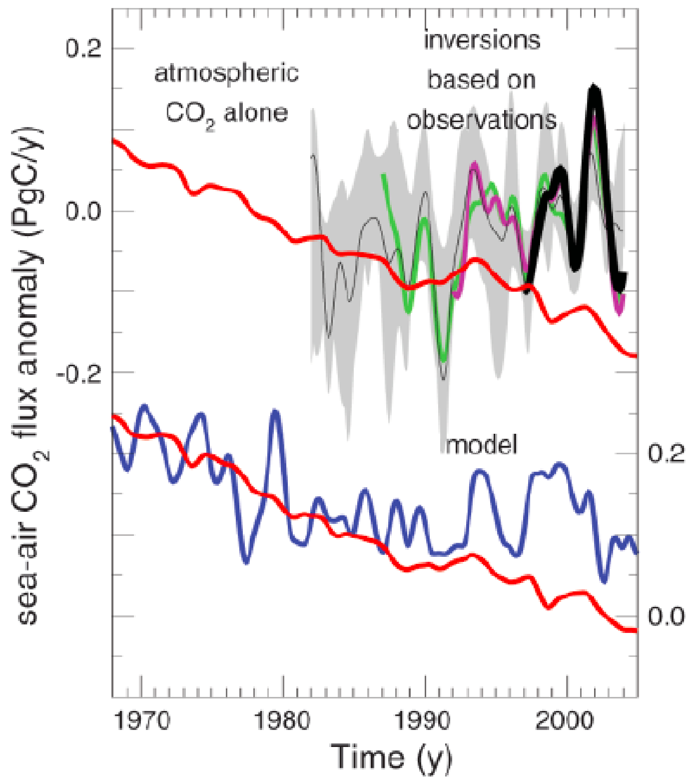
(Courtesy of D. Menemenlis, JPL)

So Similar and so Different



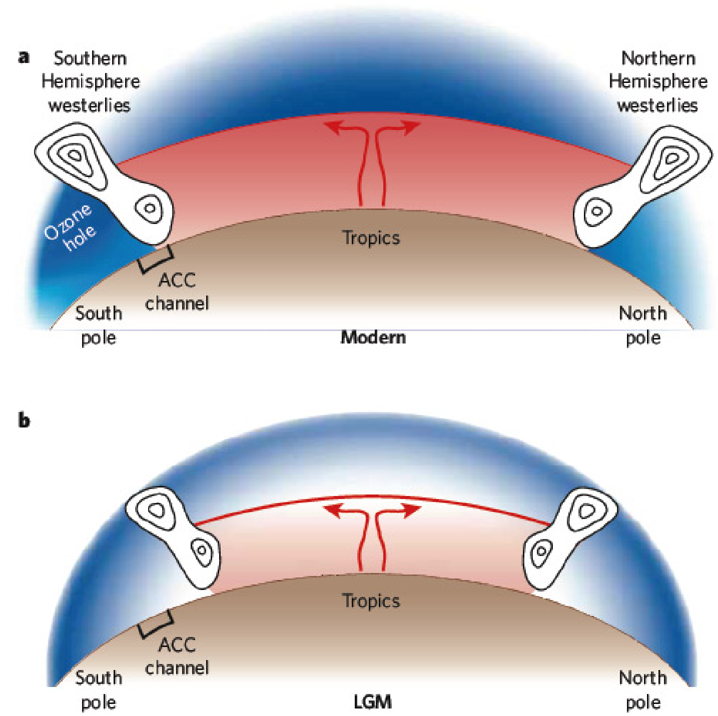
AR5, WG4, CRYOSPHERE

Different trajectories of Polar Carbon Sinks - SO



Le Quéré *et al*.(2007)

Wind dominant driver for CO_2 uptake

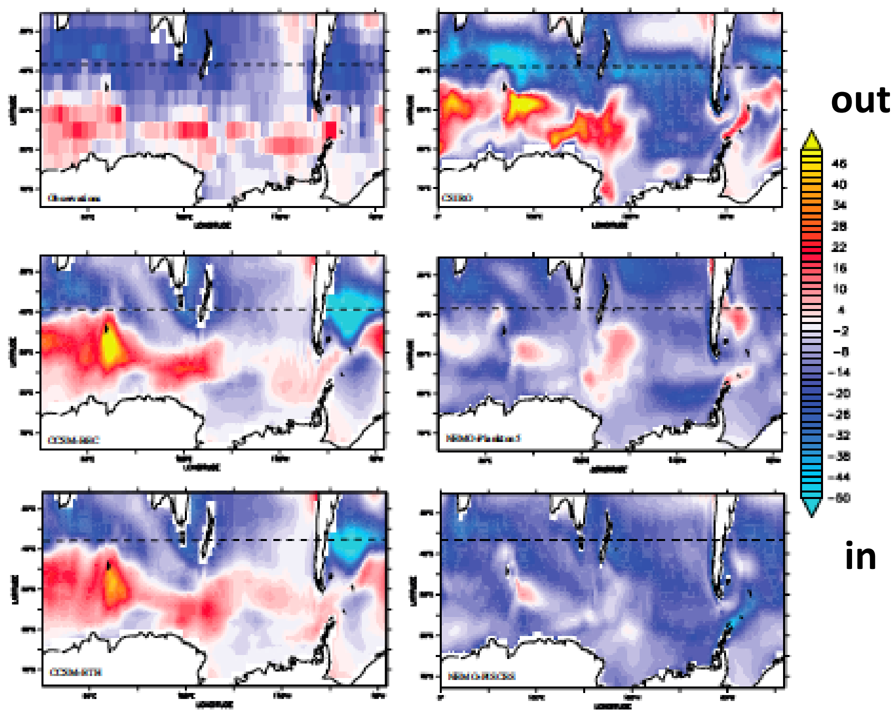


Toggweiler & Russell (2008)

Different trajectories of Polar Carbon Sinks - SO

OBSERVATIONS

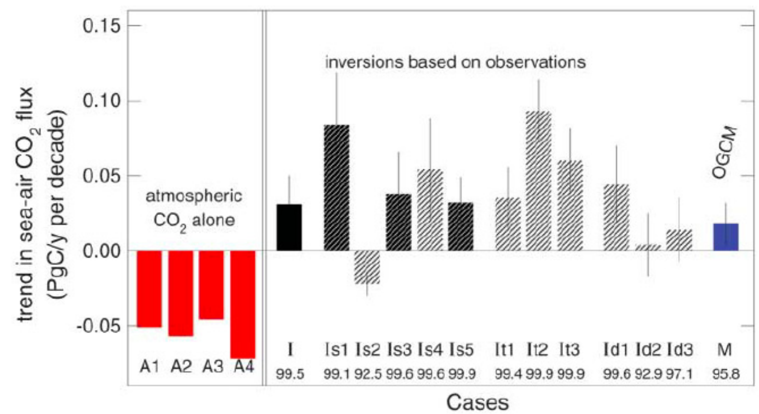
4044 A. Lenton et al.: Sea–air CO_2 fluxes in the Southern Ocean



Air-sea CO_2 fluxes

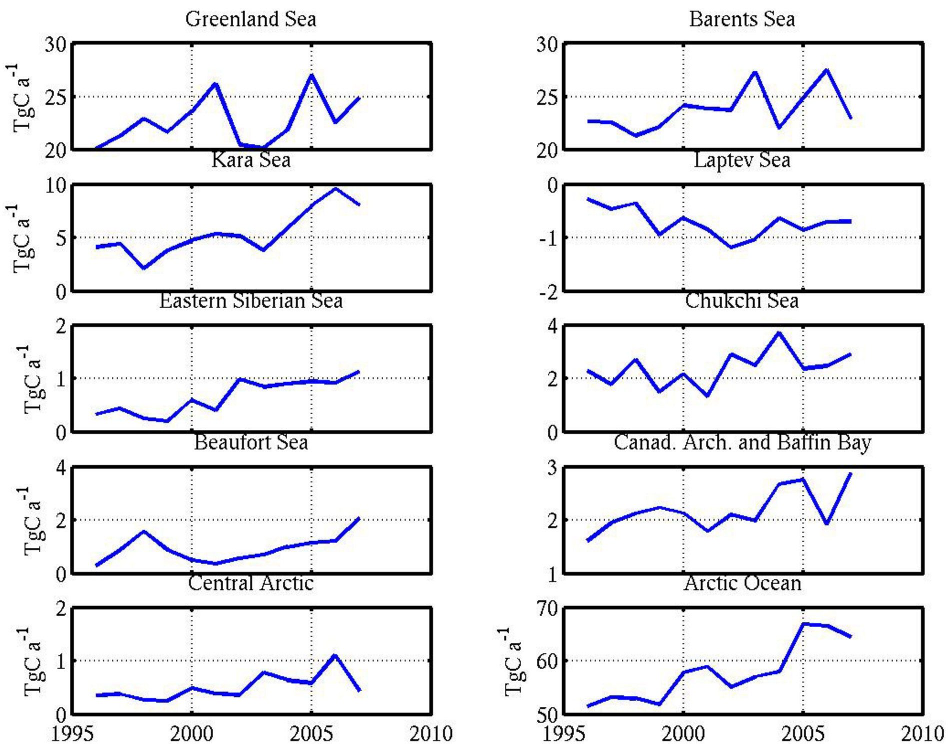
RECCAP, Lenton *et al.*, 2013

Nevertheless, in the period 1990–2009 ocean biogeochemical models do show increasing oceanic uptake consistent with the expected increase of $-0.05\,\mathrm{Pg\,C\,yr^{-1}\,decade^{-1}}$. In contrast, atmospheric inversions suggest little change in the strength of the CO_2 sink broadly consistent with the results of Le Quéré et al. (2007).



