Ocean Carbon & Biogeochemistry Summer workshop 2010

Aragonite undersaturation in the western Arctic Ocean

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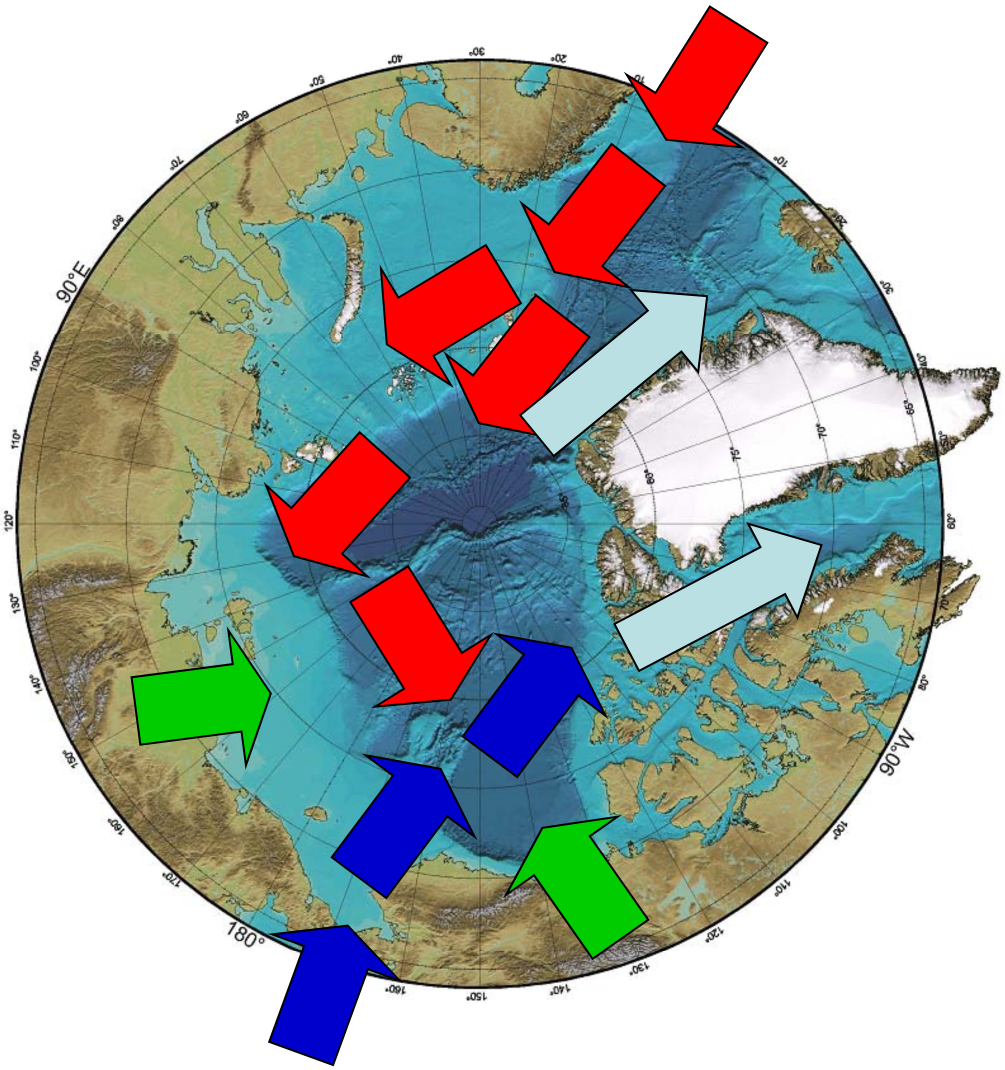
Fisheries and Oceans   Pêches et Océans

Arctic Ocean



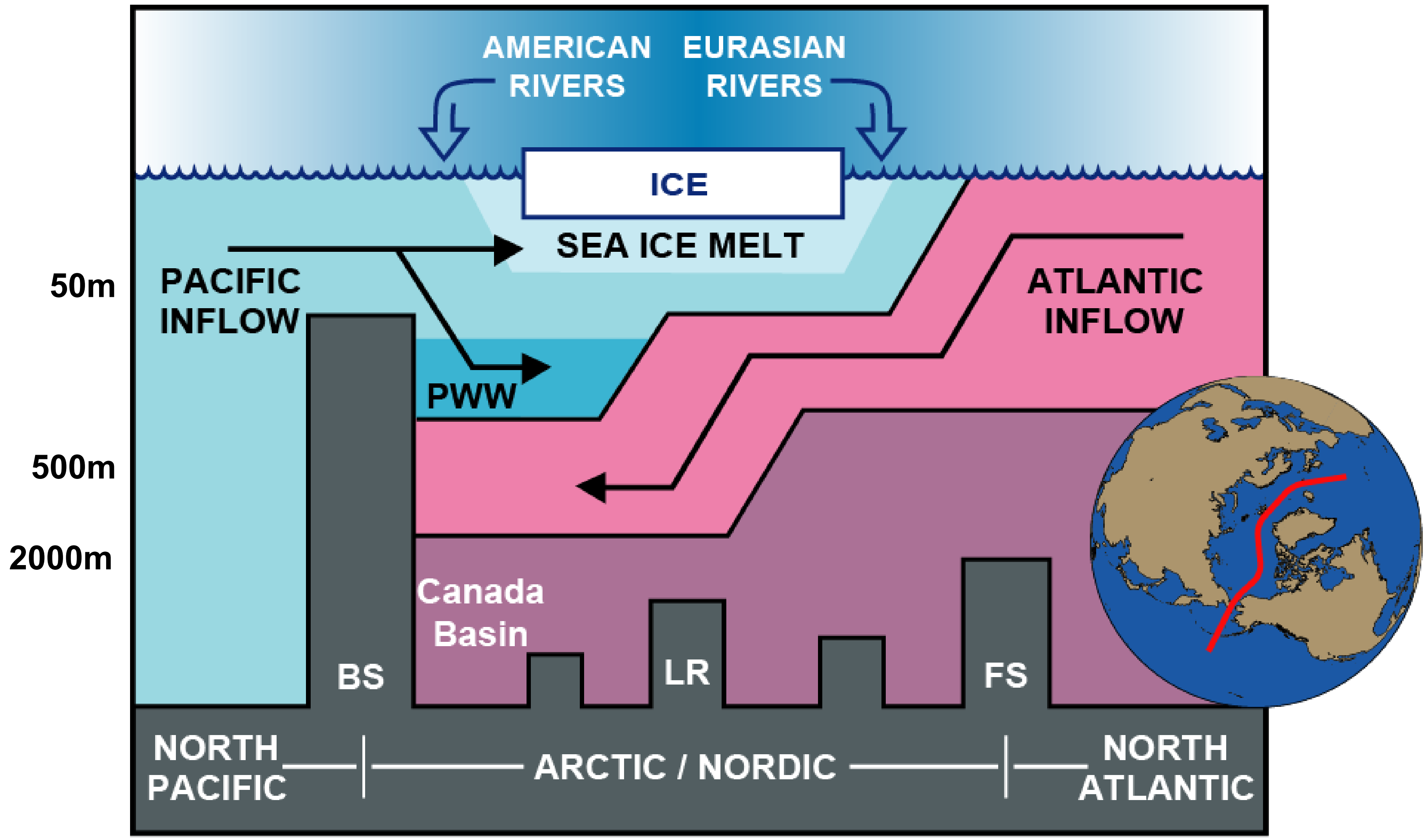
FW, OC, Fe, contaminants etc.

Surrounded by continents
~10 % of global river discharge

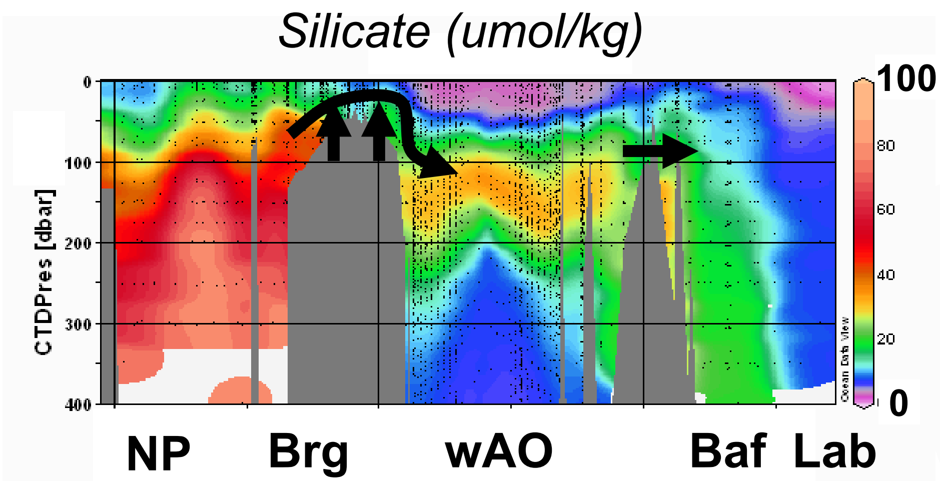
**Inflow from both
Atlantic and Pacific oceans**

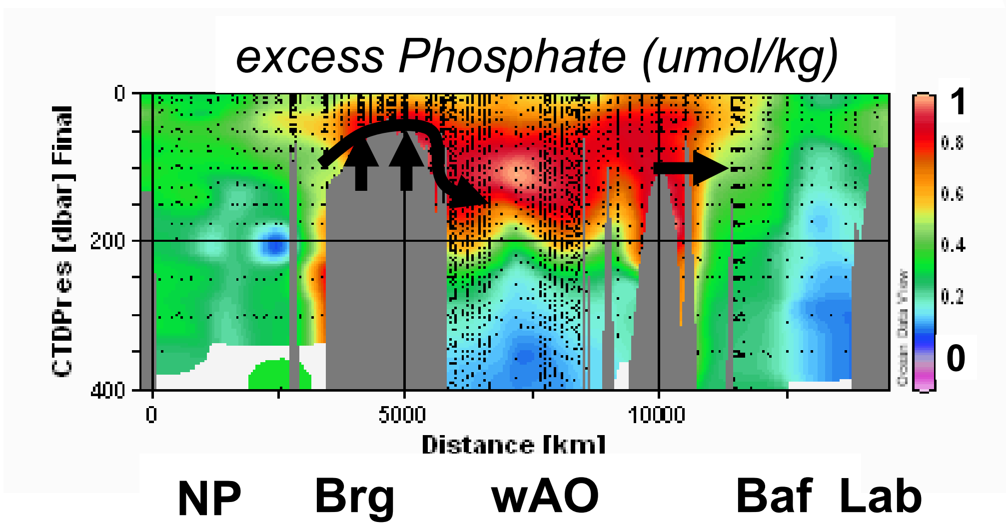
Outflow to the North Atlantic

Arctic Ocean

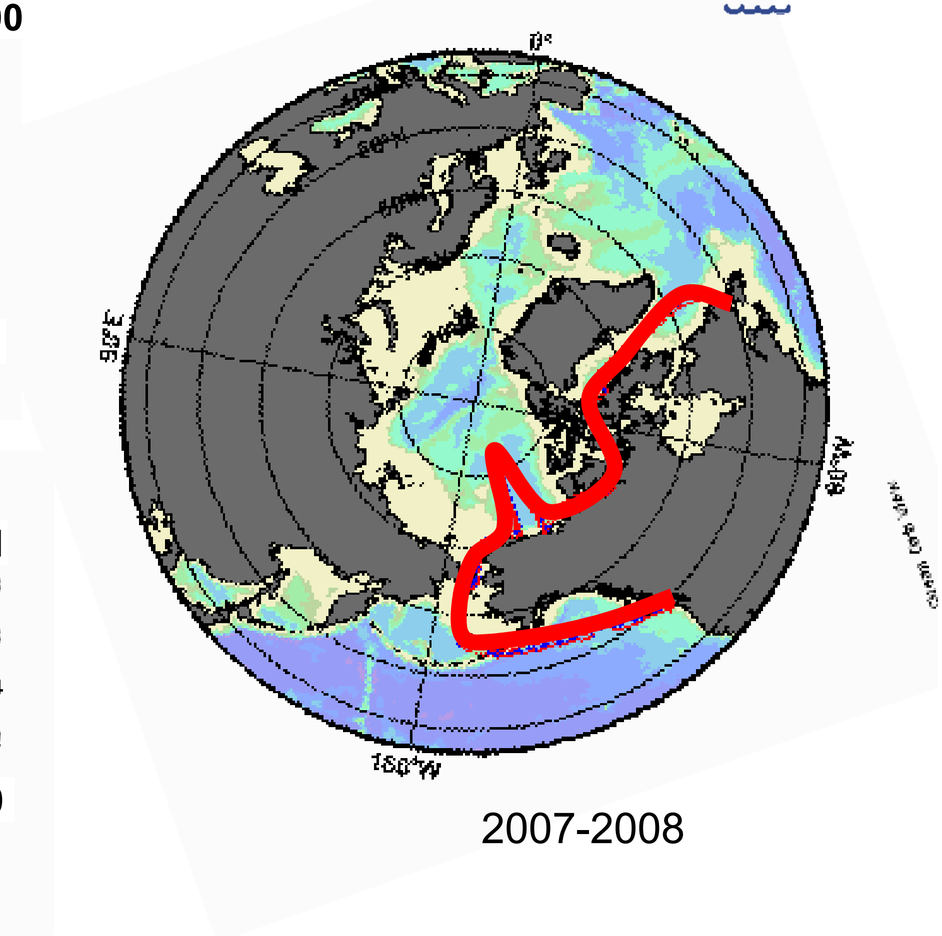


Arctic Ocean





excessP=P-1/16N

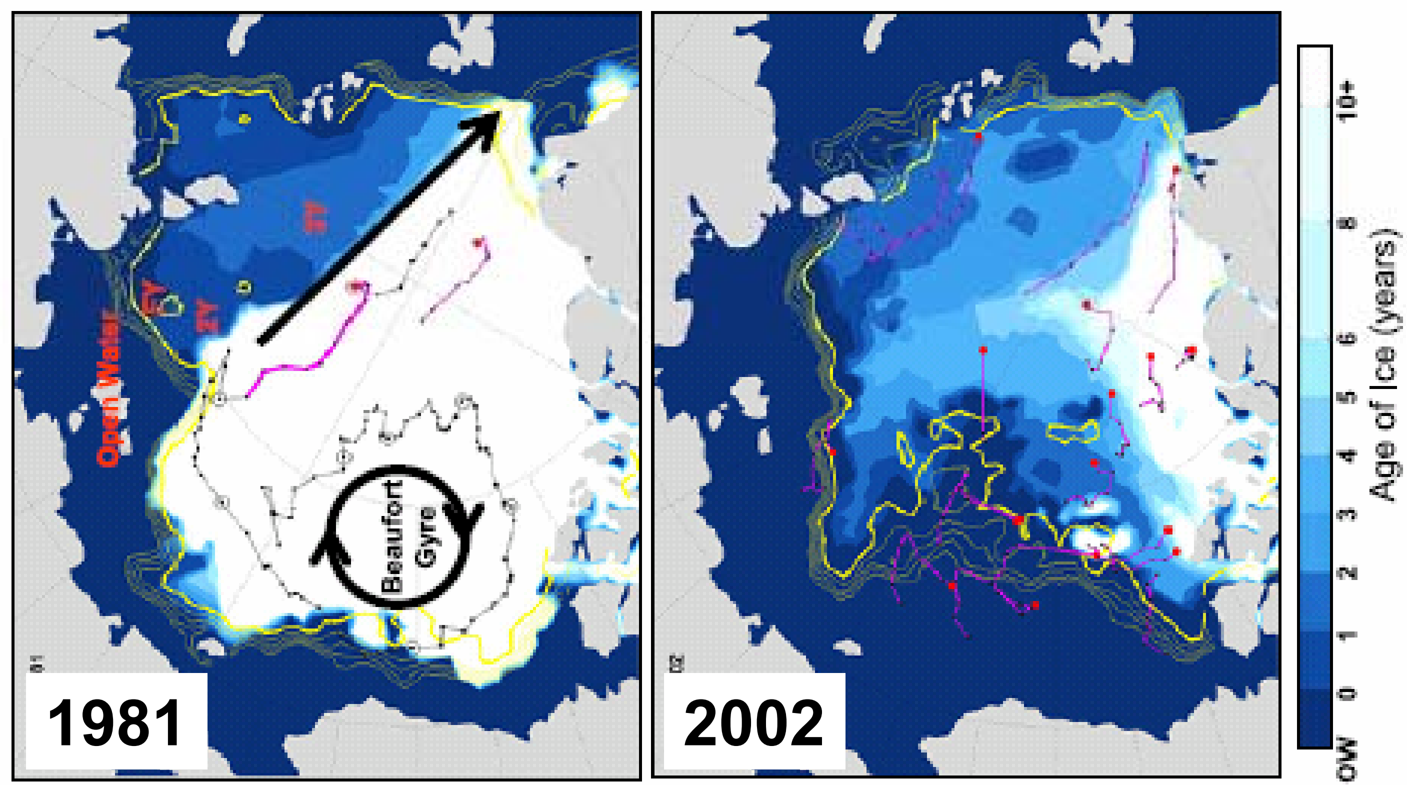


2007-2008

[Yamamoto-Kawai et al., in prep.]

[Yamamoto-Kawai et al., Nature, 2006]

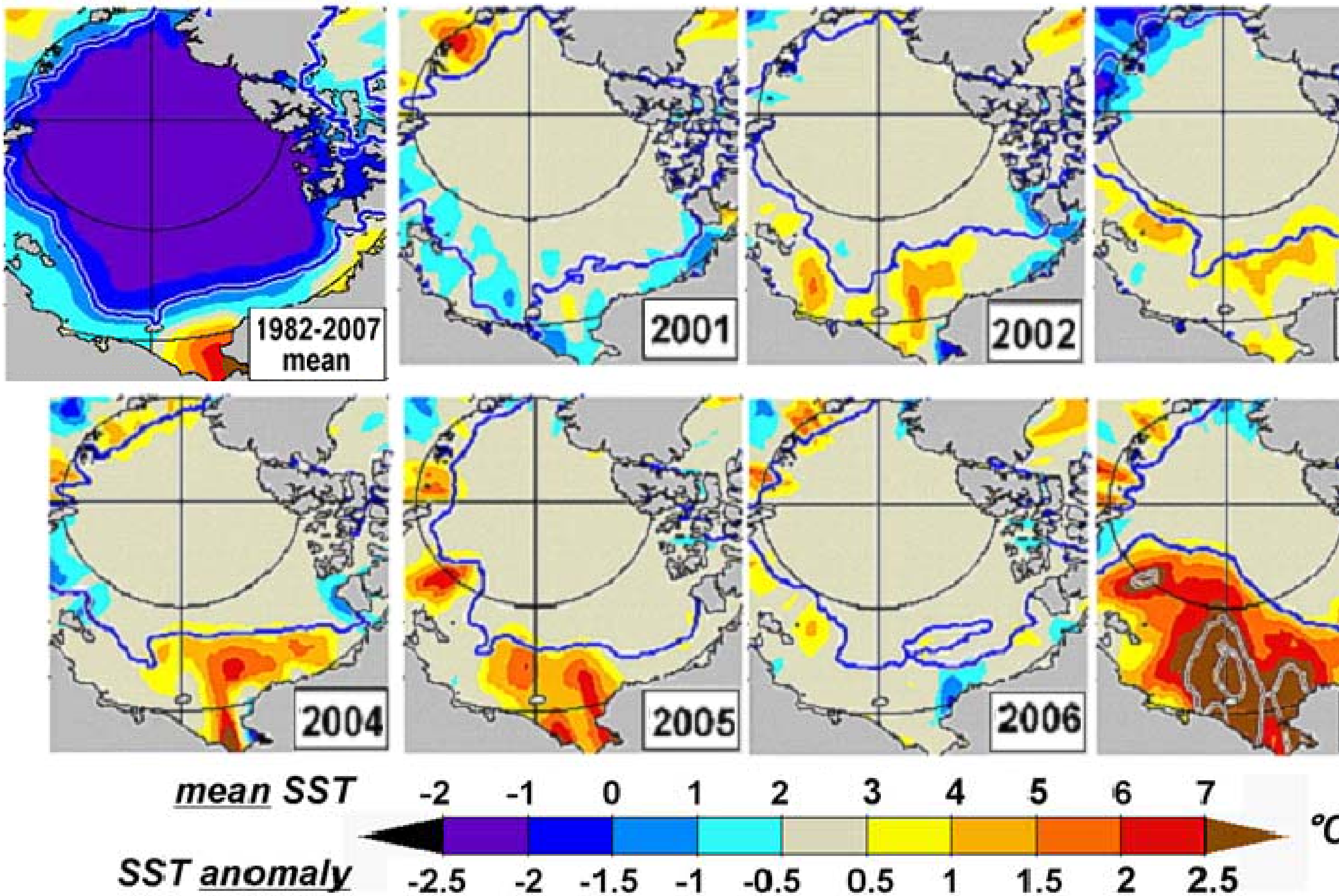
Arctic Ocean---melting



September summer sea ice extent & age of ice

[Rigor and Wallace, GRL, 2004]

