Studies of the Air-Sea CO_2 fluxes and Ocean Acidification Impacts in the Western Arctic: NOAA and the RUSALCA project

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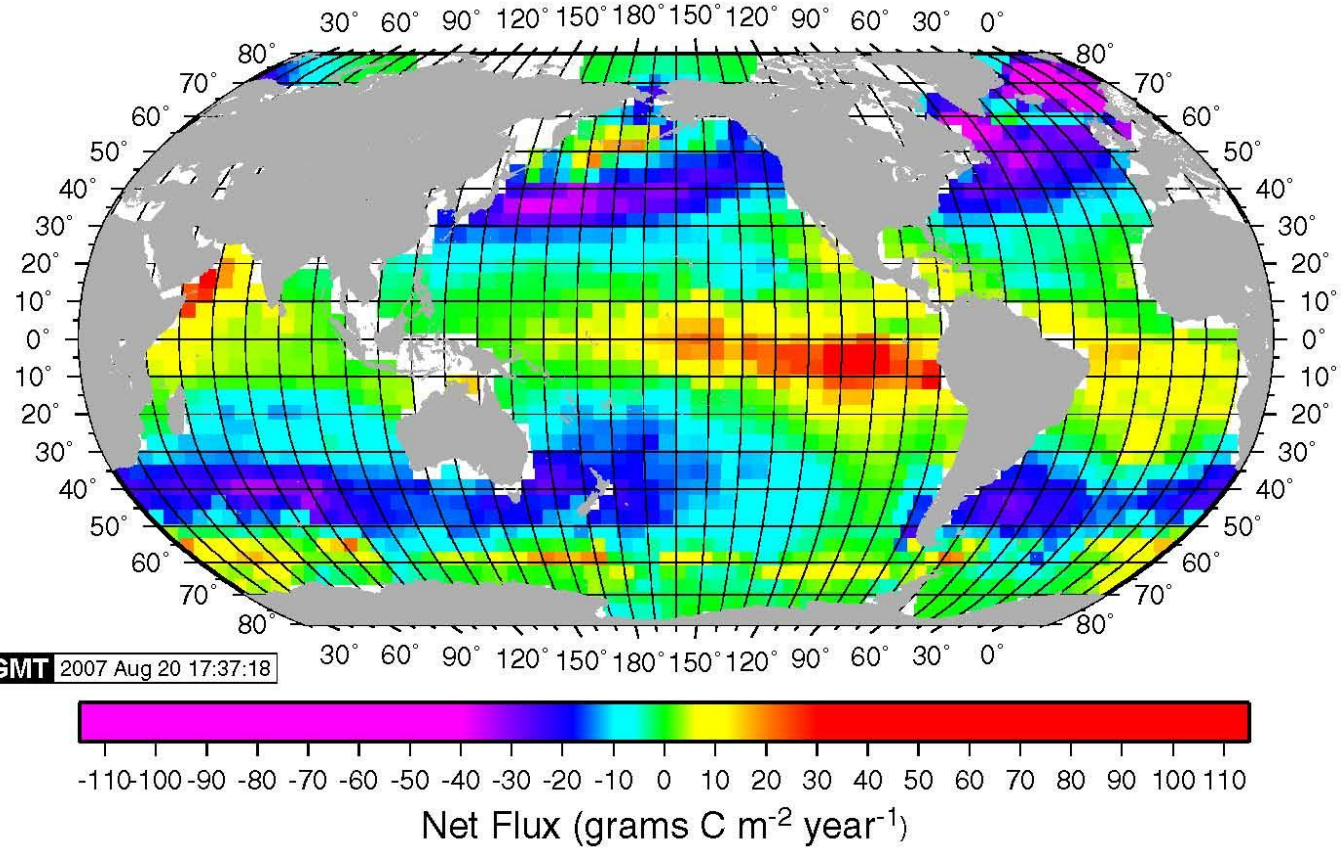
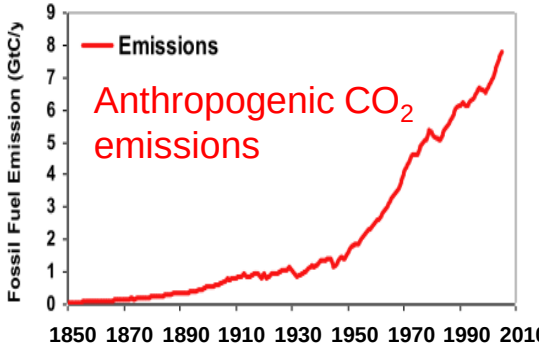
NOAA
NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION
U.S. DEPARTMENT OF COMMERCE

Thanks to:
NOAA; RUSALCA colleagues
Keven Neely, Becky Garley, Margaret Best, Monika Orchowska (BIOS)
Terry Whitledge, Jeremy Mathis (UAF), Wei-Jun Cai, Kevin Arrigo and many others

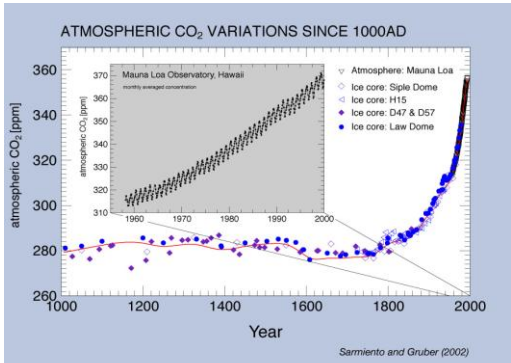
Global Ocean CO_2 Sinks/Sources

Global ocean CO_2 sink of ~1.4 Pg C year^{-1}





Atmospheric CO_2 increase



Red Areas: Oceanic Source of CO_2

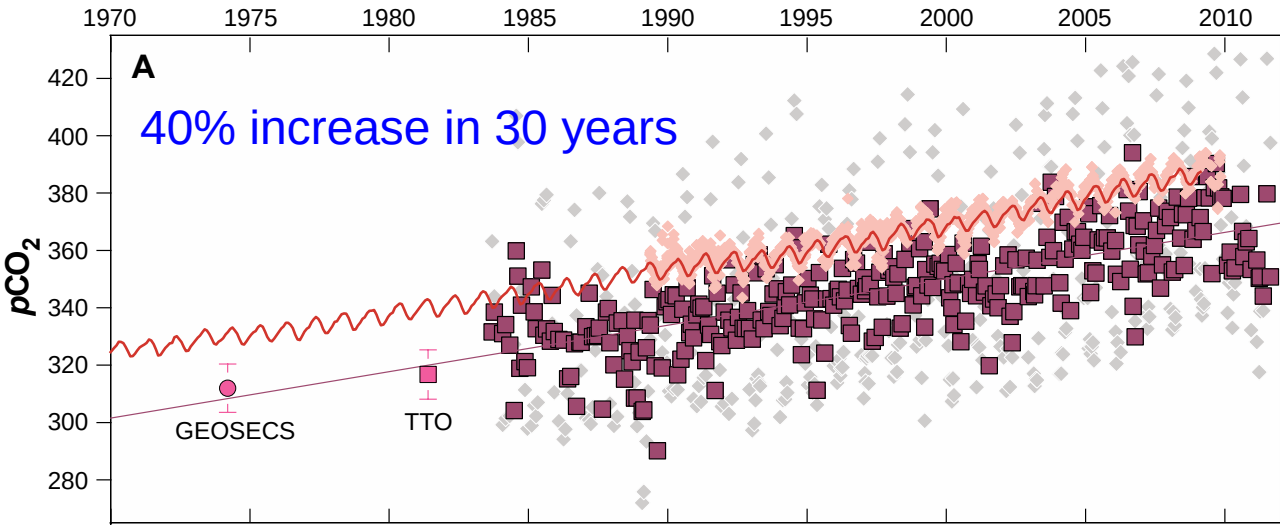
Blue Areas: Oceanic Sinks of CO_2

Takahashi et al., 2002; 2009

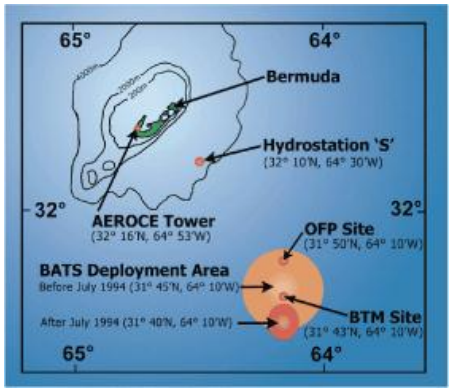
Ocean Carbon Dioxide Uptake

Increase in ocean carbon dioxide (pCO_2) in the Sargasso Sea

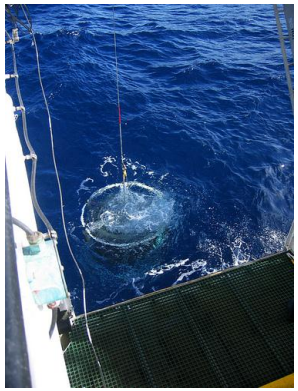
Surface ocean pCO_2 increasing at same rate as the atmosphere suggests that the North Atlantic Ocean CO_2 sink has not changed