Le Quéré *et al.*(2007)

Different trajectories of Polar Carbon Sinks - AO



Manizza *et al*., (2013)

Flux > 0 : Ocean CO_2 uptake

Trend in sea-ice tends to drive the CO_2 uptake in the AO

The AO is mosaic of different biogeochemical provinces.

Will the trend in CO_2 uptake continue in all the bgc provinces ?

Very many mechanisms will respond to climate change and drive the flux.

Different trajectories of Polar Carbon Sinks - AO

Changes in the Arctic Ocean CO_2 sink (1996–2007): A regional model analysis

M. Manizza,[1,2] M. J. Follows,[1] S. Dutkiewicz,[1] D. Menemenlis,[3] C. N. Hill,[1] and R. M. Key[4]

2013

Ocean C-Cycle Model

An increasing CO_2 sink in the Arctic Ocean due to sea-ice loss

Nicholas R. Bates,[1] S. Bradley Moran,[2] Dennis A. Hansell,[3] and Jeremy T. Mathis[3]

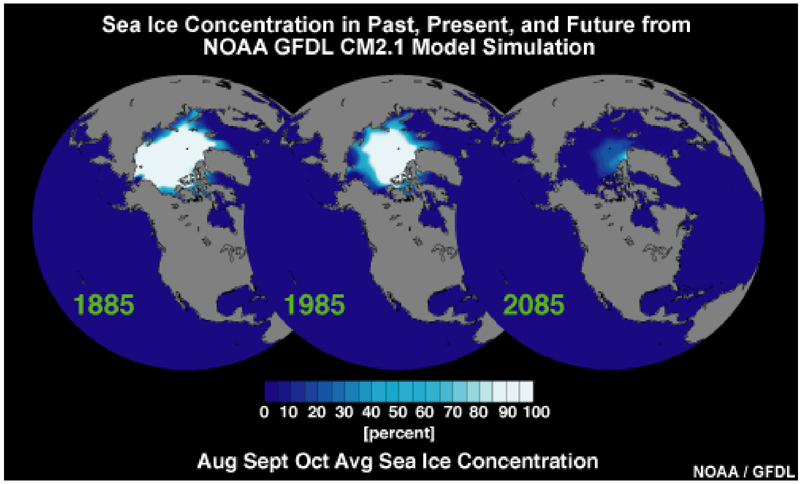
2006

Sea-Ice data + Ocean carbon obs.

CO_2 uptake increase
1.4 TgC yr^{-1}

Will it continue at the same rate, slow down, stop or reverse ?

Future (Warmer) Scenarios

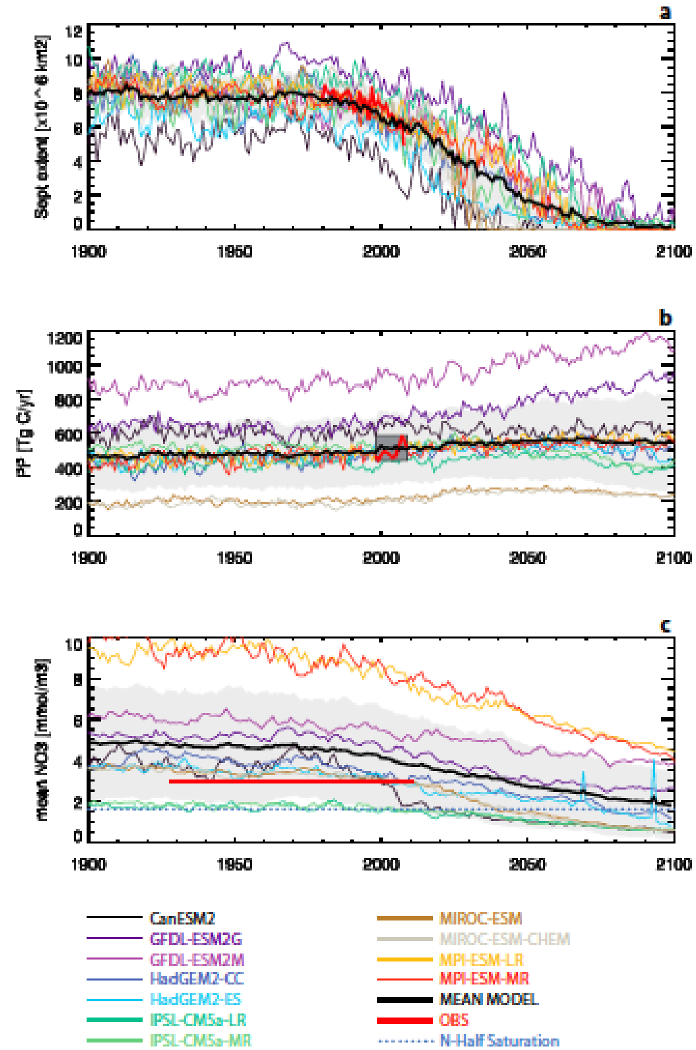


Vancoppenolle *et al*. (2013)
CMIP5 - ESMs

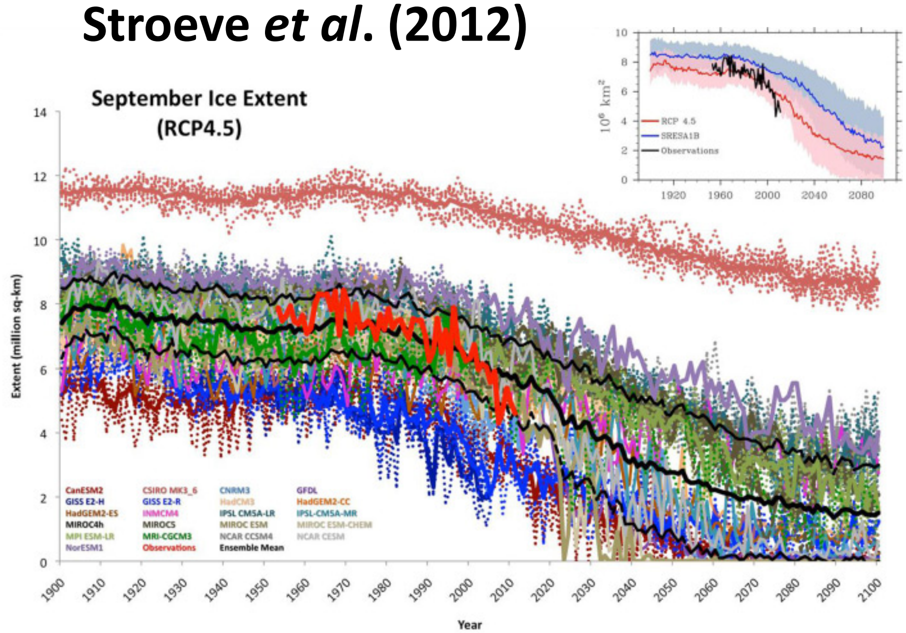
Sept. Sea-Ice Extent

PP

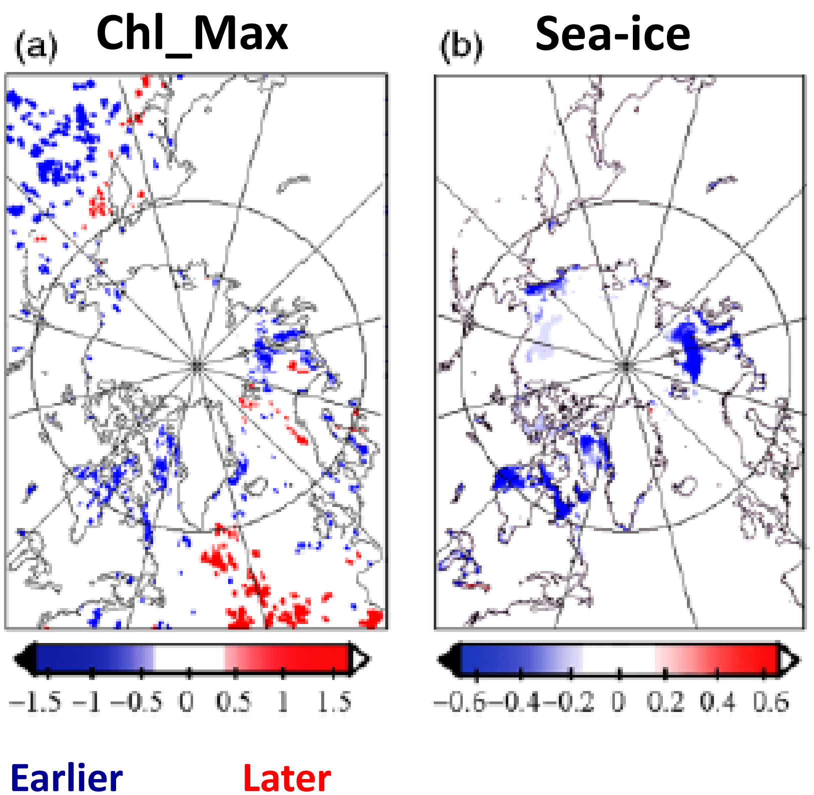
NO_3



Stroeve *et al*. (2012)



Changes in sea-ice : what does it mean for ocean bgc ?