Arctic Ocean---warming



[Steele et al., GRL, 2007]

Recent changes in seawater observed in the western Arctic Ocean

- **Aragonite undersaturation: surface & subsurface**

  [Yamamoto-Kawai et al., Science, 2009]

- Surface freshening

  [Yamamoto-Kawai et al., JGR, 2009]

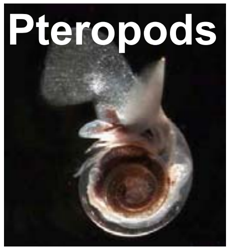
- Acceleration of ice/ocean circulation

  [Shimada et al., GRL, 2006; Rainville & Woodgate, GRL, 2009]

- changes in nutrient distribution and in plankton size

  [McLaughlin & Carmack, subm.; Li et al., Science, 2009]

Aragonite saturation state



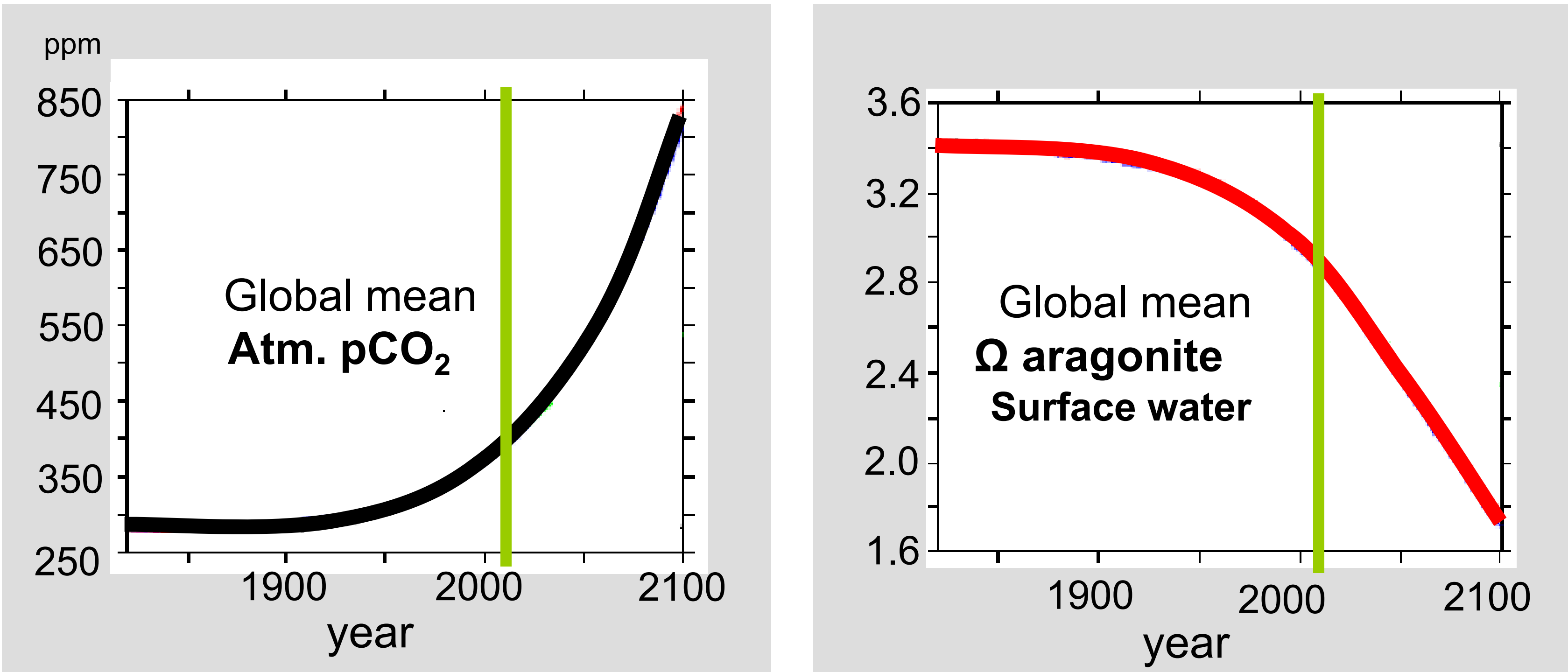
Aragonite – a form of $CaCO_3$ that is more soluble than calcite and thus is more sensitive to ocean acidification.

Calcite – the form of $CaCO_3$ that is less sensitive to acidification.
High-Mg calcite – least stable

$CaCO_3$ saturation state of seawater = Ω

Decease in Ω --- difficult to maintain $CaCO_3$ shells
Ω < 1 --- risk of dissolution

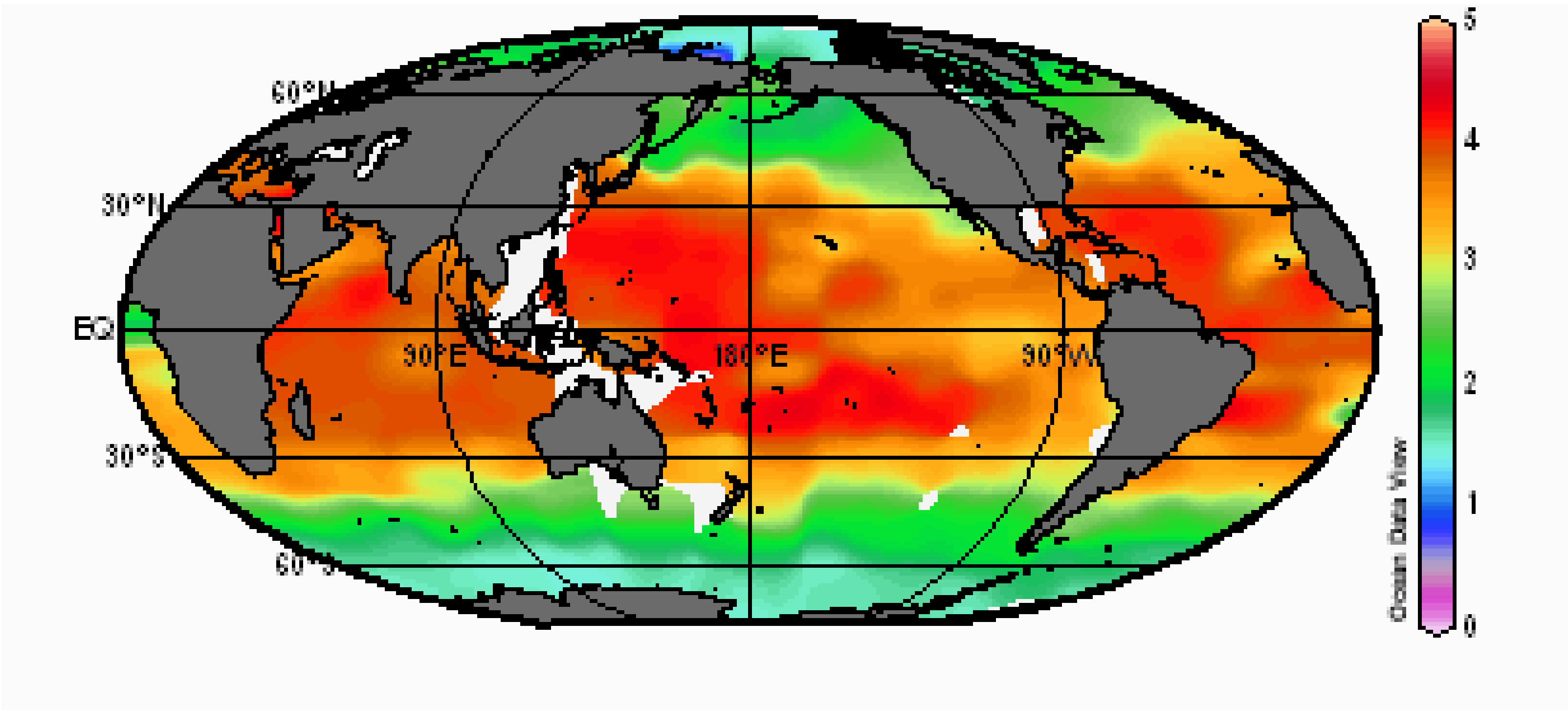
Aragonite saturation state



[Steinacher et al., Biogeosciences, 2009]

Aragonite saturation state

Ωar (surface)



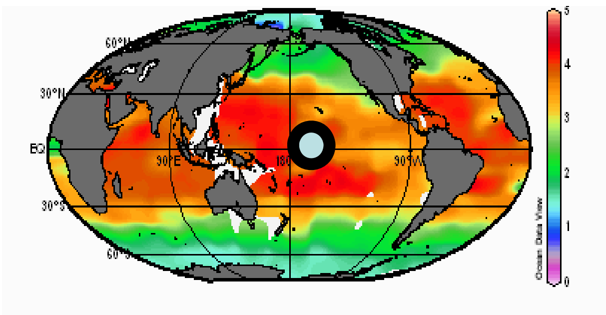
Why is surface Ω low in polar regions?

[CARINA+GLODAP]

Aragonite saturation state

Southern Ocean

- **Cooling ---** low T seawater dissolve more CO_2 (high DIC)
- **Upwelling** of DIC enriched deep water (high DIC)



S=34.6

T =29 ˚C

TA=2265 µmol/kg

pCO_2=390 µatm

e.g., Cooling of tropical surface water to -1.8˚C

DIC = 1937 umol/kg

Ω = 3.8

Cooling →

DIC = 2163 umol/kg

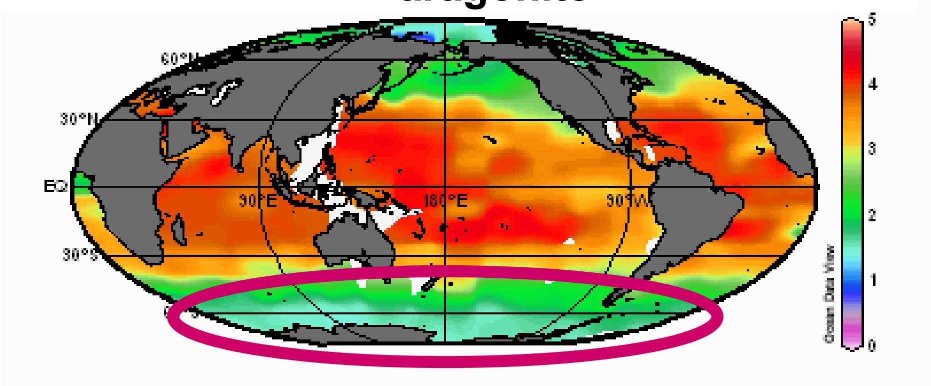
Ω = 1.3

Aragonite saturation state

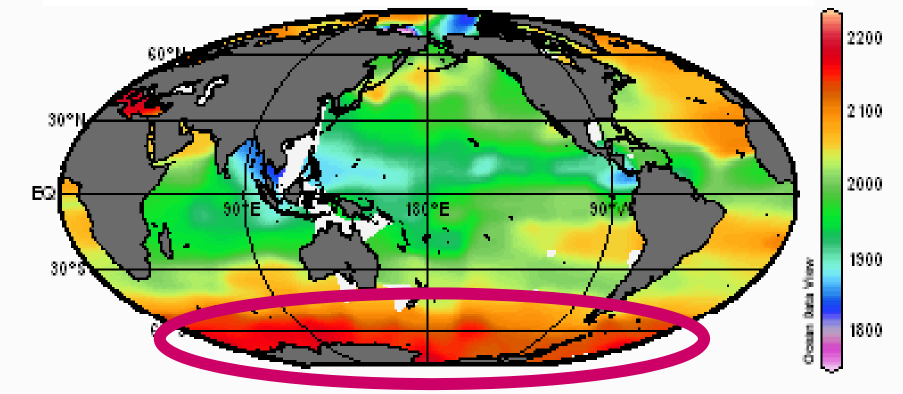
Southern Ocean

- **Cooling** --- low T seawater dissolve more CO_2 (high DIC)
- **Upwelling** of DIC enriched deep water (high DIC)

$\Omega_{aragonite}$



DIC [umol/kg]



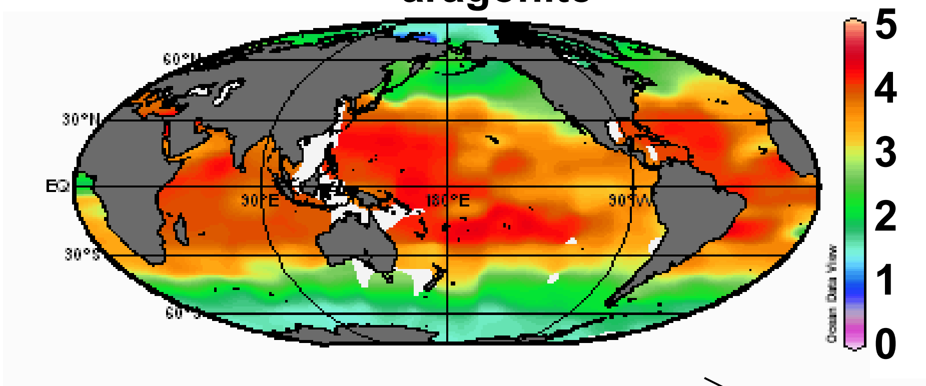
low Ω = high DIC

[CARINA+GLODAP]

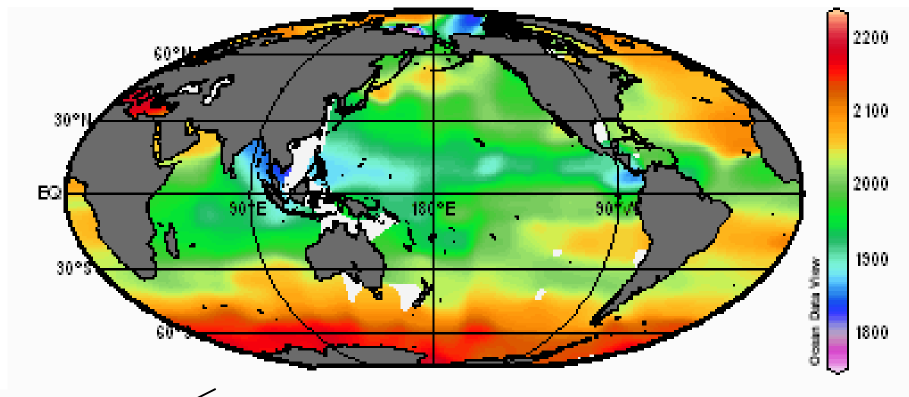
Arctic Ocean

- Cooling   Ω ↓   DIC ↑

$\Omega_{aragonite}$



DIC [umol/kg]



low Ω = high DIC

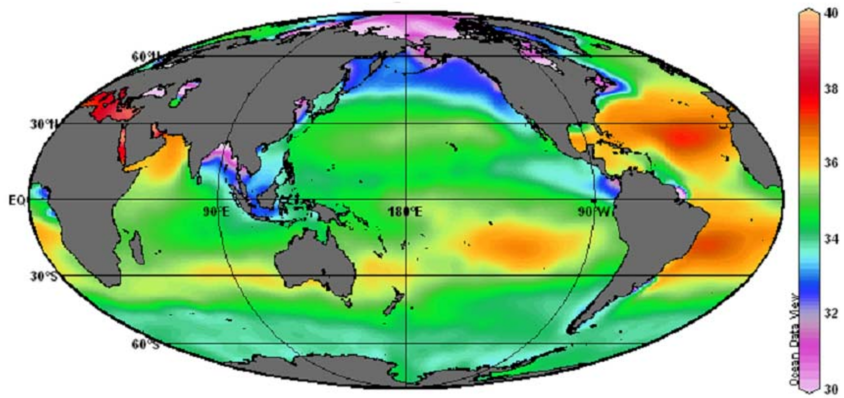
[CARINA+GLODAP]

Aragonite saturation state

Arctic Ocean

- Cooling $\Omega \downarrow$ DIC $\uparrow$
- Freshening $\Omega \downarrow$ DIC $\downarrow$ TA $\downarrow$

Surface salinity



[PHC3.0, Steele et al., J. Climate, 2001]

Pacific or Atlantic water: > 2000 umol/kg

Arctic River: TA~DIC ~ 1000 umol/kg

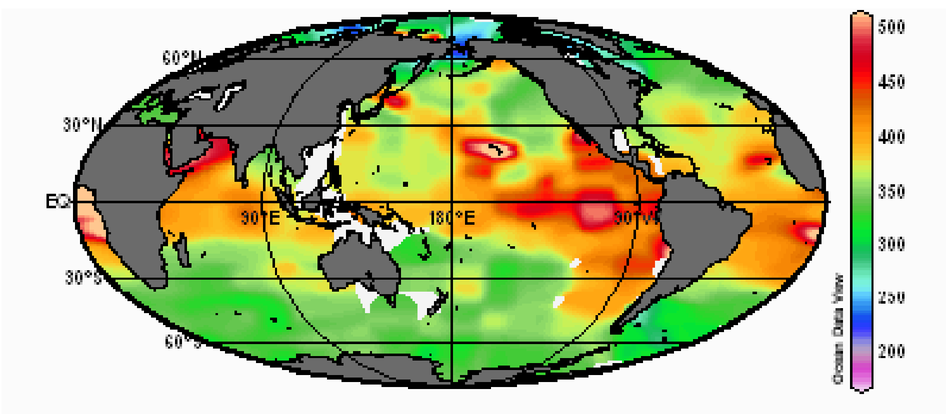
[PARTNERS 2009]

Aragonite saturation state

Arctic Ocean

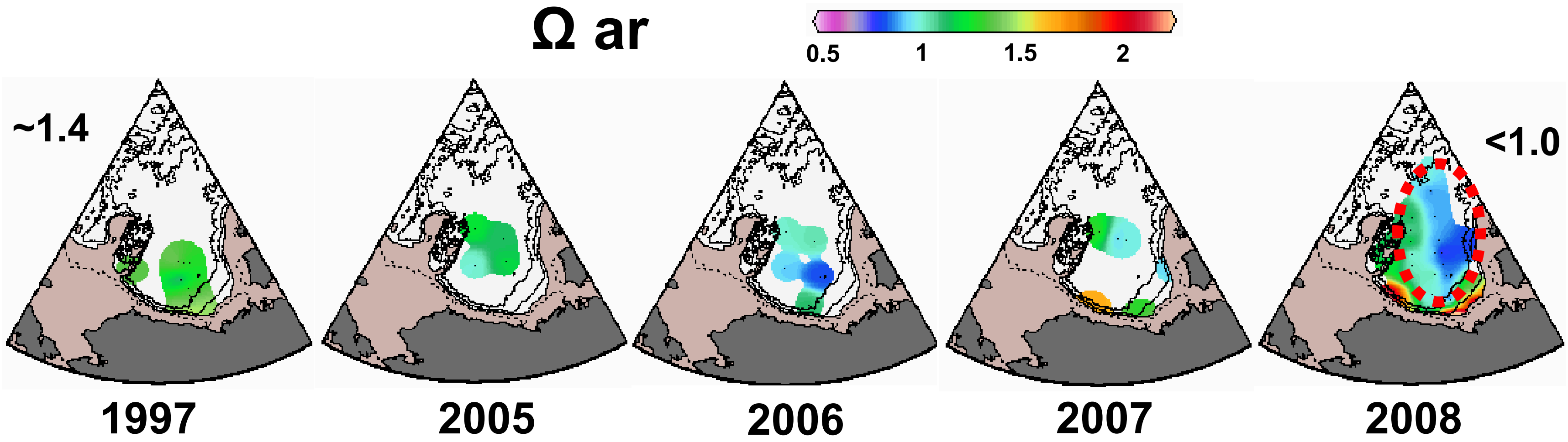
- Cooling — $\Omega \downarrow$ (↑) — DIC ↑ — **Warming**
- Freshening — $\Omega \downarrow$ (↓) — DIC ↓ — **More freshwater input**
- Low pCO_2 — $\Omega \uparrow$ (↓ ↕ P.P) — DIC ↓ — **Anthropogenic CO_2, Changes in P.P and air-sea gas exchange**

pCO_2^{sw} [µatm]



High primary productivity over shelves
Cooling
Sea ice cover

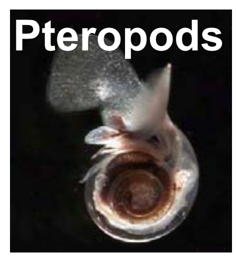
Aragonite undersaturation –western Arctic Ocean (JOIS)



Undersaturated !