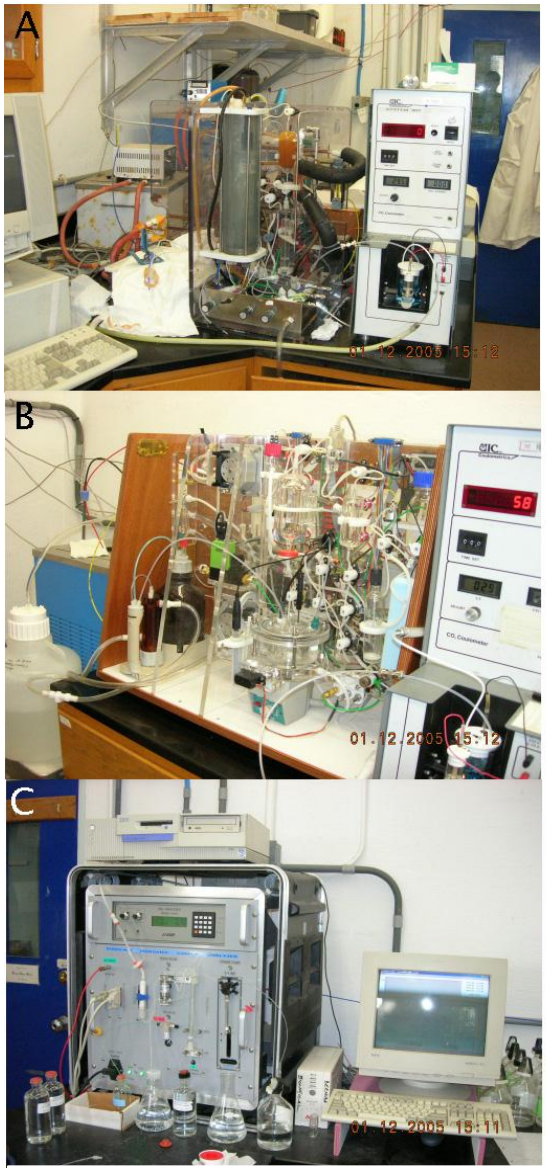


Location of BATS



Shipboard sampling



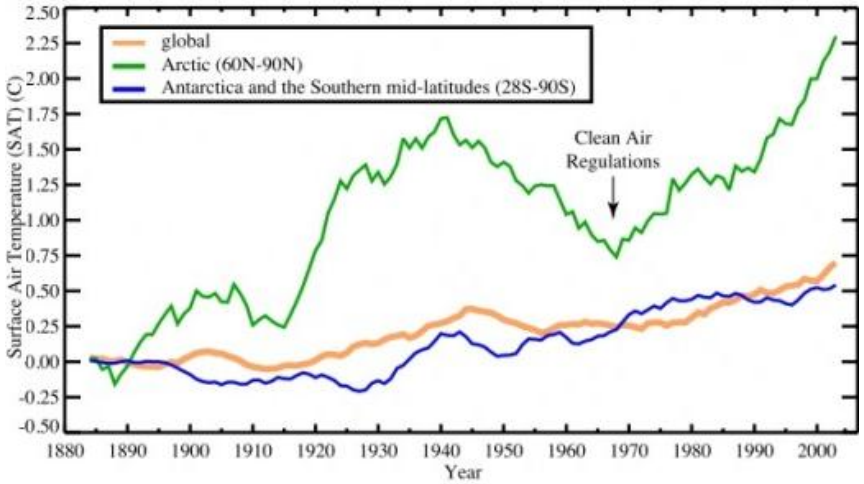


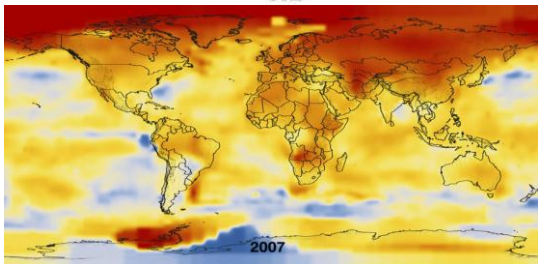
Laboratory analyses

Bates, 2001, 2007; Bates et al., 2012; IPCC 5th Assessment 2013

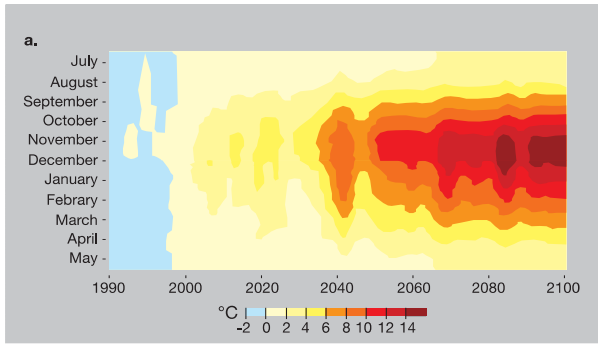
Arctic Ocean Changes

Warming in the Arctic



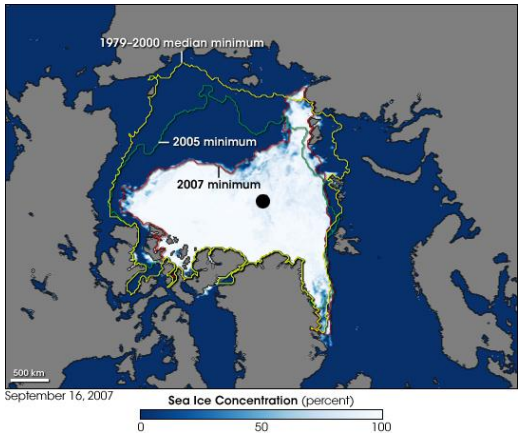


Arctic amplification of warming

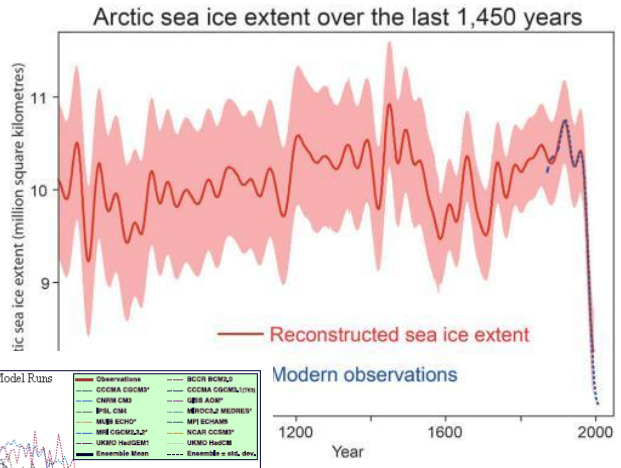


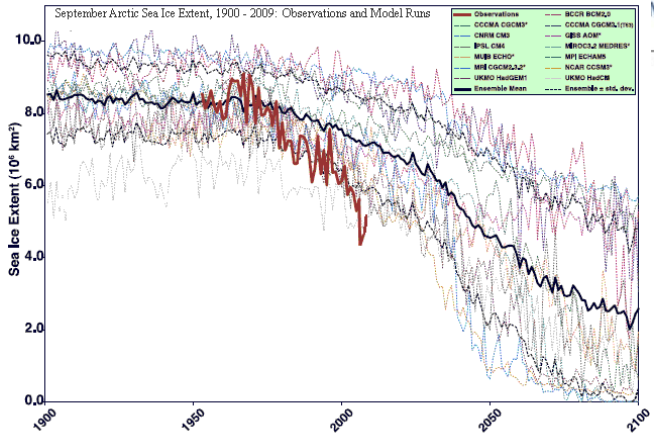
Stroeve, 2008; Kinnard, 2011

Sea Ice loss in the Arctic

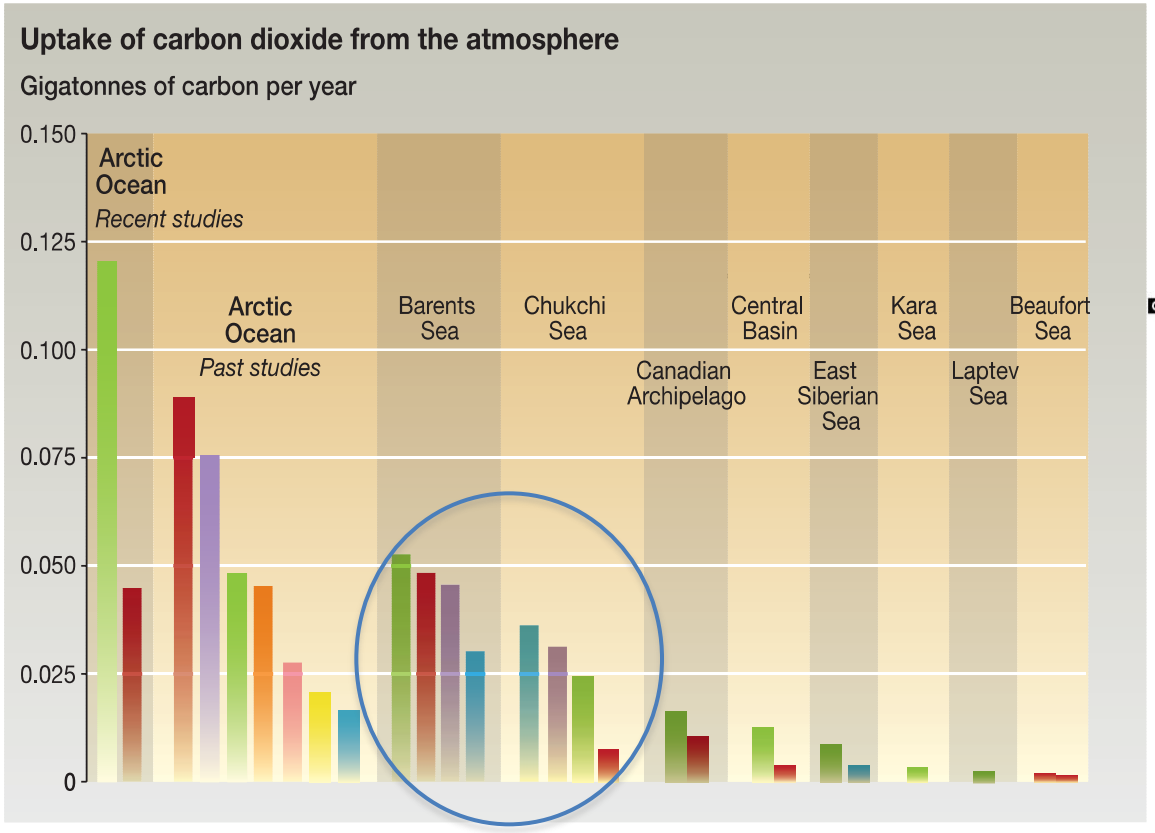


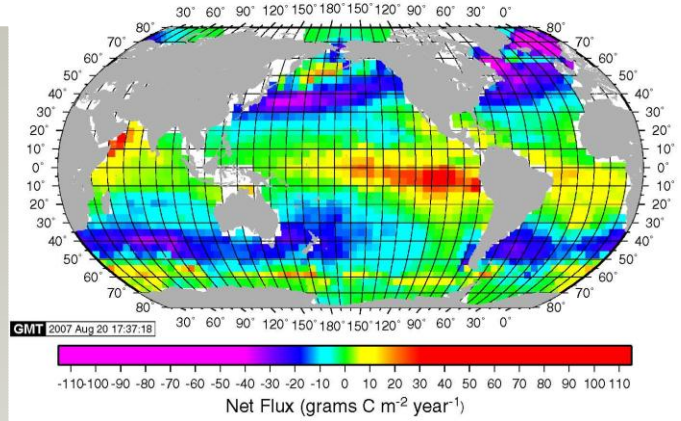
50% decrease in sea-ice over last 30 years



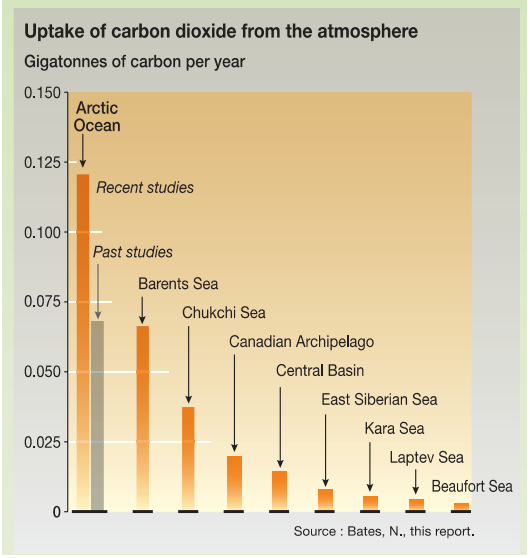


Present Arctic Ocean CO_2 Fluxes





Arctic is ~8-10% of global ocean CO_2 sink



Anderson *et al*. (1998) ~24 Tg C yr^{-1} CO_2 sink

Fransson *et al*. (2003) ~31 Tg C yr^{-1} CO_2 sink

Bates (2006) ~66 Tg C yr^{-1} CO_2 sink

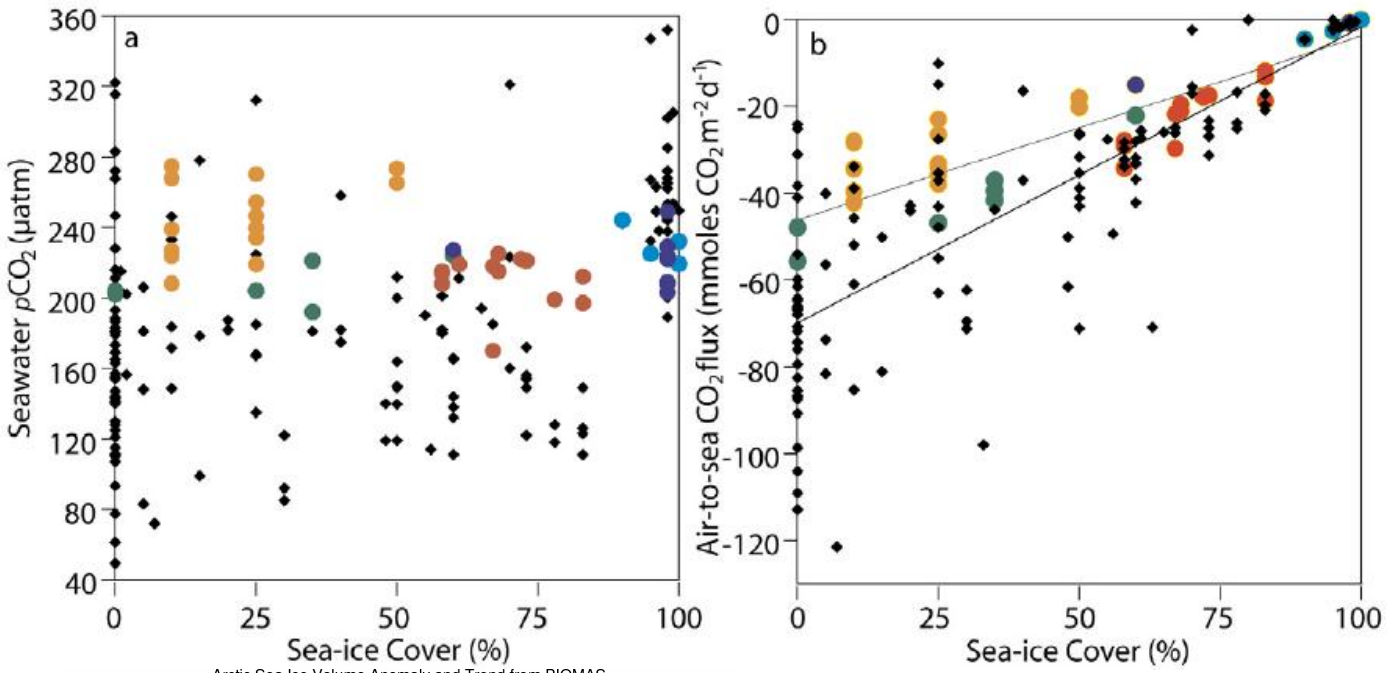
Bates and Mathis (2009) ~66-199 Tg C yr^{-1} CO_2 sink