Kahru *et al*. (2010)

Changes in the seasonal cycle of sea-ice

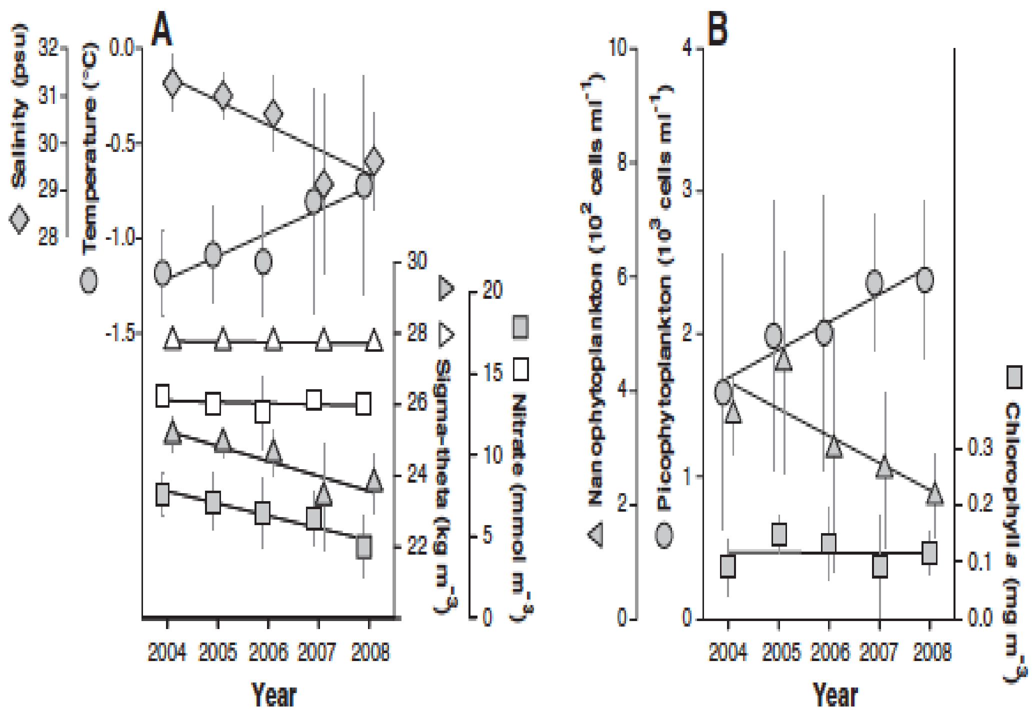
Earlier blooms in the Arctic Ocean

Consequences for :

1) C-export
2) Benthic feeders
3) Timing of migration of sea birds and large marine mammals

Sea-Ice, Plankton Ecology, and C-Cycle

Canada Basin - Western Arctic Ocean



Li *et al.*, (2009)

Arctic Freshening

Ecological Shifts
Planktonic Ecosystem

Implications for
C-export & CO_2 uptake

Polar Oceans Carbon Cycle

What do we need in our models ?

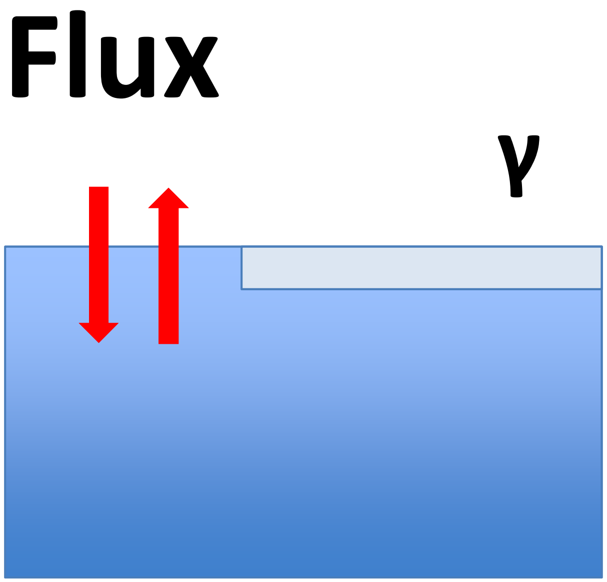
1) Correct sea-ice cover (time and space)

2) Inclusion of key-processes (physics and bgc)

3) Don't forget the data (their use + evaluation) !!

Modeling Sea- Ice

Modeling Sea-Ice Cover



$$\boxed{\text{Flux} = \alpha\ K\ (\Delta C)\ (1-\gamma)}$$

$$\gamma = f(x,y,t)$$

$$\alpha = f(SST)$$

$$K = f(\text{wind speed})$$

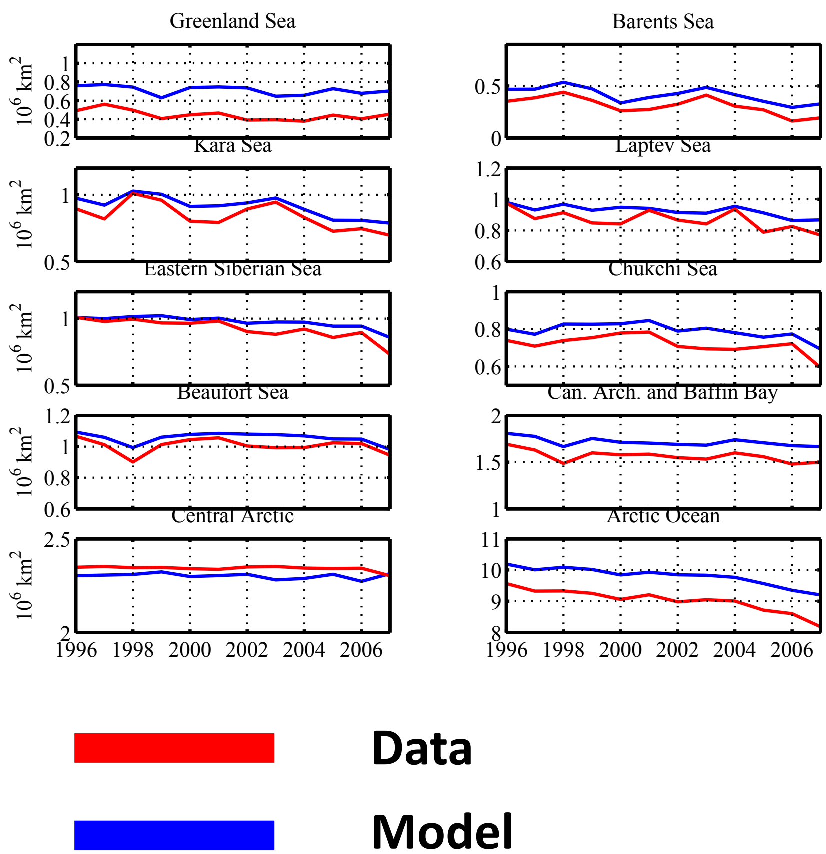
(Wanninkhof, 1992)

α = solubility factor

K = gas transfer velocity

ΔC = air-sea gas gradient

Learning from pitfalls



Standard forward run with coupled physical-biogeochemical model of polar oceans (e.g. AO)

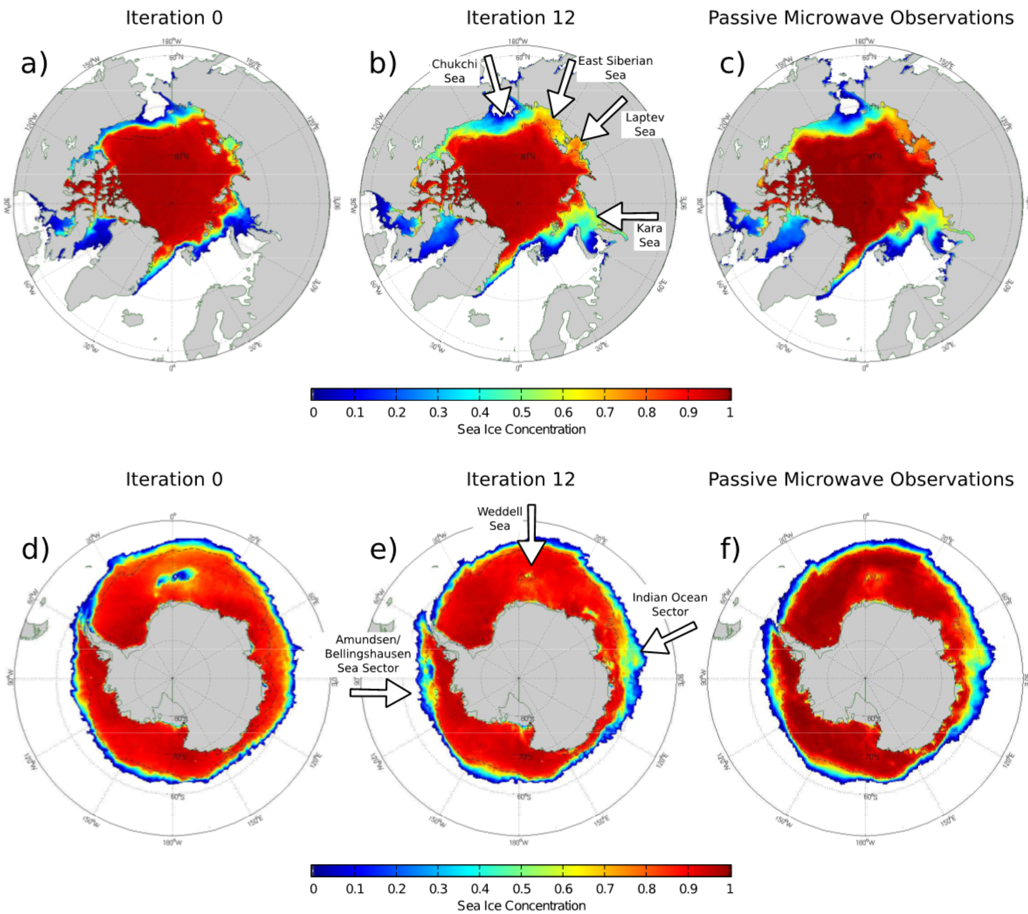
Problems with the sea-ice model can hamper our CO_2 sink estimates in the polar oceans

Can we do better than this ?