∆ -0.4/10yrs

ALOHA -0.08/10yrs



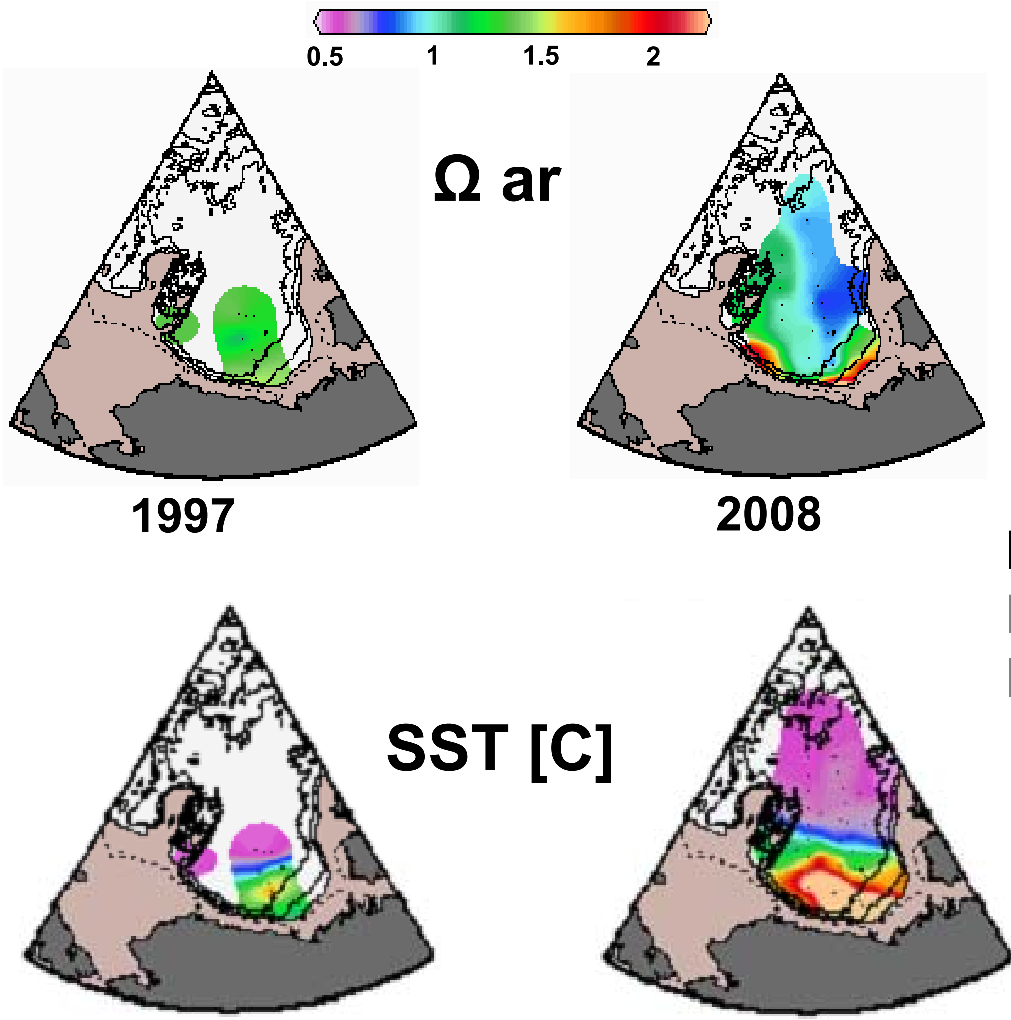
calcification rate is highly correlated to the aragonite saturation state

[Comeau et al., PLosOne, 2010]

Further cooling ?
Further freshening ?
Increase in pCO_2 ?

[Yamamoto-Kawai et al., Science, 2009]

Aragonite undersaturation –western Arctic Ocean

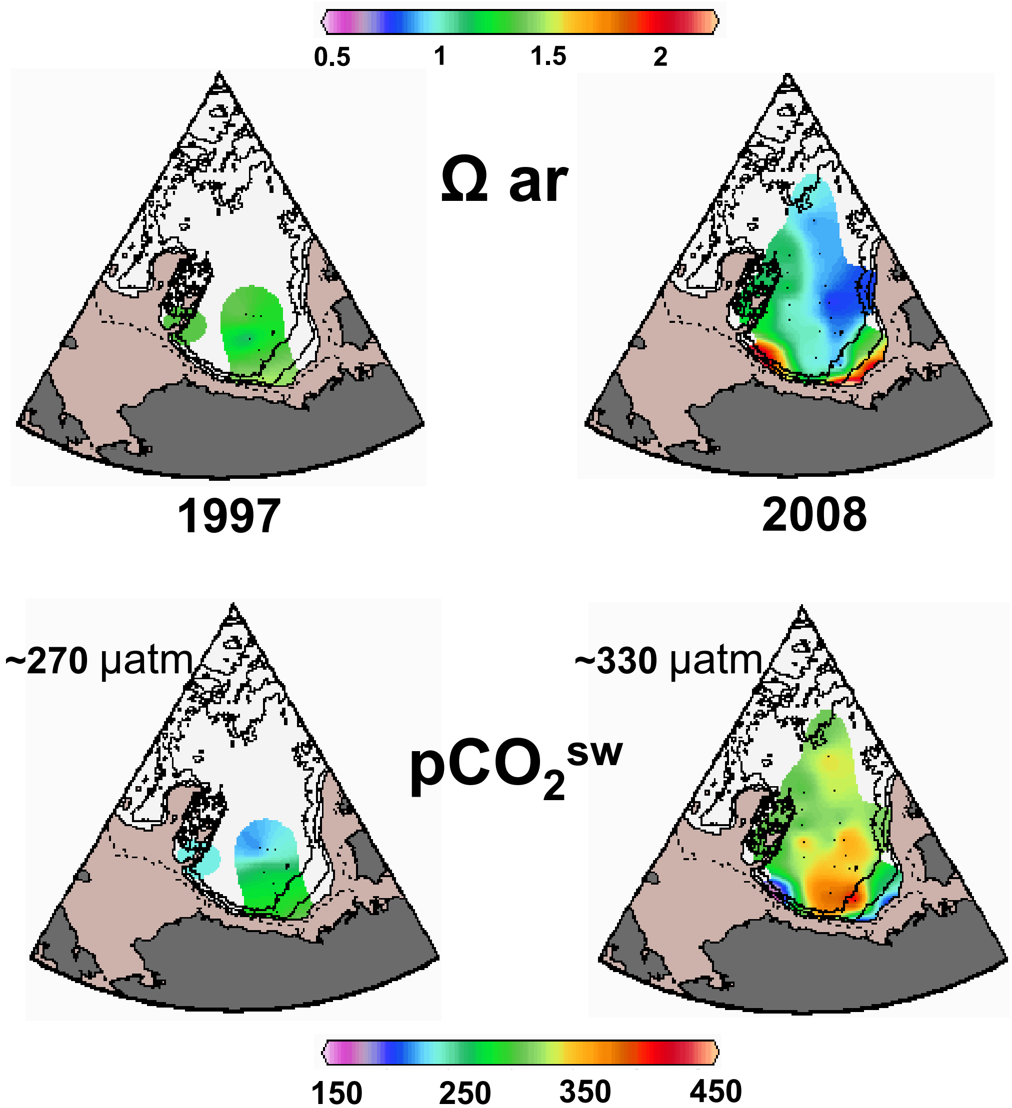


Further cooling ? **NO!**

Further freshening ?

Increase in pCO_2 ?

Aragonite undersaturation –western Arctic Ocean



Further cooling ? NO!

Further freshening ?

Increase in pCO_2 ? **YES!**

Aragonite undersaturation –western Arctic Ocean

pCO_2^{SW} Δ+60 µatm 1997 → 2008

not enough **1. Anthropogenic CO_2**

atm pCO_2 increase 1997→2008 Δ15 ppm

not likely **2. Decrease in P.P. at the surface**

P.P. increased due to longer growing season [Arrigo et al., GRL, 2008]
mean Chl.a did not change in 0-150 m layer [Li et al., Science, 2009]

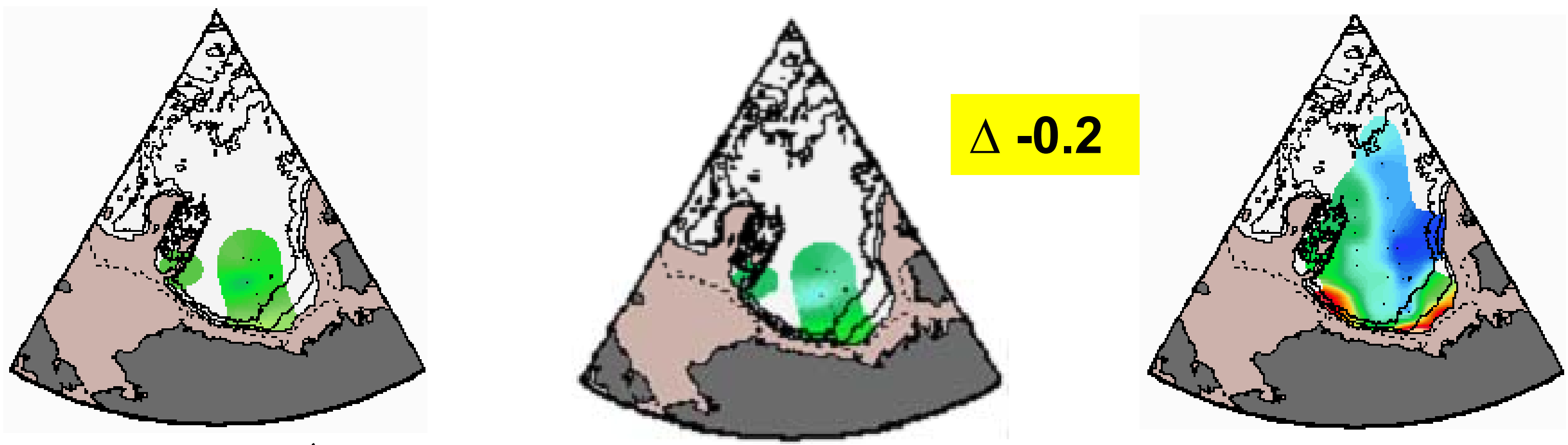
! **3. <u>Enhanced air-sea gas exchange</u>**

Less ice cover !

Aragonite undersaturation –western Arctic Ocean

pCO_2^{SW} Δ+60 µatm 1997 → 2008

<u>Can this explain the decrease in Ω ar by 0.4 ?</u>

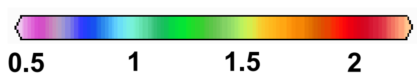


Δ -0.2

1997

1997
+ 60 µatm -pCO_2

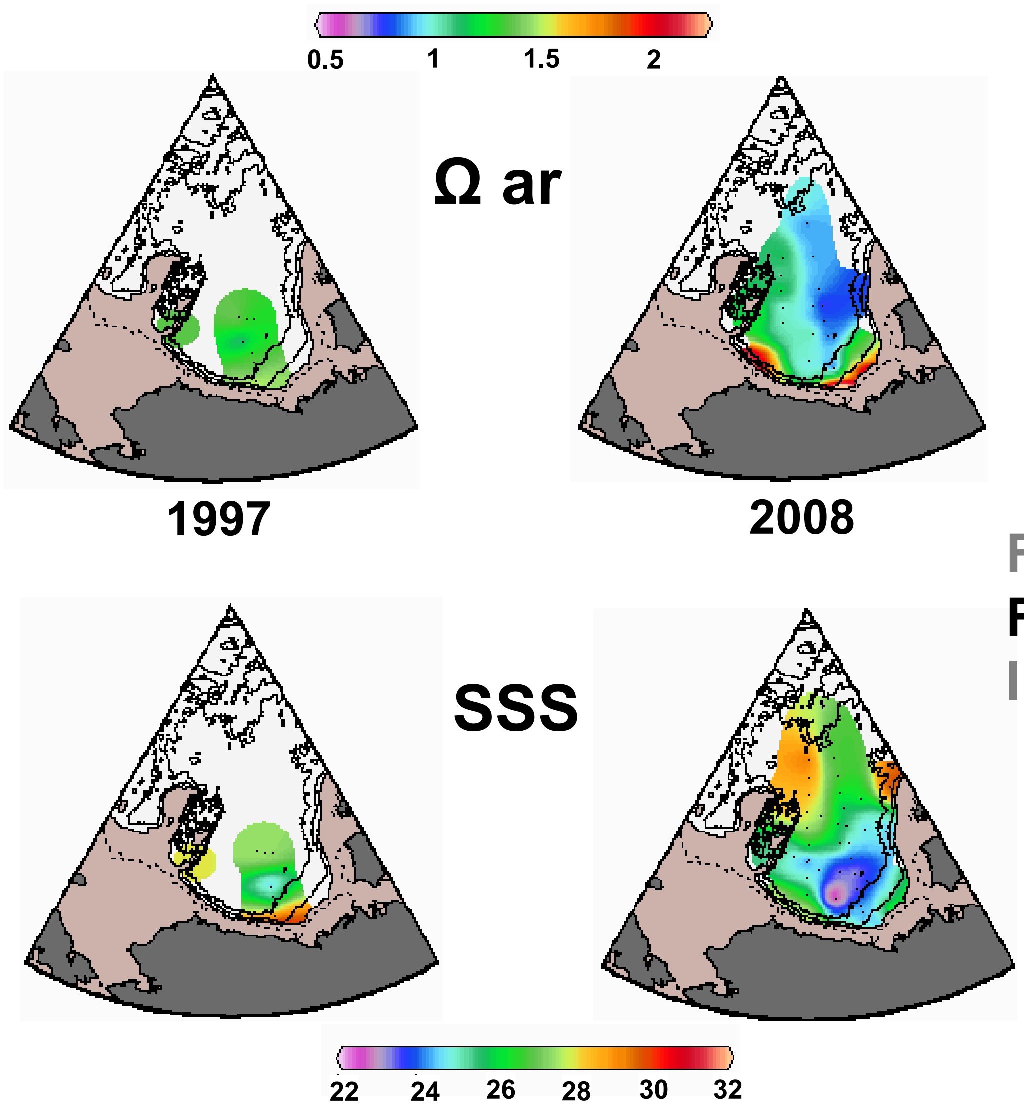
2008



T, S, TA = constant
pCO_2^{SW}+60 µatm

Ω ar

Aragonite undersaturation –western Arctic Ocean

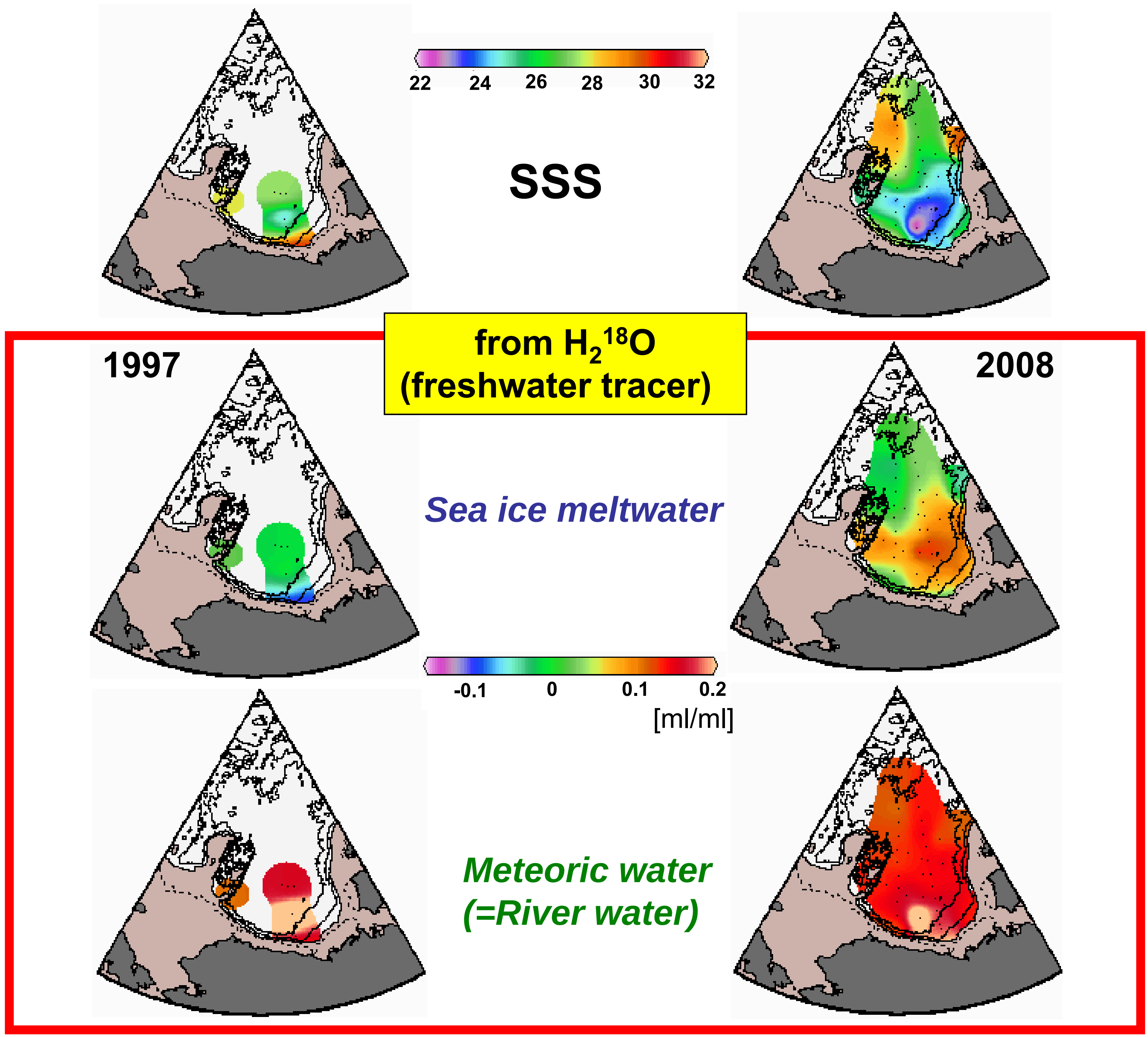


Further cooling ? NO!

Further freshening ? YES!

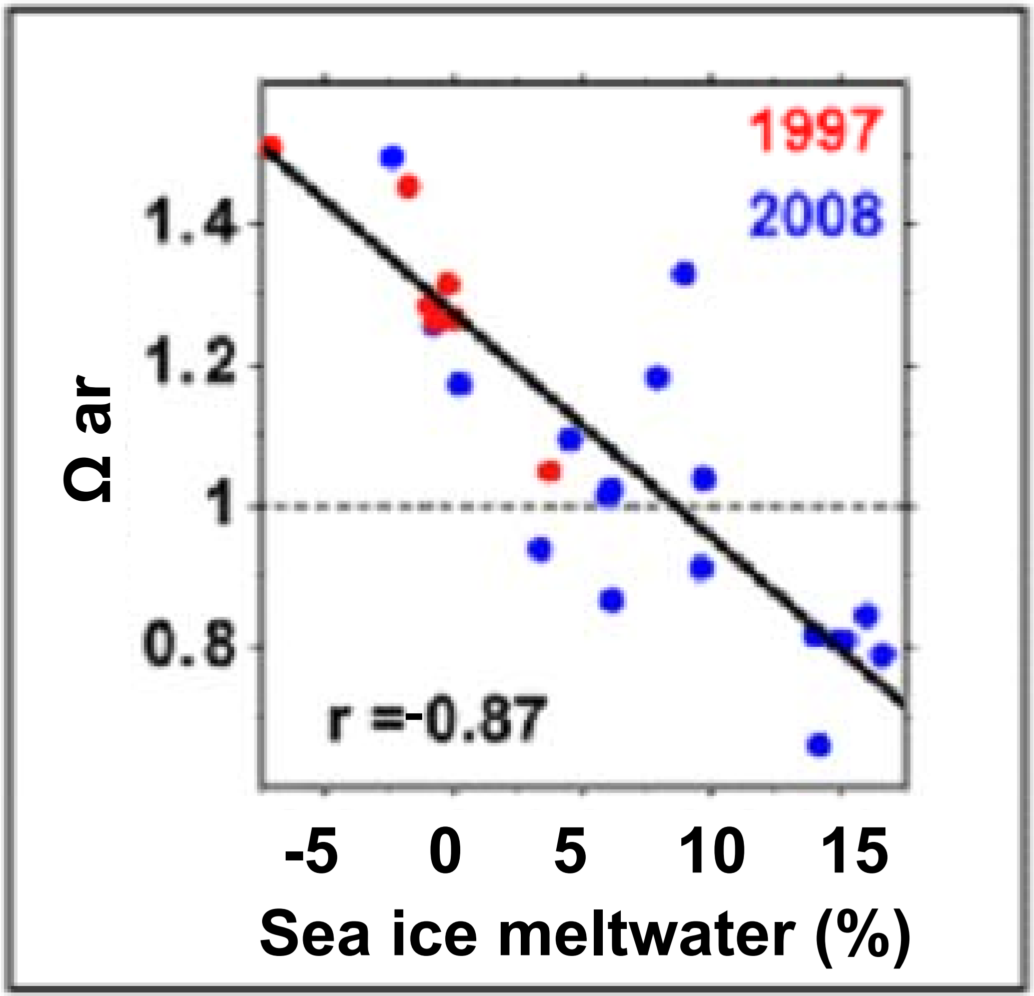
Increase in pCO_2 ? YES!

river or ice melt?