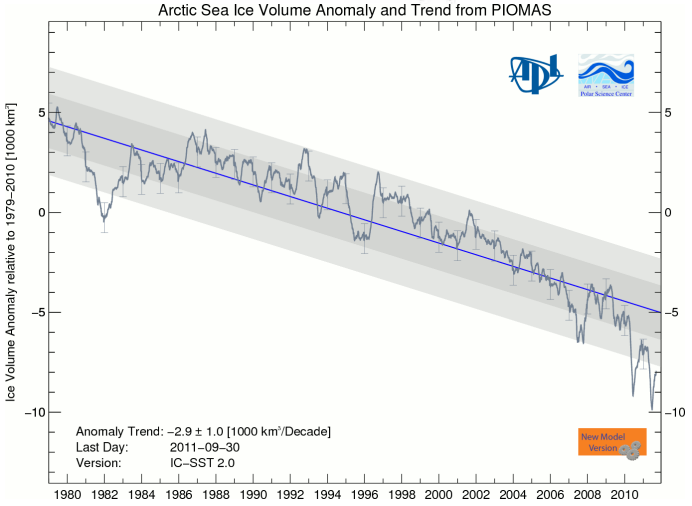
RECCAP (2012) mean of ~130 +/-35 Tg C yr^{-1} CO_2 sink

Bates and Mathis, 2009; Bates, 2009; Bates et al., 2011; Cai et al., 2012; RECCAP, 2012

Future Annual Arctic CO_2 Fluxes

Canada Basin surface waters



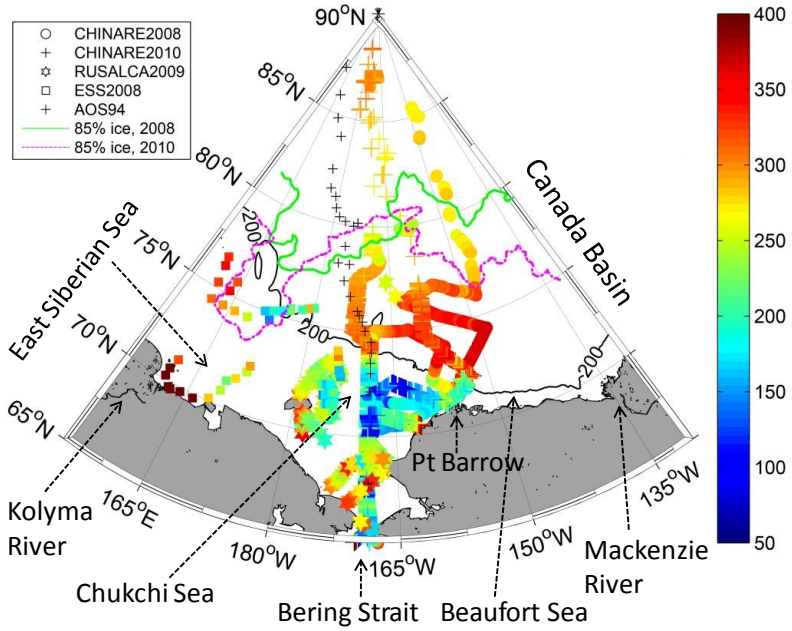


~2 Tg C/yr increase in annual Arctic Ocean CO_2 sink using 2002-2004 SBI data

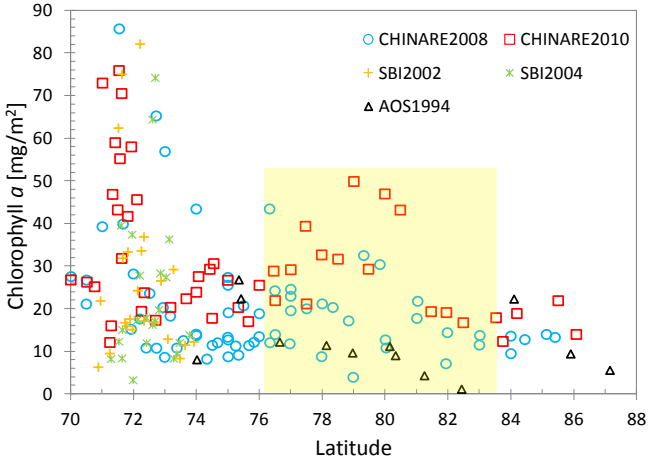
Bates 2006; Bates *et al.*, 2006

Rapidly changing Arctic CO_2 sink

Changing CO_2 sink in Canada Basin:1994-2010

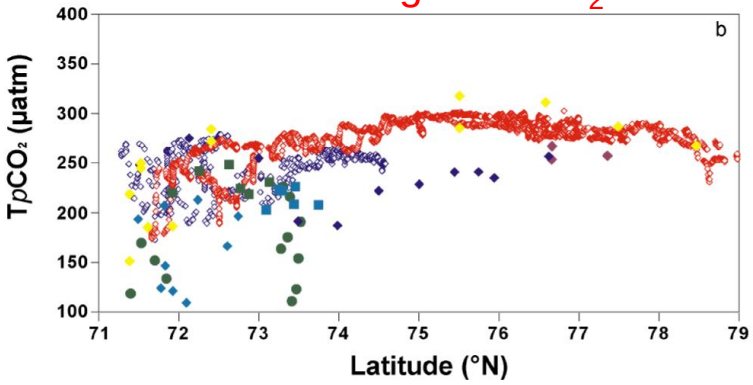


Northward shift of sea-ice edge bloom

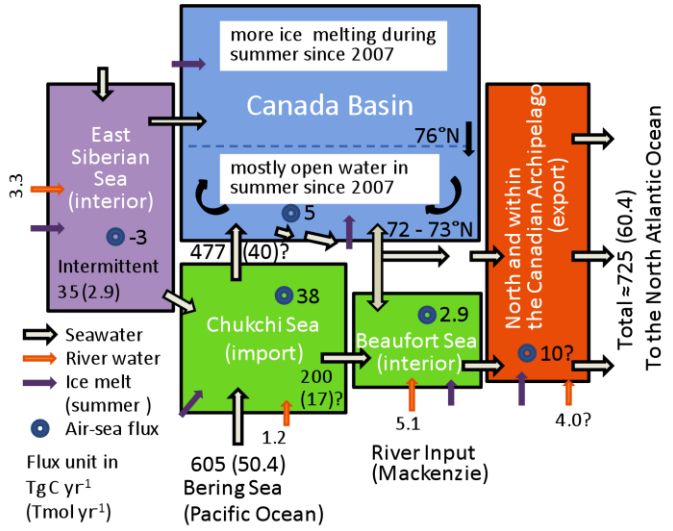


Since major sea-ice loss event in 2007, the Arctic CO_2 sink has reduced by 50-75%?

4-5% reduction in global CO_2 sink



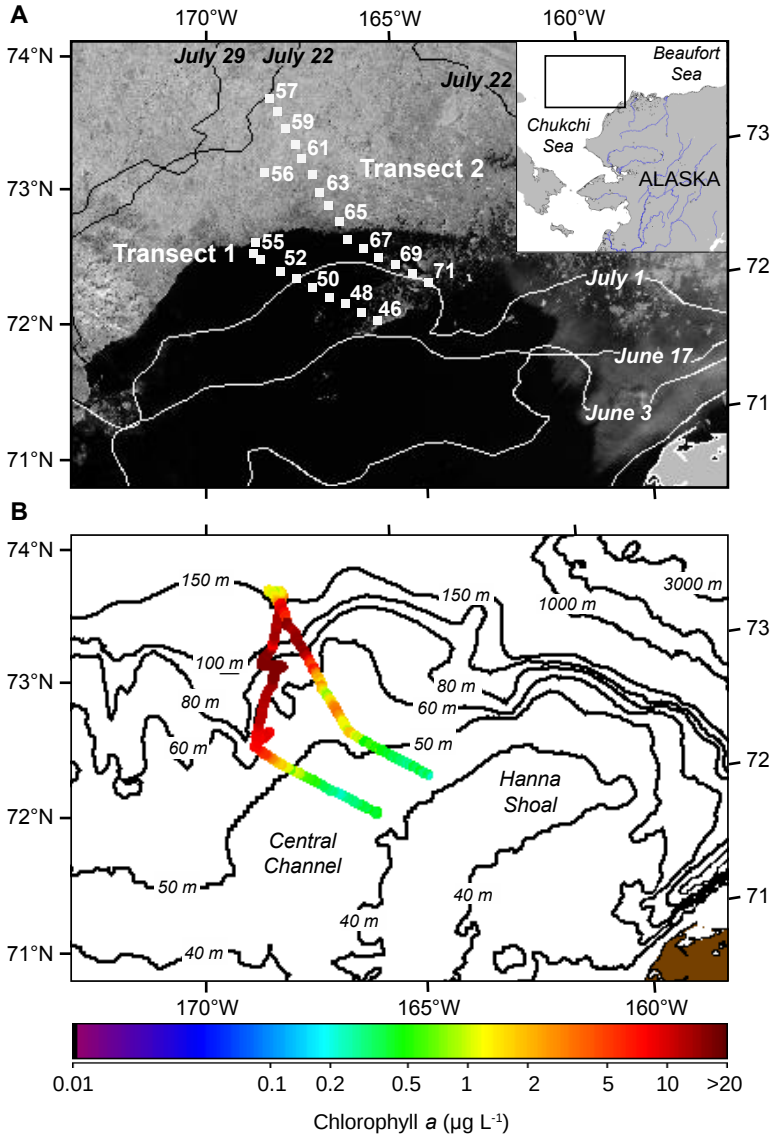
Conceptual model and boundary flux: DIC/CO_2

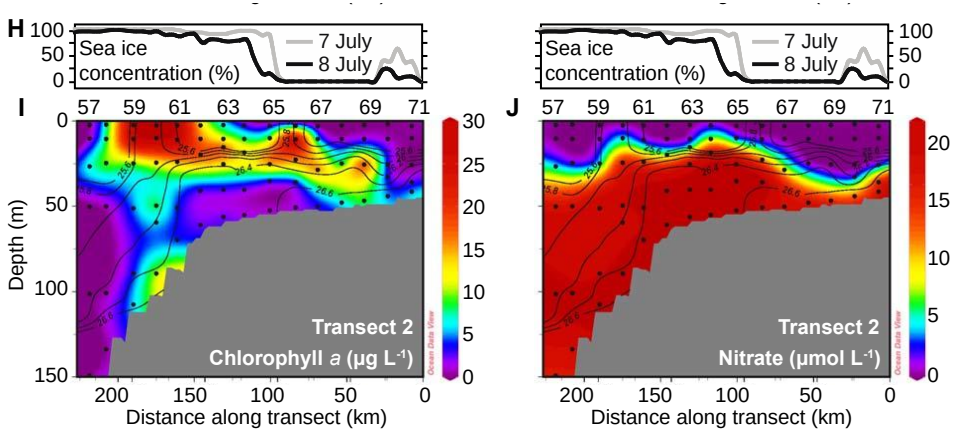


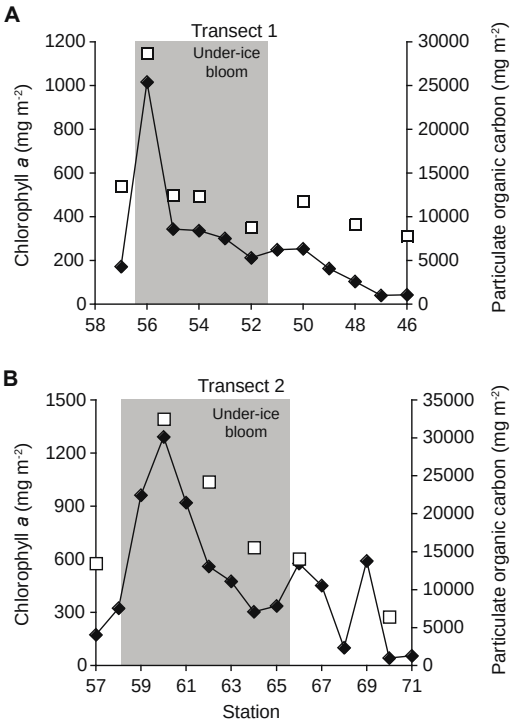
Bates, Cai and Mathis, 2011; Cai et al., 2012