YES WE CAN !!!

Manizza *et al*. (2013)

Modeling sea-ice : how can we have it right ?



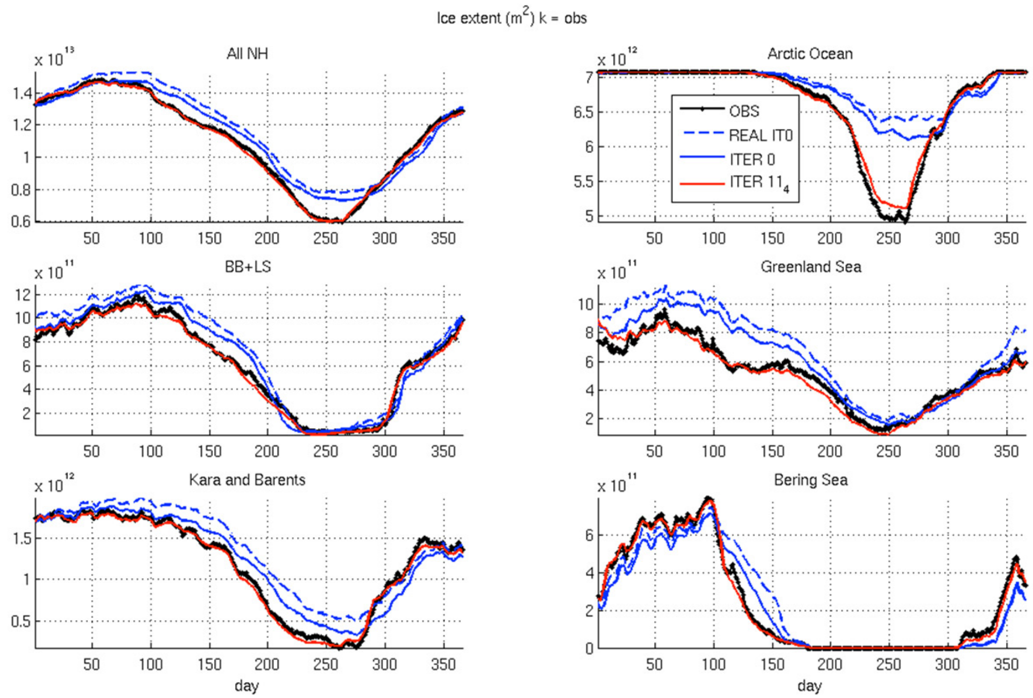
Sea-ice state estimation
Adjoint techniques
(ECCO-ICEs Effort)

Forward Model Run
+
Parameter exploration

"Hitting a target after several throws and failed attempts"

(Courtesy of D. Menemenlis & Ian Fenty, JPL)

Data-model fusion



(Courtesy of D. Menemenlis & I. Fenty, JPL)

Sea-Ice extent at different iterations

Optimized parameters for physical simulation coupled to C-cycle

Same thing for bgc state
Lots of computation !!!
e.g. : SOBOM-proposed effort (PI J. Sarmiento)

Changes in Sea- Ice
&
Implications for Biogeochemistry and Biogeophysics

Melt Ponds

Full Sea-Ice + Snow

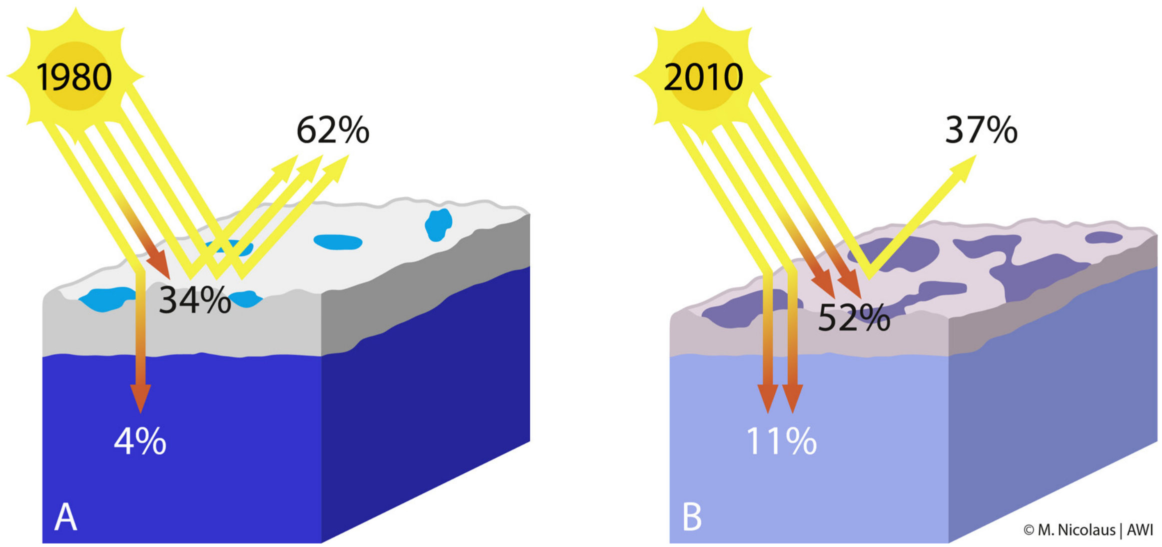
(From cutterlight.com)

VS

Sea-Ice + Melt Ponds

During ICESCAPE

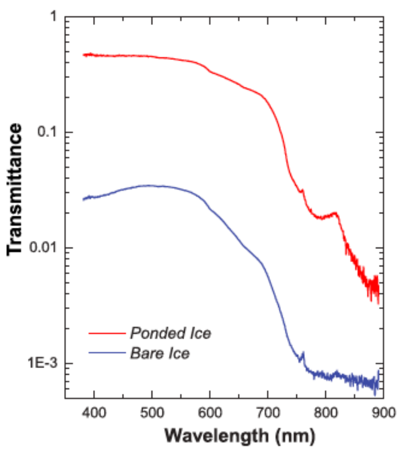
Melt Ponds : Implications for Physical Climate



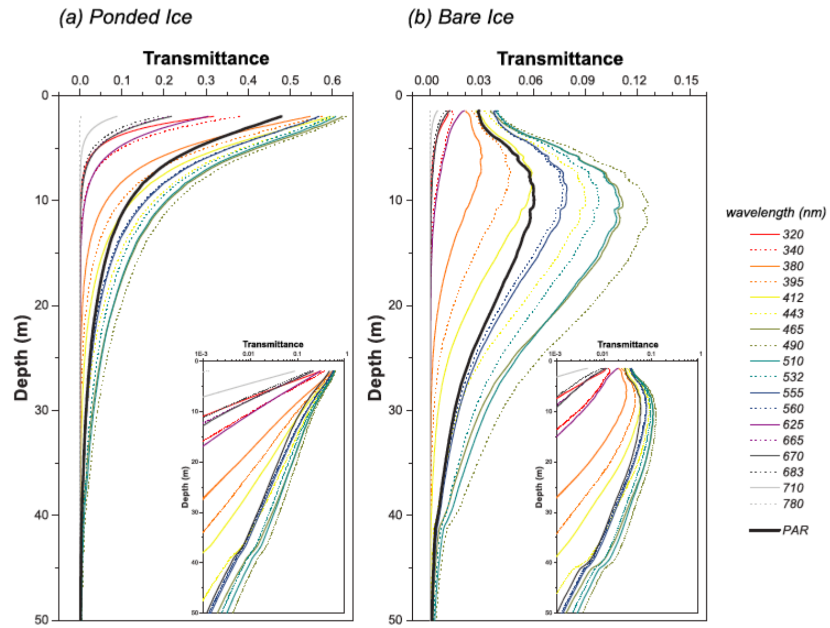
(From phys.org)

