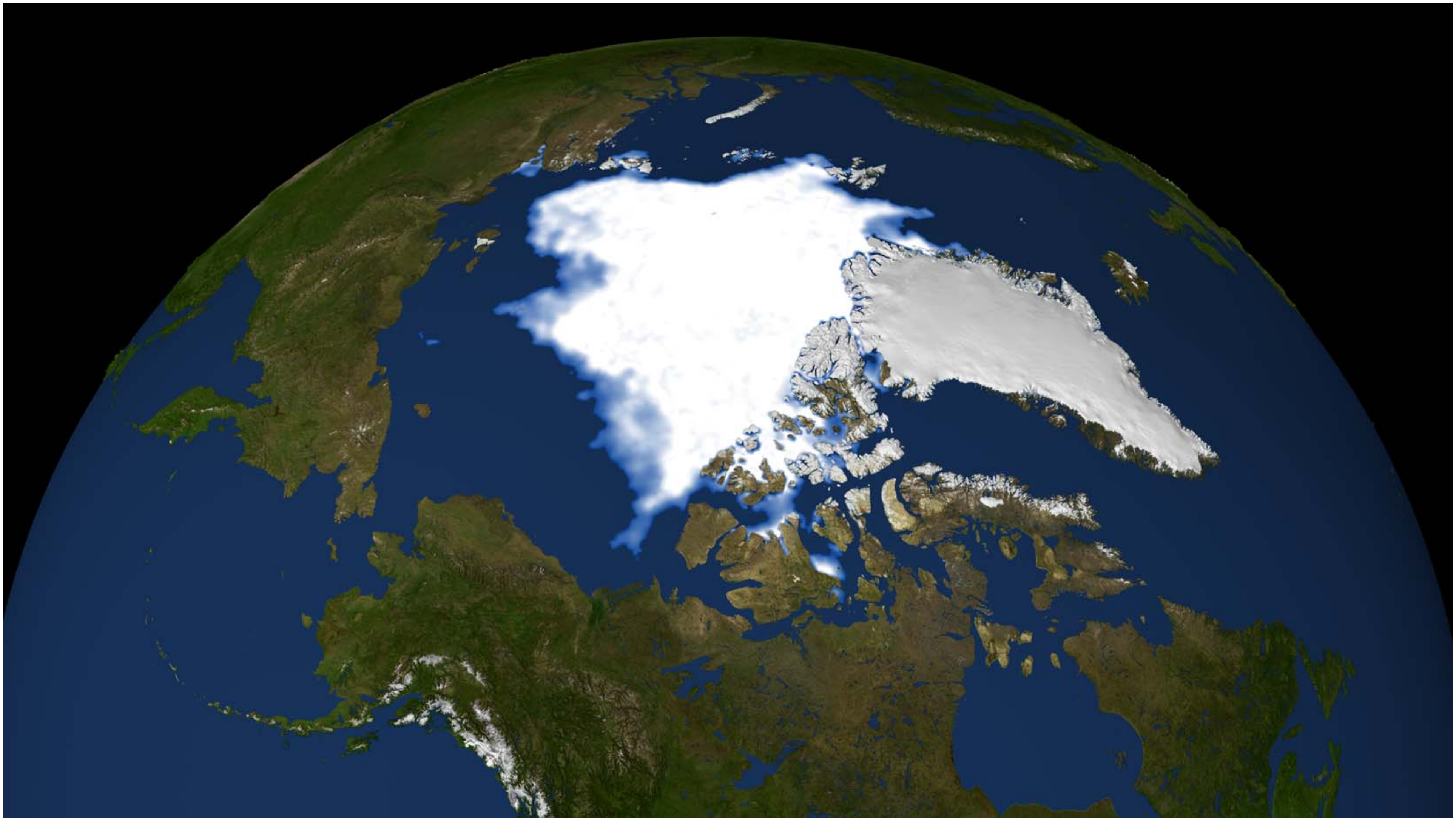
Recent changes in sea surface *p*CO_2 in the western Arctic Ocean: Responses to ice-melt

A Presentation at
The Ocean Carbon and Biogeochemistry
2010 Summer Workshop
July 19-22, 2010
La Jolla, CA
by

Wei-Jun Cai
The University of Georgia
Department of Marine Sciences
And many **coauthors**

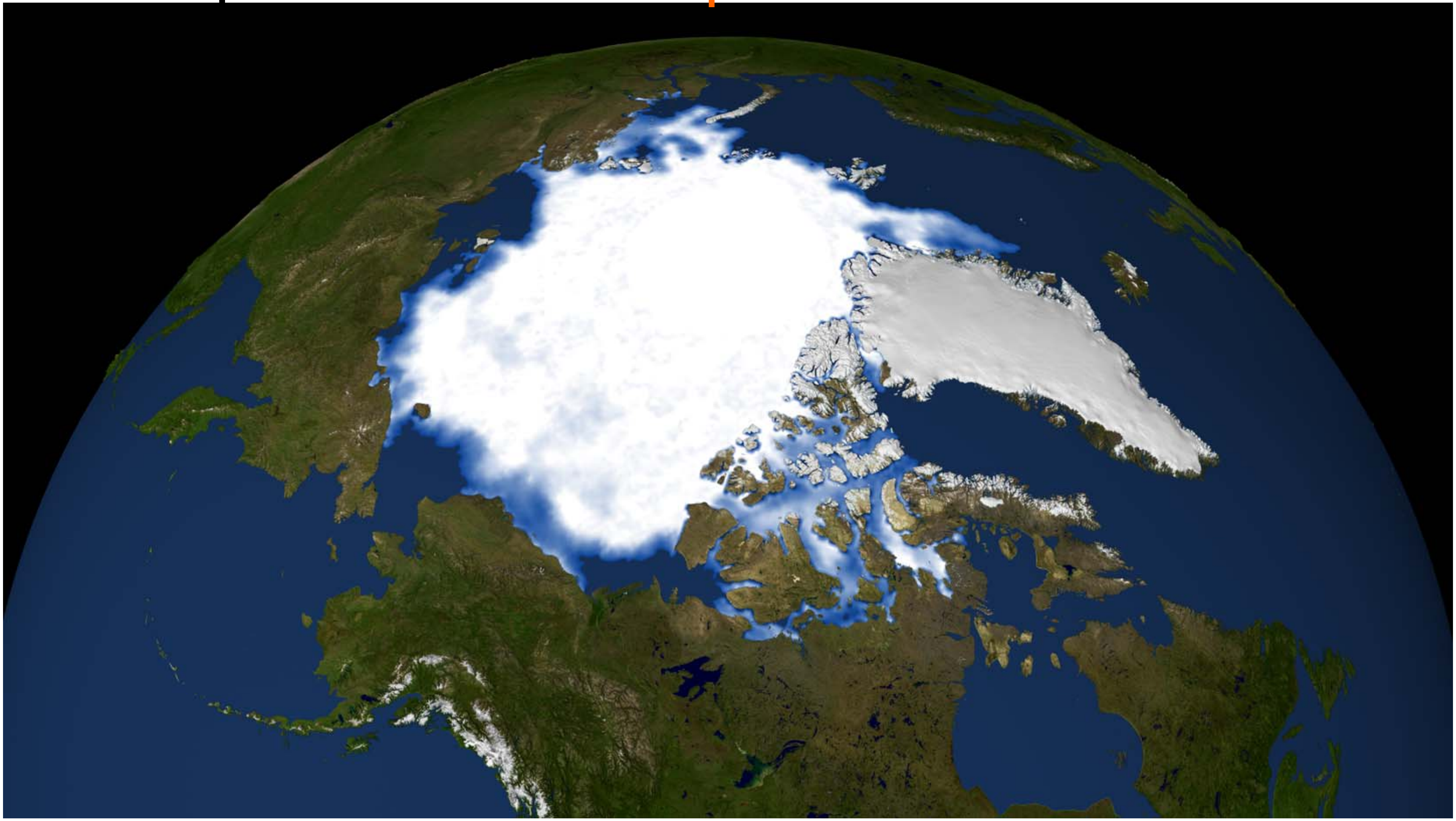
Melt of the Arctic Ocean Sea Ice



2008 Annual Minimum

Image courtesy NASA Goddard SVS

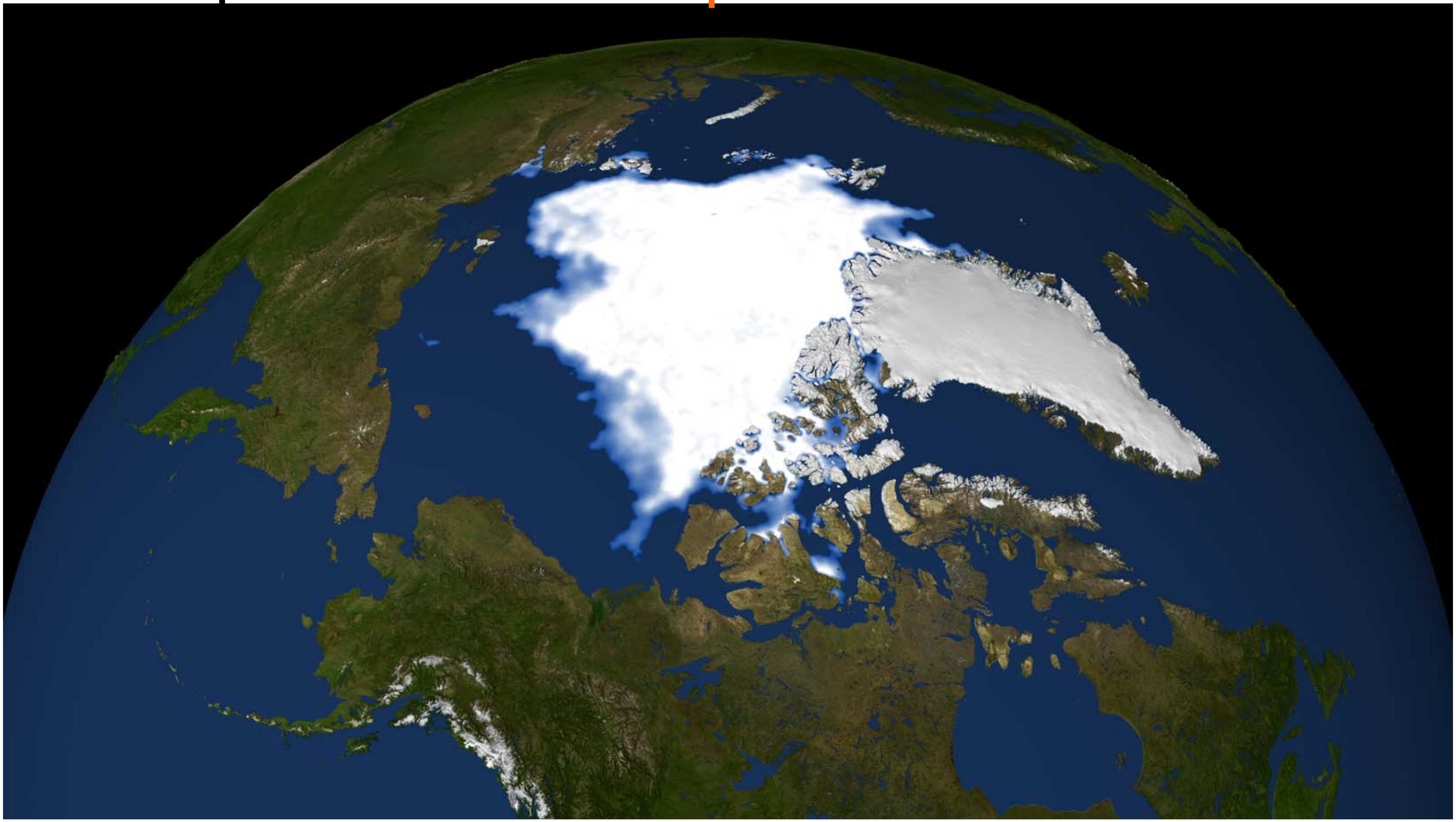
Principle 1: Show comparisons



1980 Annual Minimum

Image courtesy NASA Goddard SVS

Principle 1: Show comparisons



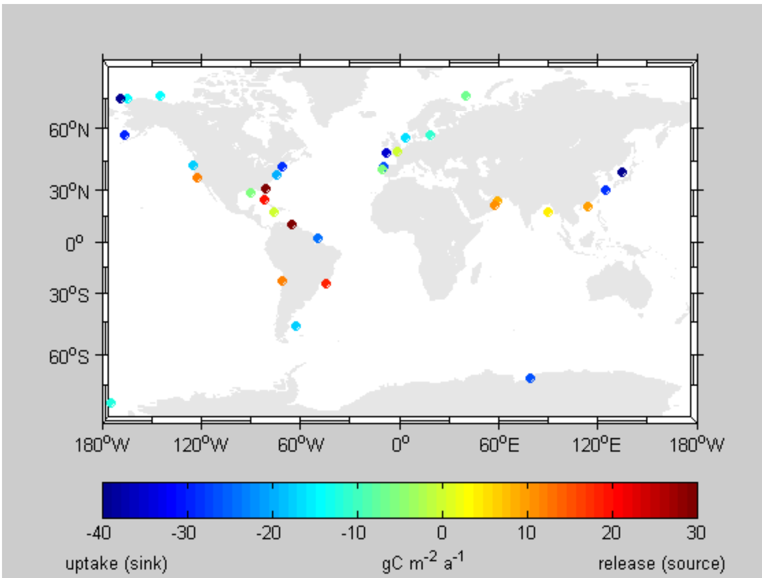
2008 Annual Minimum

Image courtesy NASA Goddard SVS

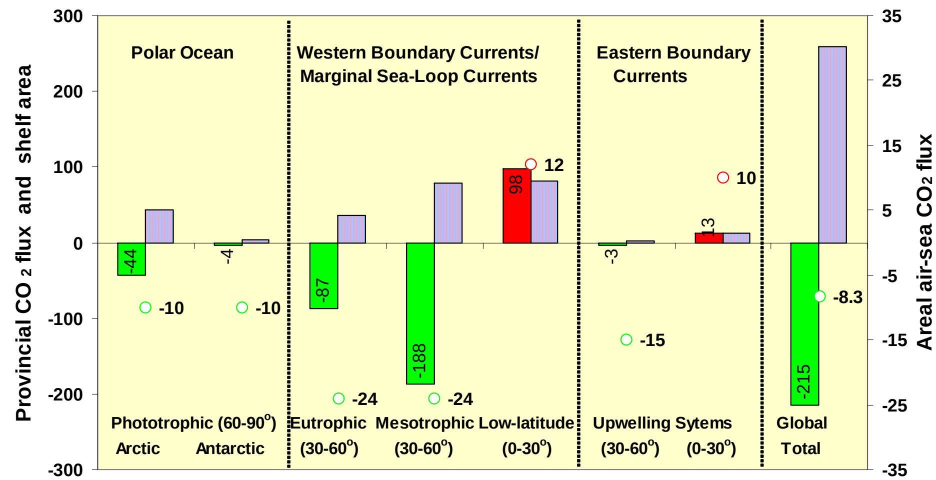
outline

- Introduction of the problem
- Background
- Results from the summer 2008 CHINARE
- Controls on the Arctic basin sea surface pCO_2
- Arctic C cycling under a rapidly changing climate
- Summary