[Yamamoto-Kawai et al., JGR, 2009+]

Aragonite undersaturation –western Arctic Ocean



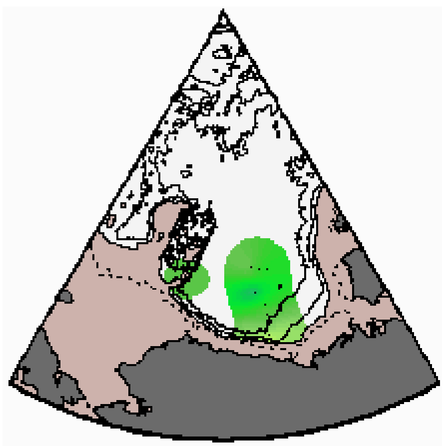
[Yamamoto-Kawai et al., Science, 2009]

Aragonite undersaturation –western Arctic Ocean

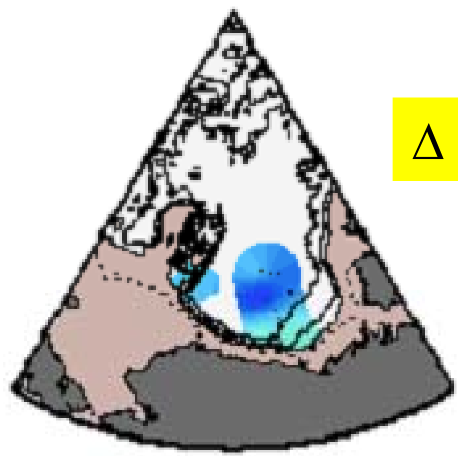
+ 60 µatm pCO_2

+ 10% sea ice meltwater

<u>**Can these explain the decrease in Ω ar by 0.4 ?**</u>

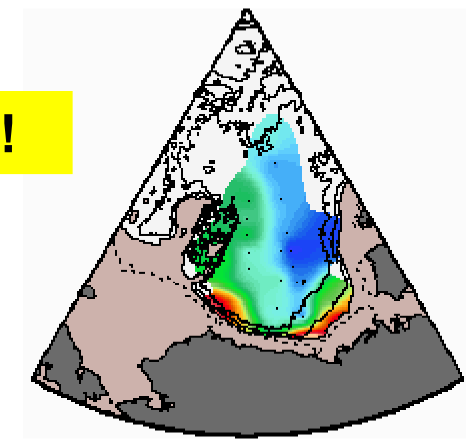


1997

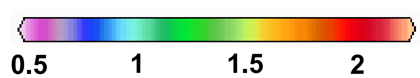


1997
+ 60 µatm -pCO_2
+10% SIM

Δ -0.4 !



2008



Ω ar

Dilute S &TA with 10% SIM

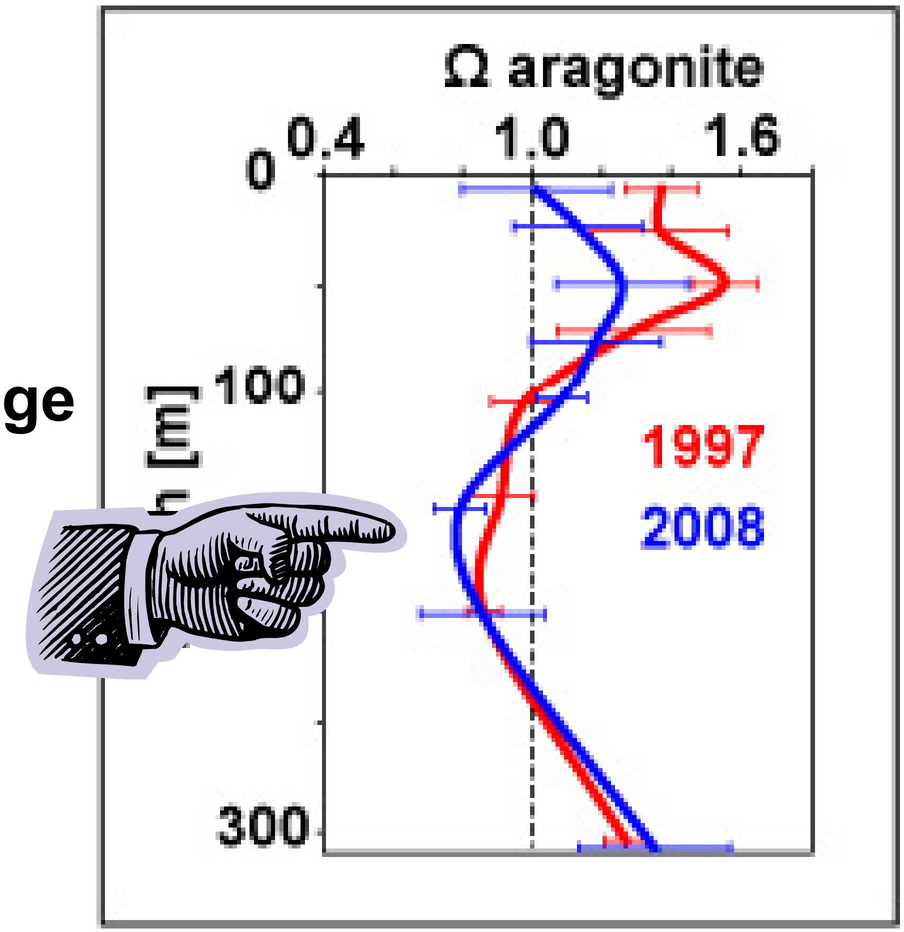
$pCO_2 = pCO_2^{1997} + 60$ µatm

Aragonite undersaturation –western Arctic Ocean

<u>melting of sea ice</u>
decreased surface Ω
in the western Arctic

Enhanced air-sea gas exchange

Dilution by sea ice melt

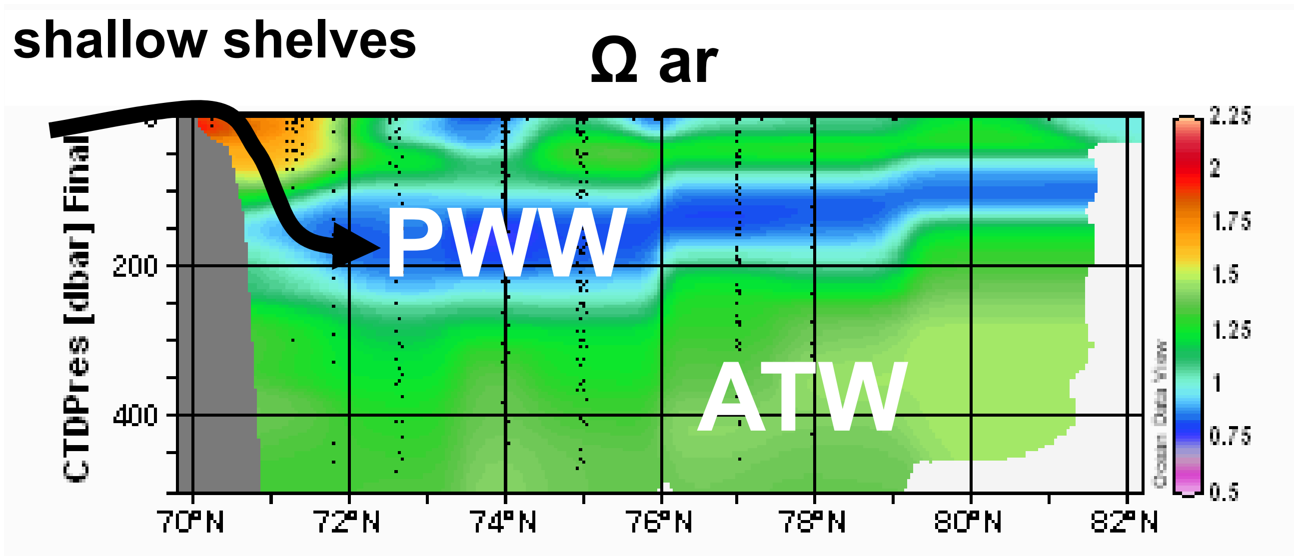


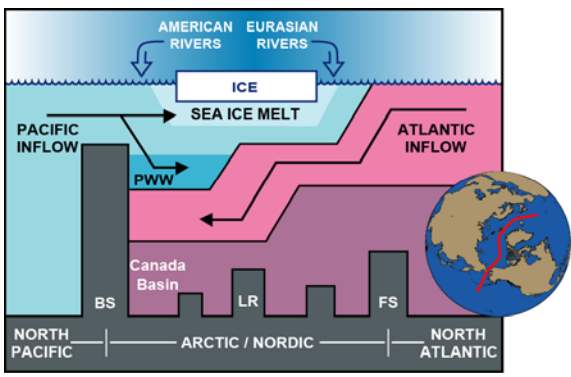
[Yamamoto-Kawai et al., Science, 2009]

Subsurface Aragonite undersaturation

cooling
remineralization
on shallow shelves

Ω ar





PWW

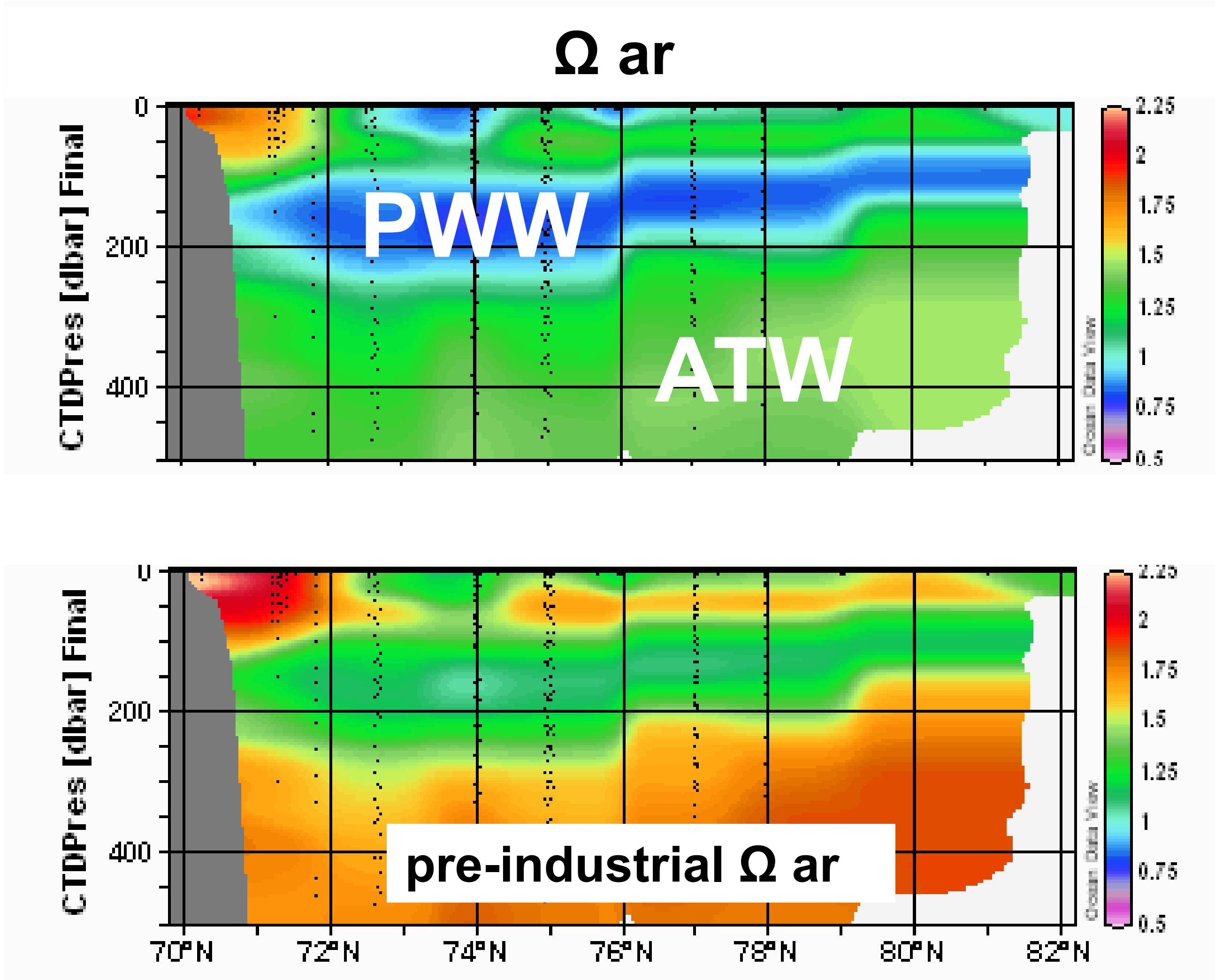
ow T, high nutrients, high DIC

→ low Ω

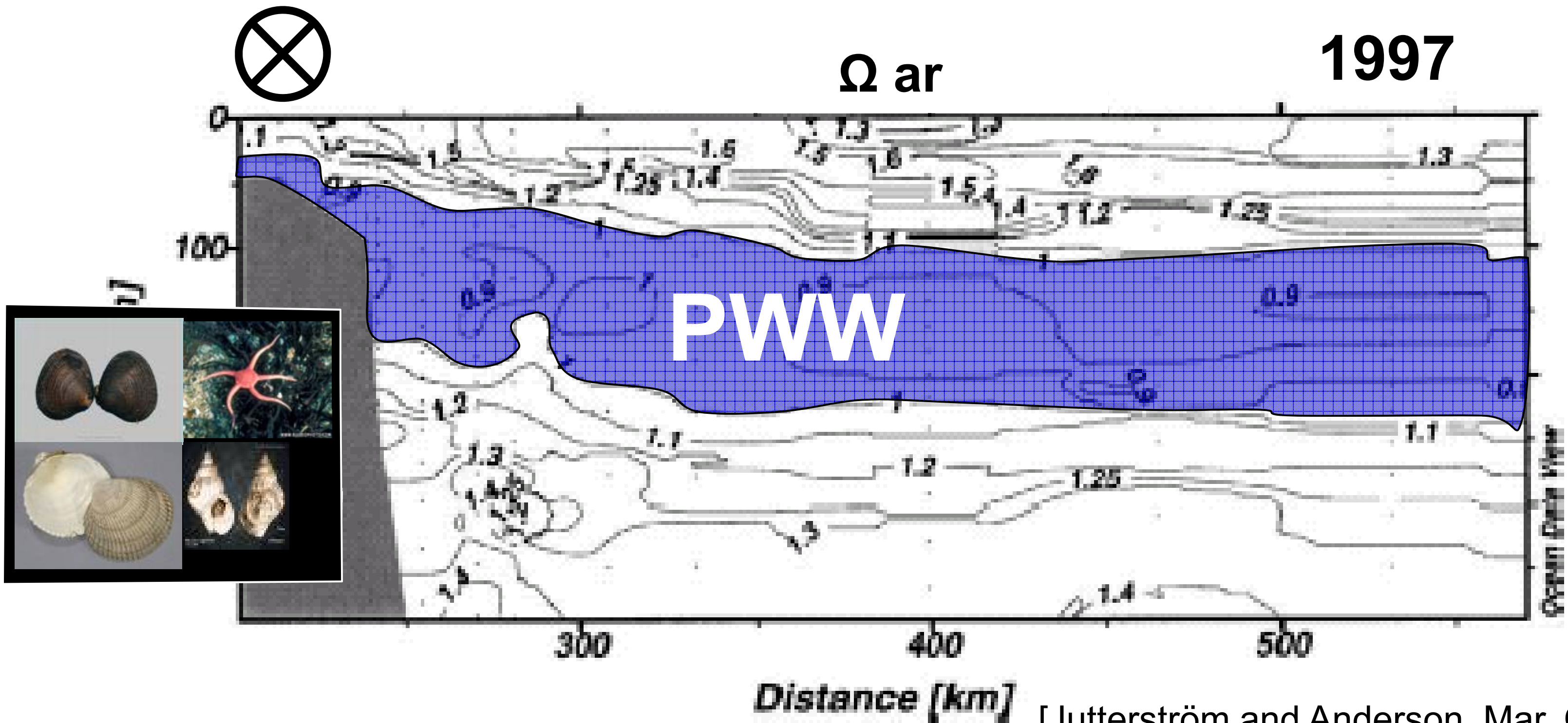
Subsurface Aragonite undersaturation

DIC ant = 40 μmol/kg (0m) ~ 30 μmol/kg (500m) [Tanhua et al., JGR, 2009]

DIC bio = ~70 μmol/kg ---from AOU and N* [Sabine et al., GBC, 2002]



Subsurface Aragonite undersaturation



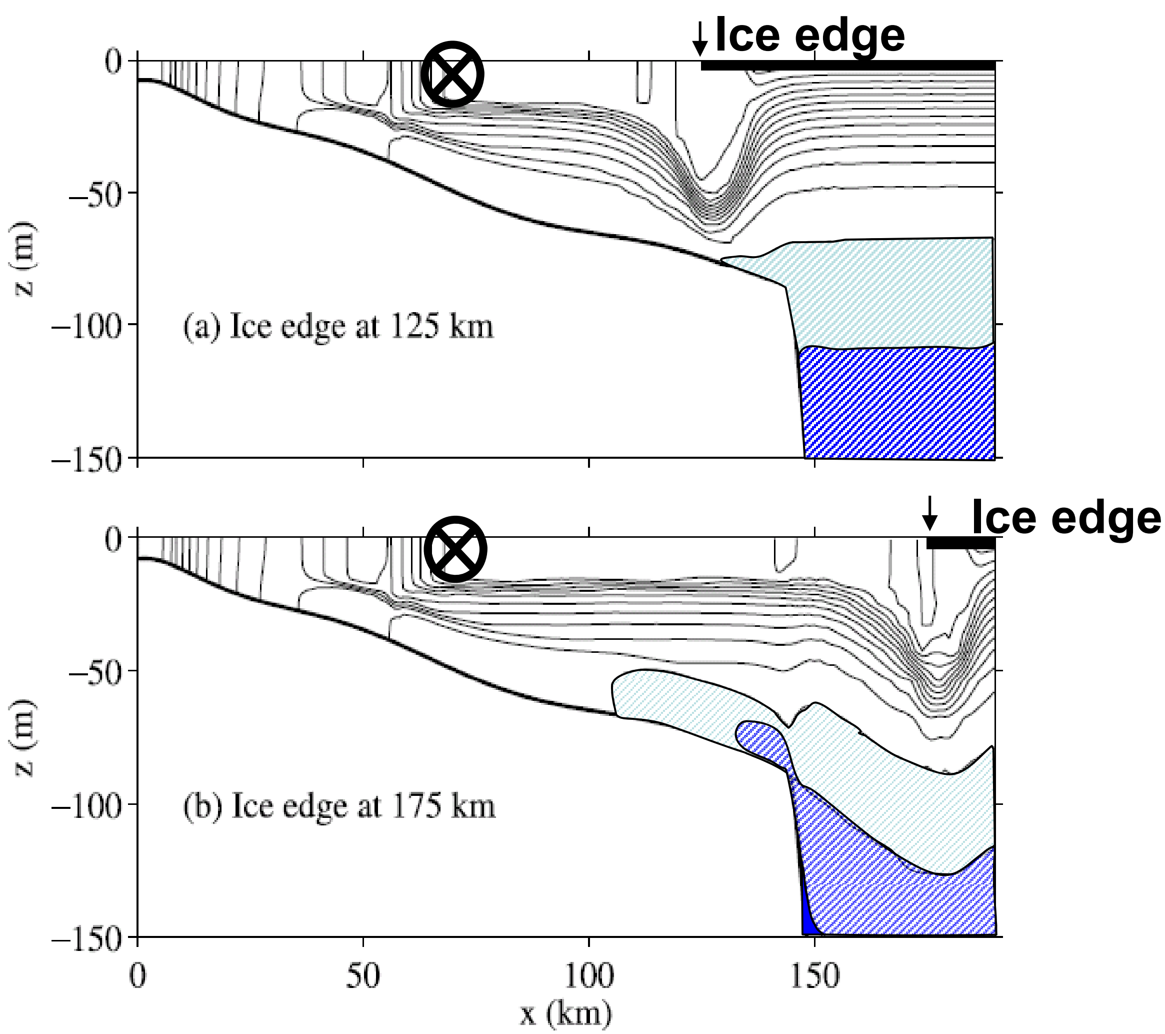
[Jutterström and Anderson, Mar. Chem., 2005]

More frequent upwelling of corrosive PWW in recent years

[Williams and Yamamoto-Kawai, in prep.]