BUT ALSO Increase in PAR for photosynthesis and Primary Production under ice

Melt Ponds : Implications for Biogeochemistry

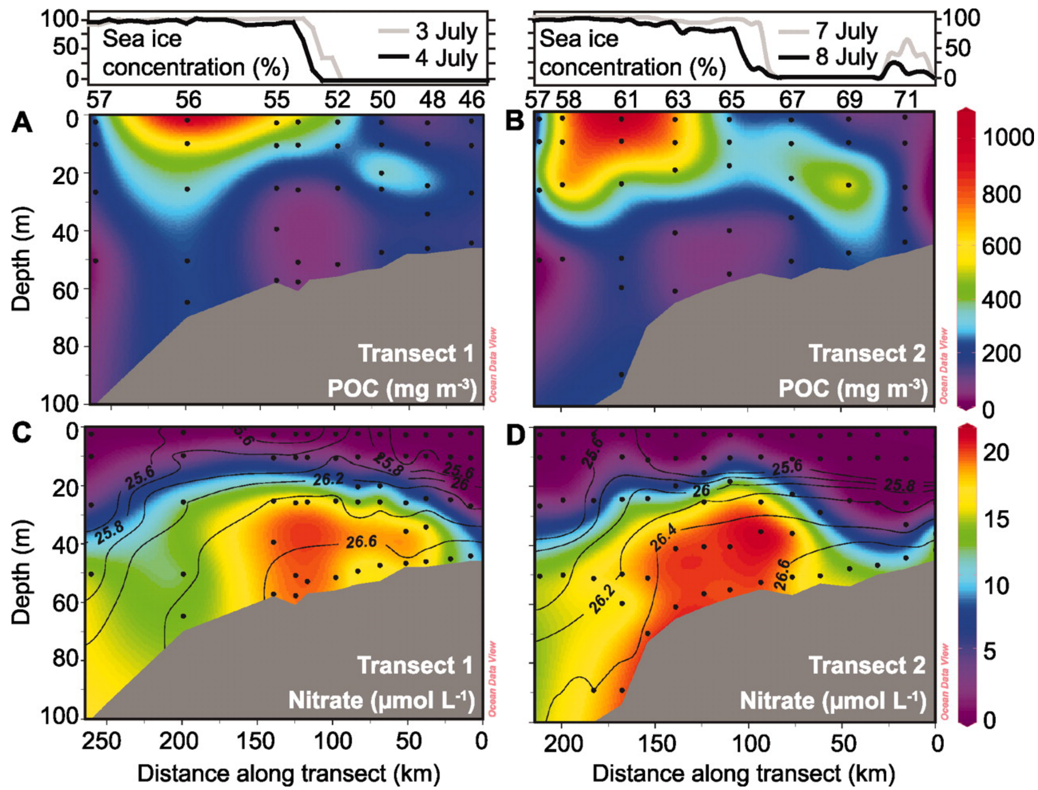


Just below sea-ice



Frey *et al*. (2011)

Melt Ponds : Observations, Processes & Models



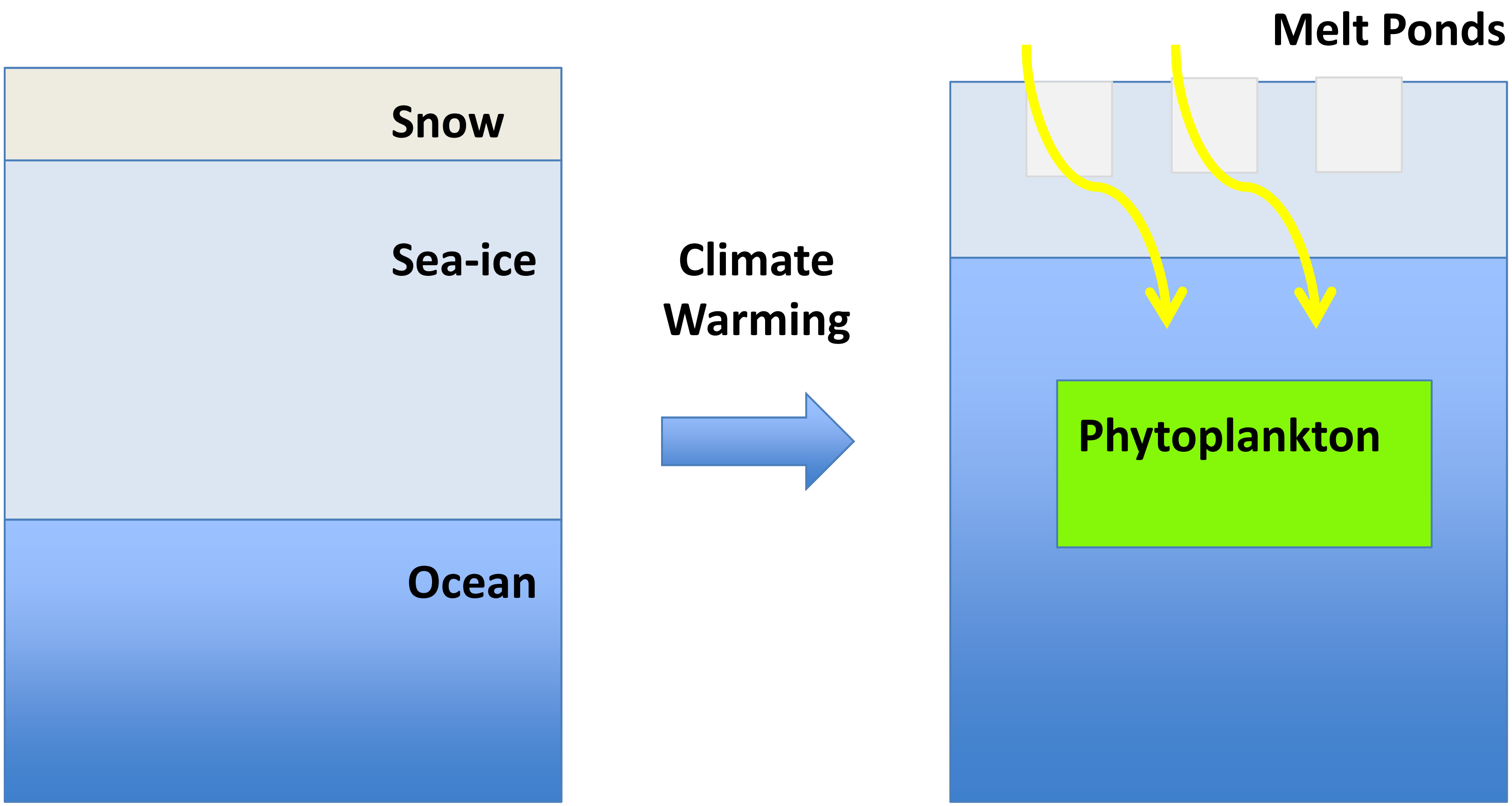
A snapshot from
a Transition Scenario ?

Towards a more oligotrophic
Arctic Ocean ?

CMIP5 models suggest
a future reduction in Arctic PP
per unit of ocean area
(Vancoppenolle *et al*., 2013)

ICESCAPE - Arrigo *et al*., (2012)