Arctic Ocean margin CO_2 uptake increases greatly over recent years

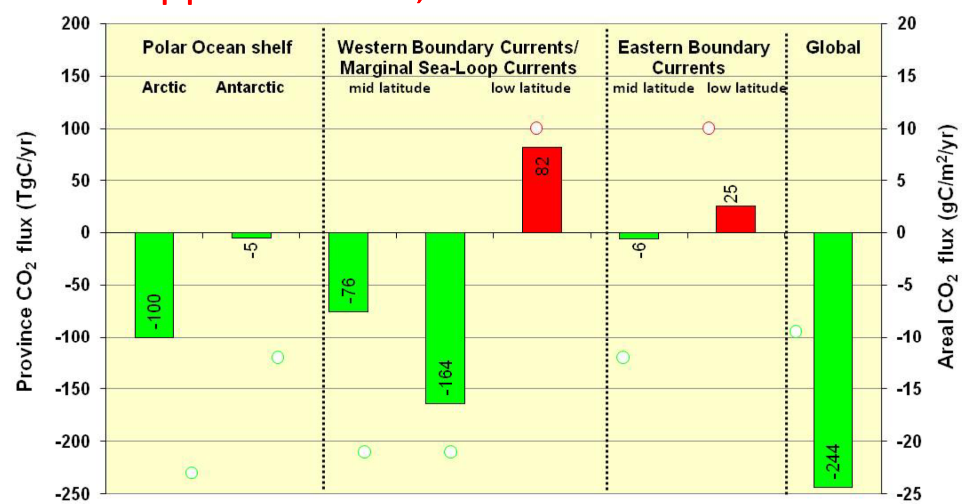


Coastal ocean CO_2 synthesis using a province-based approach
Cai et al. 2006, GRL



Upper: Cai talk, OCB 2005 & GRC 2005

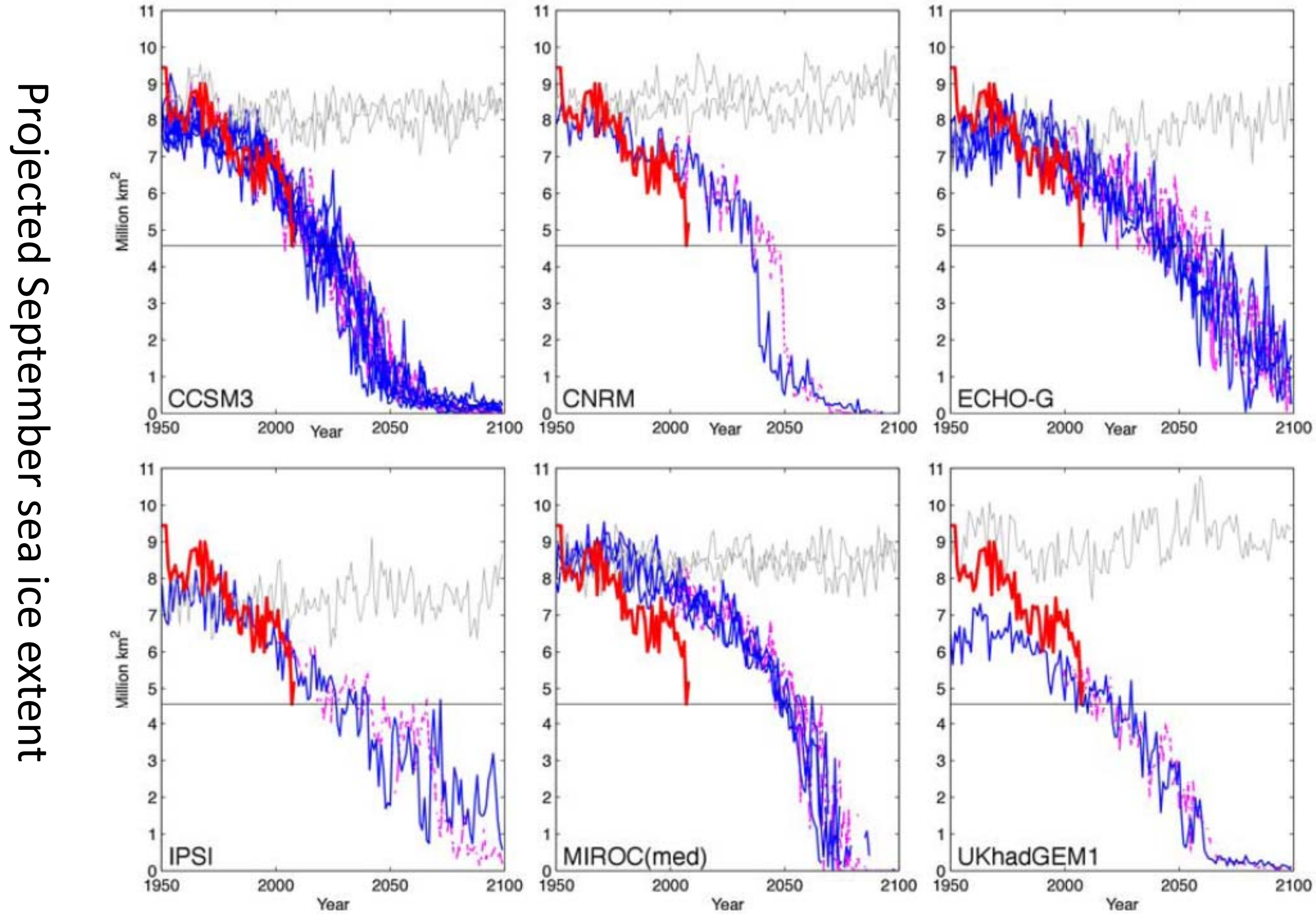
Upper: Cai talk, OCB 2008 & GRC 2009



A sea ice free summer Arctic within 30 years?

Muyin Wang[1] and James E. Overland[2]

GEOPHYSICAL RESEARCH LETTERS, VOL. 36, L07502, doi:10.1029/2009GL037820, 2009

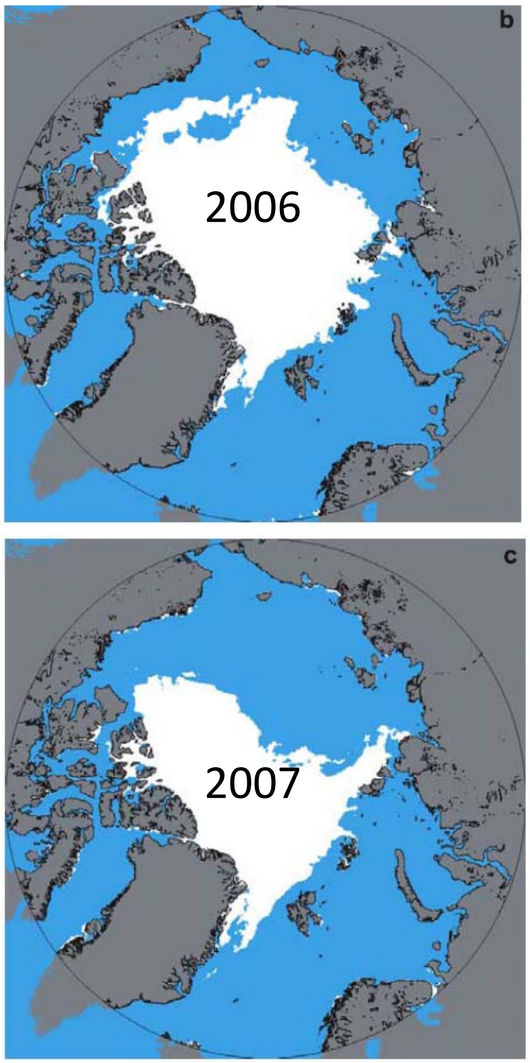


Ice-free sumer by 2040!

Projected with 6 climate models, each under 2 emission scenarios (blue & purple lines). Red line: observation, Hadley Centre sea ice concentration analysis (HadISST).

Major ice melt and PP in 2007, Arrigo, GRL 2008

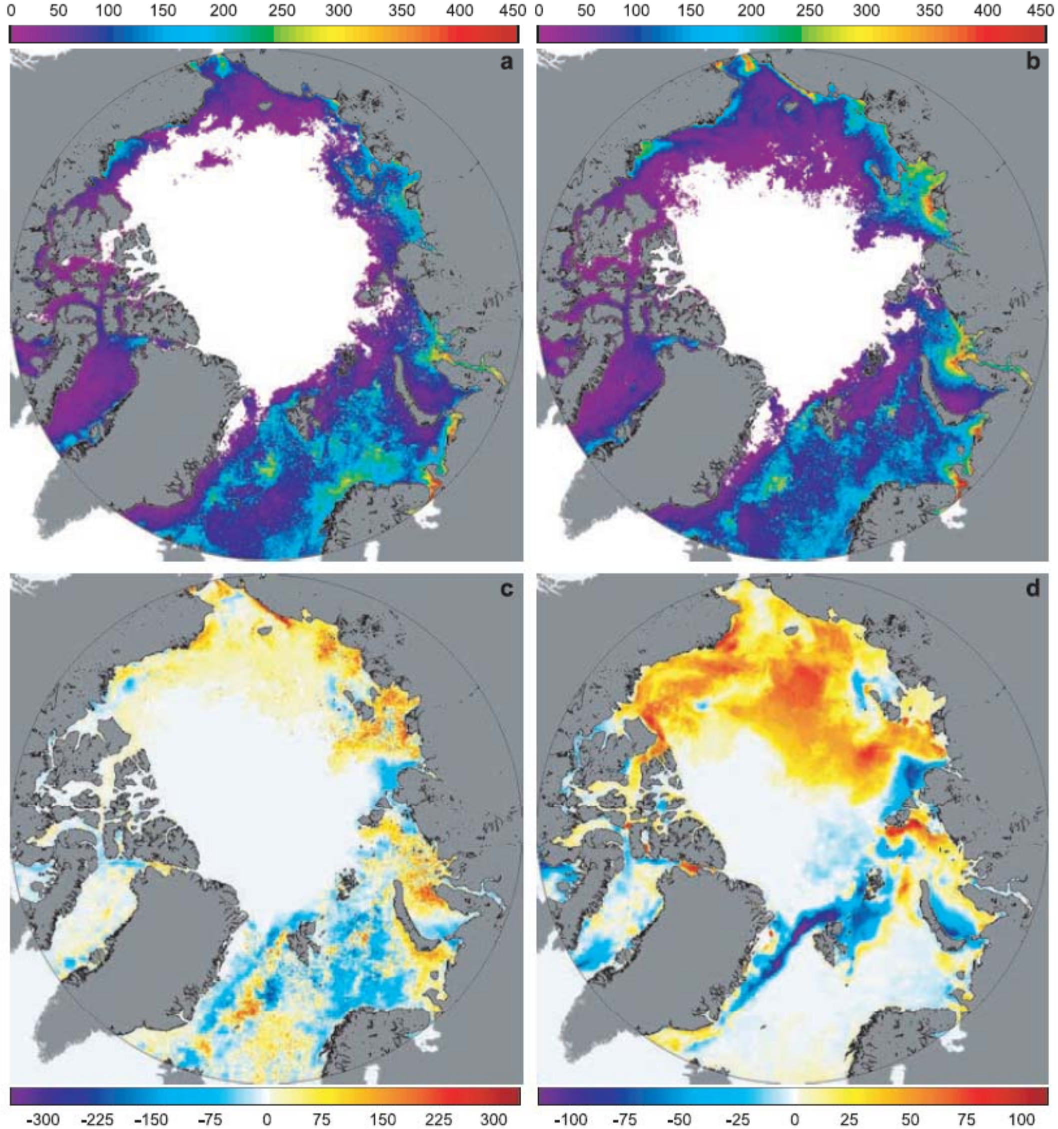
Minimum sea ice extent, 2006



Minimum sea ice extent, 2007

Annual primary production in 2006 (g C m^{-2} yr^{-1})

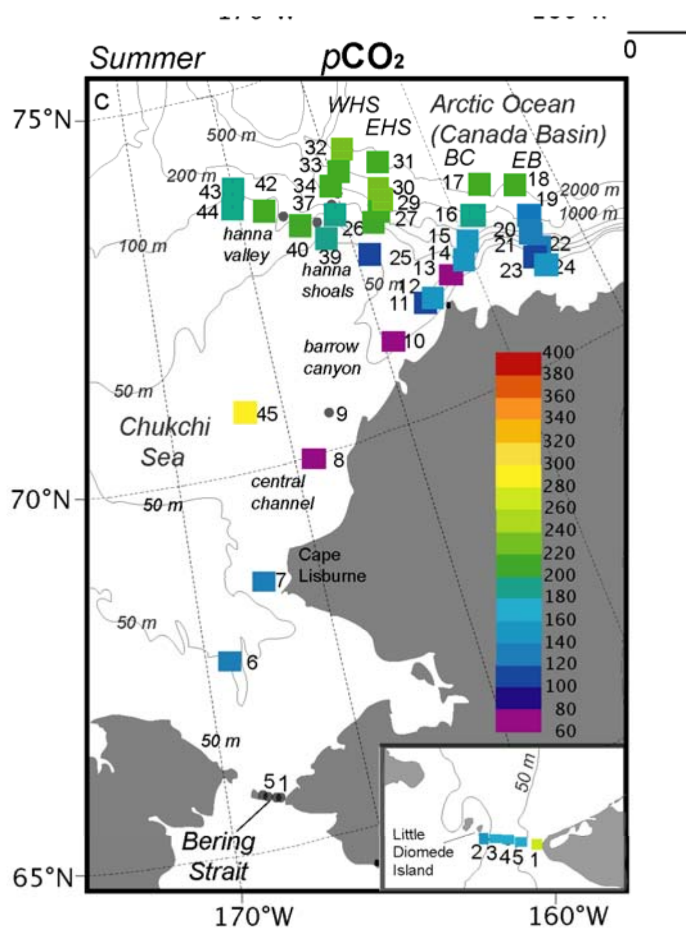
Annual primary production in 2007 (g C m^{-2} yr^{-1})