Subsurface Aragonite undersaturation

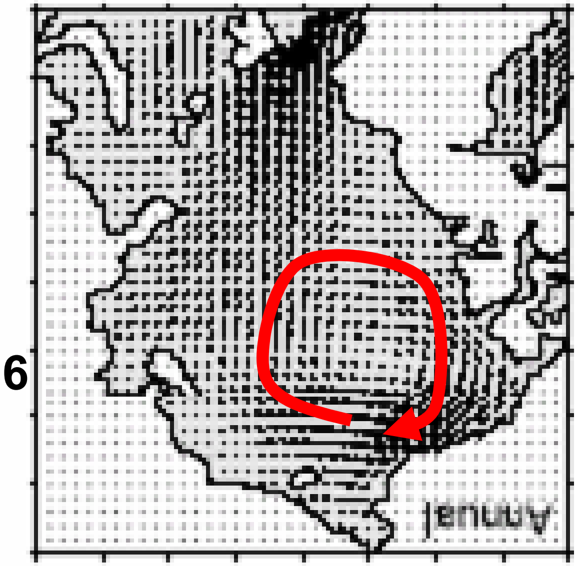
melting of sea ice enhances upwelling of corrosive subsurface water



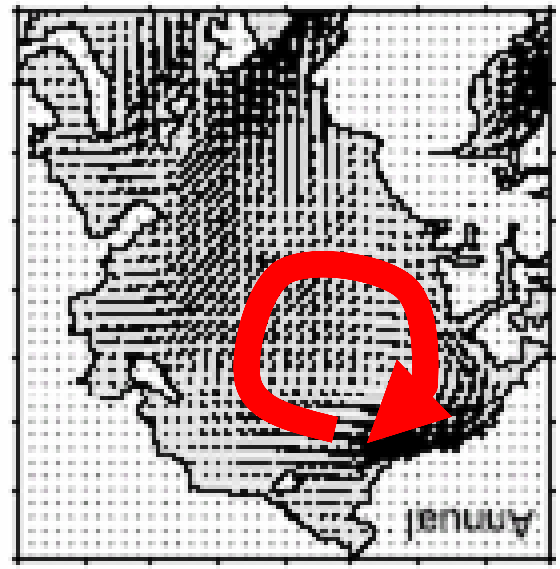
[Carmack & Chapman, GRL, 2003]

Upwelling is also enhanced by accelerated motion of upper ocean

1979-1986

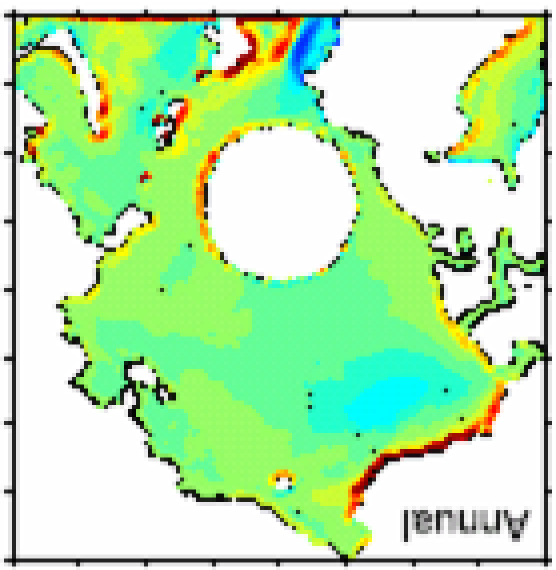


sea Ice motion

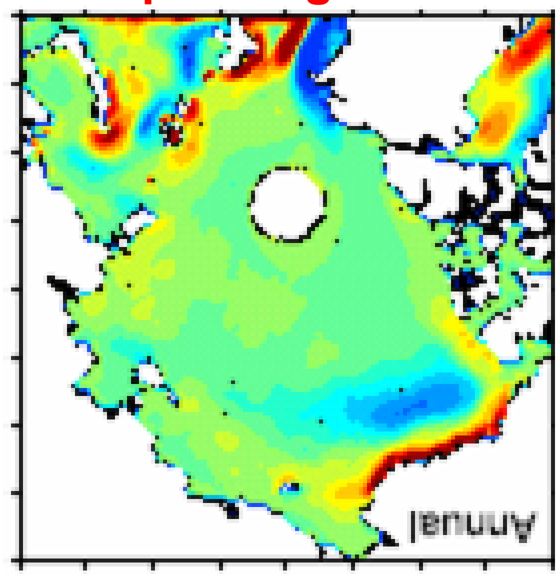


1997-2004

More mobile ice → more upwelling at shelf break

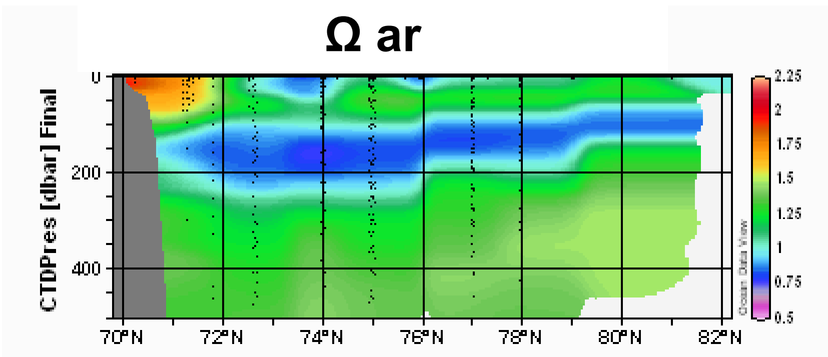


Upwelling (cm/day)



[Yang, JGR, 2009]

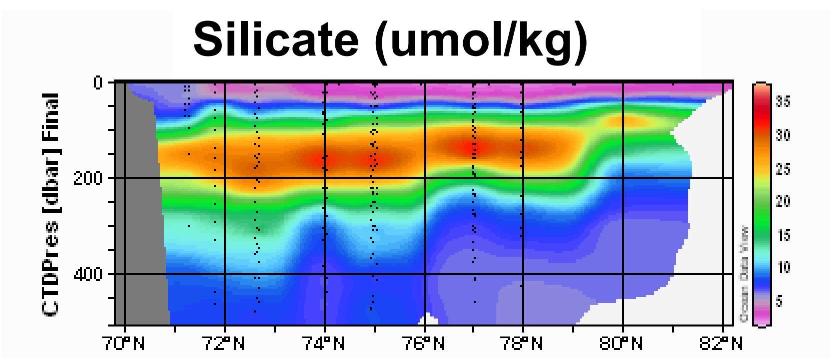
On the shelf



Up-welling of <u>subsurface water</u>

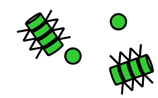
Aragonite undersaturated

→ Negative impacts on Benthos



Nutrient enriched

→ Positive impacts on P.P.



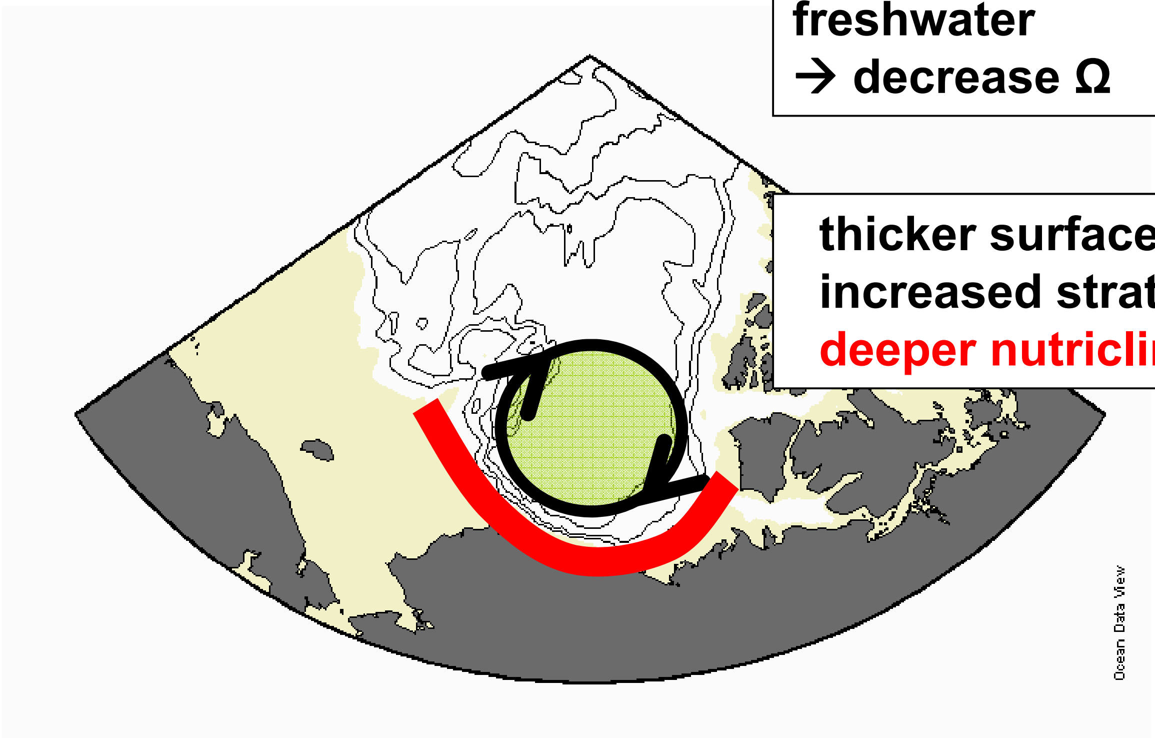
On the shelf ≠ In the Basin

Up-welling

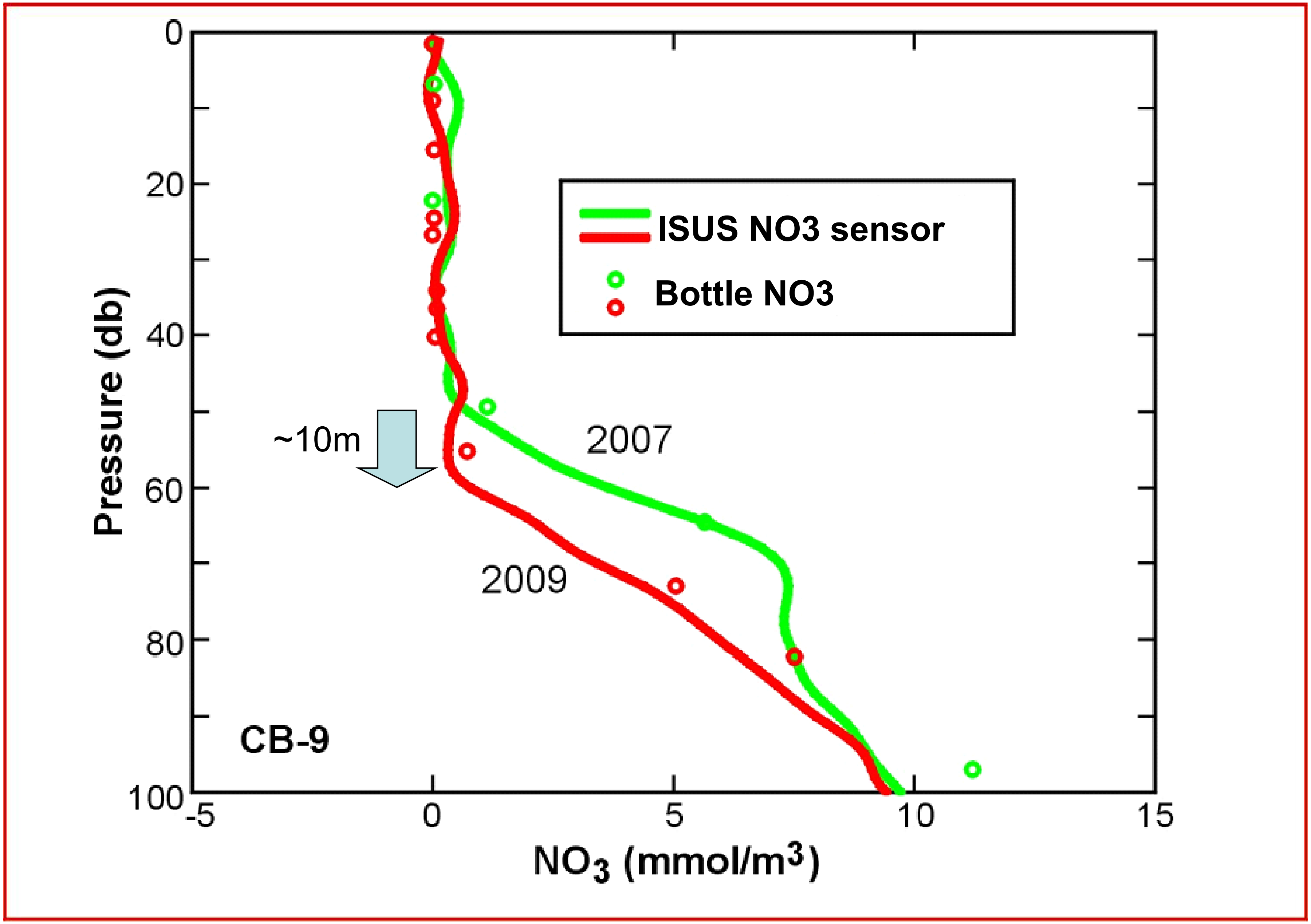
Down-welling

accumulate surface freshwater
→ decrease Ω

thicker surface layer
increased stratification
deeper nutricline

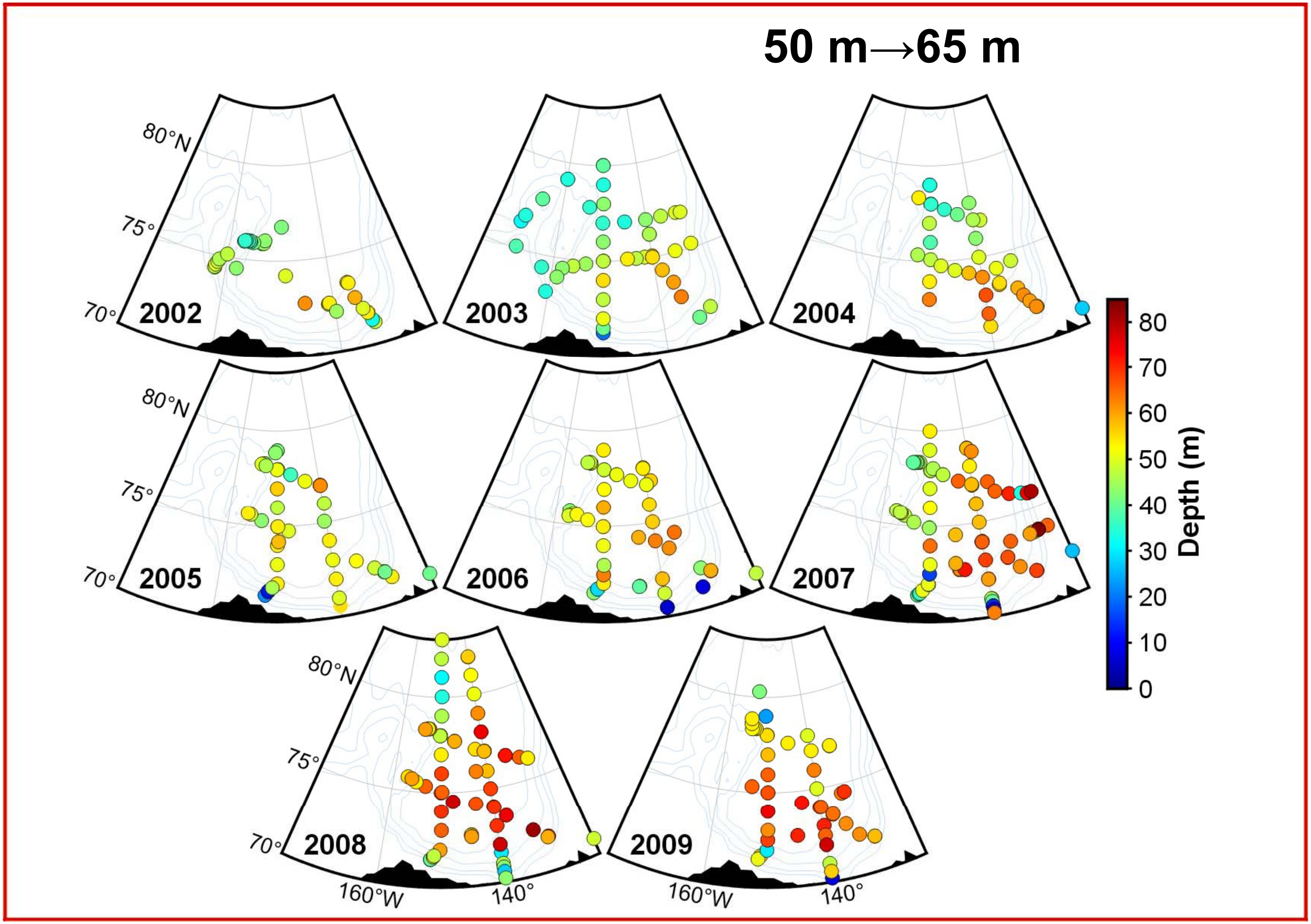


Deepening of nutricline



[McLaughlin & Carmack, subm.]

Deepening of Chl.a maximum depth



[McLaughlin & Carmack, subm.]

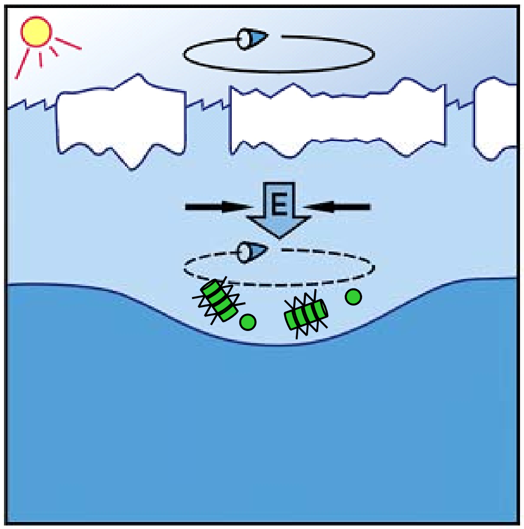
Melting of more sea ice and/or less ice formation

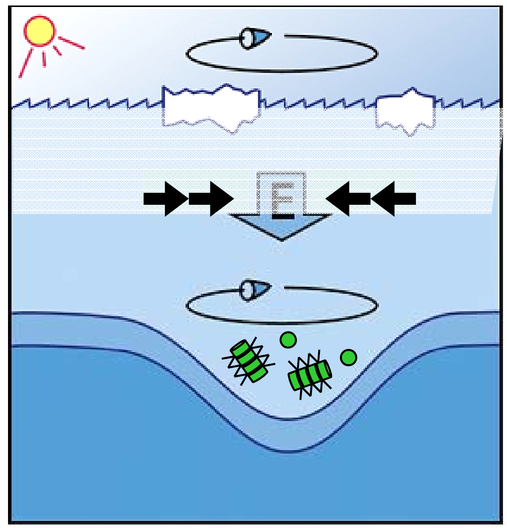
↓

Increased atm-ocean coupling:
increased ice drift velocities
increased Ekman pumping

→

thicker surface layer
increased stratification
deeper nutricline





↓

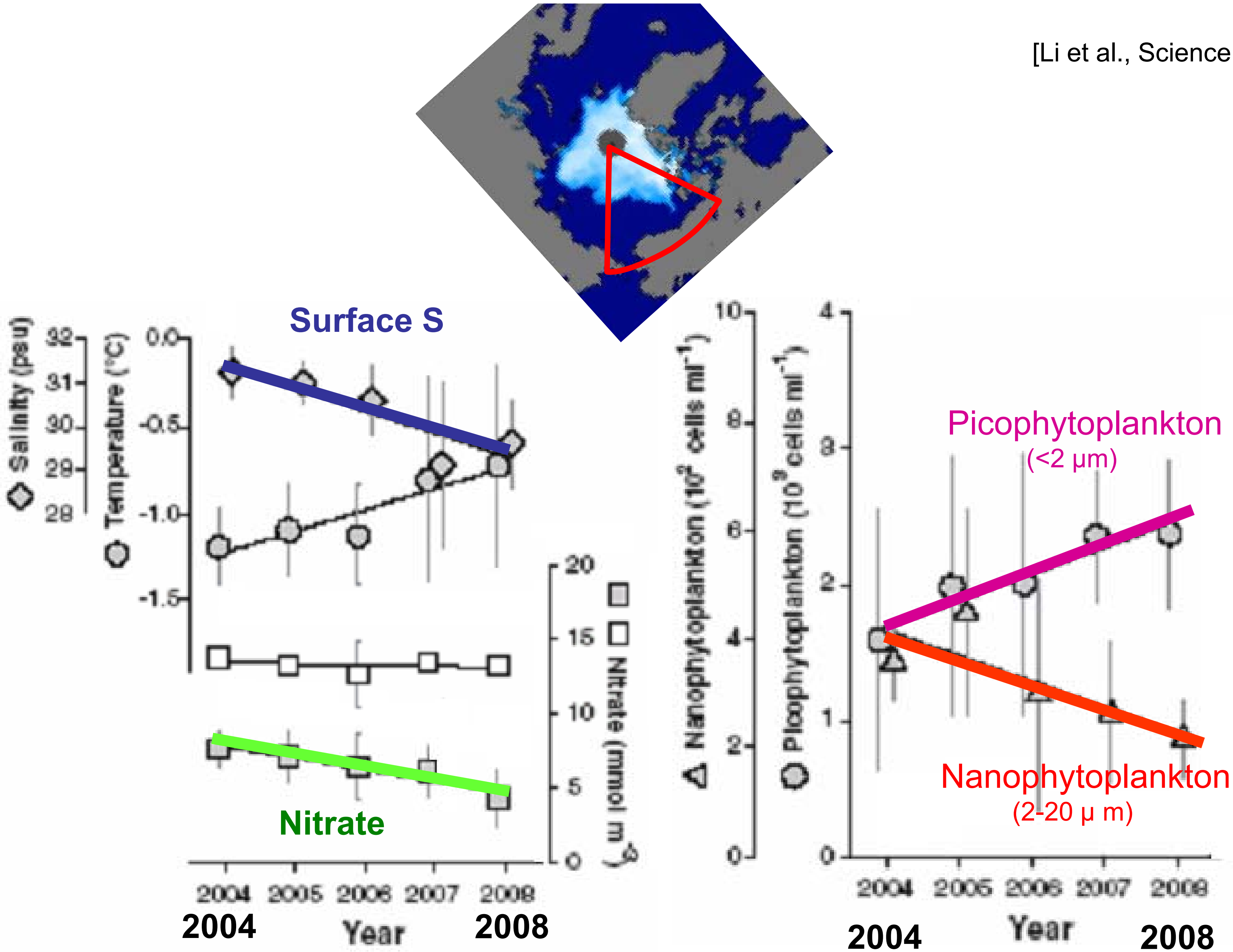
nutricline and chlorophyll maximum have deepened

.....