Intense blooms under sea-ice in the Arctic

2010-2011 NASA ICESCAPE project



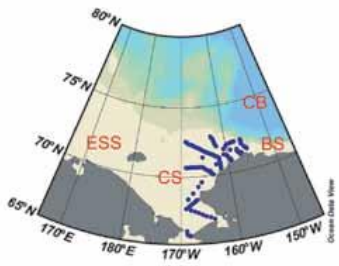


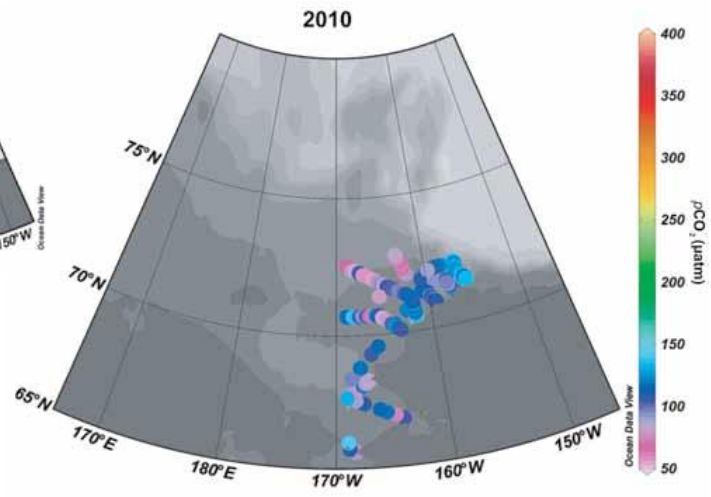


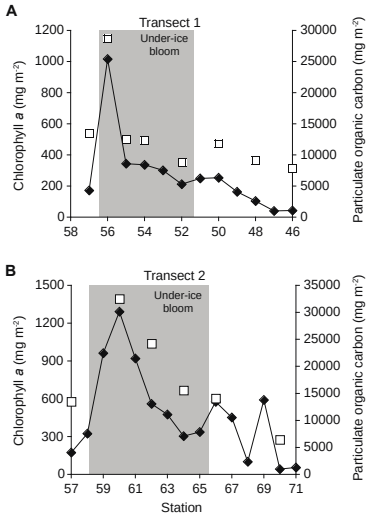
Arrigo et al., 2012

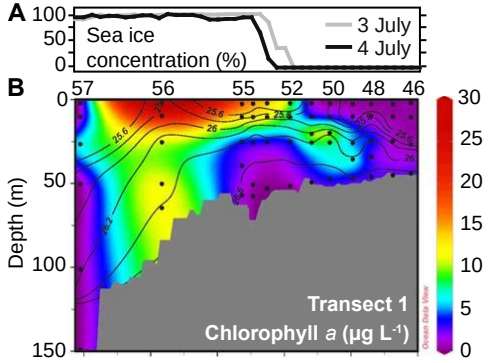
Arctic Ocean Large Ocean CO_2 Sinks

During summertime sea-ice retreat away from the polar shelves in the Arctic



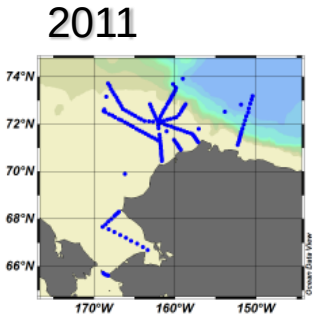


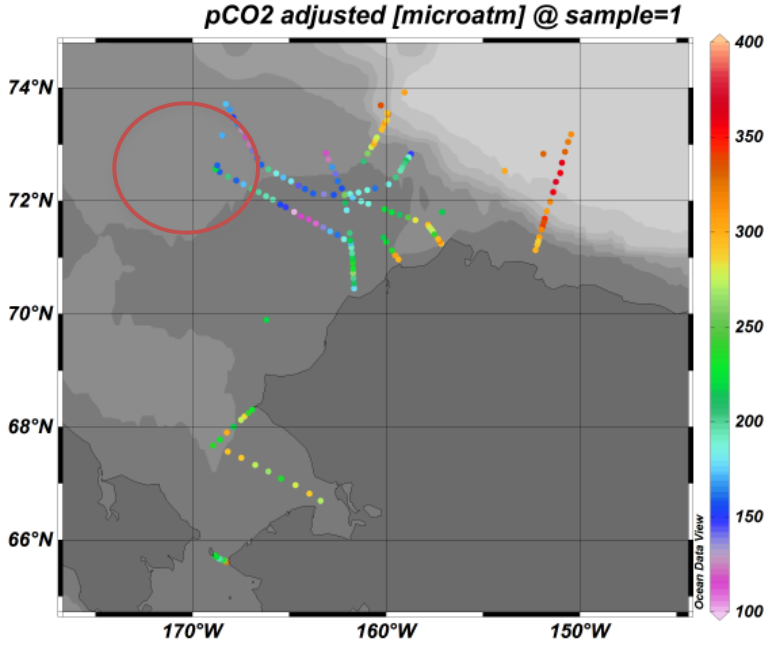




Lowest seawater pCO_2 (~50 µatm) observed in surface waters anywhere in the global ocean

Highest CO_2 uptake observed in surface waters and large CO_2 sink

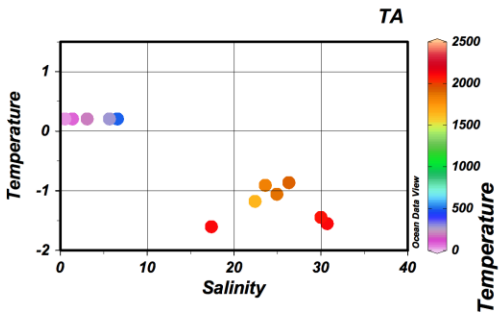


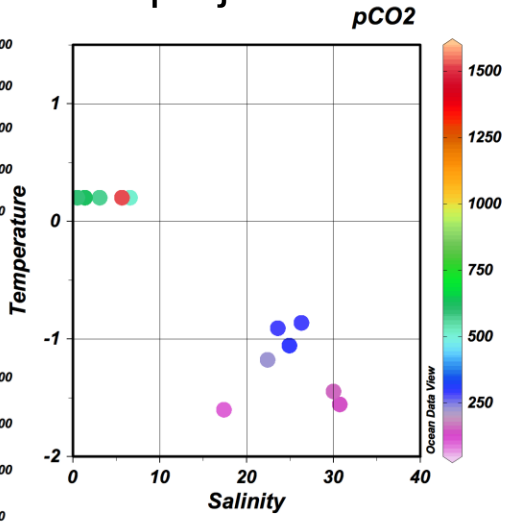


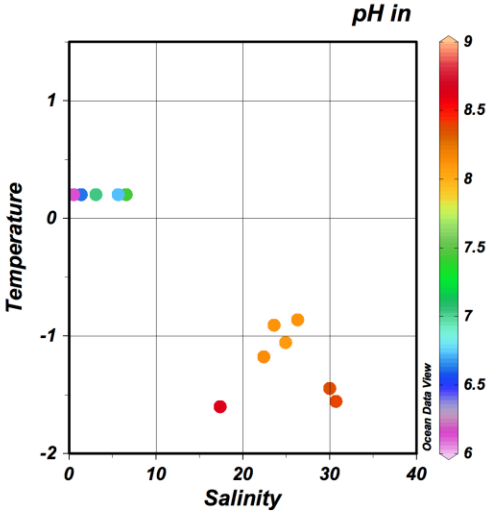
Bates et al., 2011; Arrigo et al., 2012; Bates, Mathis, Garley, 2012

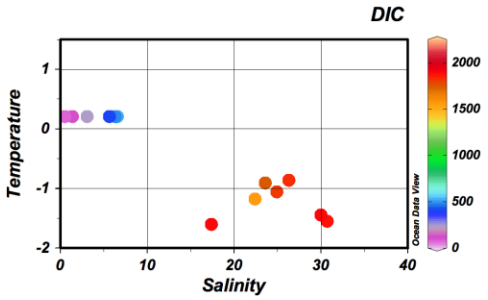
Arctic Ocean Melt Pond CO_2

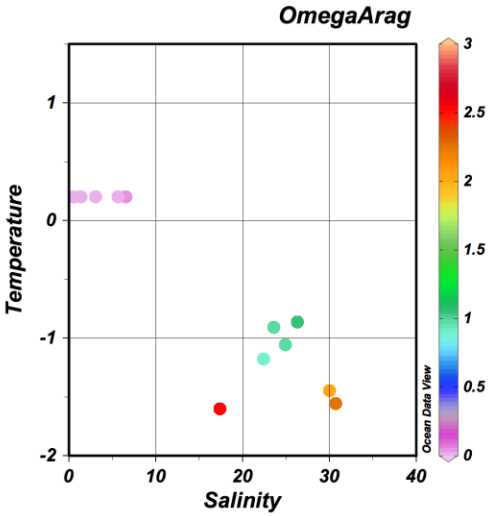
2010-2011 NASA ICESCAPE project

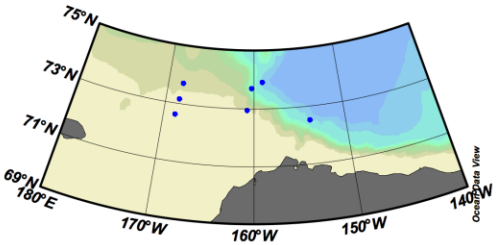












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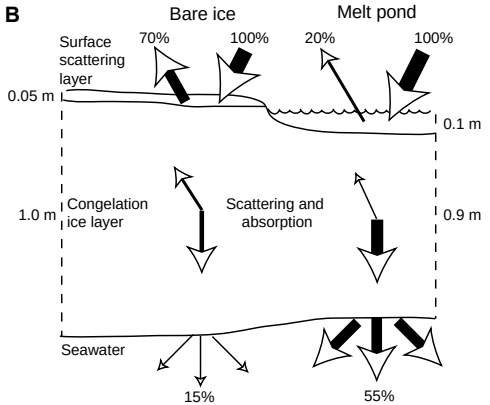
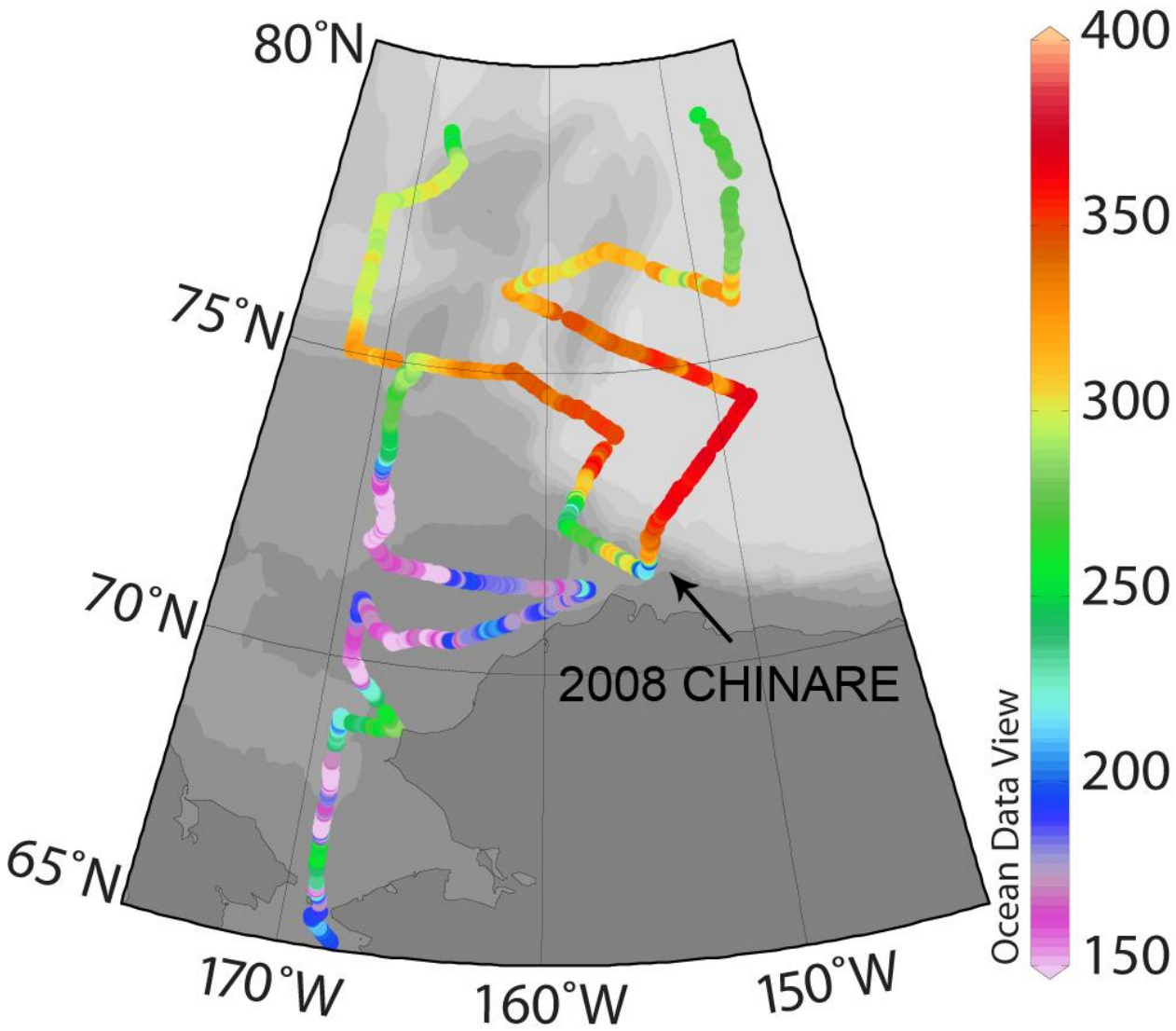


Sea-ice melt and increased river fluxes also reducing Arctic and in global CO_2 sink