Difference in annual production, 2007-2006 (g C m^{-2} yr^{-1})

Difference in growing season, 2007-2006 (days)

Previous CO_2 survey (margins)



Shelf-Basin Interaction (SBI) 2002
Bates et al. 2006, JGR

A. Fransson et al. / Continental Shelf Research 29 (2009) 1317–1328

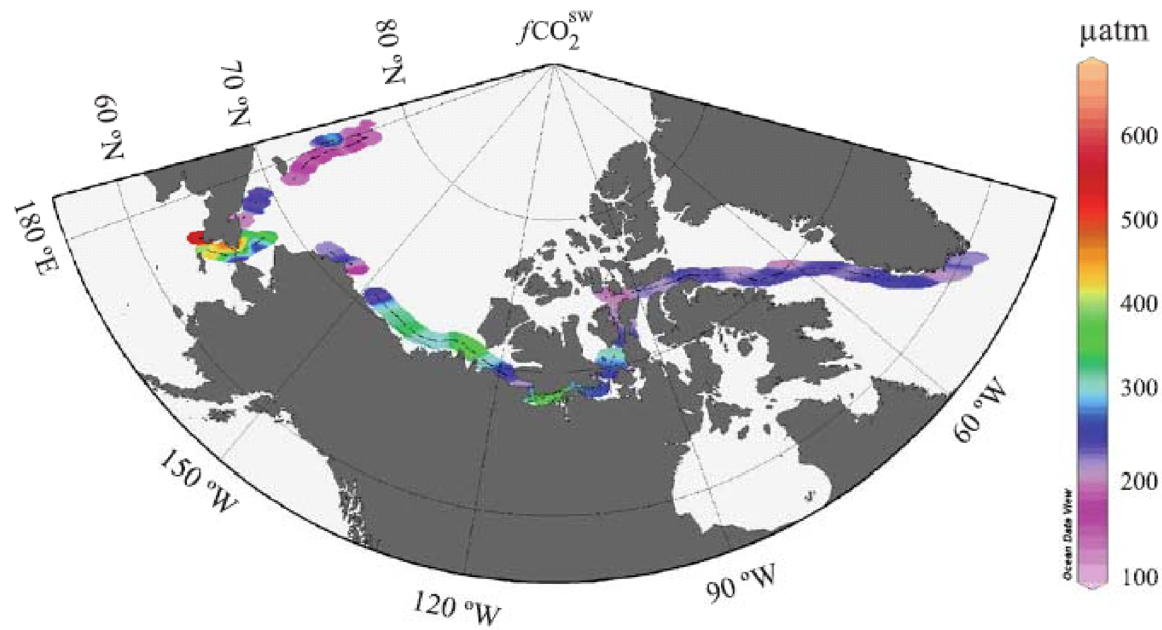
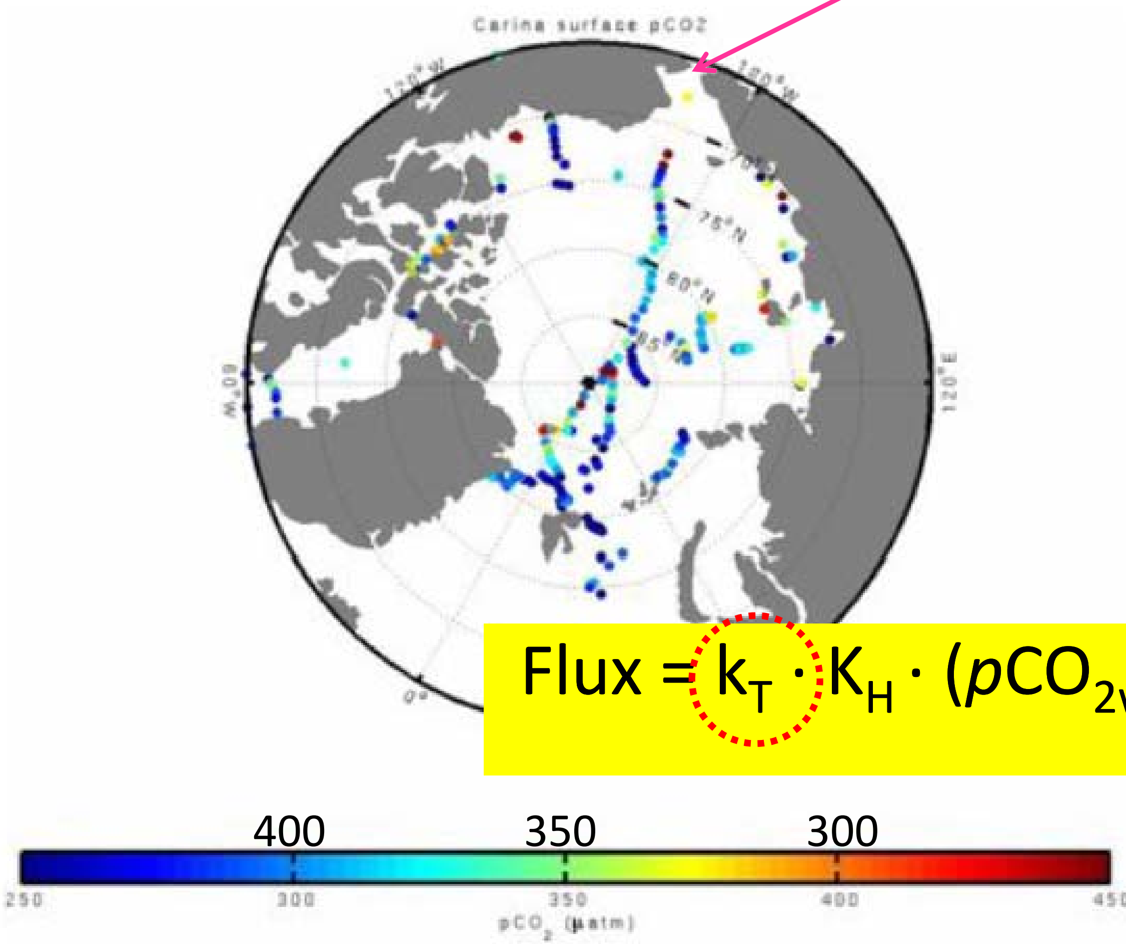


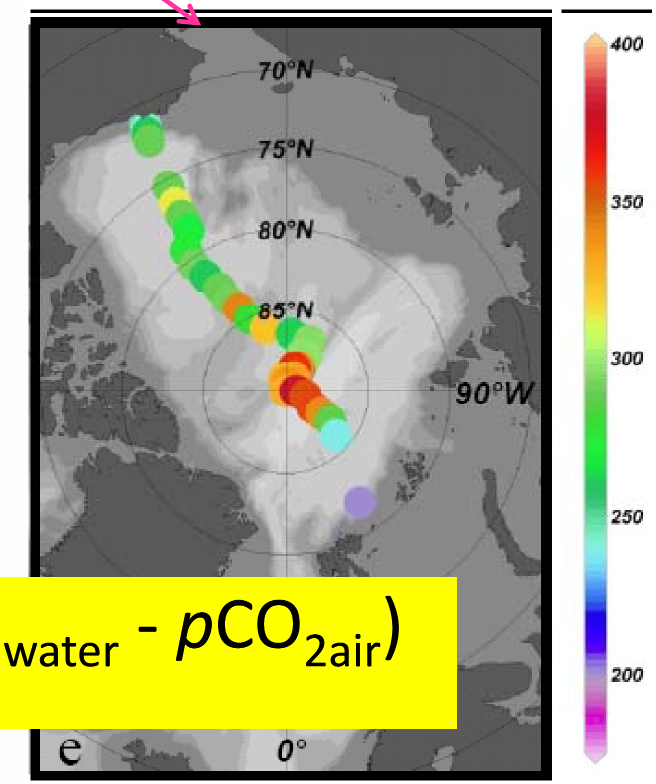
Fig. 6. The fugacity of CO_2 in the surface water (fCO_2^{sw}, µatm).

summer 2005, pan Arctic margin survey

Previous CO_2 survey (basins)

Bering Strait





$$\text{Flux} = k_T \cdot K_H \cdot (pCO_{2water} - pCO_{2air})$$

- Arctic Ocean Section (AOS) 1994
- IAOE91; JOIS 1997
- Synthesized by Bates and Mathis, BG, 2010

Beringia 2005.
S. Jutterström & L. Anderson
Mar Chem (2010), in press.

Prediction and problems

- It is predicted that melt of sea ice in the Arctic Ocean basins will allow for a large extra uptake of the atmospheric CO_2.

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- It is predicted that melt of sea ice in the Arctic Ocean basins will allow for a large extra uptake of the atmospheric CO_2.
  - However, this prediction was made based on observations from either highly productive ocean margins or ice-covered basins prior to the recent major ice retreat .
  - It is also important to understand how various factors may control sea surface pCO_2 variability in the Arctic Ocean, which we don't have yet.

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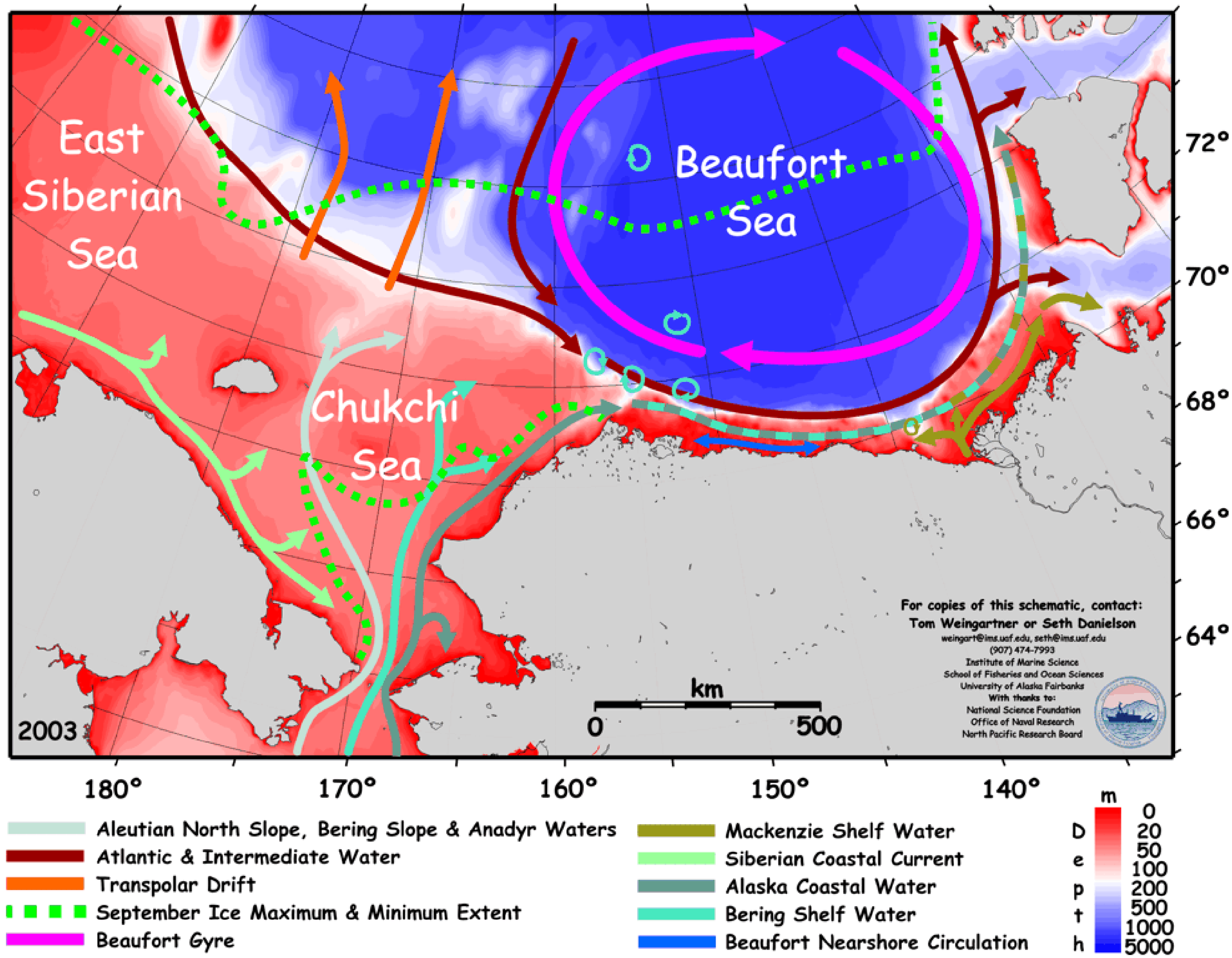
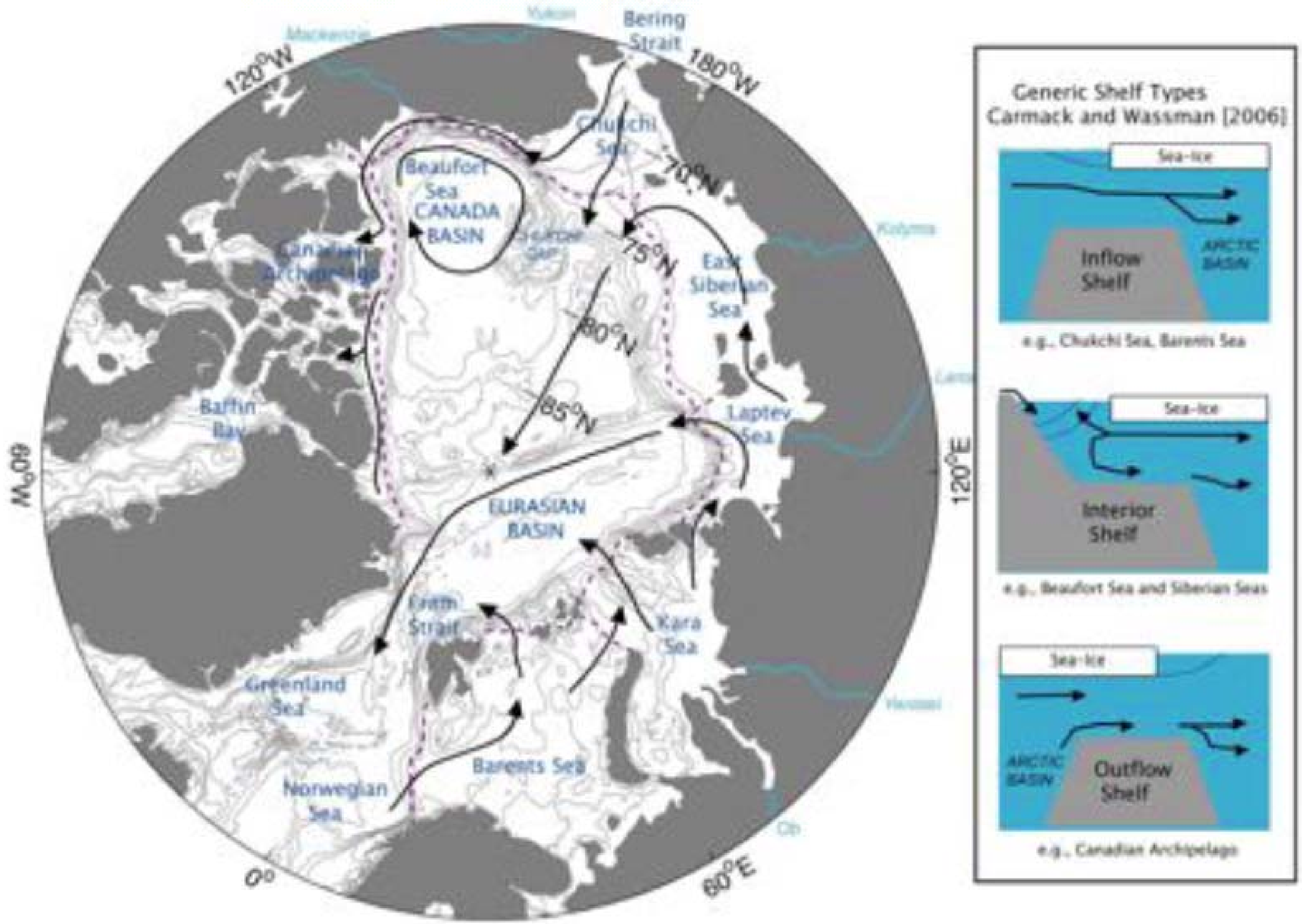
Circulation of the western Arctic Ocean