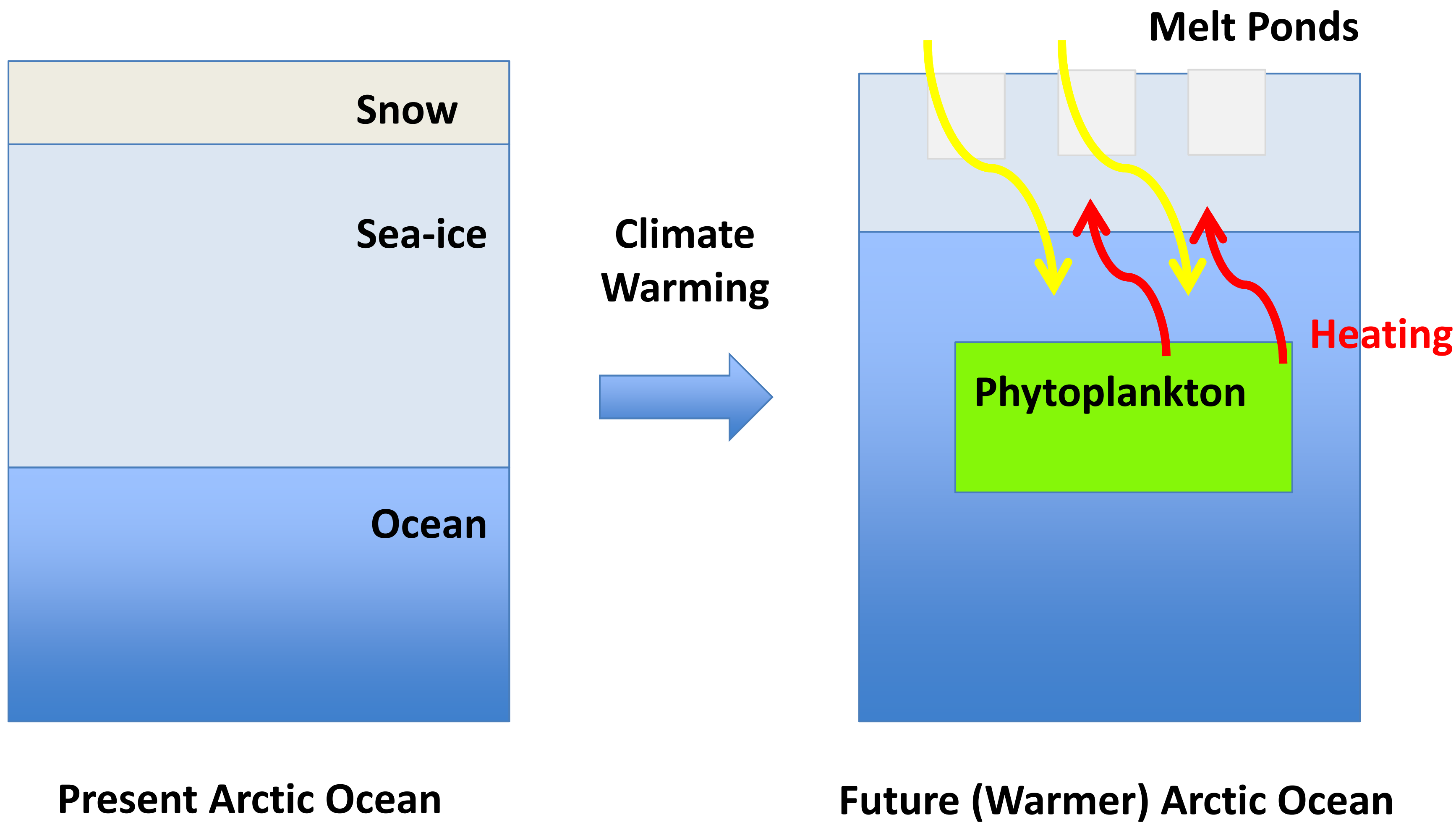
Other Potential Effect of Melt Ponds



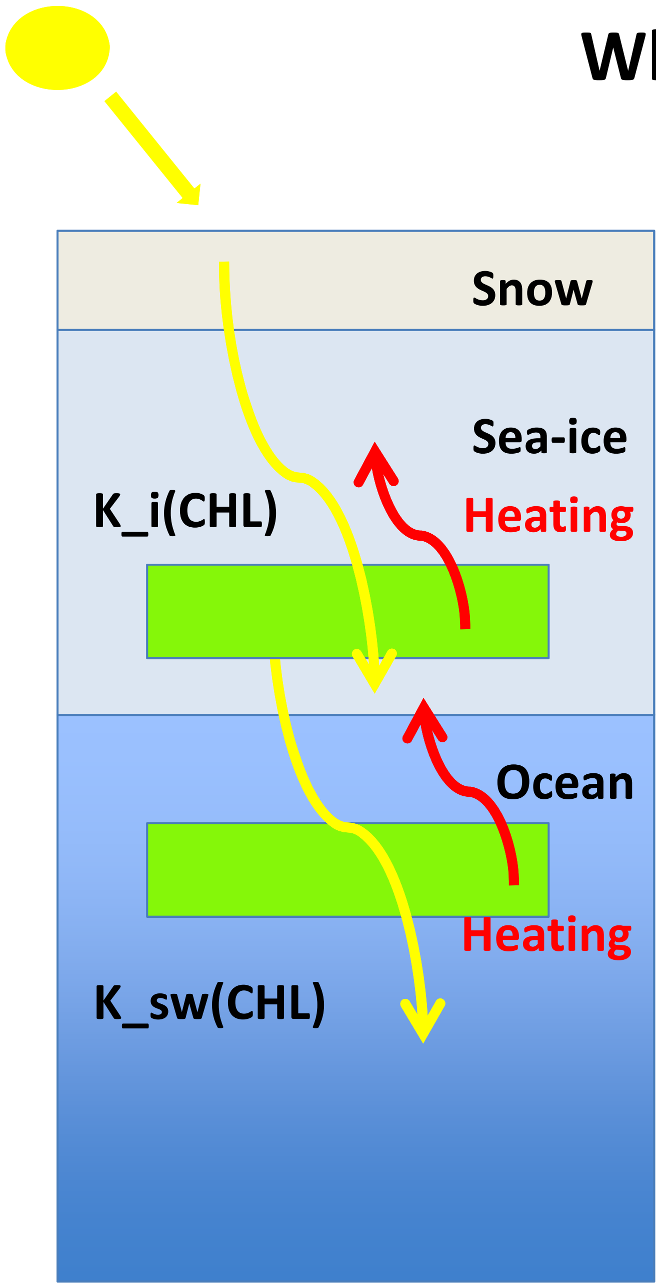
Present Arctic Ocean

Future (Warmer) Arctic Ocean

Other Potential Effect of Melt Ponds



What do we need ?



K_i = Light Attenuation Coefficient in Sea-ice

K_i = f(Chl)

Zeebe *et al*., (1996)

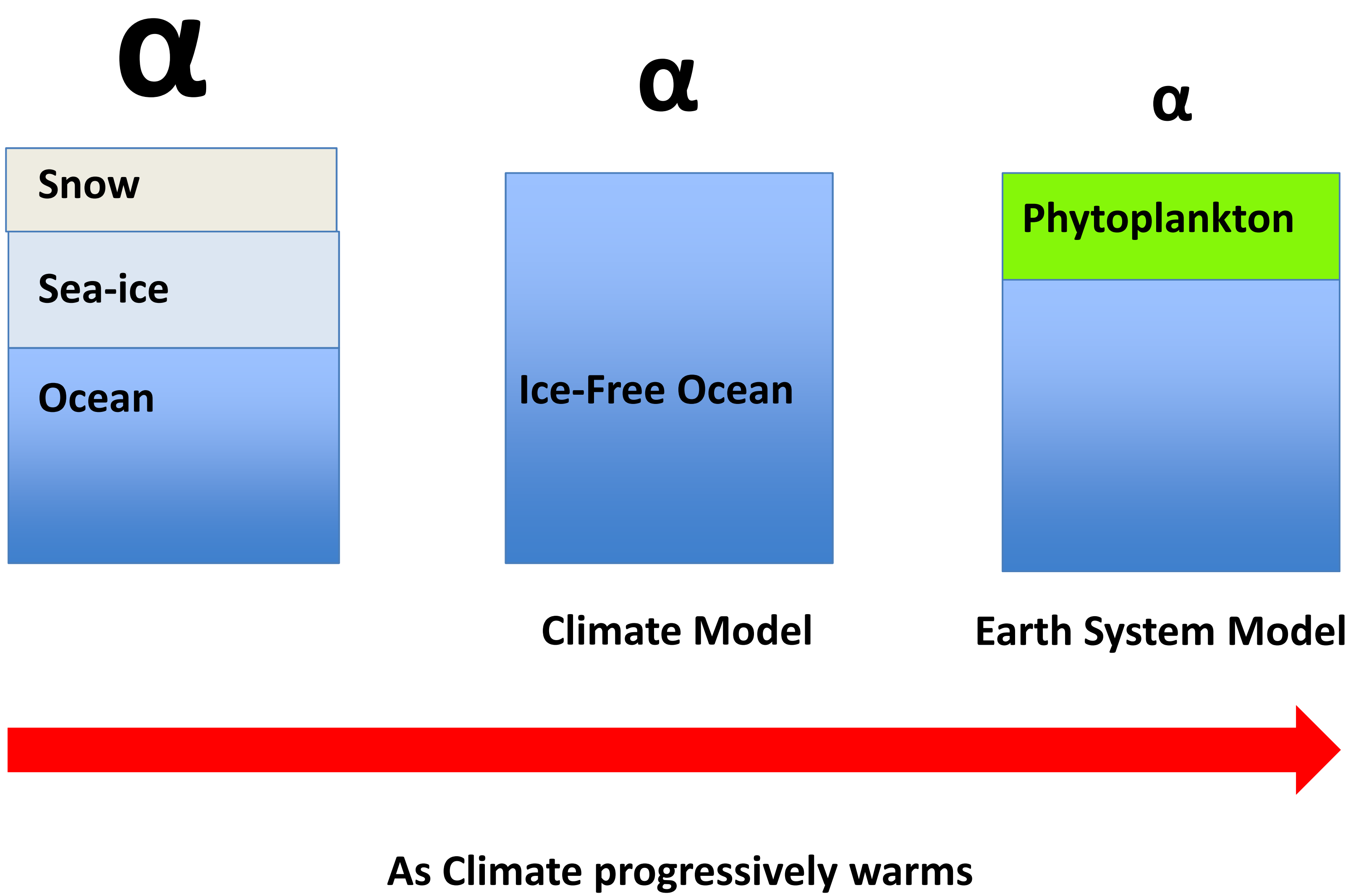
K_sw = Light Attenuation Coefficient in Water

$$k_{(\lambda)} = k_{sw(\lambda)} + \chi_{(\lambda)} \cdot [Chl]^{e(\lambda)}$$

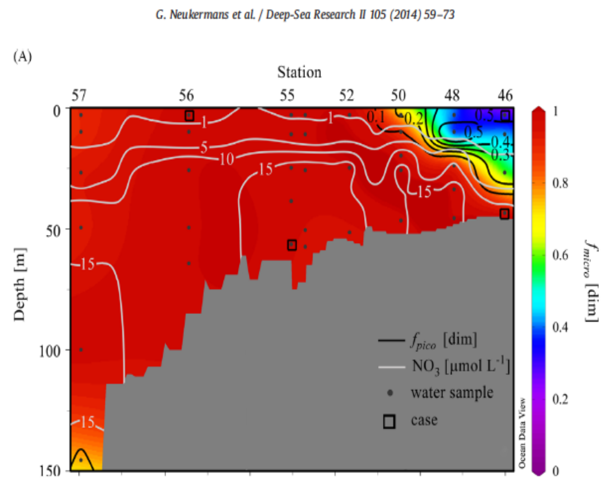
Phytoplankton influence on ocean physics and sea-ice in the polar zones

Manizza *et al*., (2005)

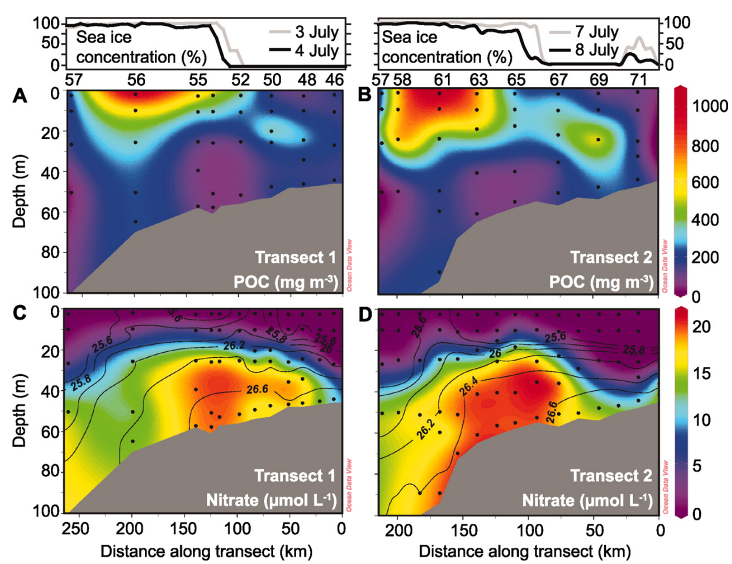
Future “greening” of the polar oceans ?