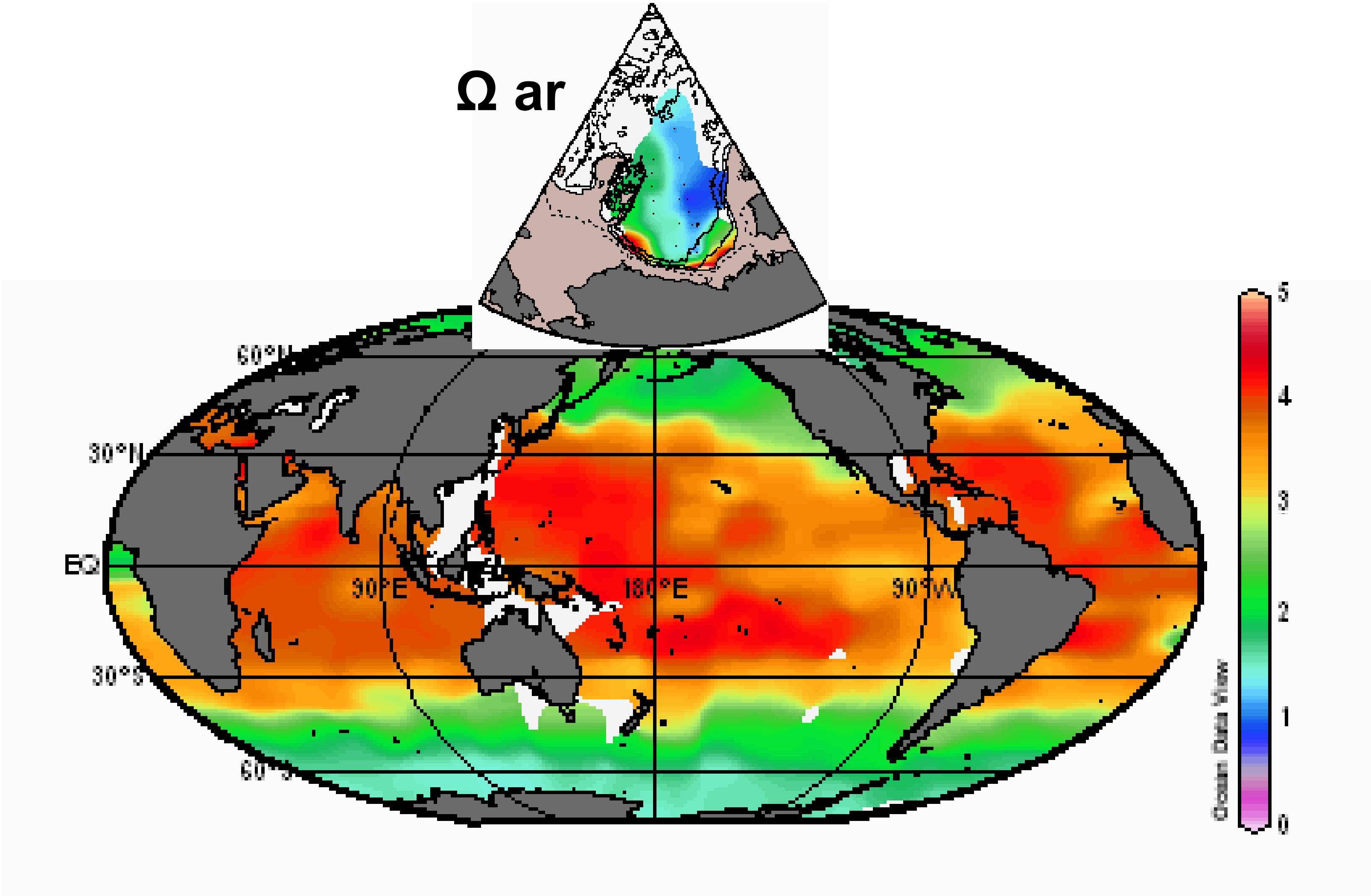
- **Light limitation may play a greater role now in P.P.**

[McLaughlin & Carmack, subm.]

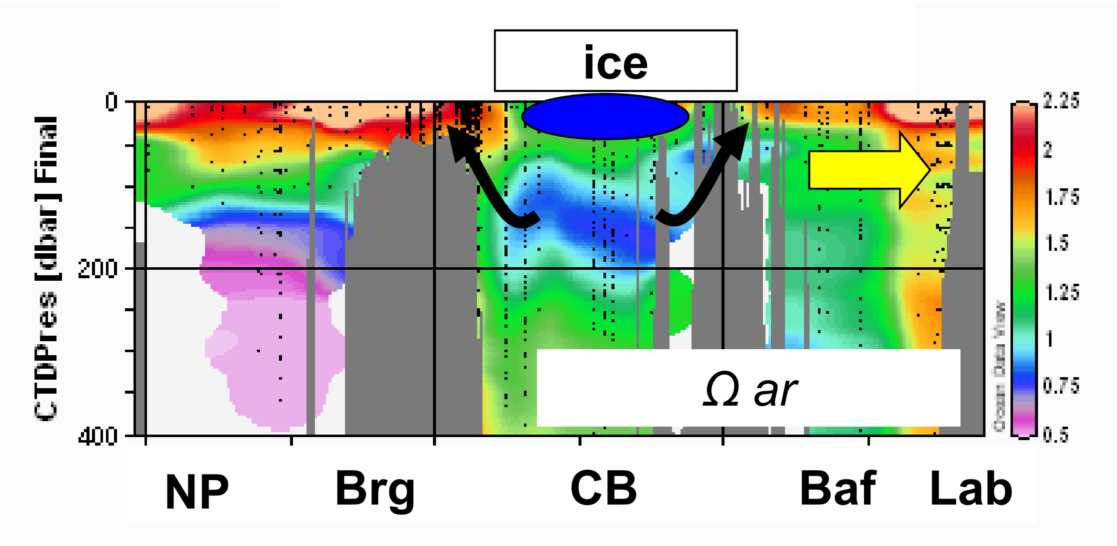
[Li et al., Science, 2009]

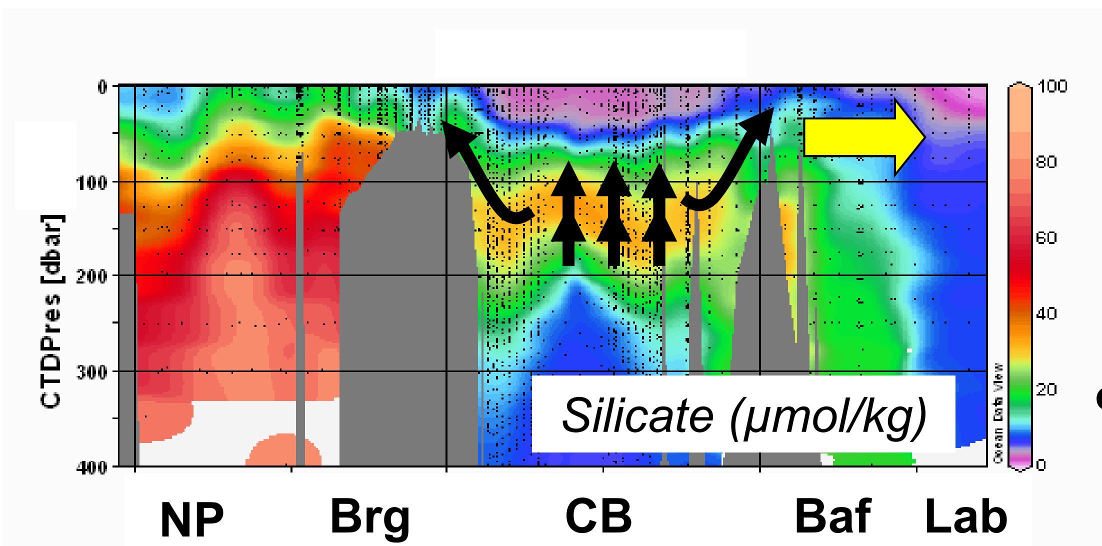


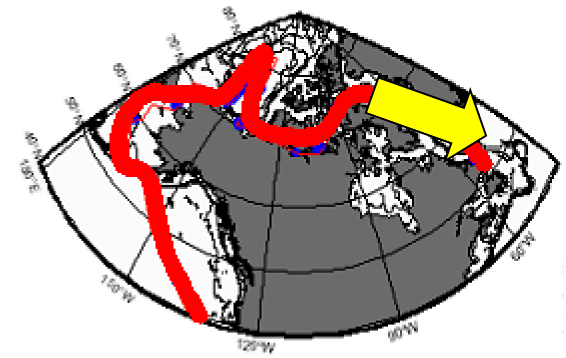
Summary



Summary







Melting of sea ice

Basin

Surface freshening
Increased pCO_2
Aragonite undersaturation in surface water

Increased Ekman Pumping
Deepening of nutricline
Deepening of Chl.a max

Shelf

Enhanced Upwelling of corrosive acidified water onto the shelf bottom
Supply of nutrients

Concluding remarks

Winter observations

:Sensor, automatic seawater sampler, AUV

Shelf-basin feedback

:–high PP on shelf—high nutrients/low omega PWW-upwelling onto shelf– high PP on shelf–

Coastal erosion, methane seeps, permafrost thawing

Changes are happening right now!
& likely continue until multi-year ice disappears (~2030?)
: **monitoring of the changing Arctic** for future prediction/adaptation in the Arctic and other oceans

Many thanks to

Fiona McLaughlin (Canada/IOS)
Eddy Carmack (Canada/IOS)
William Williams (Canada/IOS)
Andrey Proshutinsky (US/WHOI)
Shigeto Nishino (Japan/JAMSTEC)
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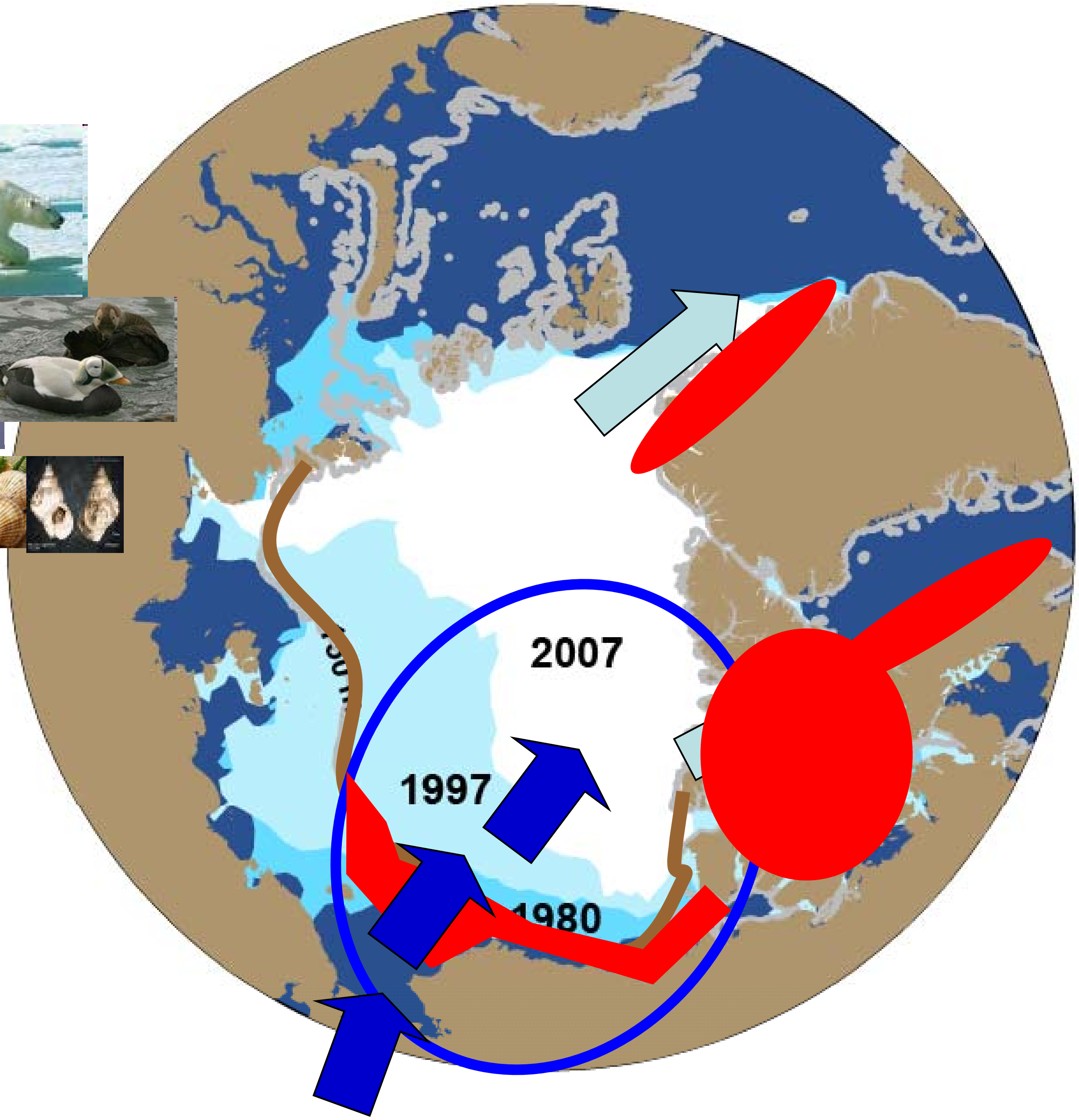
Members of the IOS & Mirai science teams
Captains and crew of the *CCGS St-Laurent, Laurier* and the *R/V Mirai*
DFO, Cdn IPY Office, NSF, JAMSTEC

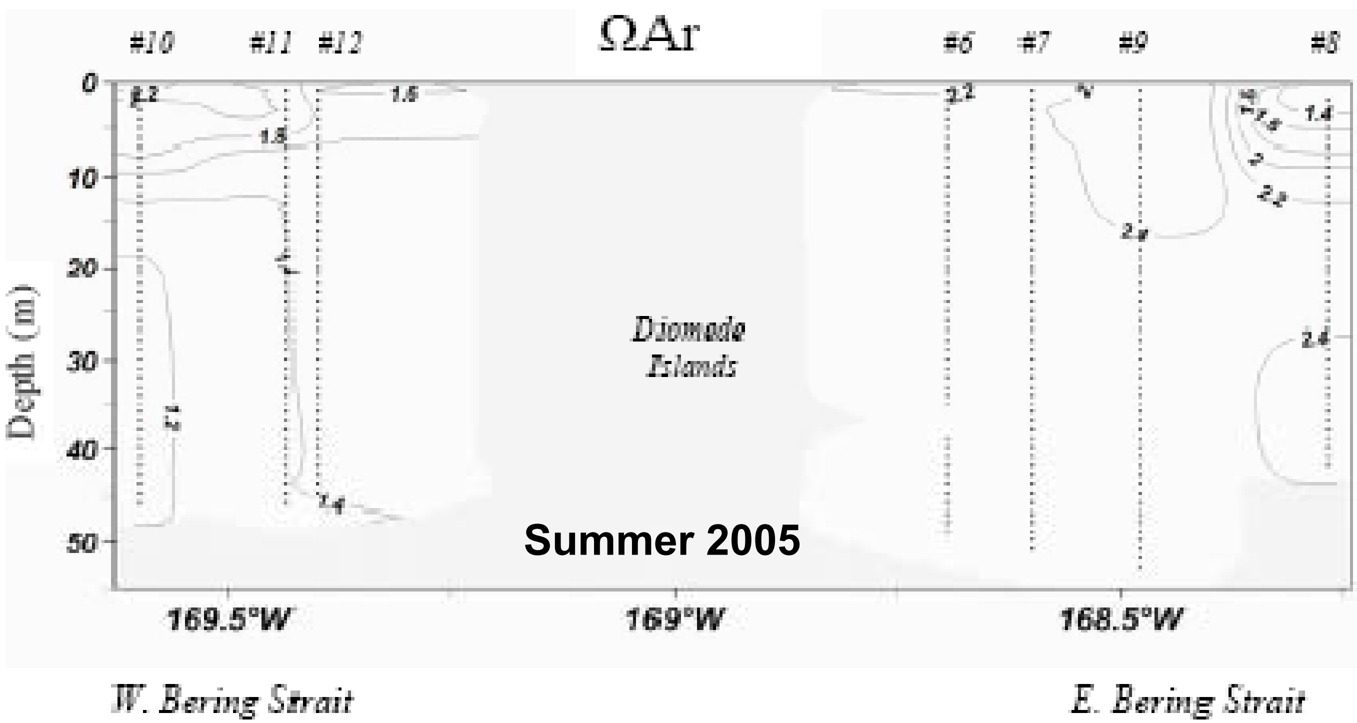
Fisheries and Oceans | Pêches et Océans

IPY 2007-2008 API

ARC PAC ATL C3O Canada's Three Oceans

Shelf edge & summer sea ice cover



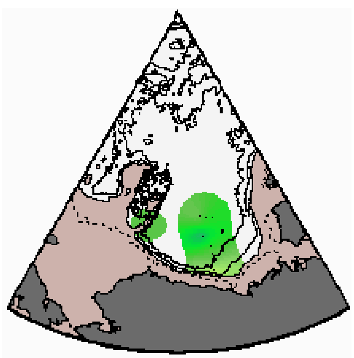


[Chierici & Fransson, BGD 2009]