(marginal Seas)



Circulation of the western Arctic Ocean



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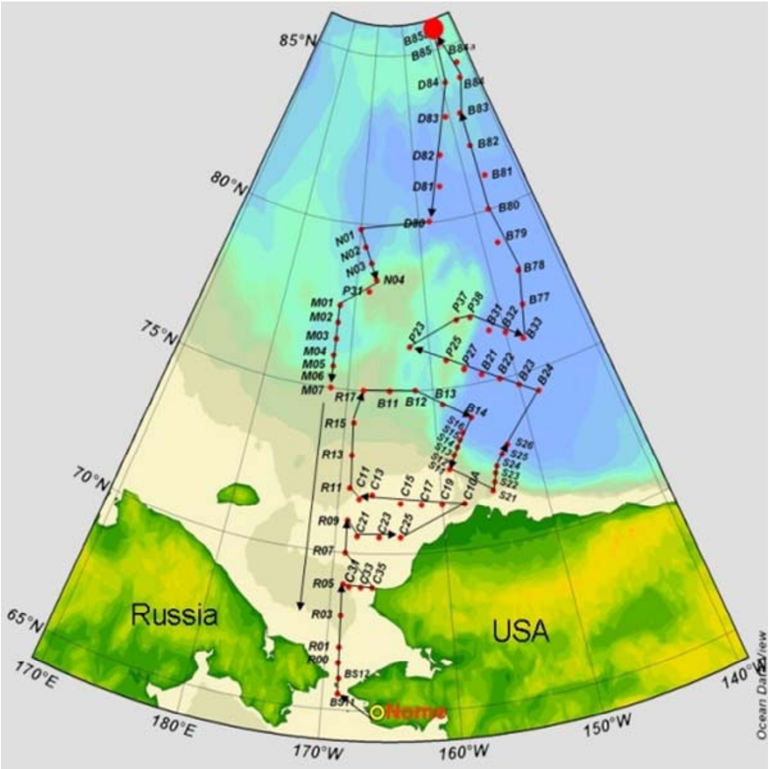
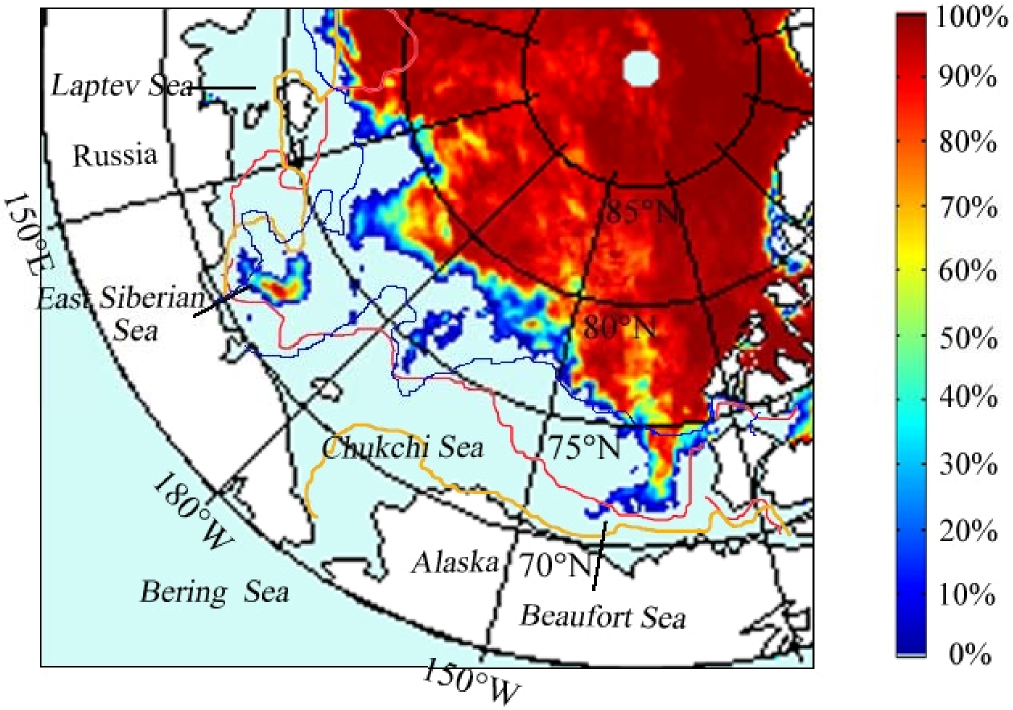
CHINARE cruise track and major ice melt in the Canada Basin in summer 2008



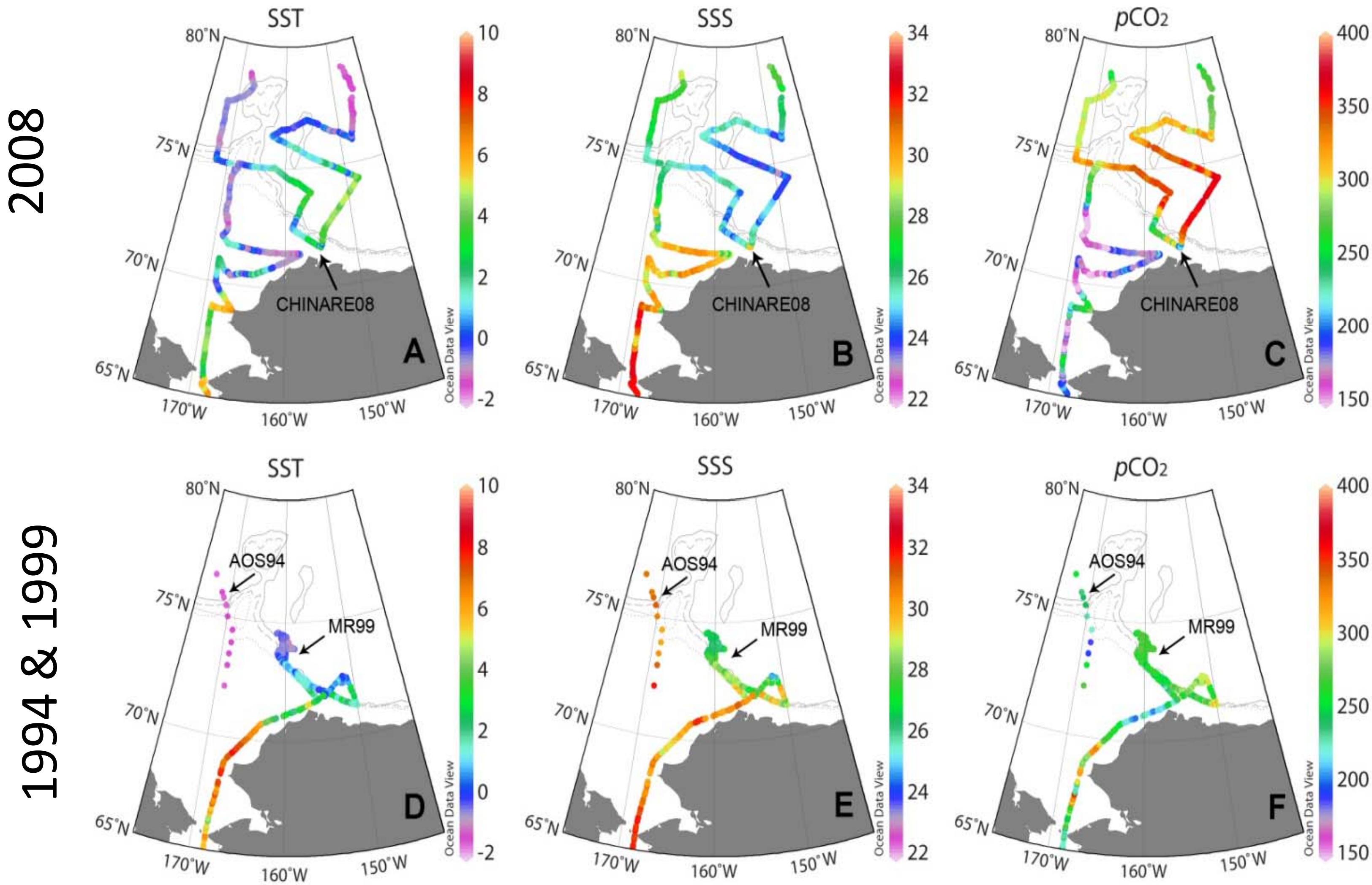


Cruise track (left) and Ice concentration map (right), 1st week of Sept. 2008, superimposed with Blue line: Aug.12, 2008; Gold line: Sept. 1994 and Red line: Sept. 1999.

Substantial sea ice melt in the western Arctic Ocean basin, at 84°N/144°W on September 1, 2008

Credit: Dr. Zhongyong Gao, State Ocean Administration of China–Third Institute of Oceanography, Xiamen, China.

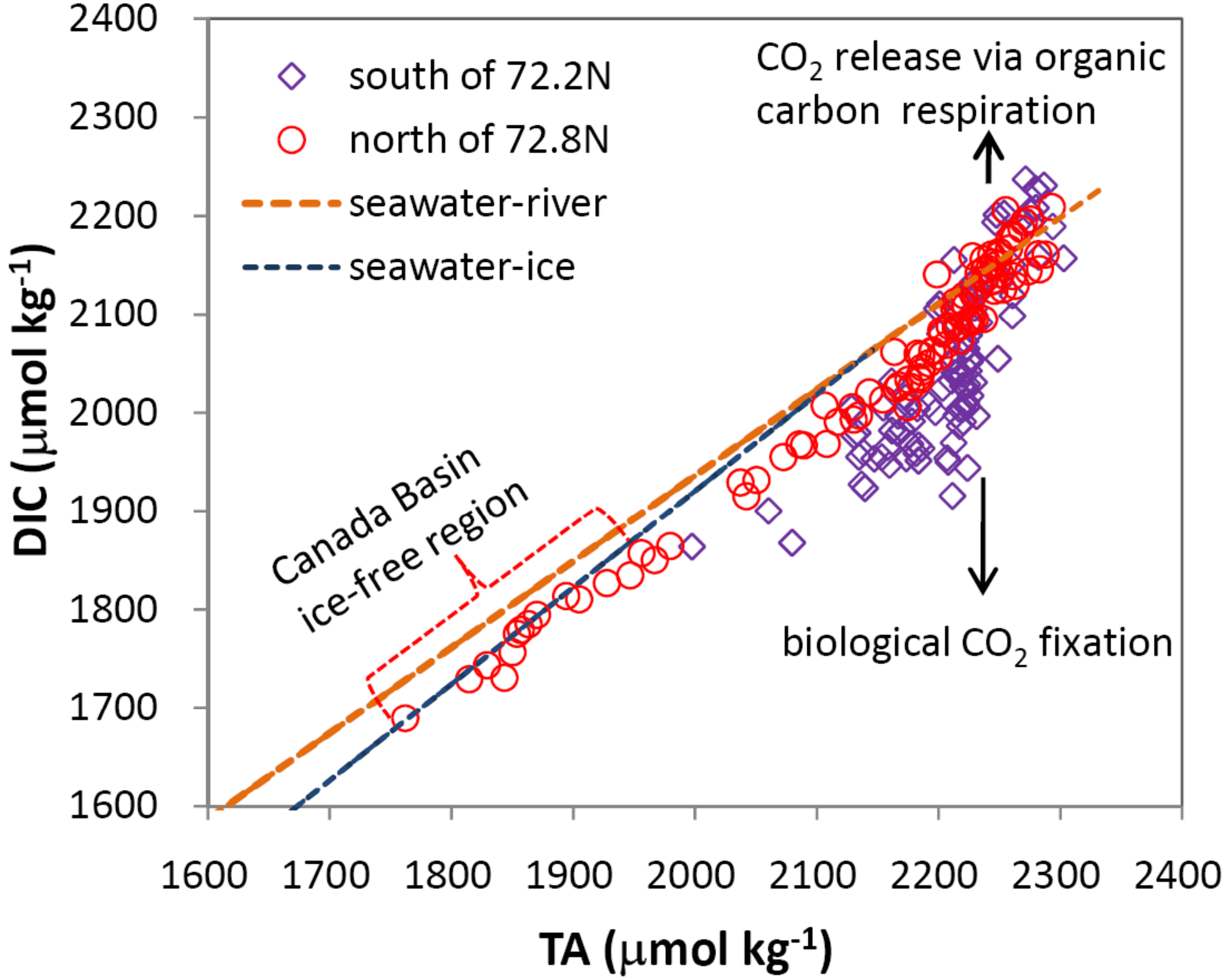
Underway data compared to earlier data



Cai et al. *Science* 2010 (in press)