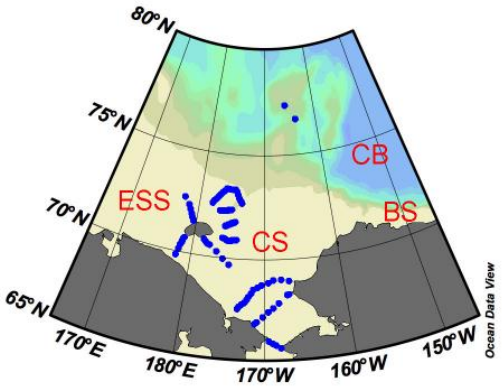
Arrigo et al., 2012; Bates, Mathis, Garley and Frey, 2012

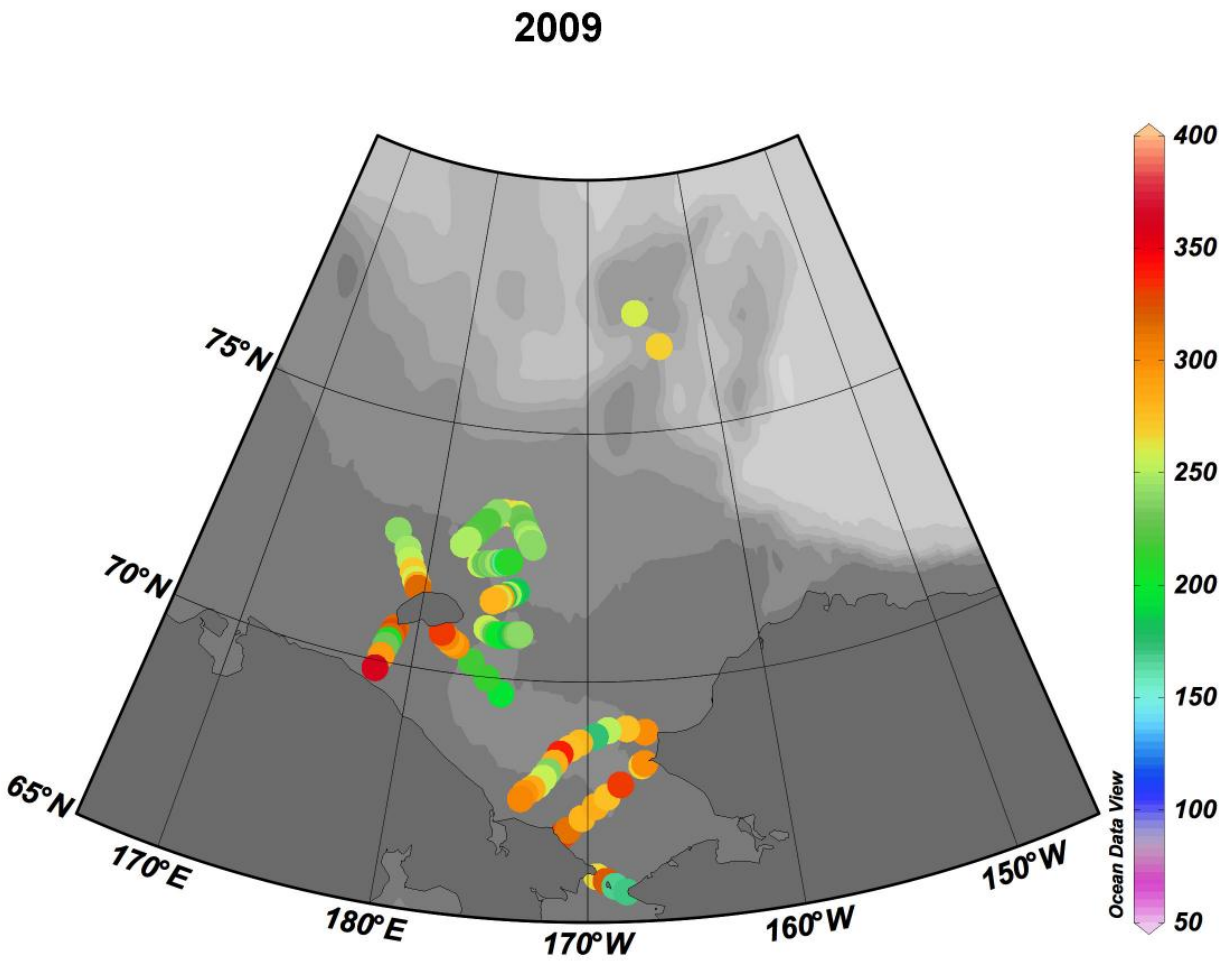
Surface pCO_2 (2008 CHINARE)



Bates *et al*., 2011

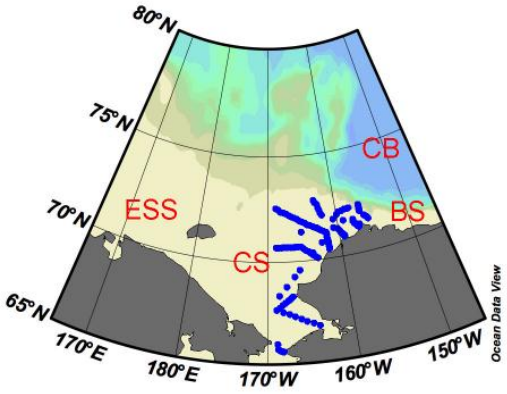
Surface pCO_2 (2009 RUSALCA)

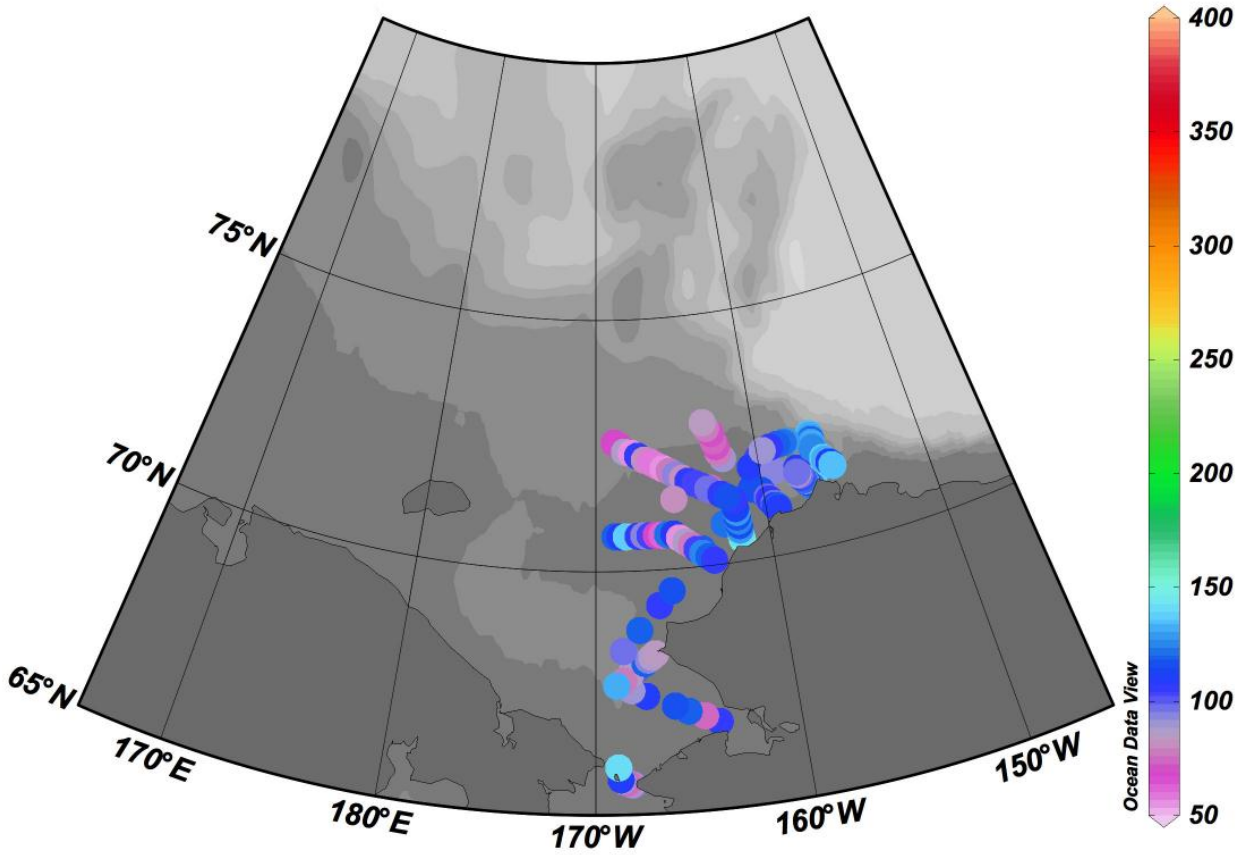




Bates *et al*., 2011

Surface pCO_2 (2010 ICESCAPE)



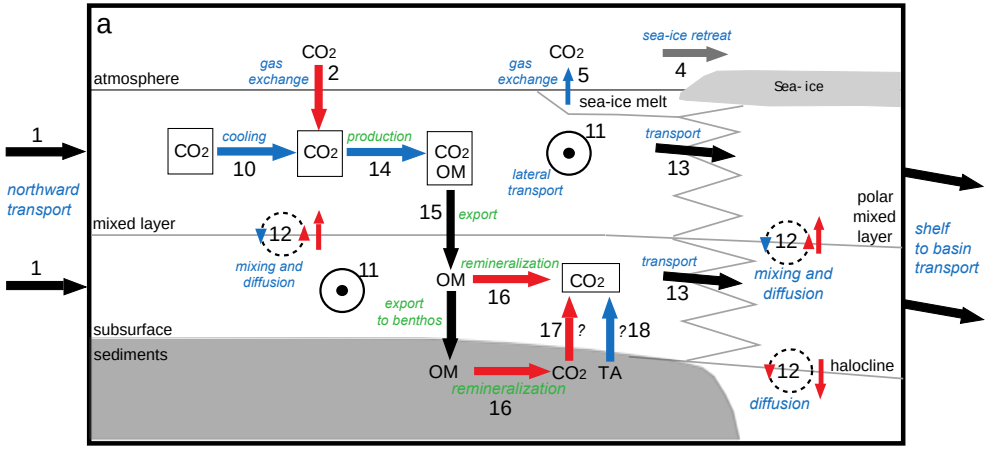


Bates *et al*., 2011

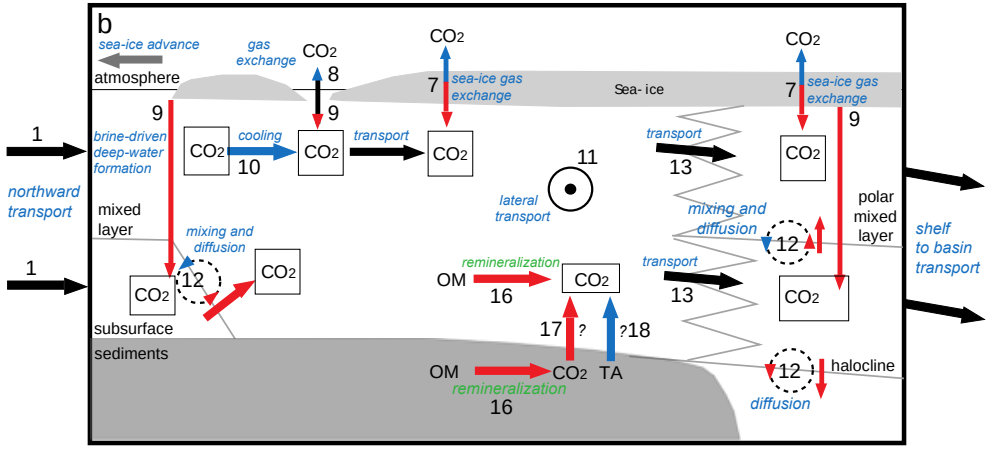
Chukchi Sea “Inflow Shelf”

Inflow Shelf (e.g., Chukchi and Barents Sea)

Summer Conditions (sea-ice free period)