Aragonite saturation state –western Arctic Ocean

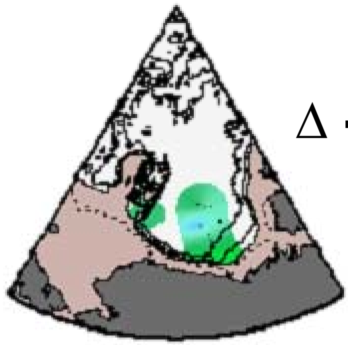
+ 60 µatm pCO_2

+ 10% sea ice meltwater



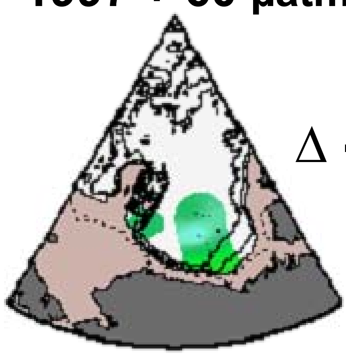
1997

1997 + 10%SIM

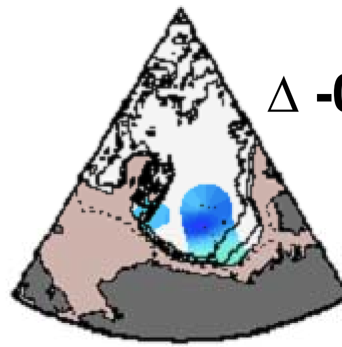


Δ -0.2

1997 + 60 µatm

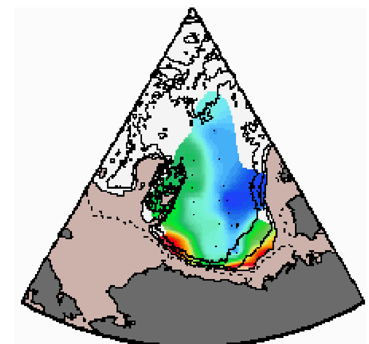


Δ -0.2



Δ -0.4

1997 + 60 µatm + 10%SIM

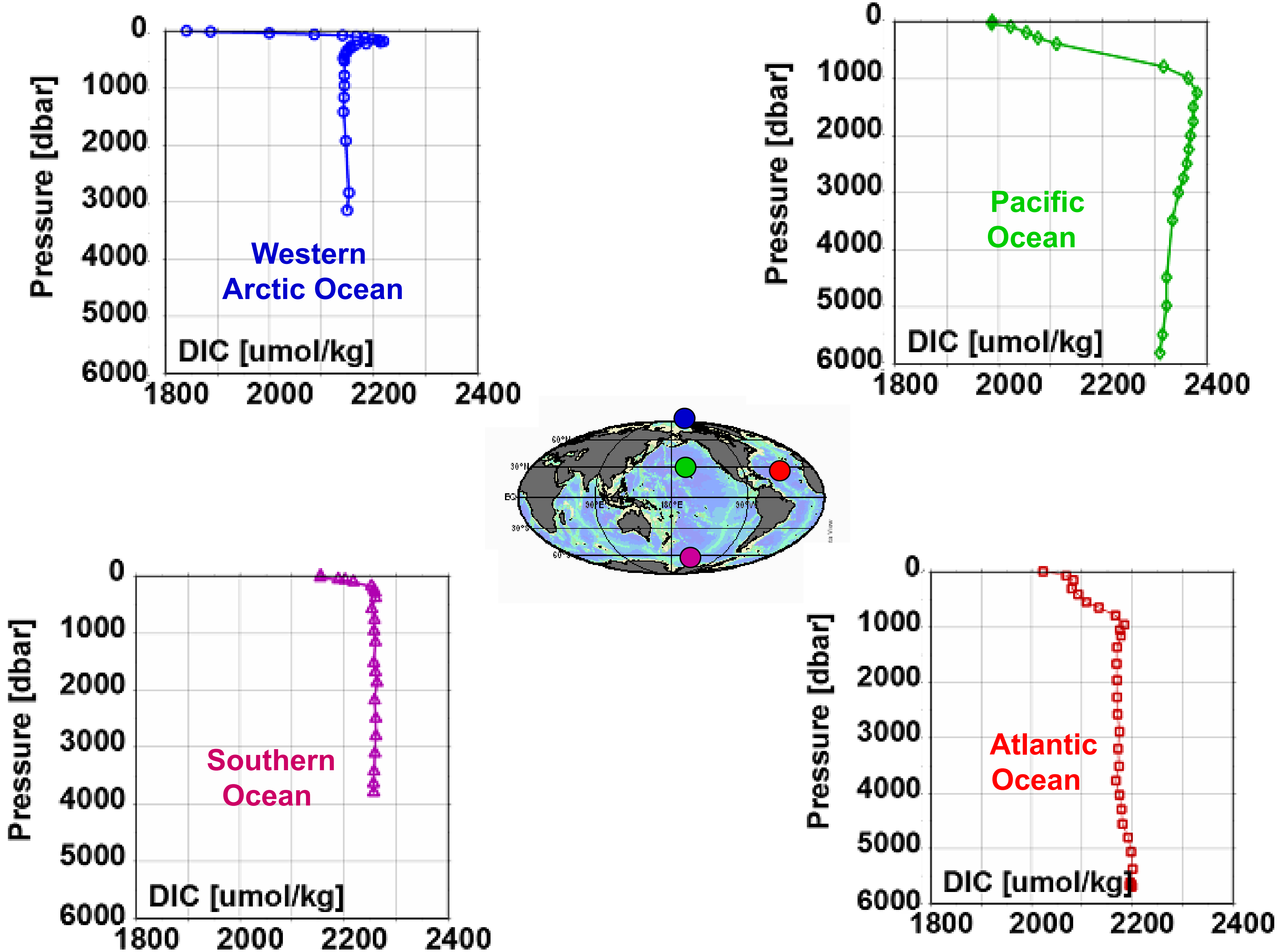


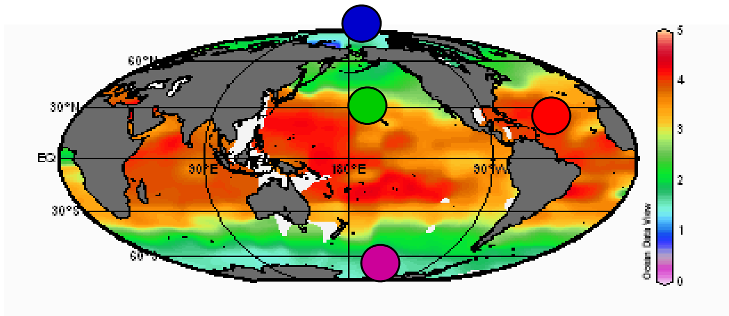
2008

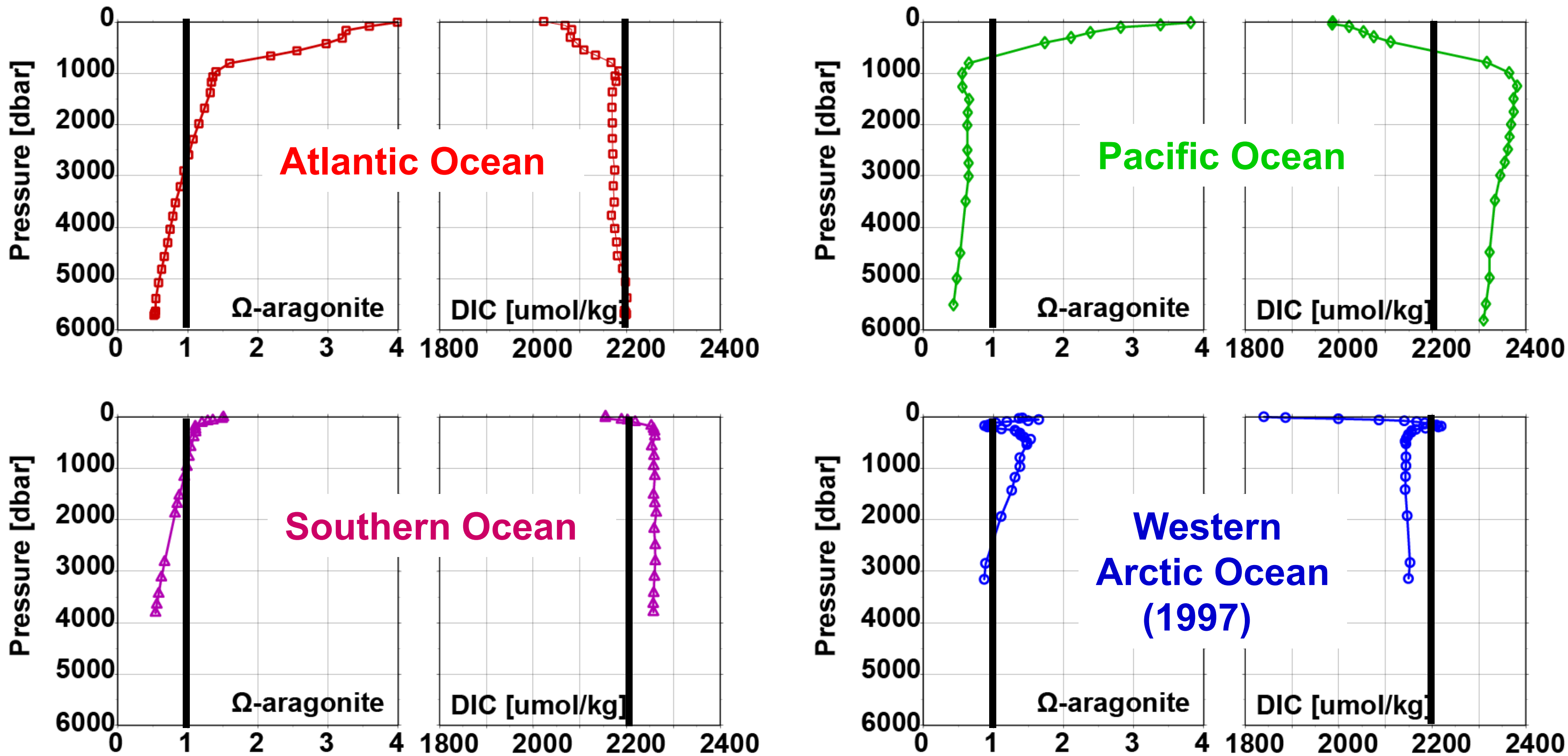
Ω ar

Upwelling-enhanced P.P. → lower omega → upwelling

Surface tropical seawaters are generally supersaturated with respect to the carbonate minerals (e.g. calcite, aragonite, and high-magnesium calcites) from which marine organisms construct their shells and frameworks. At deeper water depths, seawater becomes undersaturated and these minerals begin to dissolve, imparting an important control (amongst other factors) on the distribution of coral reefs. We refer to the degree to which seawater is saturated with respect to these minerals as 'saturation state' and denote it using the Greek term Ω (omega).


Western
Arctic Ocean
Pressure [dbar]
DIC [umol/kg]
0
1000
2000
3000
4000
5000
6000
1800
2000
2200
2400
Pacific
Ocean
Pressure [dbar]
DIC [umol/kg]
Southern
Ocean
Pressure [dbar]
DIC [umol/kg]
Atlantic
Ocean
Pressure [dbar]
DIC [umol/kg]



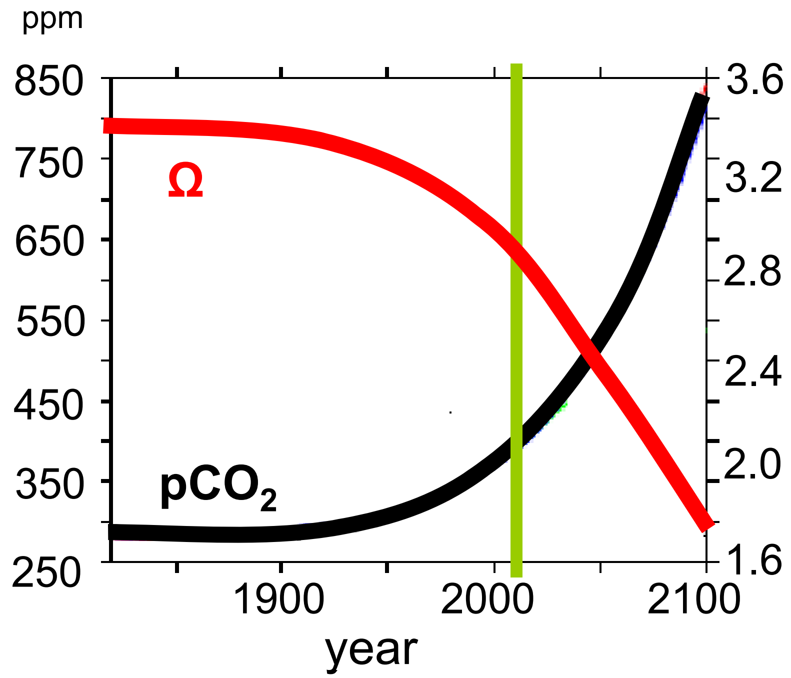


[CARINA+GLODAP]

Ocean Acidification

$CO_2 + H_2O \Leftrightarrow H^+ + HCO_3^-$ — pH ↓

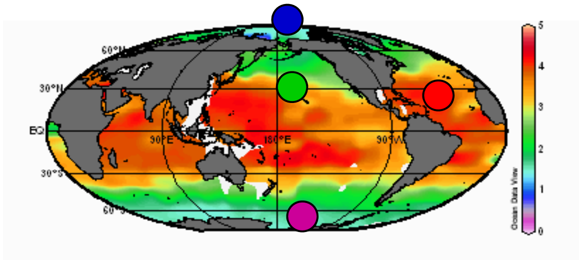
$H^+ + CO_3^{2-} \Leftrightarrow HCO_3^-$ — CO_3^{2-} ↓

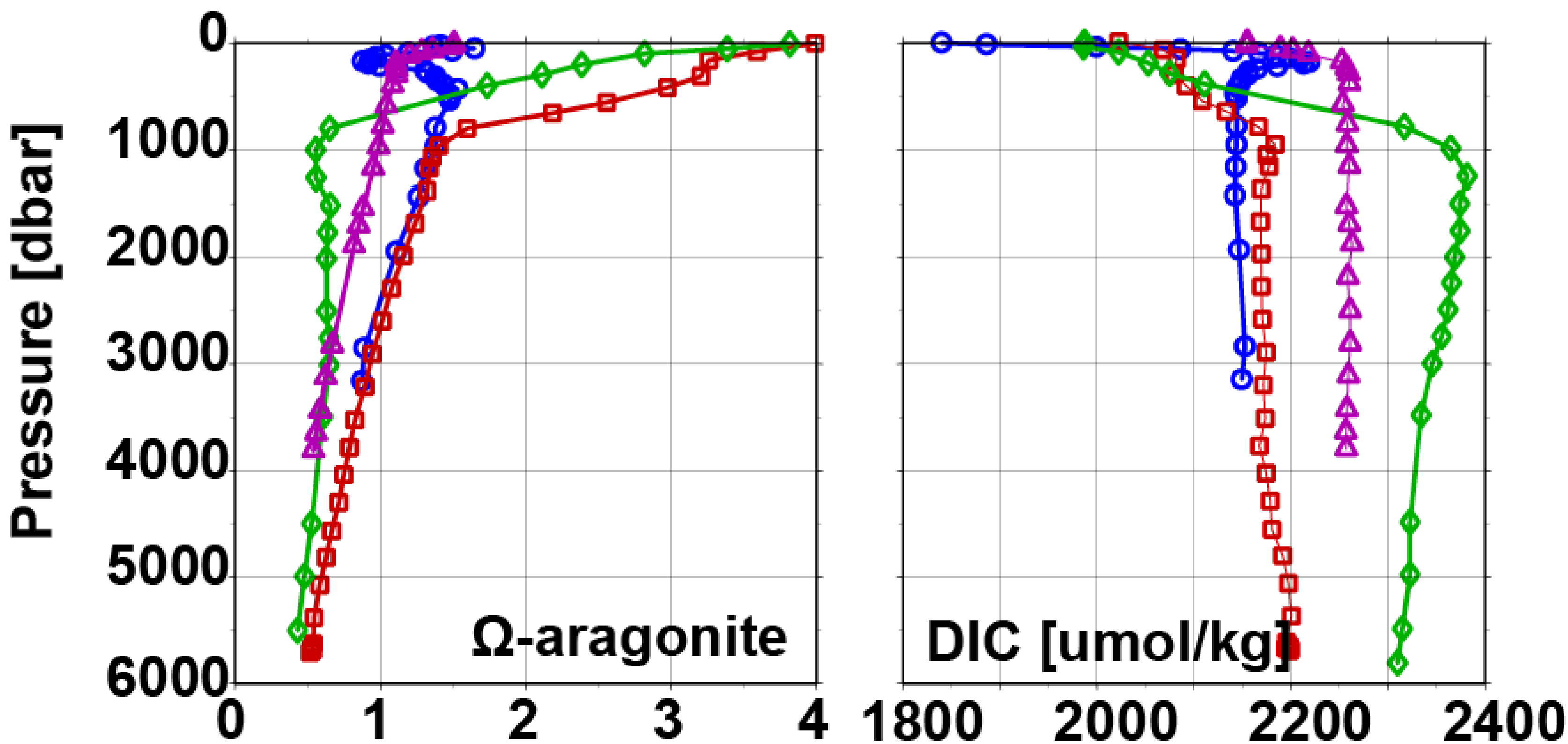


$CaCO_3$ saturation state

$$\Omega = \frac{[Ca^{2+}]_{sw}\,[CO_3^{2-}]_{sw}}{[Ca^{2+}]_{sat}\,[CO_3^{2-}]_{sat}} \quad [Ca^{2+}]_{sat}\,[CO_3^{2-}]_{sat} = Ksp^*$$

[Steinacher et al., Biogeosciences, 2009]





[CARINA+GLODAP]

Clams (*Mercenaria mercenaria*)

Arg>>HMgC

memo

aragonite (corals, mussels)
high-magnesium calcite (sea urchins)

pCO_2 sensor---U of Montana Mike DeGrandpre

Pacific inflow の水温・ 塩分の経年変化は？

底層のpHが下がると、リンが溶出しやすくなる？

脱窒が変化しないなら、大西洋へのPの供給が増える→海洋への窒素供給が増える→CO_2が下がる？→負のフィードバック

CARINA (CARbon dioxide IN the Atlantic Ocean)

Polar science center Hydrographic Climatology (PHC)

Omega計算のパラメータ選択＆ODVのパラメータをメモすること！

High-Mg calcite について勉強　北極では？

Bering shelfのココリスブルームは97、98、00に大きくて、あとは小さい。
Murata 2006によると、Calcification-photosynthesis で、正味18 μatm程度の p CO_2引き下げ。

2007 のBering inflowは水温高い & Flux多い—Wind, Pacific-Arctic pressure head [Woodgate et al., 2010]
2004年以前と以降では以降の方が熱Flux多い(Volume&temperature) [Mizobata et al., 2010]

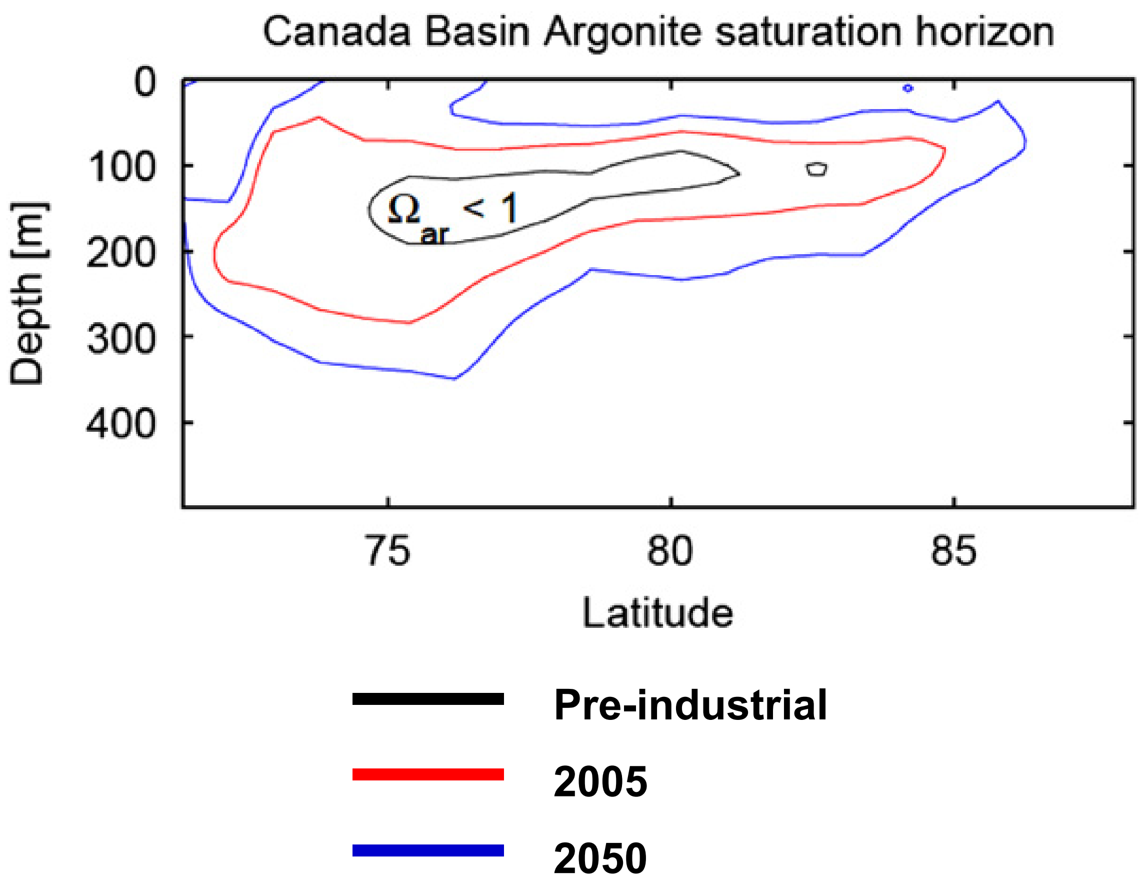
Southern CB, surface T was also high in 2008 but low in 2009 (but 1 month later)