22 July 2010, http://www.sciencexpress.org

Evidence of biological CO_2 fixation



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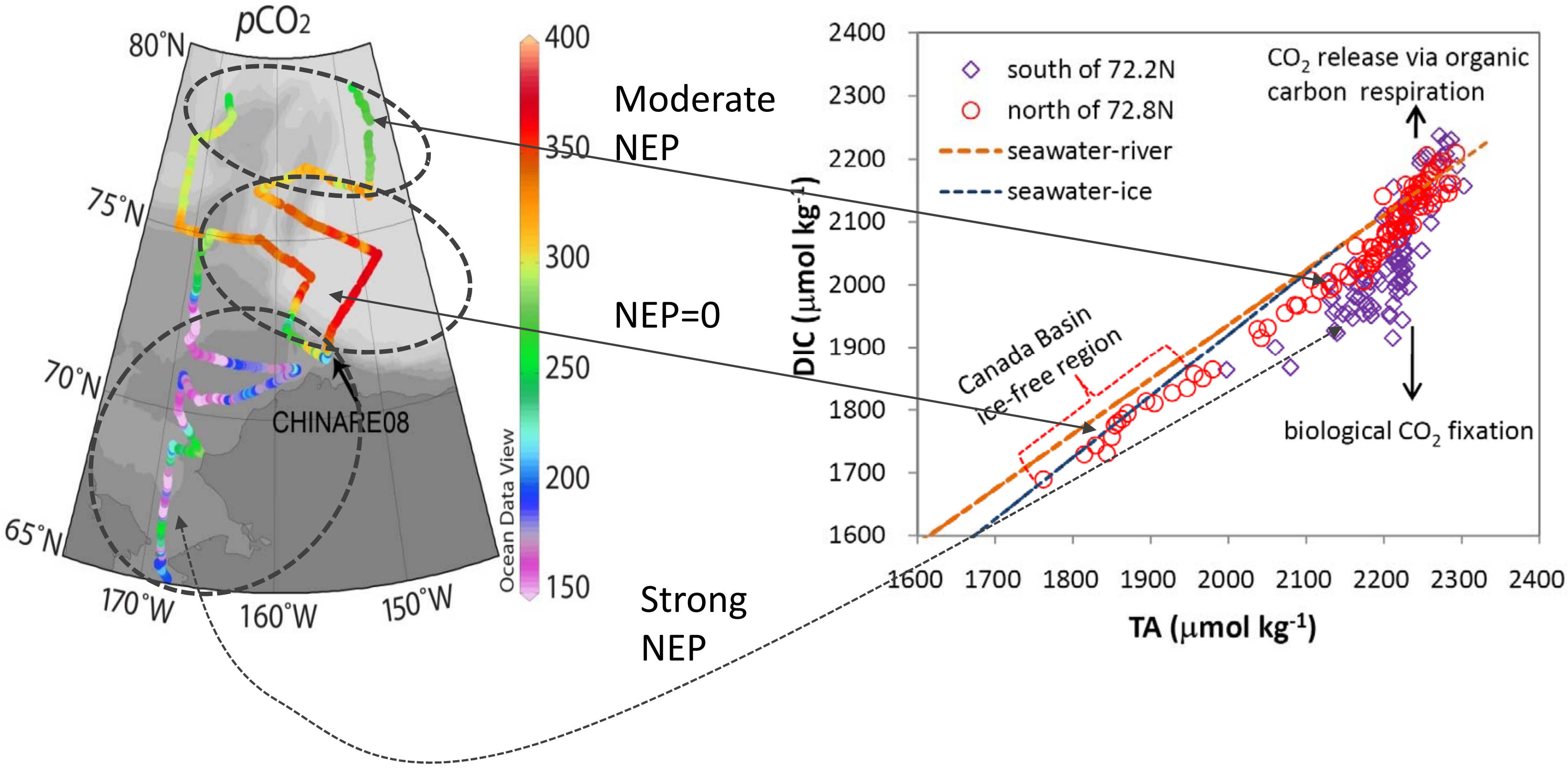
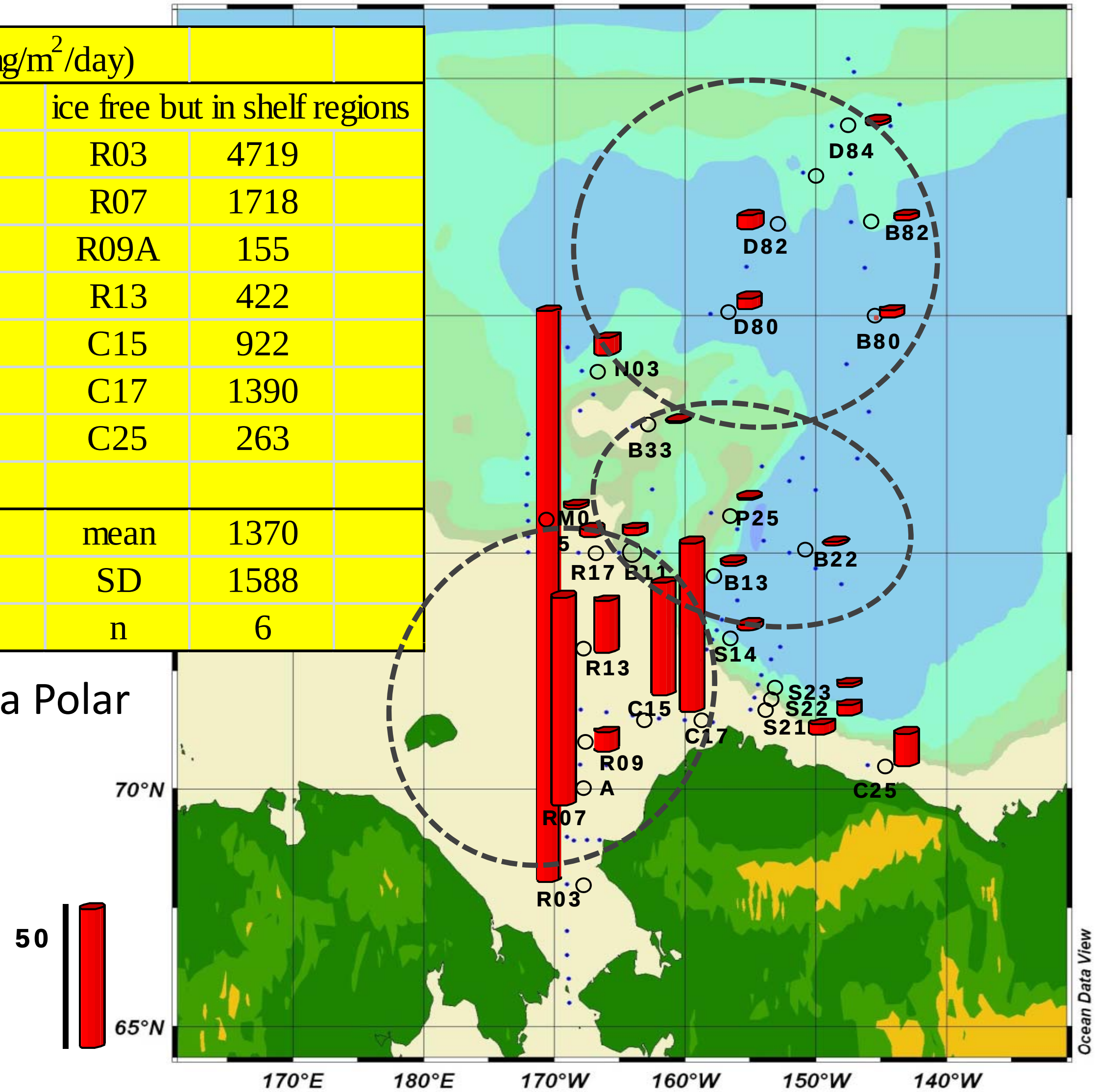


Primary production rates in summer 2008

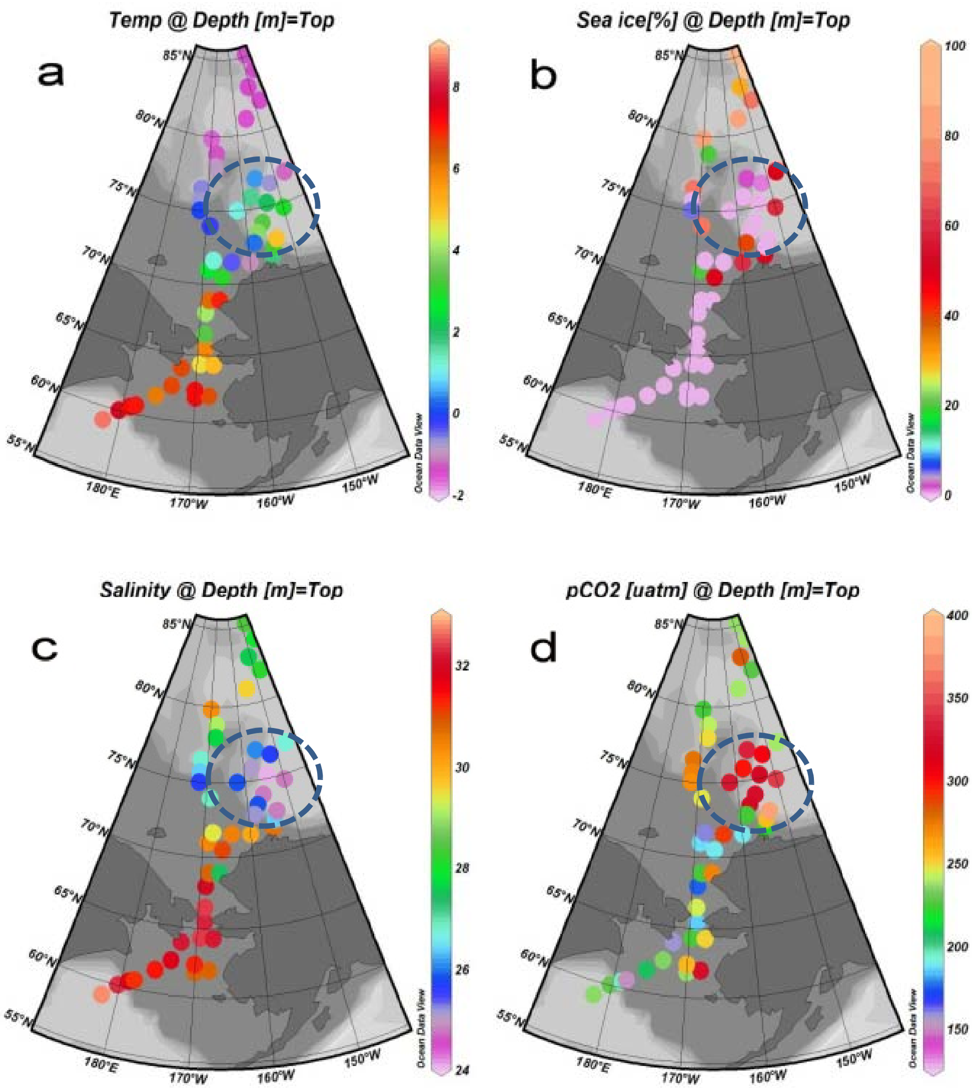
Primary production measured in summer 2008 (mg/m²/day)					
Ice floating area		Ice free stations		ice free but in shelf regions	
D80	85.2	B33	11.5	R03	4719
D82	104.2	P25	10.3	R07	1718
D84	26.2	B22	18.0	R09A	155
B80	51.6	B13	28.6	R13	422
B82	32.2	S14	44.4	C15	922
N03	141.6	M05	24.2	C17	1390
		S23	20.6	C25	263
mean	73.5	mean	22.5	mean	1370
SD	45.0	SD	11.6	SD	1588
n	6	n	7	n	6

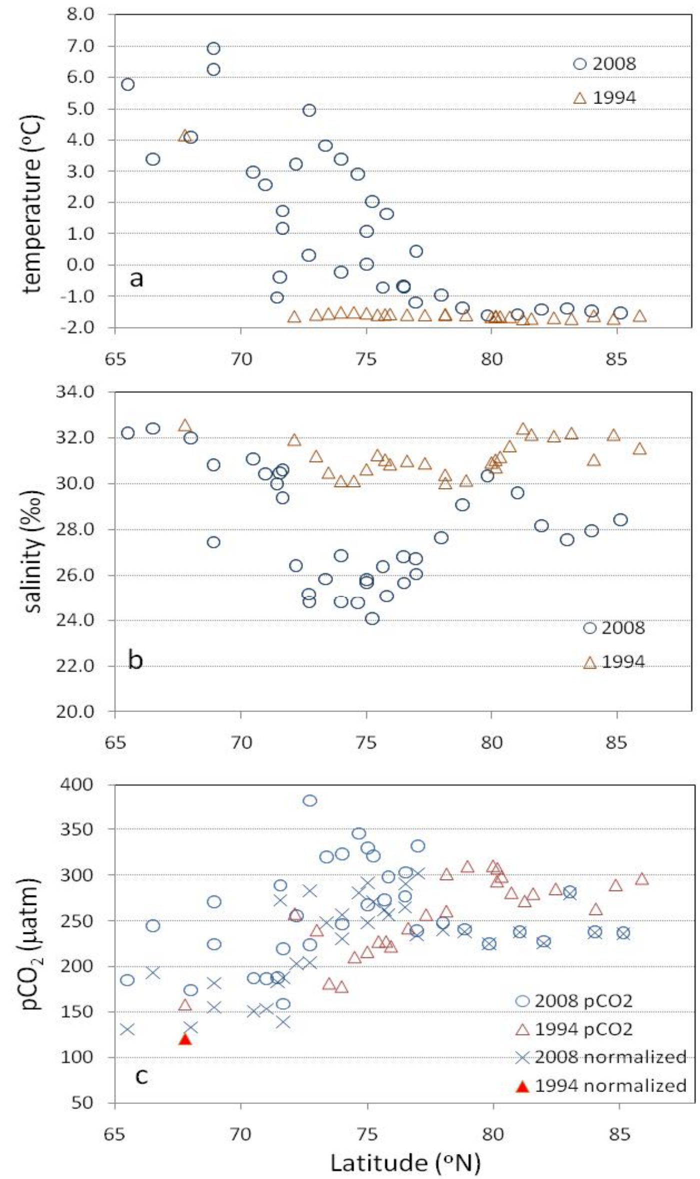
Measured by Sang H Lee's lab, Korea Polar Research Institute.