Sea-ice presence & planktonic assemblages



ICESCAPE - Neukermans *et al.*, (2014)



Ice-covered vs Open Water

Phytoplankton assemblages
Ecological Shits

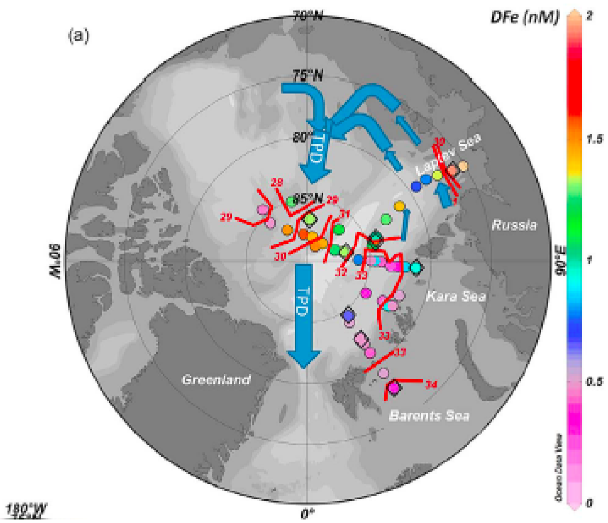
Need for models with several
Plankton Functional Types
(Le Quéré *et al.*, 2005)
(Follows *et al.*, 2007)

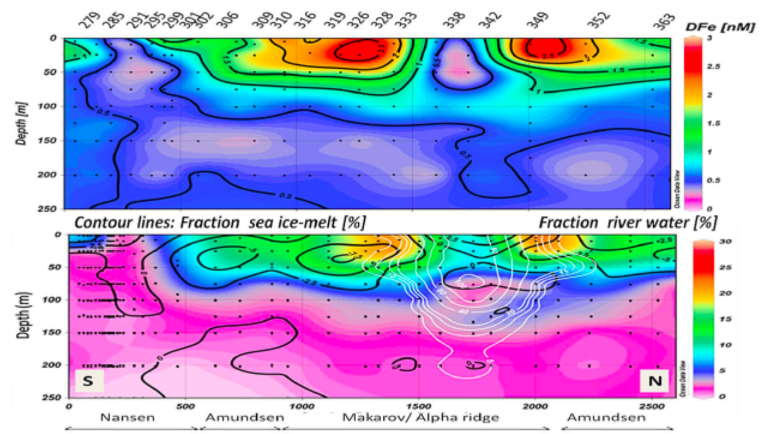
Impact on
C-export & CO_2 uptake

Sea- Ice
&
Nutrients

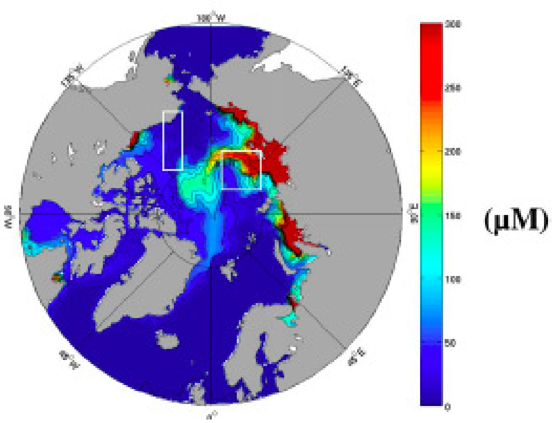
Iron in the Arctic Ocean

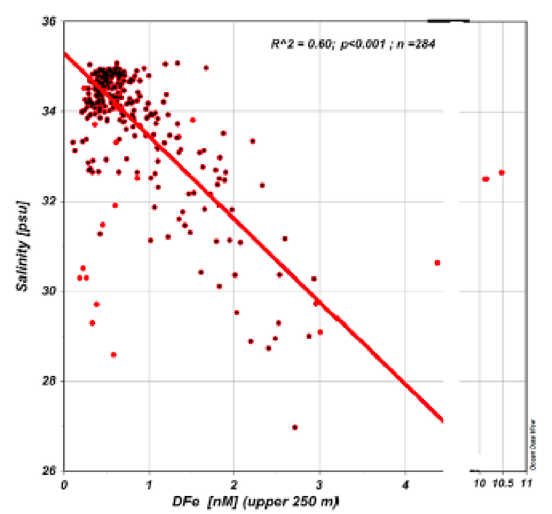
KLUNDER ET AL.: Fe IN ARCTIC SHELF SEAS AND SURFACE





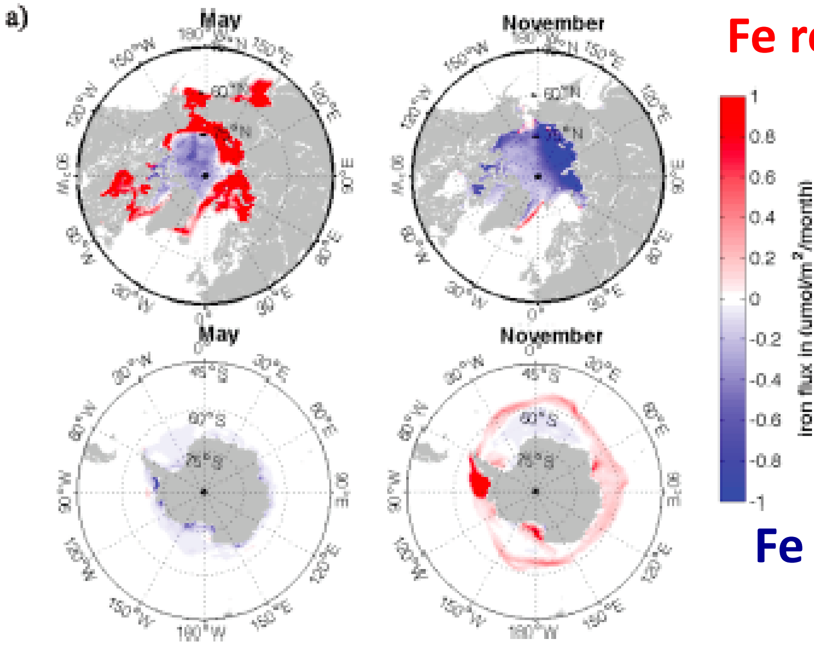
Klunder *et al*. (2012)





Manizza *et al*. (2009)

Iron & sea ice in the Arctic Ocean



Fe release from sea-ice into seawater

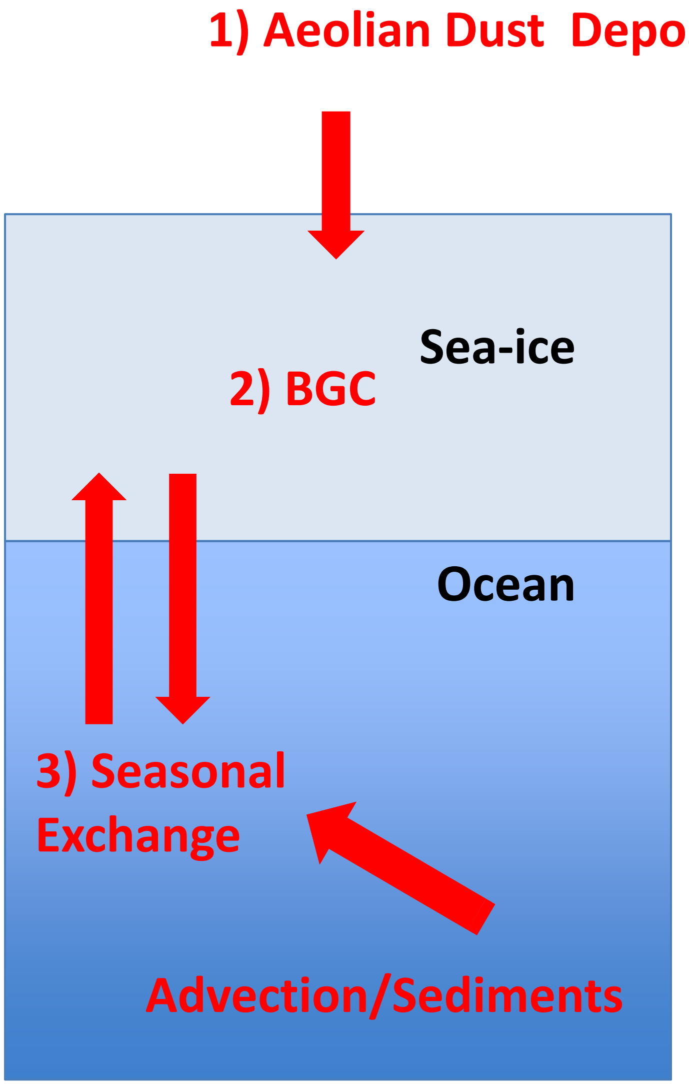
Fe uptake by sea-ice from seawater

Wang *et al*. (2014)

WHAT IF summer sea ice disappears in the Arctic Ocean ?