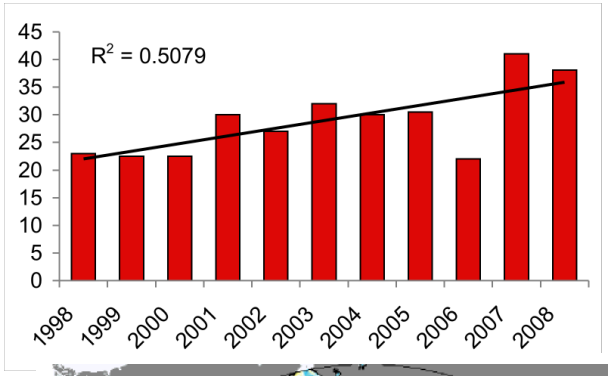


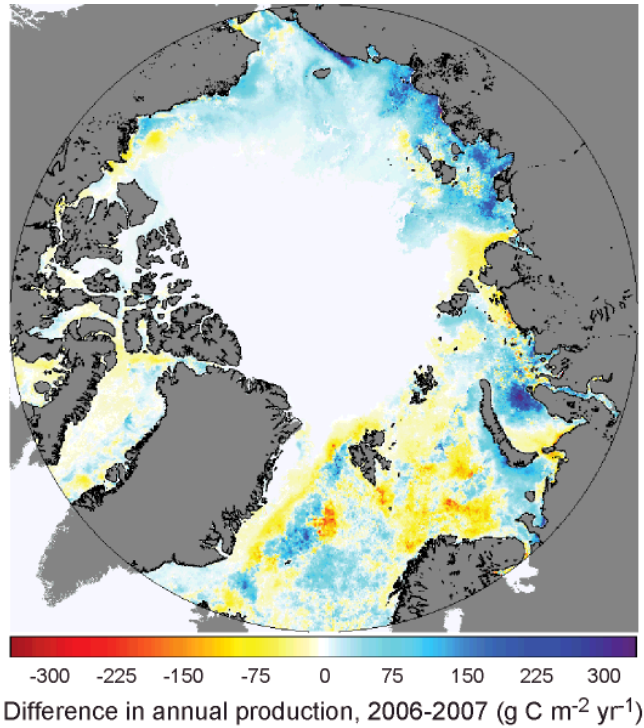
Winter Conditions (sea-ice cover period)



Bates *et al.*, 2011

Chukchi Sea





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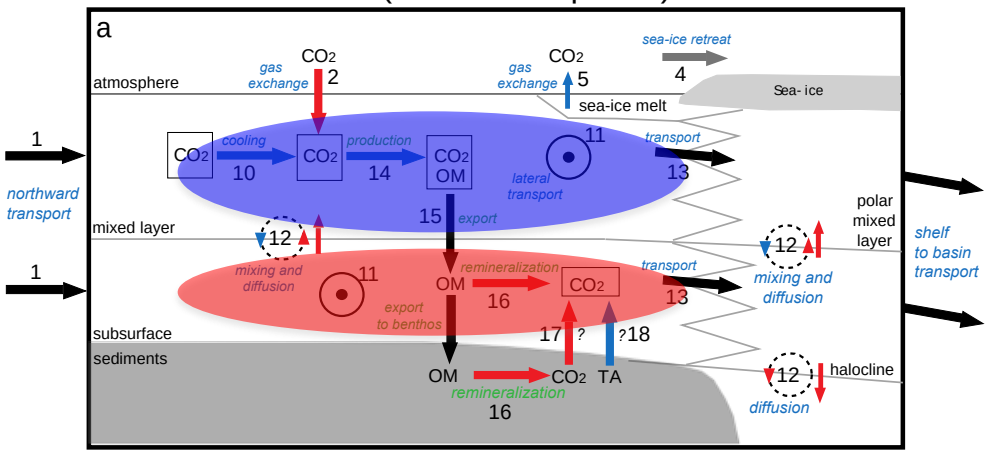

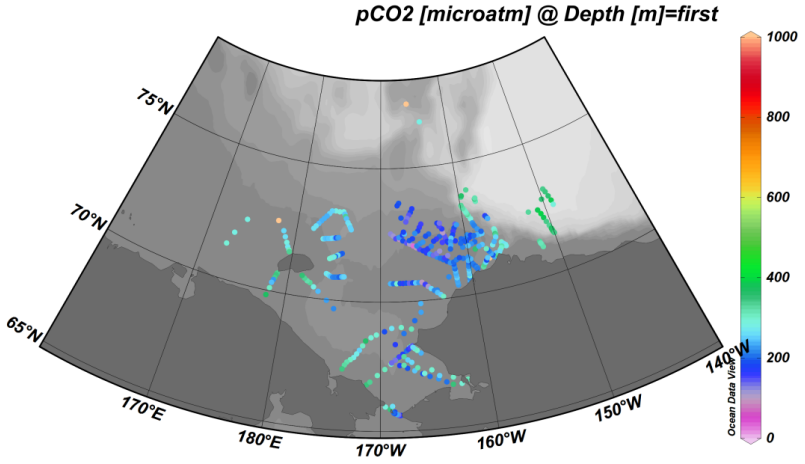

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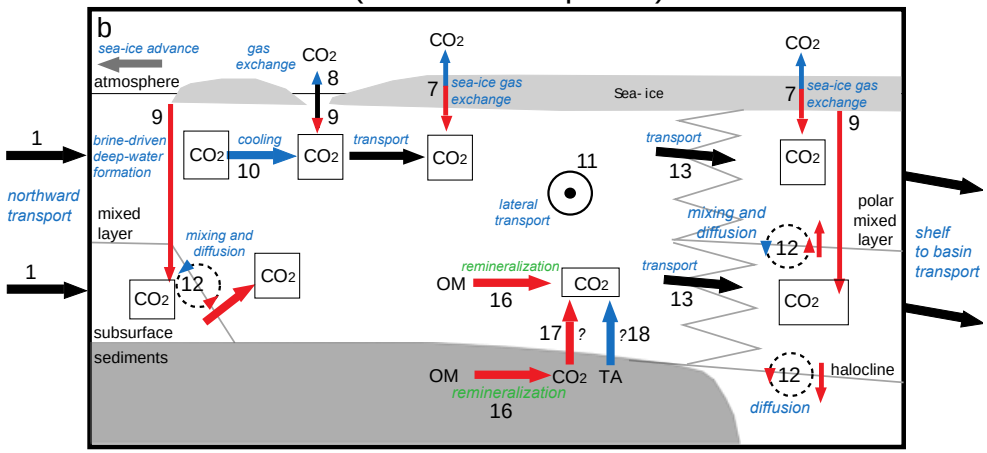
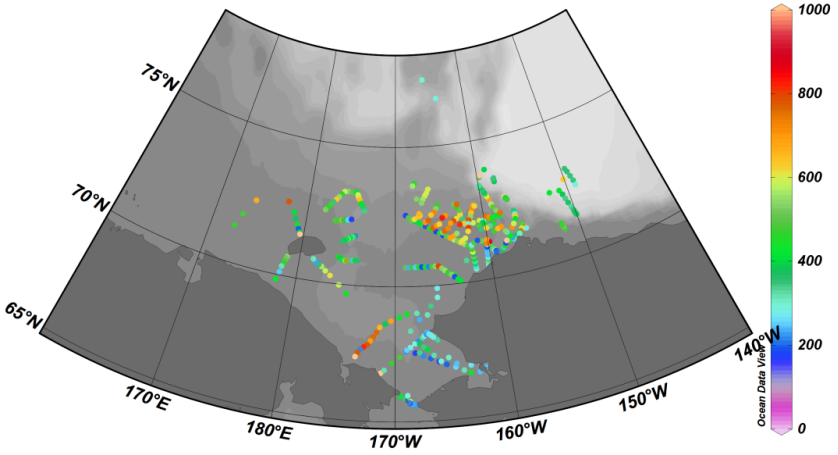
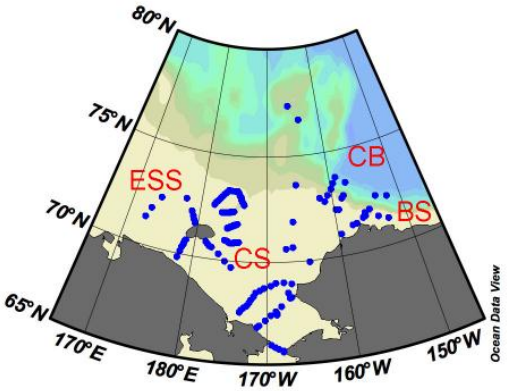
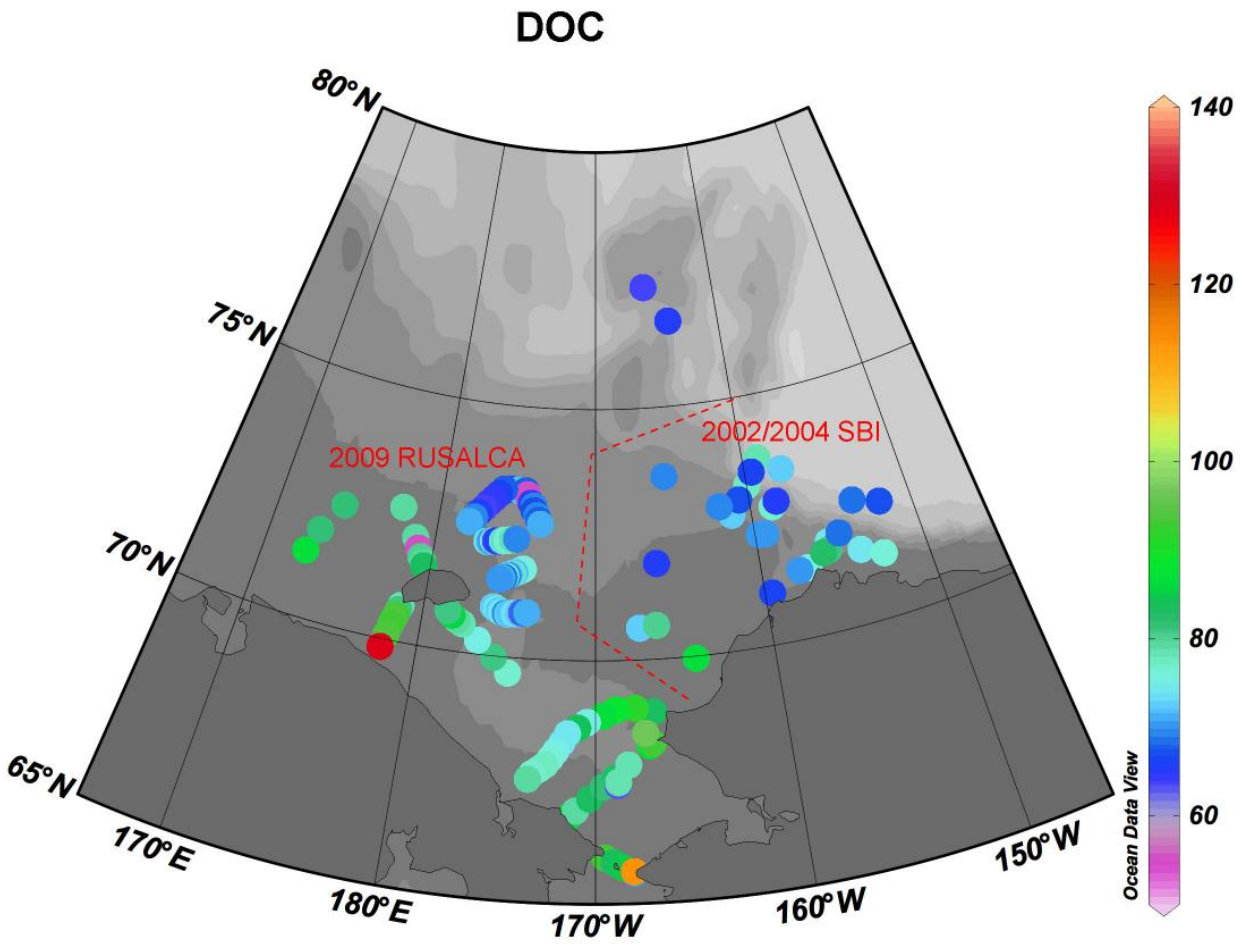




Bates *et al*., 2011

Surface dissolved organic carbon (DOC)