PP measured under
ice-covered condition
in summer 1994
= 30 mg/m2/day
(Gosselin et al. 1997)

T, S, Ice, and pCO_2





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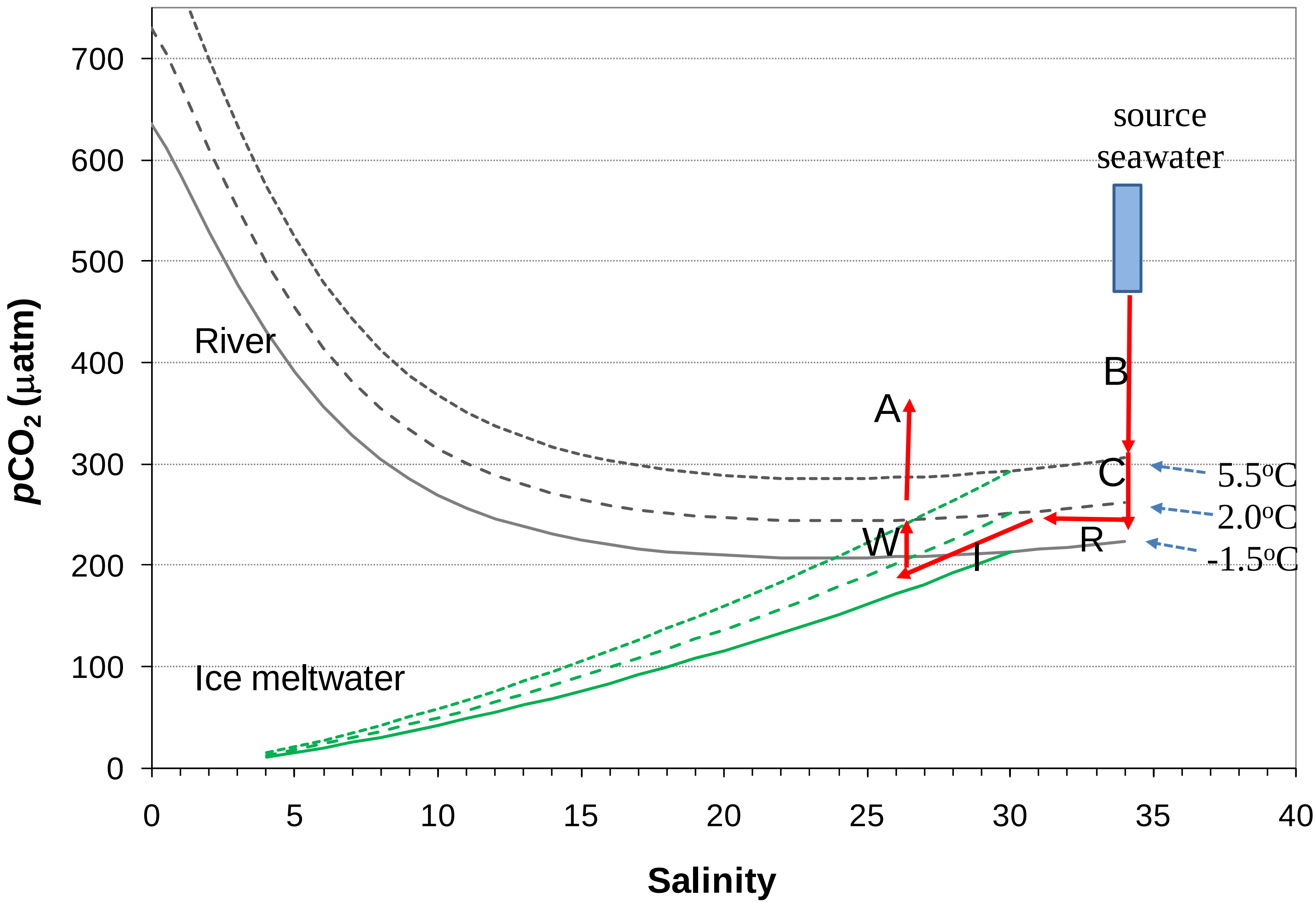
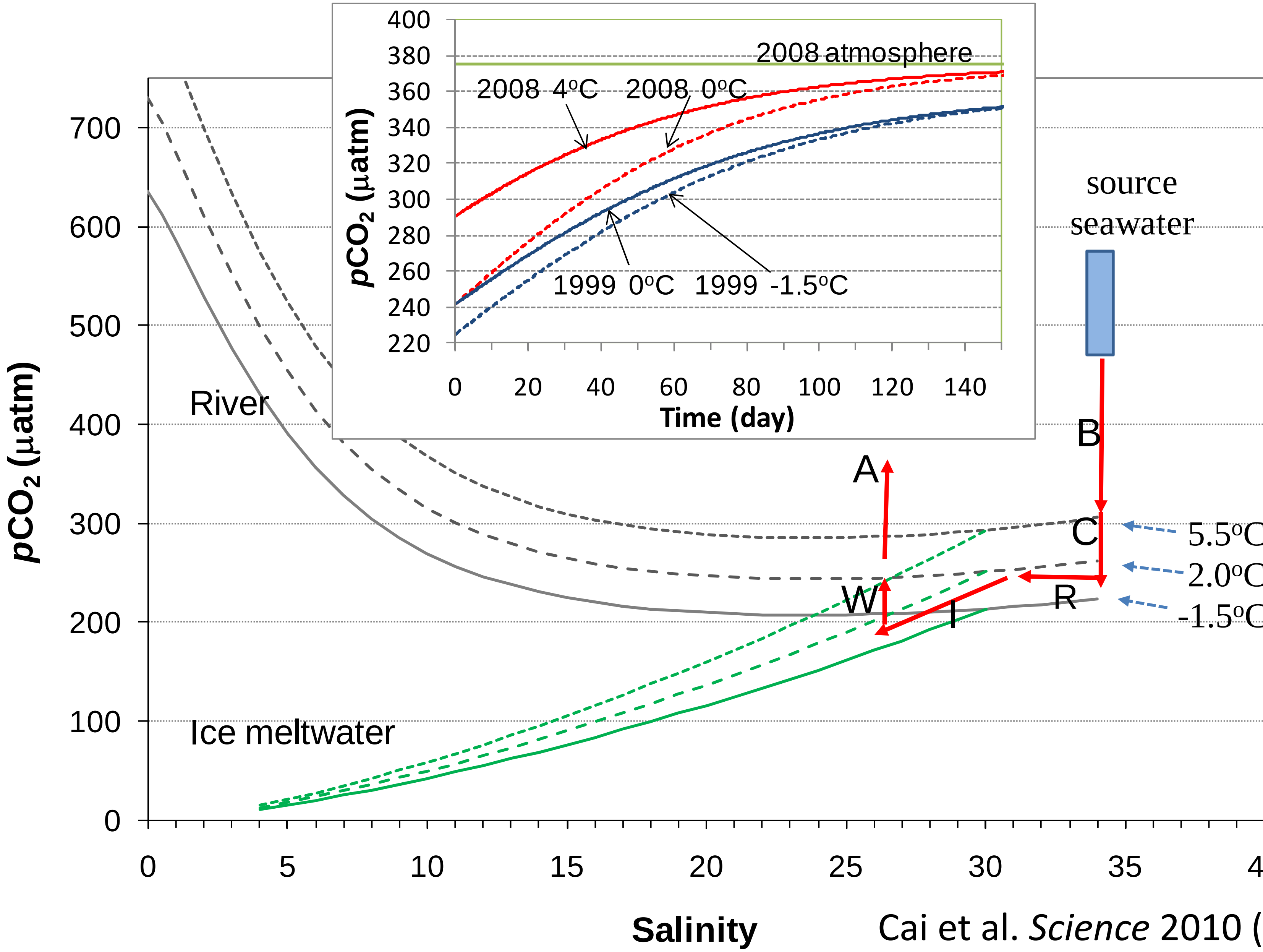
Controls on the Arctic basin sea surface *p*CO_2

- Controls:
  - Biology
  - Temperature
  - River Water
  - Ice Meltwater
- How do we separate them?
- What conservative tracers can we use to separate River from Ice meltwaters?

What controls surface water pCO_2 distribution?

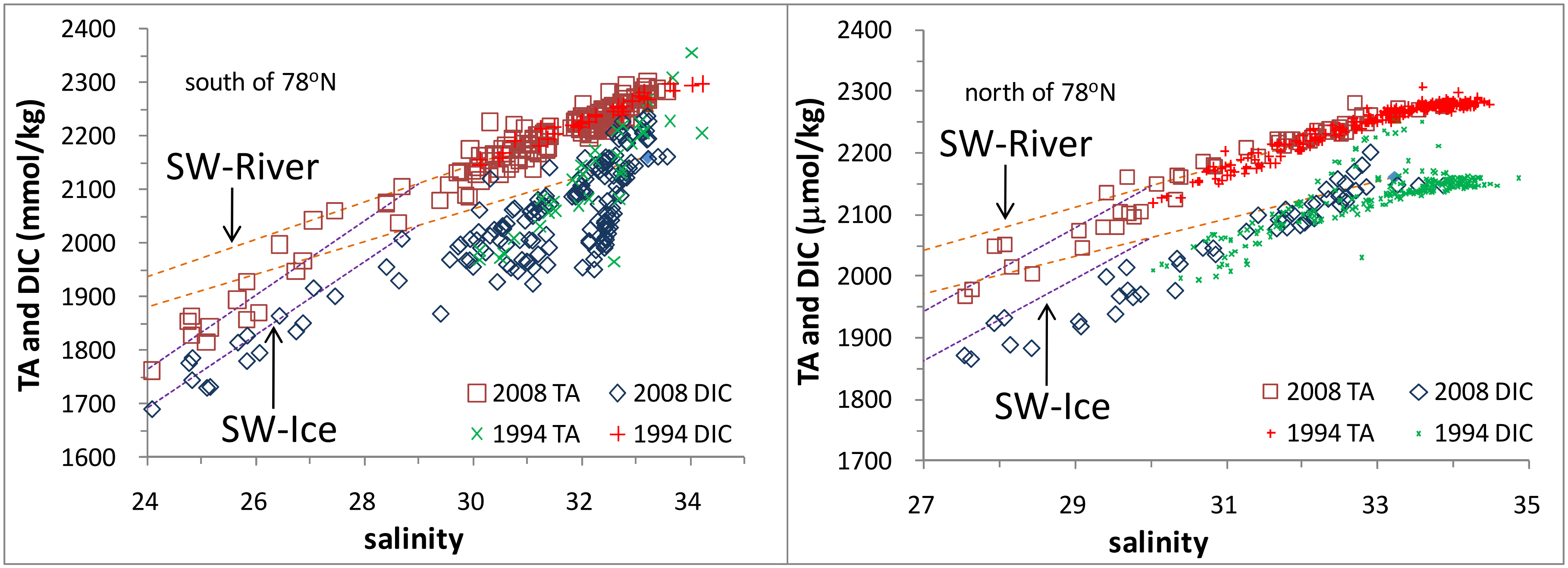


What controls surface pCO$_2$ distribution?



Cai et al. *Science* 2010 (in press)

TA is conservative to Salinity though not necessarily in one straight line



End-members:

sw: S = 33.218±0.046, TA = 2257.9±16.2 µmol/kg, and DIC = 2161.4±3.4 µmol/kg.

River: S=0, TA = 1100 µmol/kg, and DIC = 1150 µmol/kg.

Meltwater: S=5, TA = 450 µmol/kg, and 400 µmol/kg.

Salinity and O^{18} were used as conservative tracers to separate the contributions of seawater, river and ice end-members

- $f_{sw} + f_{ice} + f_{river} = 1$
- $f_{sw}S_{sw} + f_{ice}S_{ice} + f_{river}S_{river} = S_{sample}$
- $f_{sw}O_{sw} + f_{ice}O_{ice} + f_{river}O_{river} = O_{sample}$

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- $f_{sw} + f_{ice} + f_{river} = 1$

- $f_{sw}S_{sw} + f_{ice}S_{ice} + f_{river}S_{river} = S_{sample}$

  ↑ 33.1 ↑ 4 ↑ 0

- $f_{sw}O_{sw} + f_{ice}O_{ice} + f_{river}O_{river} = O_{sample}$

  ↑ -1.1 ↑ -2.0 ↑ -20

ALK is a conservative tracer that has distinct values for all three end-members

- $f_{sw} + f_{ice} + f_{river} = 1$

- $f_{sw}S_{sw} + f_{ice}S_{ice} + f_{river}S_{river} = S_{sample}$

- $f_{sw}A_{sw} + f_{ice}A_{ice} + f_{river}A_{river} = A_{sample}$

ALK is a conservative tracer that has distinct values for all three end-members

- $f_{sw} + f_{ice} + f_{river} = 1$

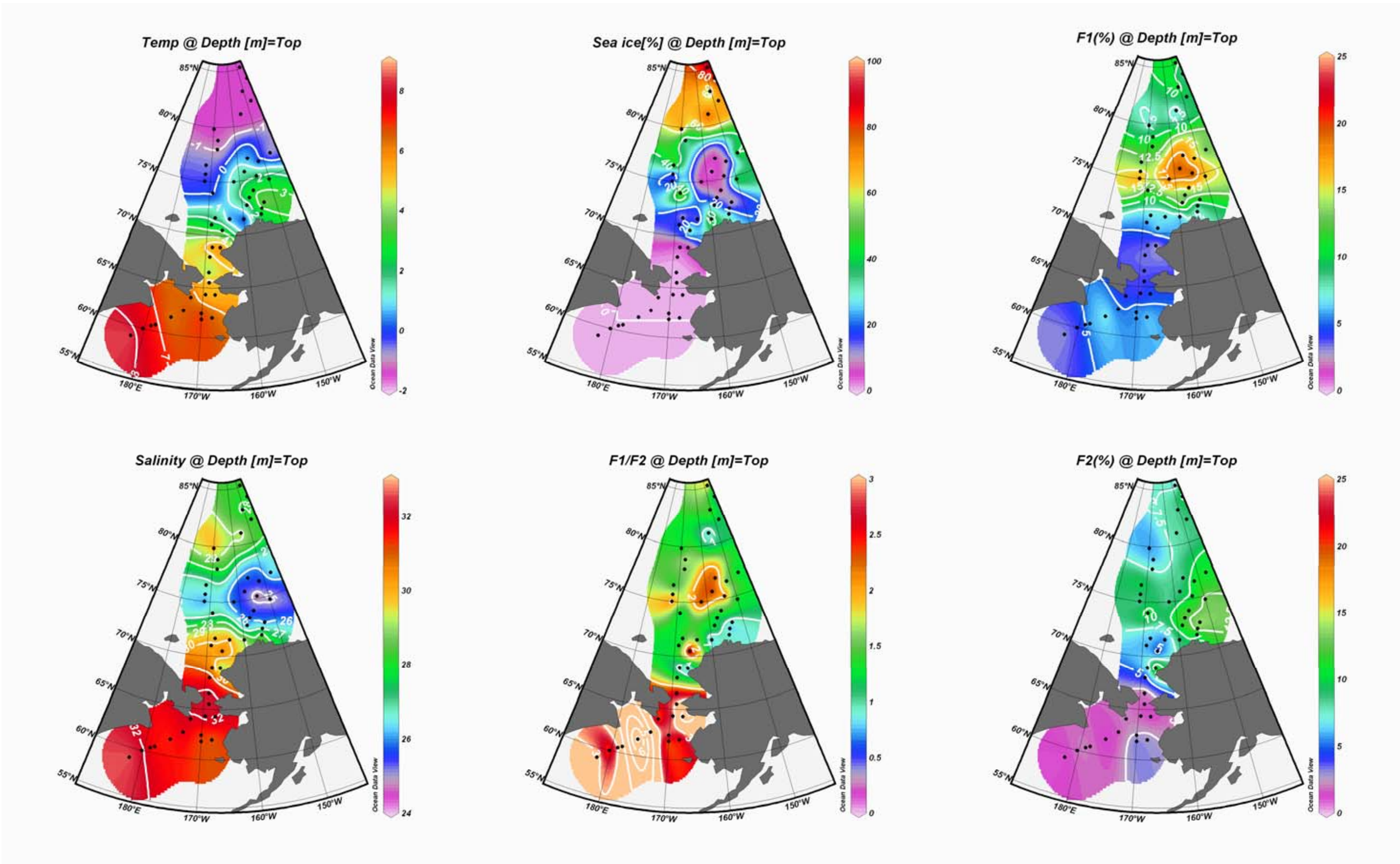
- $f_{sw}S_{sw} + f_{ice}S_{ice} + f_{river}S_{river} = S_{sample}$