Li のデータは何メーターのもの？150m以浅と150m以深

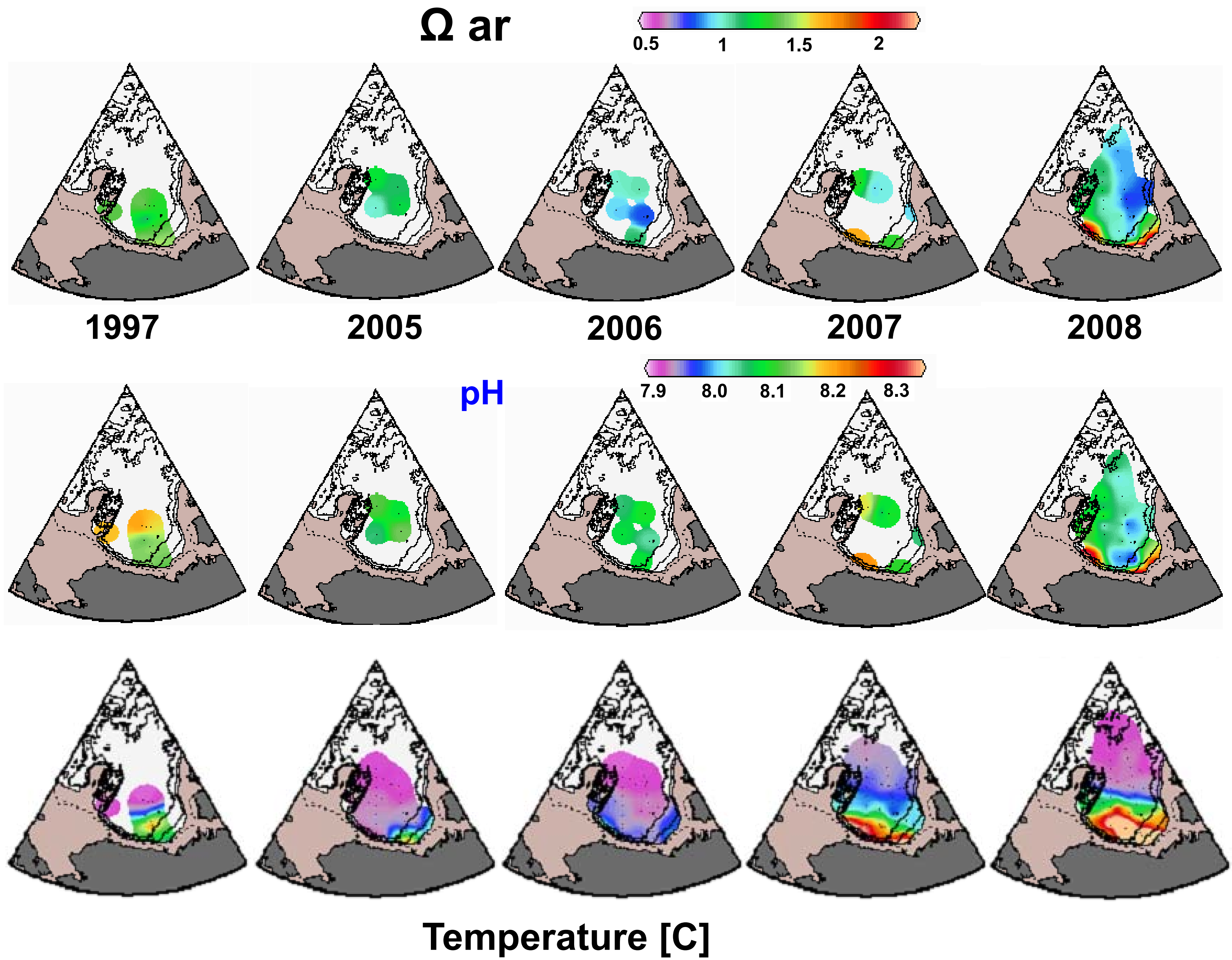
種類はどう変わったの？減ったナノは珪藻？増えたのは？

Arctic deep water residence time ~400 yrs

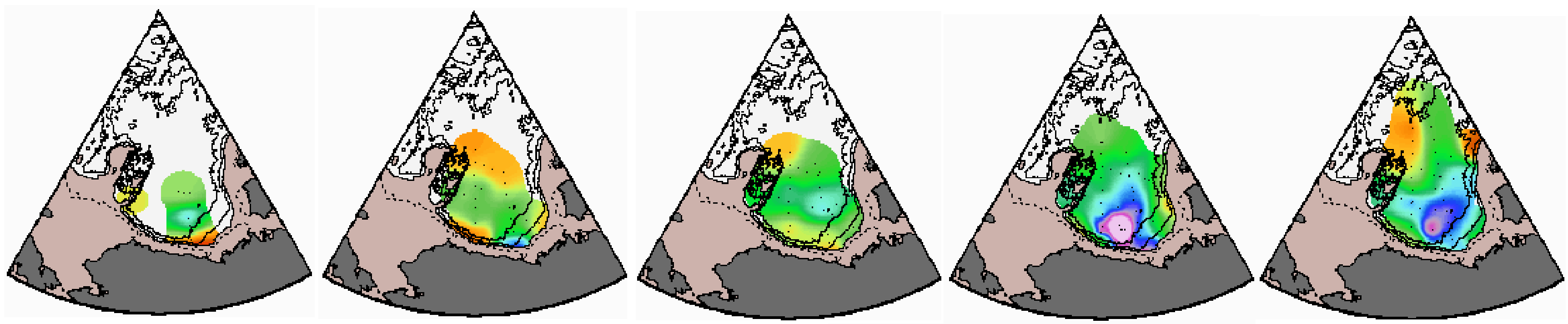
炭酸カルシウムは塩分高い方が溶けやすい。



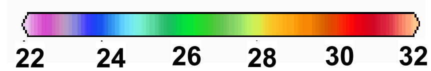
[Anderson et al., DSR, 2010]

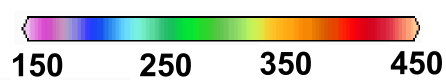


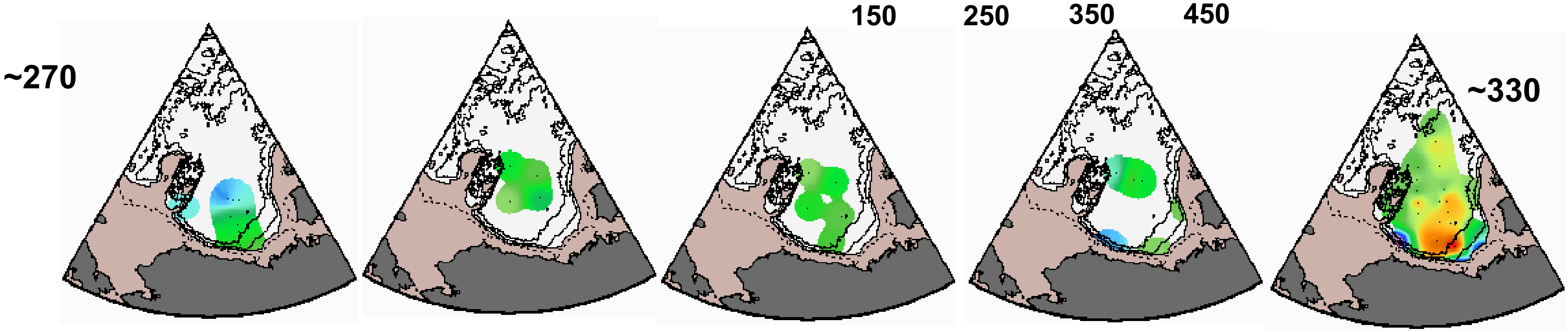
[Yamamoto-Kawai et al., 2009b+]



sea surface salinity

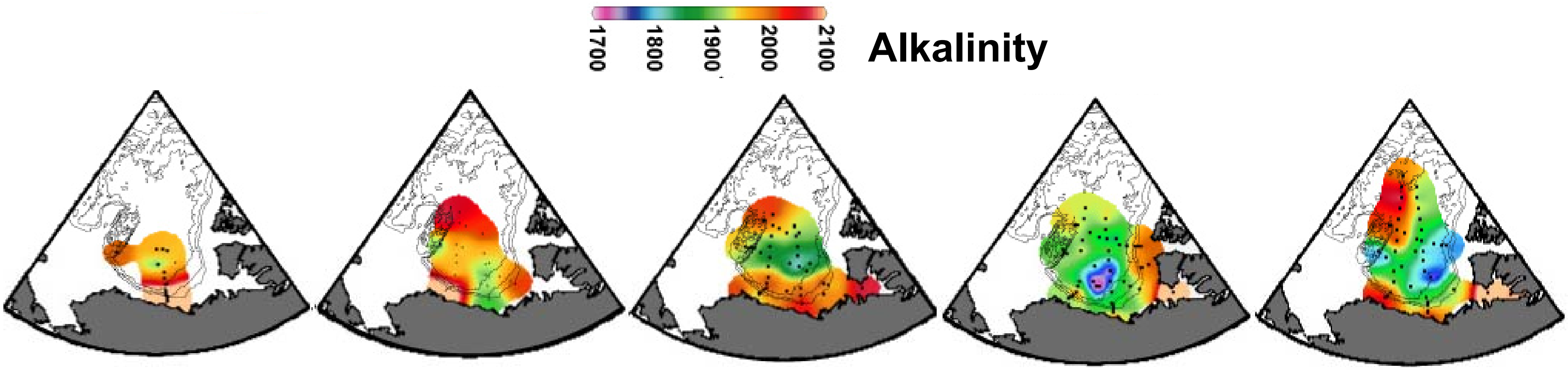






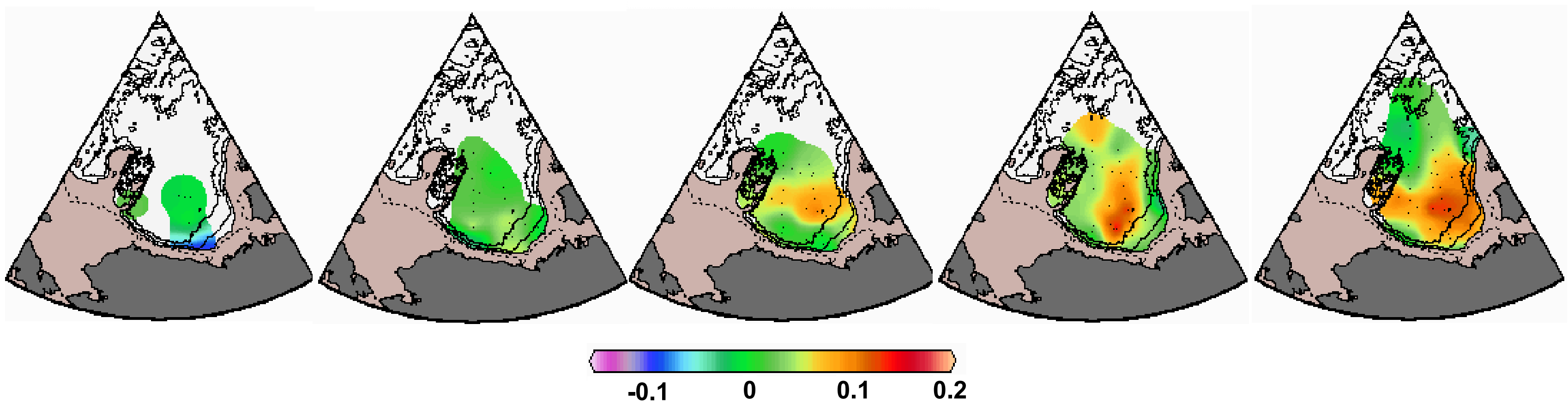
pCO2

[Yamamoto-Kawai et al., 2009b+]

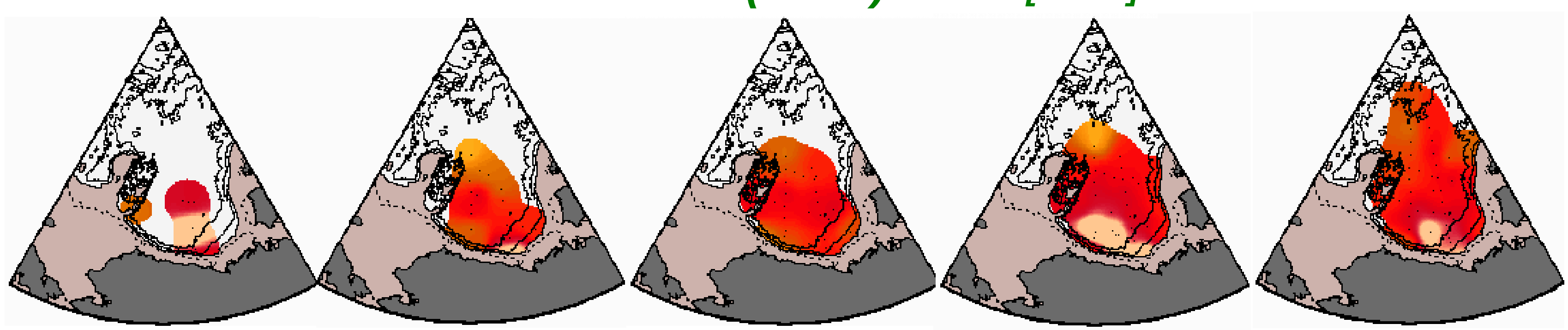


1700
1800
1900
2000
2100
Alkalinity

Sea ice meltwater [ml/ml]

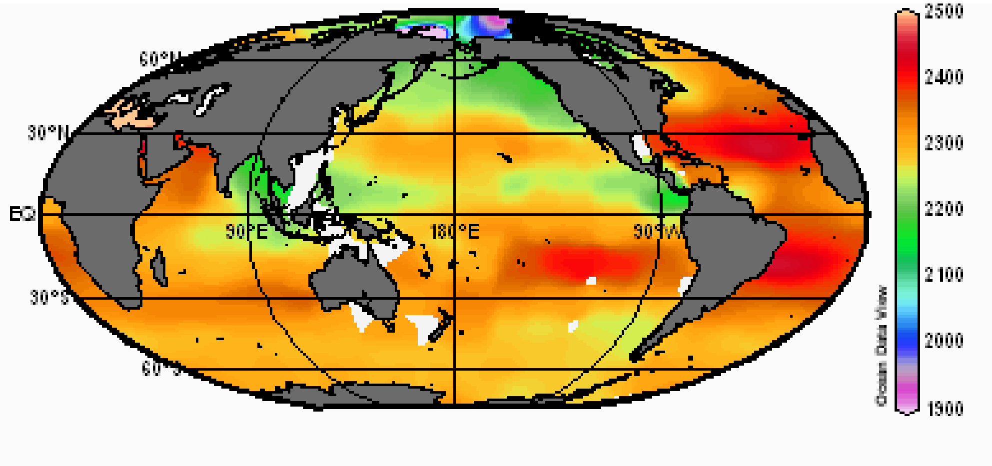


Meteoric (River) water [ml/ml]

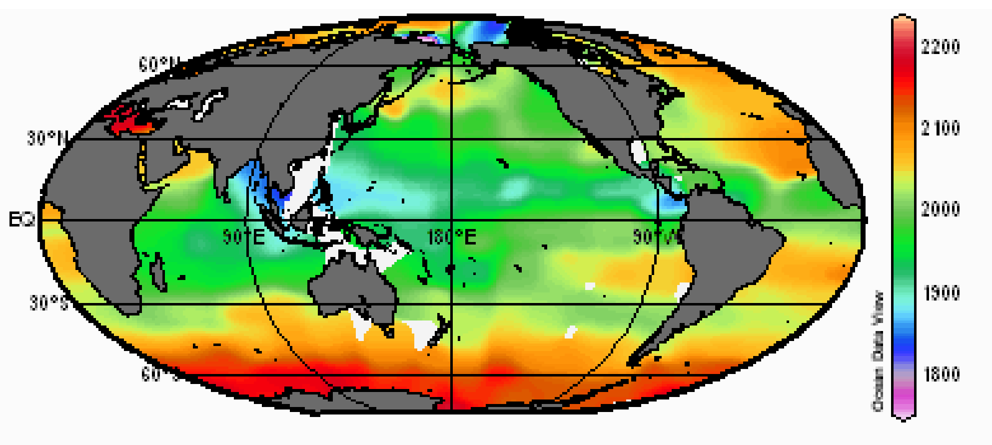


[Yamamoto-Kawai et al., 2009a+]

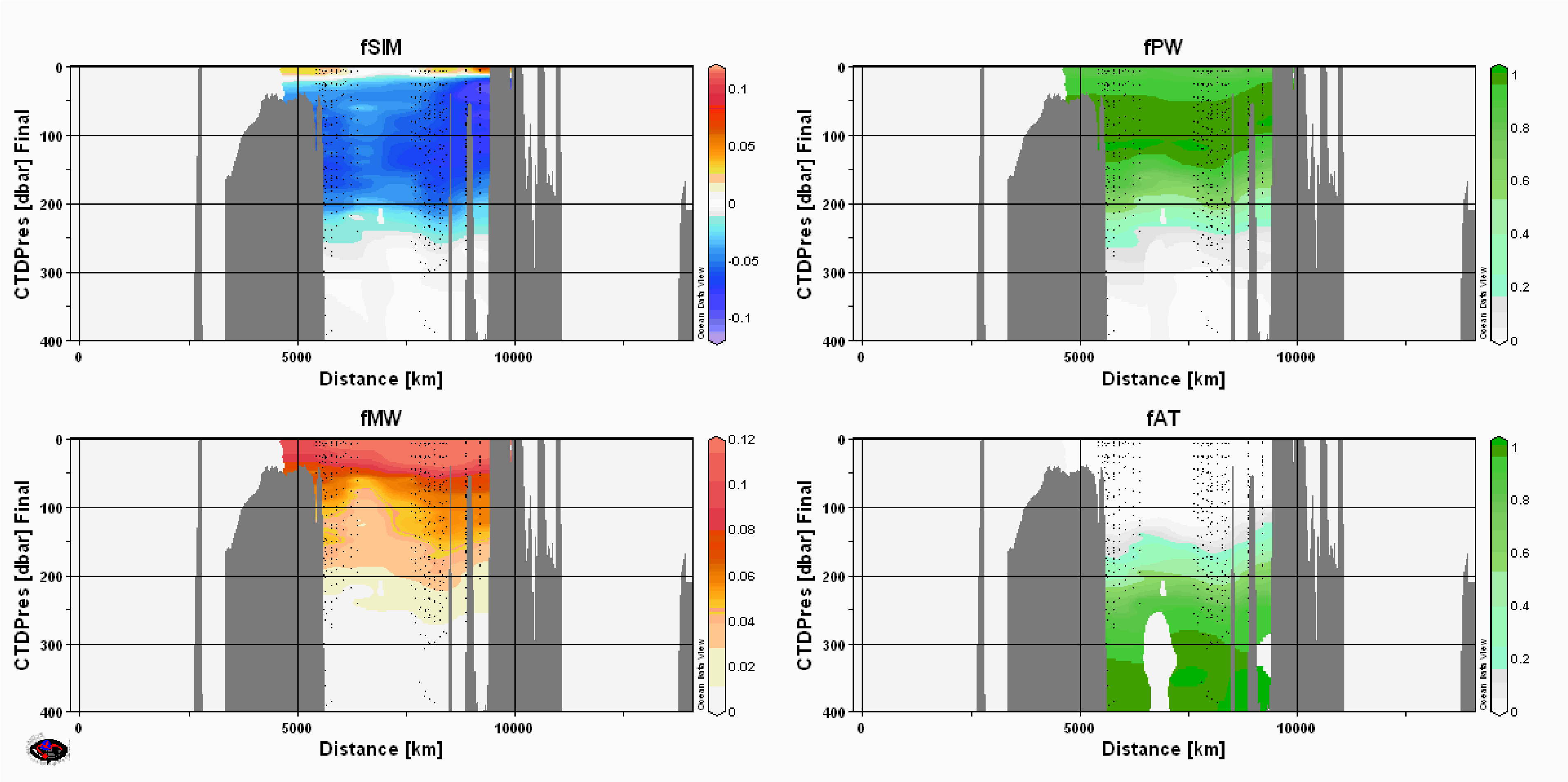
Sea Surface Alkalinity [umol/kg]



Sea Surface DIC [umol/kg]



[CARINA+GLODAP]


fSIM
fPW
fMW
fAT
CTDPres [dbar] Final
Distance [km]
0
100
200
300
400
0
5000
10000
0.1
0.05
0
-0.05
-0.1
1
0.8
0.6
0.4
0.2
0
0.12
0.1
0.08
0.06
0.04
0.02
0
Ocean Data View

2003-2005