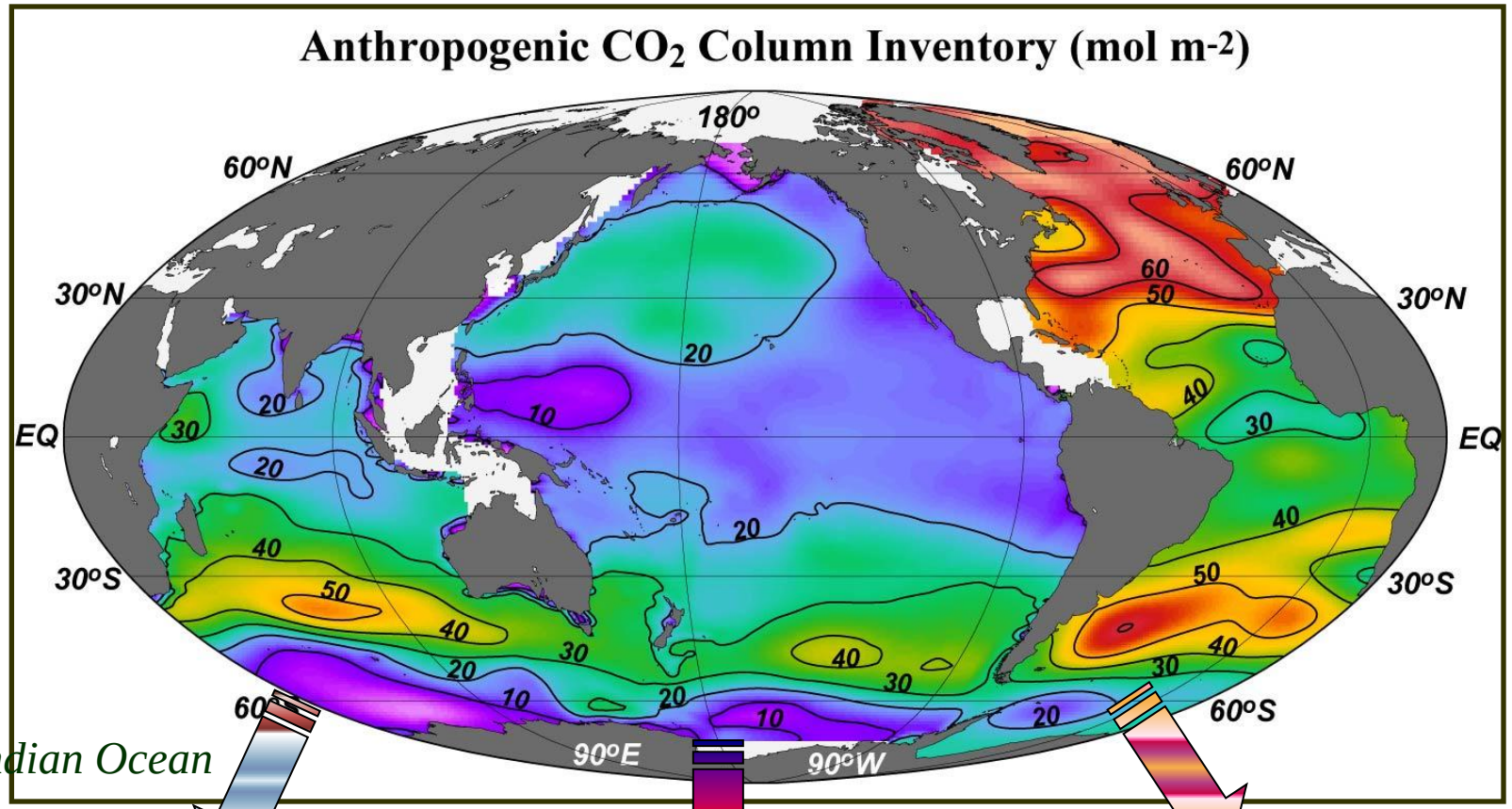




Bates *et al*., 2011

Ocean Uptake of Anthropogenic CO_2

Large CO_2 uptake in the Sargasso Sea



Indian Ocean

Pacific Ocean

Atlantic Ocean

Sabine et al., 2004

20.3 ± 3 Pg

(Sabine et al, 1999)

44.5 ± 5 Pg

(Sabine et al, 2002)

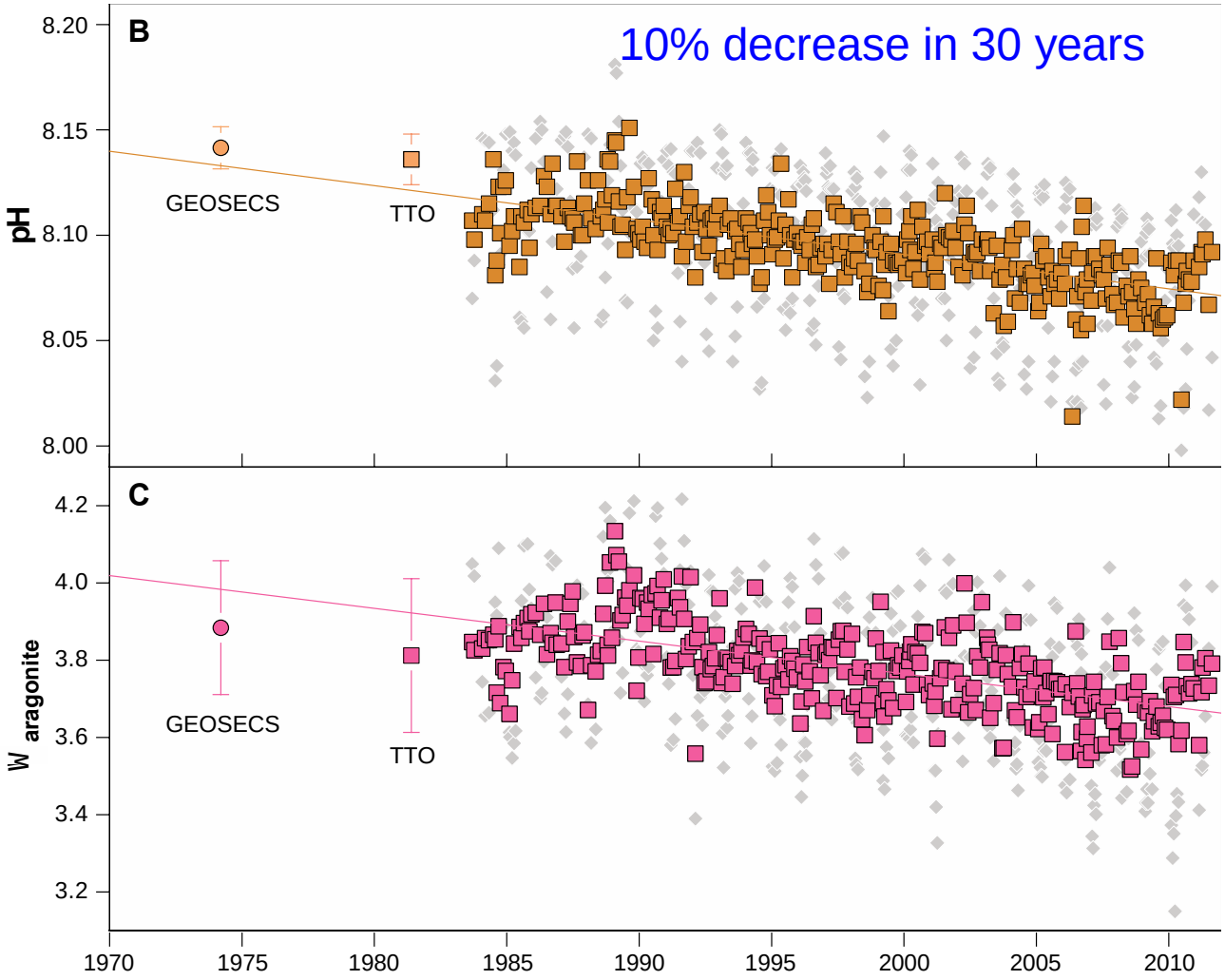
44.8 ± 6 Pg

(Lee et al., 2003)

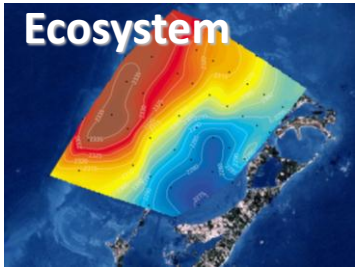
Total Global Inventory (1994) = 110 ± 13 Pg C

Ocean Acidification

Decrease in ocean pH and saturation state
of calcium carbonate minerals in the Sargasso Sea



Impact on Bermuda

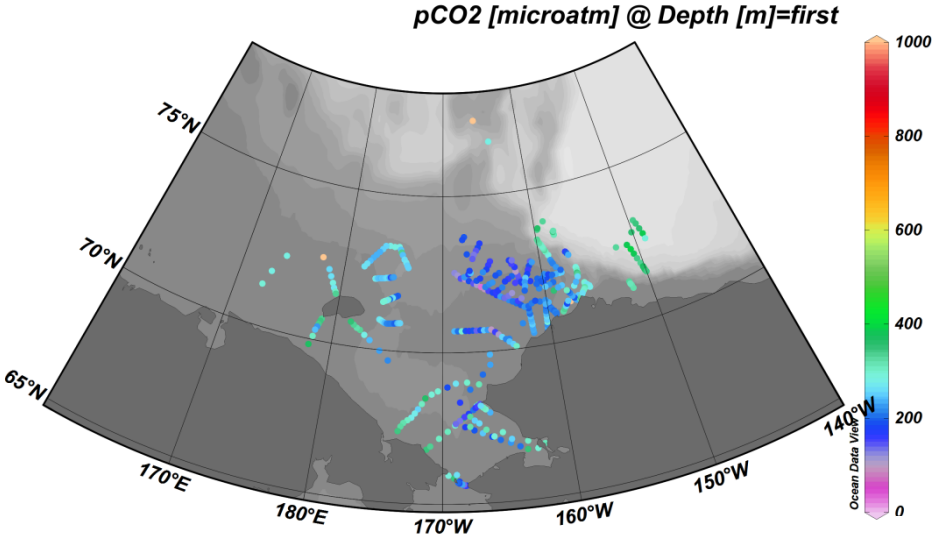


BEACON project

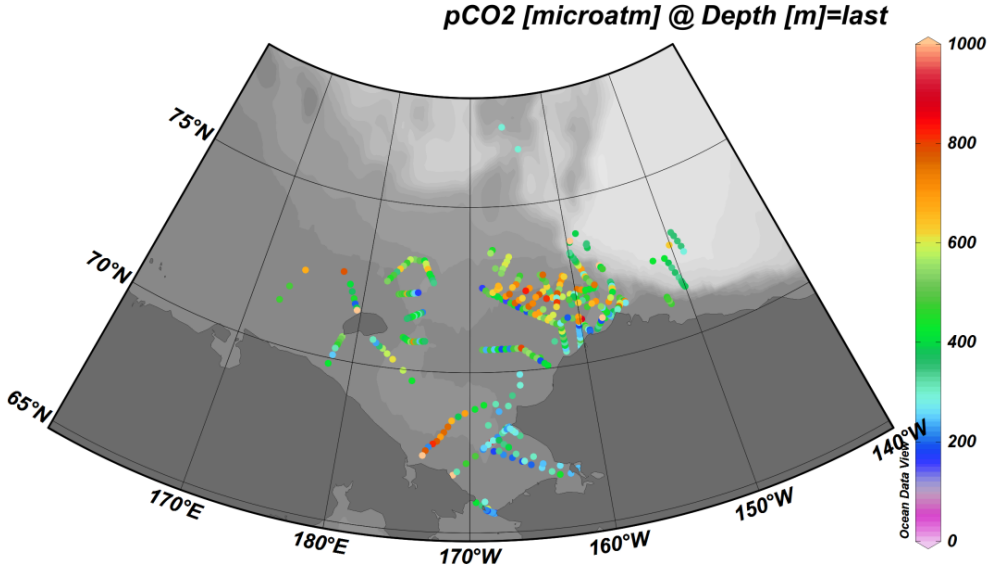
Bates, 2001, 2007; Bates et al., 2012; IPCC 5th Assessment 2013

Surface and Nearest to Seafloor pCO_2

surface



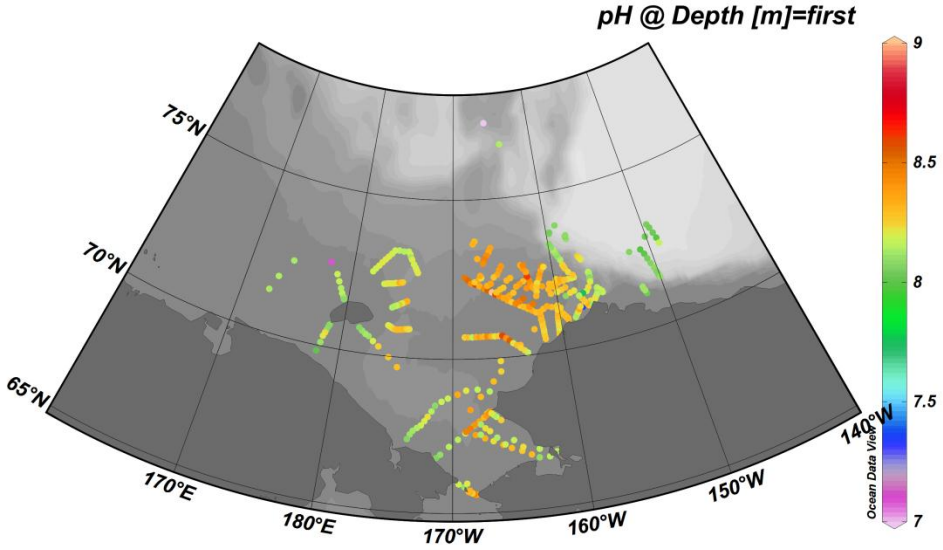
Next to seafloor



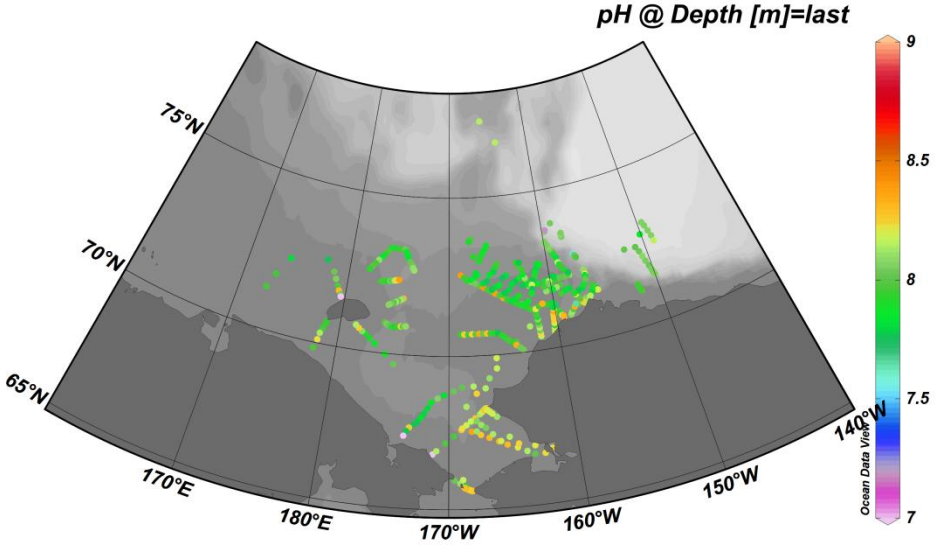
Bates, Orchowska, Garley, Mathis *et al*., 2011