  33.1 4 0

- $f_{sw}A_{sw} + f_{ice}A_{ice} + f_{river}A_{river} = A_{sample}$

  2300 400 1100

Relative contribution of river vs. ice



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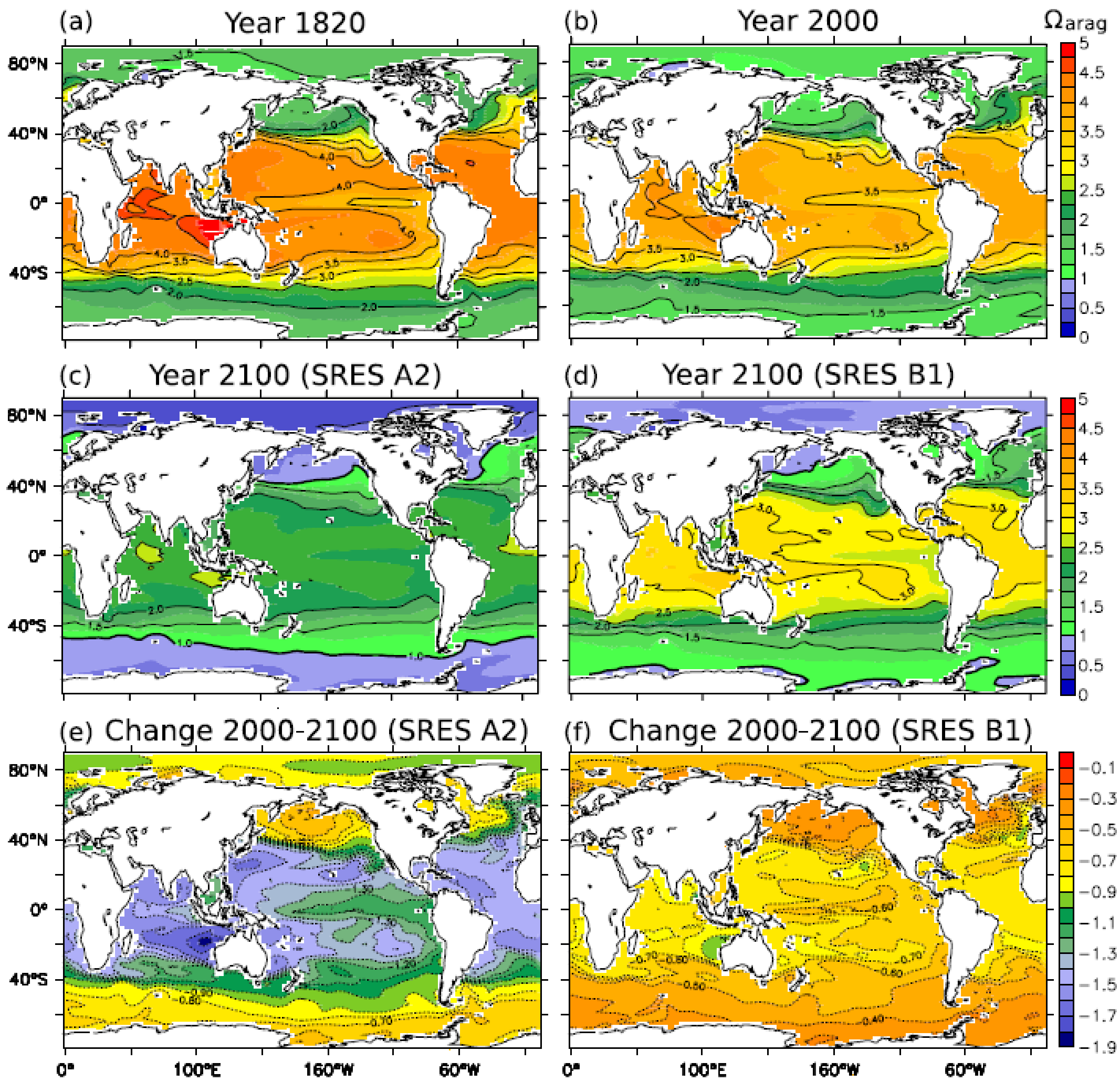


Ocean acidification

OA is most significant in the Arctic Ocean

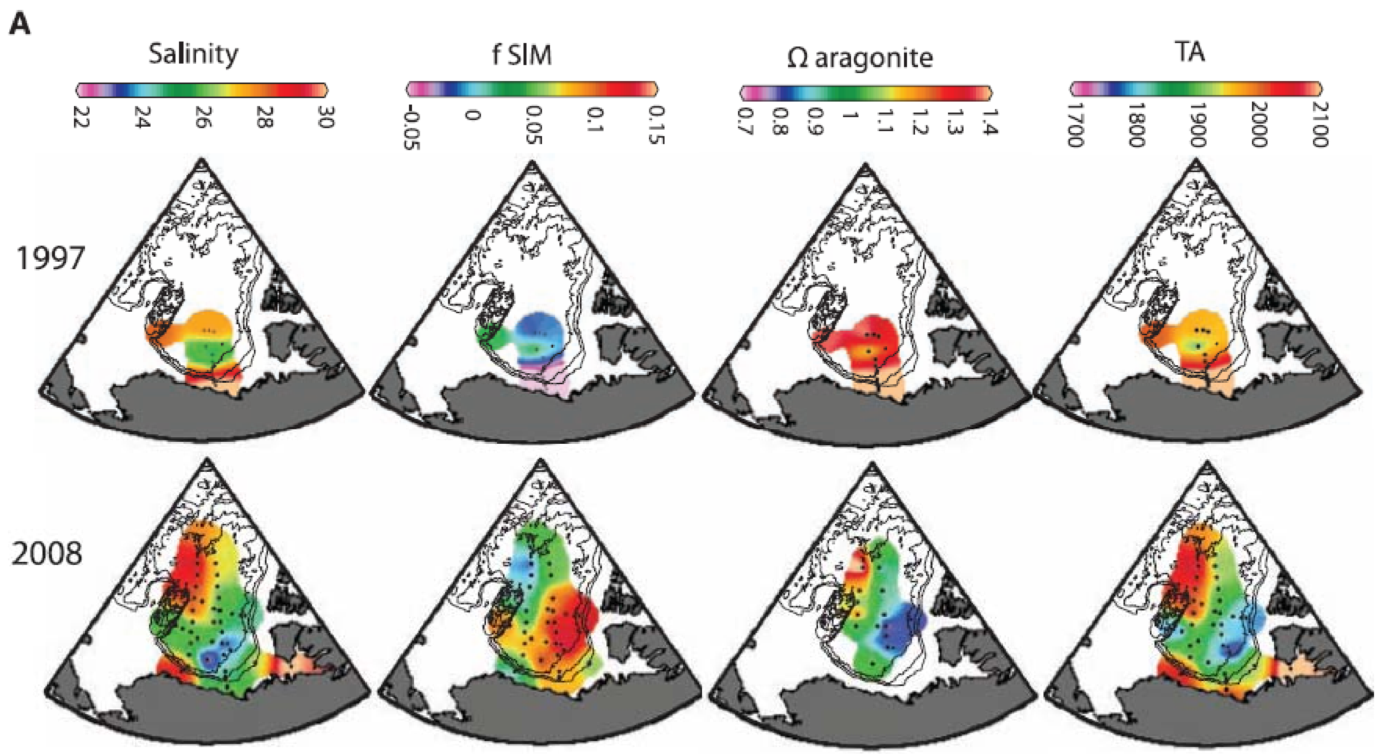
Steinacher et al. GB 2009

Science
AAAS

Aragonite Undersaturation in the Arctic Ocean: Effects of Ocean Acidification and Sea Ice Melt

Michiyo Yamamoto-Kawai, *et al.*

Science **326**, 1098 (2009);
DOI: 10.1126/science.1174190



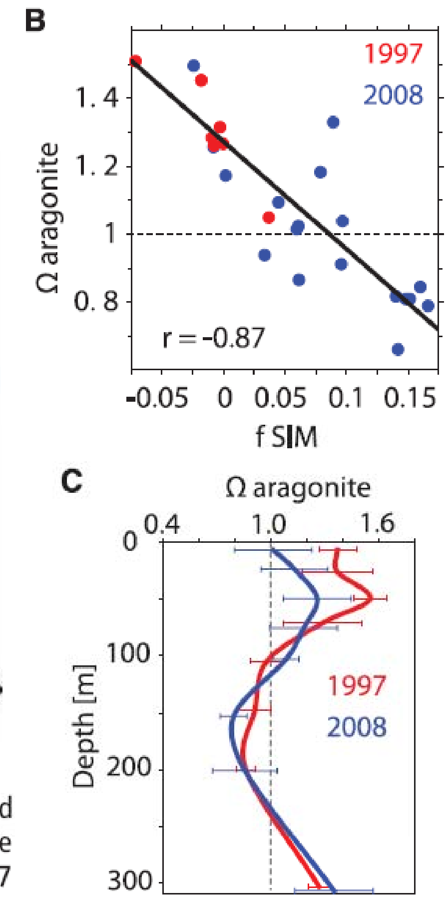
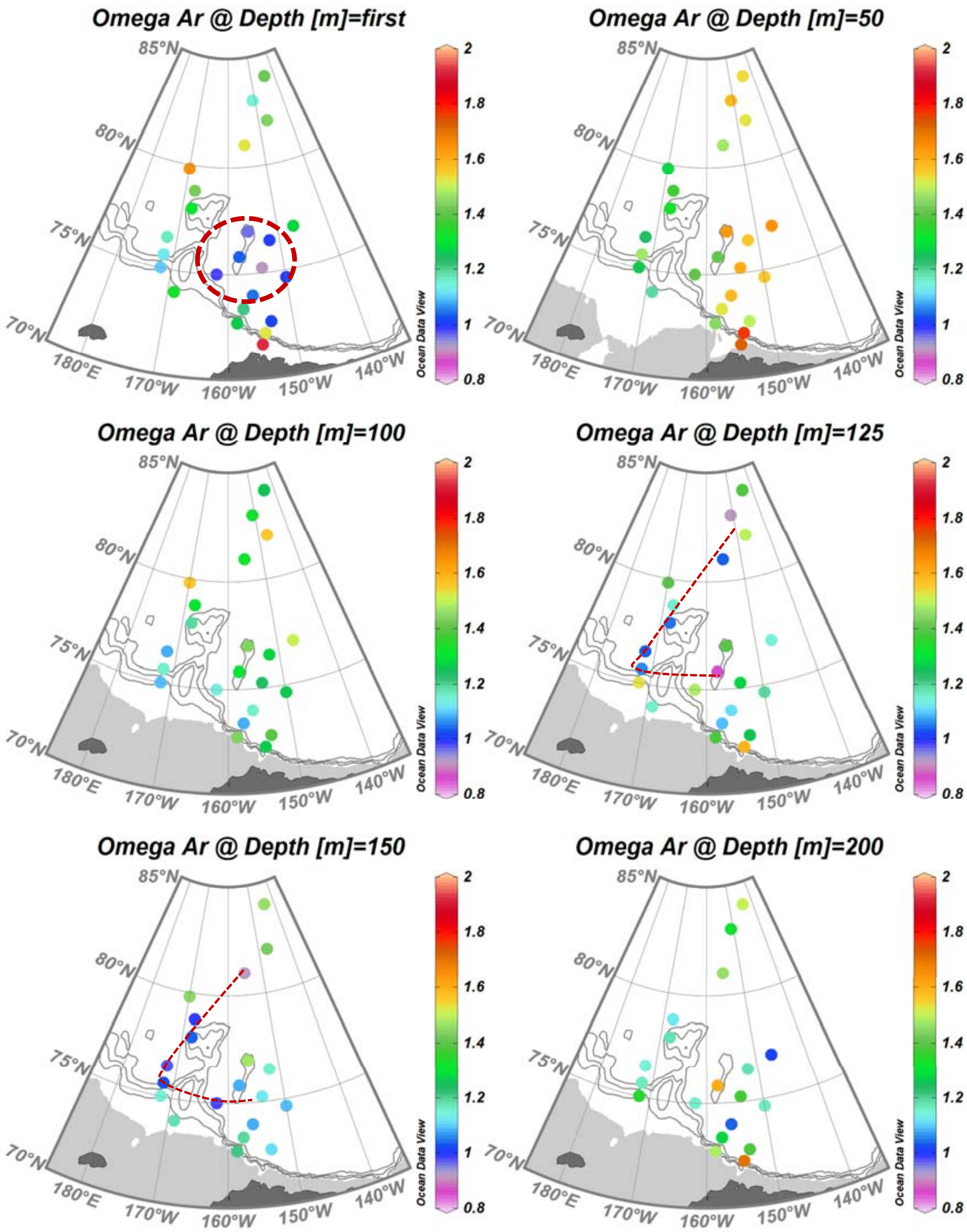