A Fe-limited Future Arctic Ocean ?

The case of Iron in sea ice



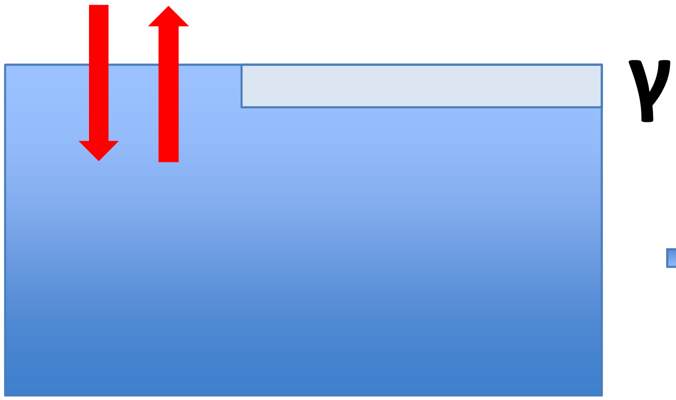
$$d(Fe\_si)/dt = 1 + 2 + 3$$

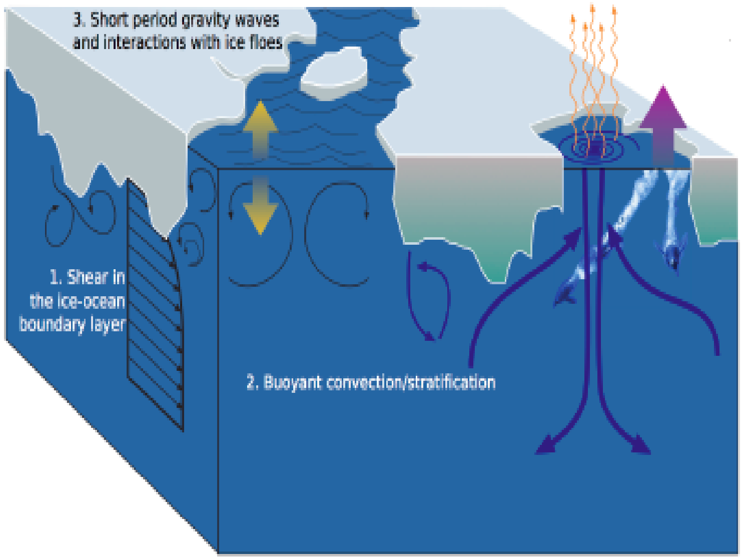
Activity of Sea-ice biota might control the availability of Fe for water column phytop.

Sea- Ice
&
Air-Sea Gas exchange

Just a Simple Lid ?

$$\text{Flux} = \alpha \ K \ (\Delta C)\ (1-\gamma)$$





Loose *et al.*, 2014

α = solubility factor

K = gas transfer velocity

ΔC = air-sea gas gradient

Moving forward

$$F = k_{\mathrm{eff}} \Delta C,$$

$$k_{\mathrm{eff}} = (1 - f)k_{\mathrm{ice}} + (f)k,$$

f is the fraction of open water

K = gas transfer velocity

MODEL INPUT PARAMETERS :

1) **Wind Speed**
2) **Air-temperature**
3) **Sea-Ice velocity**
4) **Sea-Ice concentration**

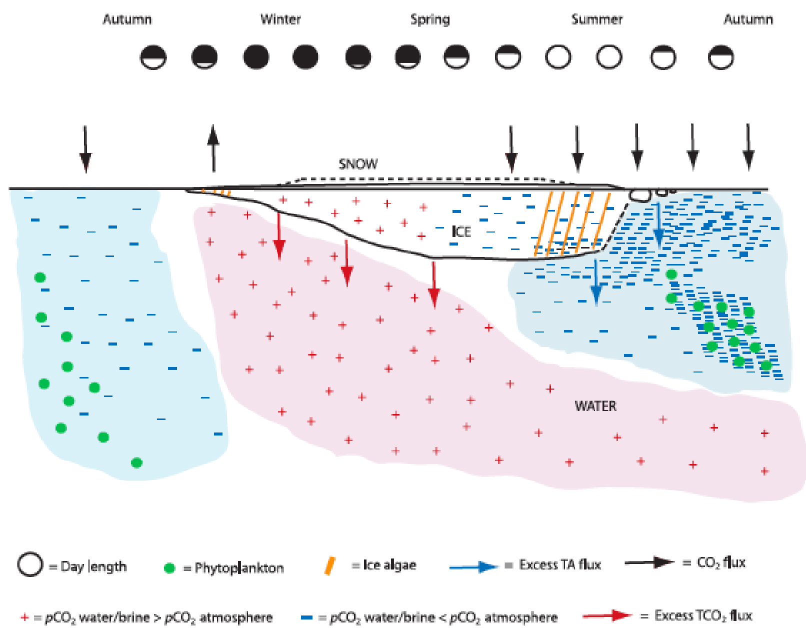
MECHANSIMS TO MODEL

1) **Buoyancy/Stratification**
2) **Sea-Ice/Water Shear**
3) **Gravity Waves/ice floes**

(Loose et al., 2014)

OGCM + C-CYLE MODEL OF POLAR OCEANS

Still a long way to go…



Rysgaard *et al*. (2011)

Two Missing Processes :

1) **Brine & CO_2 rejection:** Deep water formation process and CO_2 uptake.

2) **Sea-ice Decay & ALK release :** Enhances CO_2 uptake at sea-ice margin during summer melting

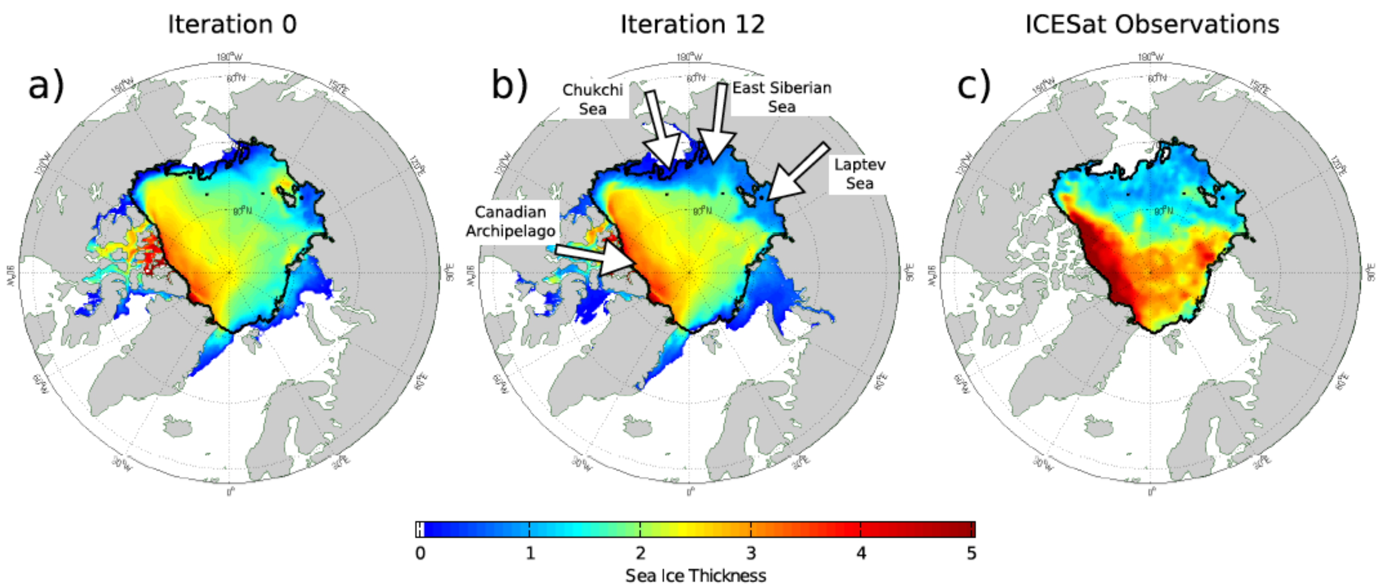
CONCLUSIONS & FUTURE DIRECTIONS

THOUGHTS : Changes in sea-ice will play an important role at modulating the CO_2 uptake in the polar oceans both in the near and distant future as climate continues to change due to anthropogenic activities.

GOALS : Incorporation of new processes in ocean biogeochemical models will help us to better understand and predict the response of the ocean carbon cycle to the modifications of sea-ice due to climate change.

NEEDS : Extensive observational programs and tools are and will remain VITAL to our community to understand the changing carbon cycle of the polar oceans and predict its impact on Earth's climate. This will help us to monitor the changes, constrain the rates of processes, and improve our models.

Sea-Ice thickness estimation



Improved representation of ice thickness during the Oct 3-Nov 8, 2004 ICESat campaign following the synthesis of sea ice concentration data

(Courtesy of D. Menemenlis & I. Fenty, JPL)