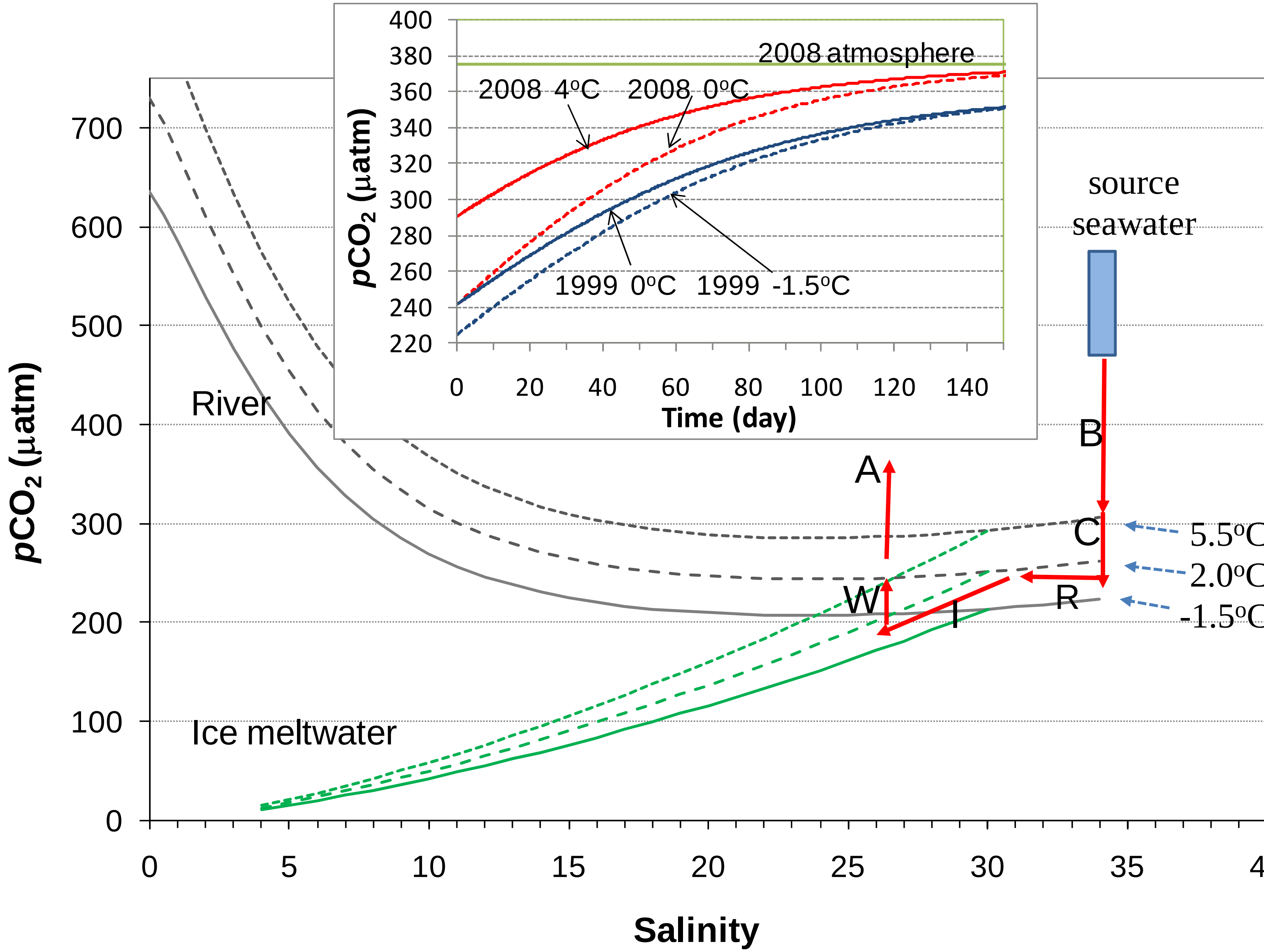
Fig. 1. (**A**) Surface distributions of Ω aragonite, S, fraction of sea ice meltwater (f SIM), and TA in surface water observed between depths of 0 and 20 m. f SIM was estimated by using $\delta^{18}O$ and S measurements (*12*, *13*). Gray contour lines indicate isobaths of 1000, 2000, and 3000 m. (**B**) Relationship between Ω aragonite and f SIM in surface water observed in 1997 (red) and 2008 (blue). (**C**) Mean vertical profile of Ω aragonite in the upper 300 m of the Canada Basin in 1997 (thick red line) (*14*) and in 2008 (thick blue line). Observations at stations where the bottom depth was >2000 m were used to calculate mean and SD (error bars) at each depth.



Ocean Acidification in the Arctic

- Surface OA caused by atm CO_2 invasion
- Subsurface acidification caused by biological recycling of OC

What controls surface pCO_2 distribution?



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Biogeosciences, 6, 1–27, 2009
www.biogeosciences.net/6/1/2009/

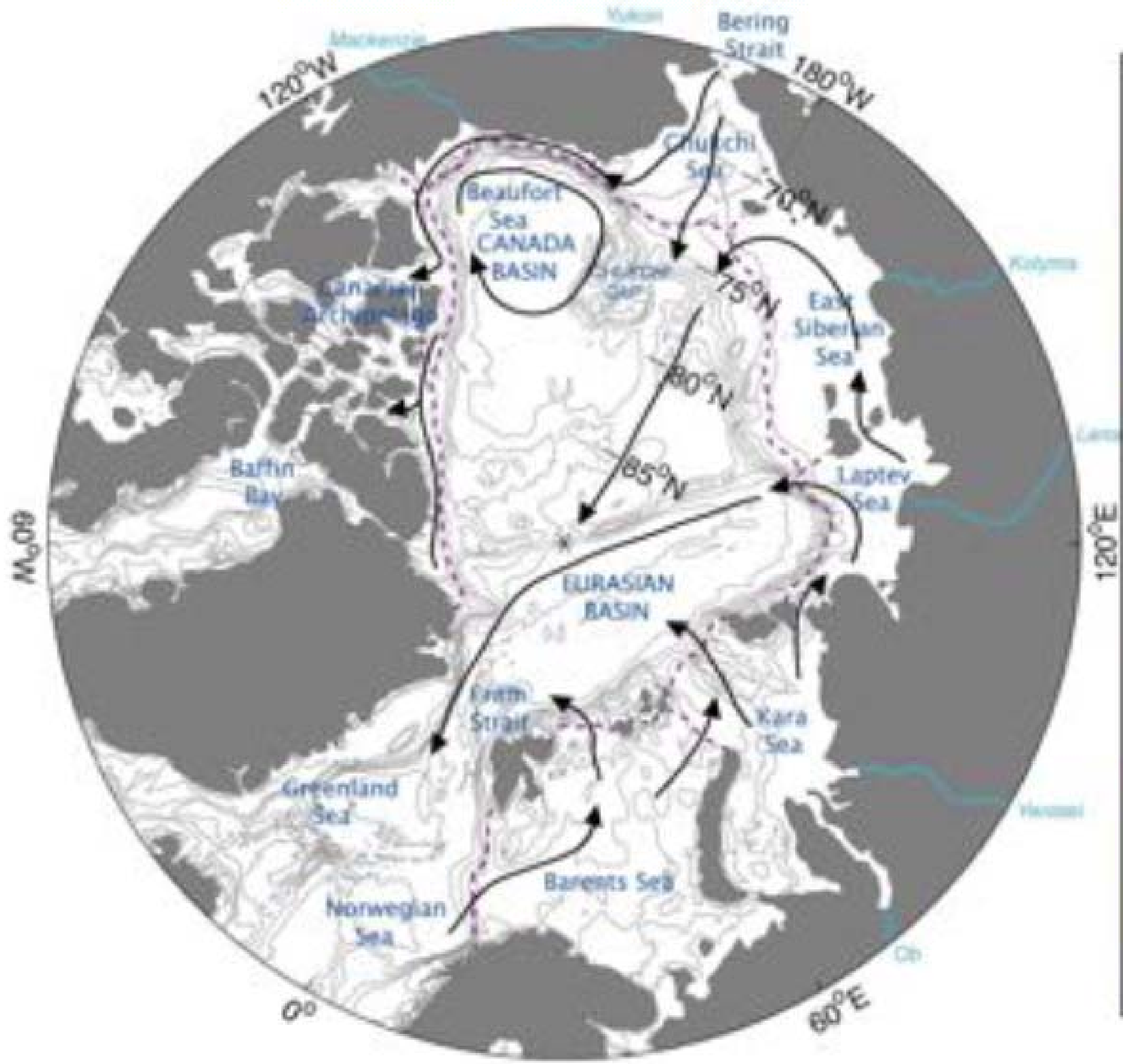
Biogeosciences

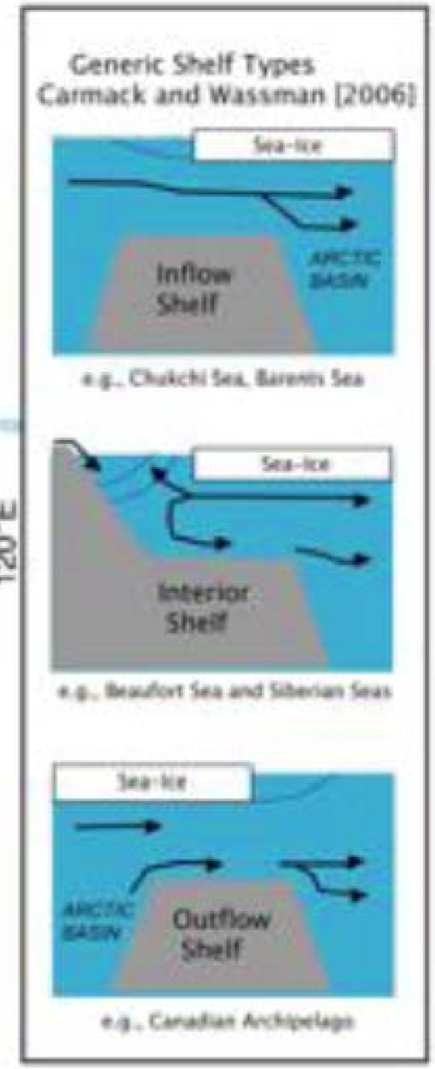
The Arctic Ocean marine carbon cycle: evaluation of air-sea CO_2 exchanges, ocean acidification impacts and potential feedbacks

N. R. Bates[1] and J. T. Mathis[2]

[1]Bermuda Institute of Ocean Sciences, Ferry Reach, Bermuda
[2]School of Fisheries and Ocean Sciences, University of Alaska Fairbanks, Fairbanks, Alaska, USA

Circulation of the western Arctic Ocean





- the net role of increased stratification versus sustained wind mixing in these newly ice free regions
- Wind-driven upwelling and mixing of nutrient and CO_2 rich subsurface water is expected or already has been shown to have a major impact on carbon dynamics and ecosystem in the Arctic or Antarctic marginal areas.

- In addition, warmer temperatures likely would enhance microbial respiration of organic carbon, potentially reducing net community production.
- Moreover, increased warming also would promote permafrost thawing and coastal erosion in the Arctic continents, increasing riverine inputs of organic carbon that is subsequently metabolized to CO_2, thus further contributing to the elevated pCO_2.
- In future years, when sea surface temperature further increases after all ice is melted during summertime, as is predicted to
- occur within 30 years, the Arctic Ocean basin CO_2 uptake capacity would reduce further because of the warming effect on surface-water pCO_2.

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Summary

- Arctic Ocean margins and basins are experiencing rapid changes.
- Carbon cycle, in particular, CO_2 behavior, also experiences rapid changes.
- Margins are large CO_2 sinks, but basins are not.
- Rapid CO_2 invasion from the atmosphere into the highly stratified and shallow surface water (caused by ice melt, warming) is the main reason for the limited CO_2 uptake capacity.
- Surface water is being acidified by this CO_2 invasion.
- Future warming may further reduce this CO_2 uptake capacity.

Measuring Surface Water pCO_2 in the Polar Oceans: Outfitting and Initial Operation of a pCO_2 System on the Chinese Icebreaker *Xue Long*

Partners:

- Prof. Liqi Chen *of the Third Institute of Oceanography, SOA, in Xiamen, PRC.*
- Dr. Rik Wanninkhof *of AOML/NOAA in Miami Fl, USA;*
- Prof. Wei-Jun Cai *of the University of Georgia, Athens, GA, USA*
- In collaboration with the Polar Research Institute of China (PRIC), Shanghai PRC.

NOAA support: Office of oceanic and atmospheric research (OAR), Climate program office, Polar Programs, Global Carbon Cycle Program

Duration: 1 February 2005 - 31 January 2008 (no cost extension to April 2009

Objectives:

- Train scientists from PRC in modern methods of CO_2 analysis
- Scientific Exchanges Install underway pCO_2 system on *Xue Long*
- Training of Personnel in operation of system
- Interpretation of results of Cruises to Artic and Antarctic

Future:

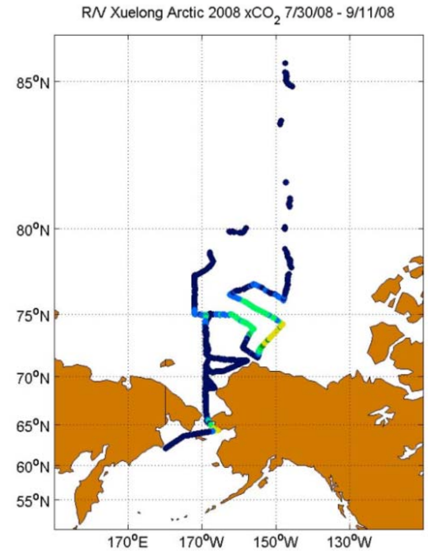
- Joint SINO-US Scientific efforts on Chinese Polar Cruises

First meeting of partners, Xiamen, July 2006

Setup of Automated pCO_2 System on Xue Long, Shanghai 2007

Upon Arrival: The *Xue Long* is undergoing major Renovations

A week later: Installation complete



Icebreaker *Xue Long* at the Ice Station near 85°N in the western Arctic Ocean

Credit: Mr. Yong Wang, State Ocean Administration of China -the Chinese Arctic and Antarctic Administration, Beijing, China.

中国第四次北极科学考察
CHINARE 2010