Surface and Nearest to Seafloor pH

surface



Next to seafloor



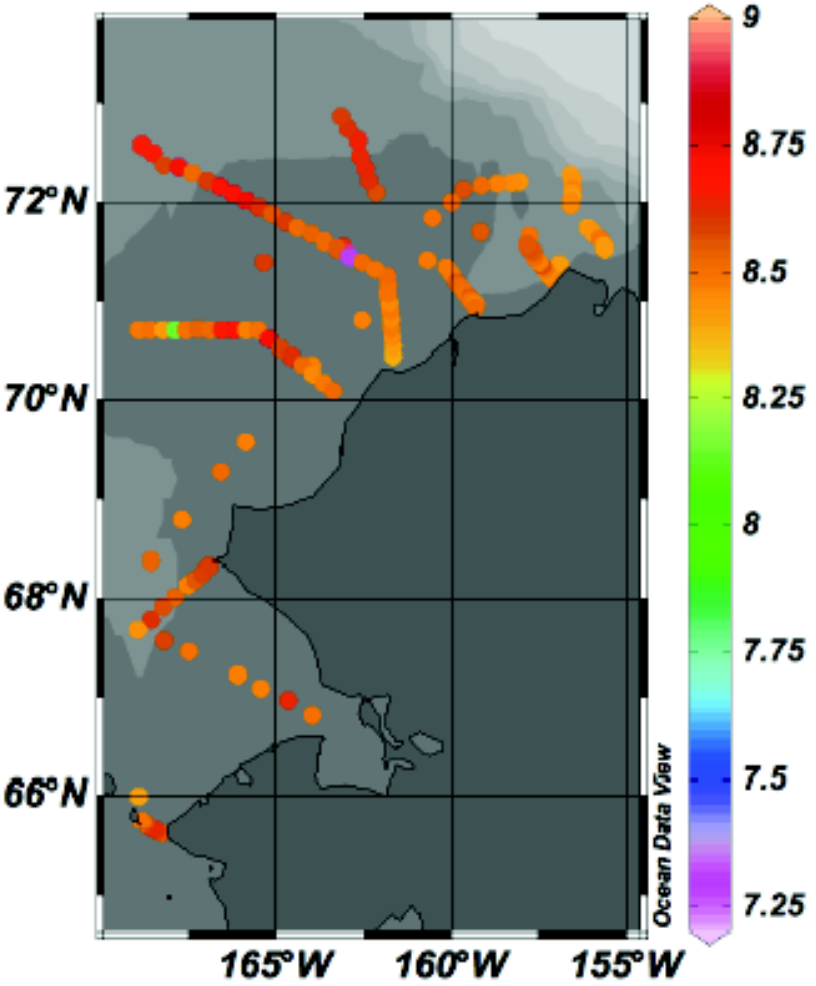
Bates, Orchowska, Garley, Mathis *et al*., 2011

2010 ICESCAPE Ocean Acidification

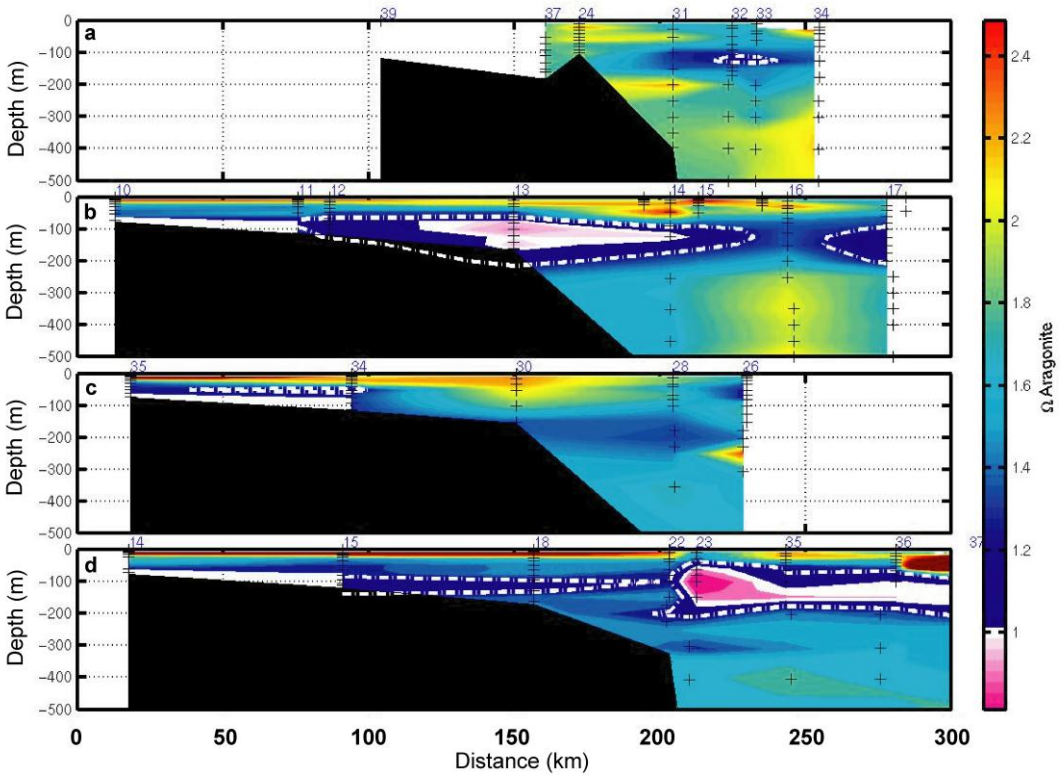
Surface pH distributions and water column aragonite saturation states

Comparisons to 2002-2004 SBI II Project

pH



Ocean acidification already impacts seafloor benthos



Note: Magenta areas denote aragonite undersaturation

P.I.'s Nick Bates, Jeremy Mathis

Bates et al., 2009; Bates et al., 2011

Biological Mediated Seasonality of Aragonite Saturation States "PhyCASS"

"PhyCASS" hypothesis: Phytoplankton $CaCO_3$ saturation state interaction

Table 1. Averages and standard deviation of $\Omega_{aragonite}$ values for water masses located at Bering Strait, and on the Chukchi Sea shelf and slope (bottom depth of 500 m). $\Omega_{aragonite}$ values are binned into 50 m layers in the upper 200 m.

	0-50 m	50-100 m	100-150 m	150 m-200 m	Bering Strait
a. 2002					
Spring	1.54 ±0.28	1.53 ±0.22	1.43 ±0.21	1.43 ±0.25	1.49 ±0.13
Summer	1.92 ±0.71	1.31 ±0.24	1.09 ±0.11	1.16 ±0.14	2.70 ±0.56
b. 2004					
Spring	1.68 ±0.40	1.46 ±0.31	1.43 ±0.31	1.30 ±0.12	2.08 ±0.26
Summer	1.95 ±0.55	1.41 ±0.41	1.32 ±0.26	1.30 ±0.22	2.16 ±0.41

Seasonal increase in Ω

Seasonal decrease in Ω

Note: no Ω undersaturation in pre-industrial times

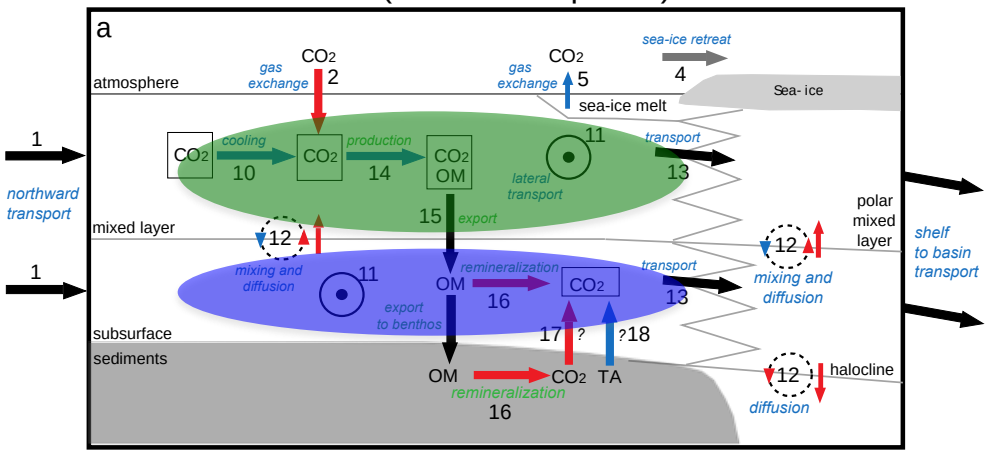
~40 µmoles kg^{-1} anthropogenic CO_2 = 0.3 Ω decrease

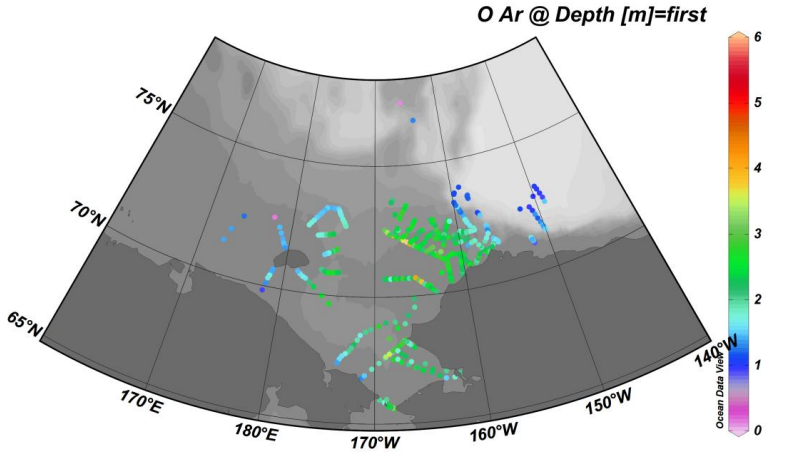
Bates et al. 2009; Mathis et al., 2010; Bates et al., 2011: Cai et al., 2012

Chukchi Sea “Inflow Shelf”

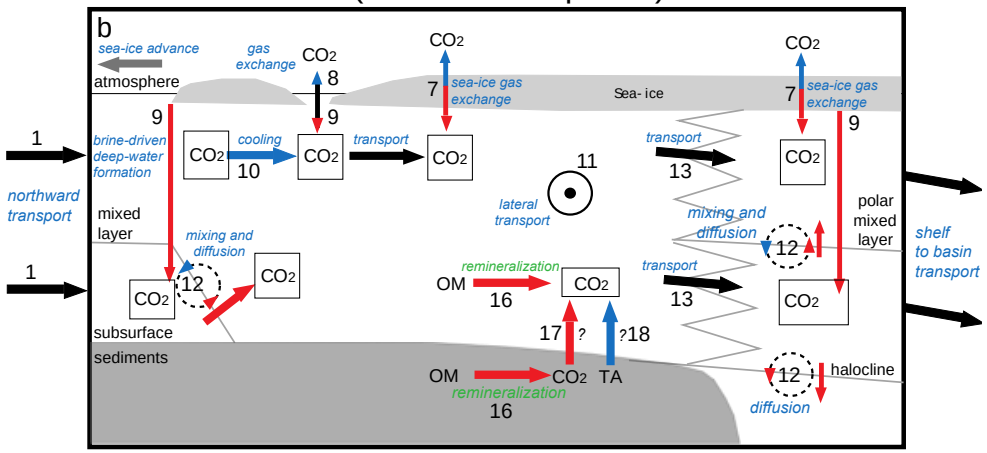
Inflow Shelf (e.g., Chukchi and Barents Sea)

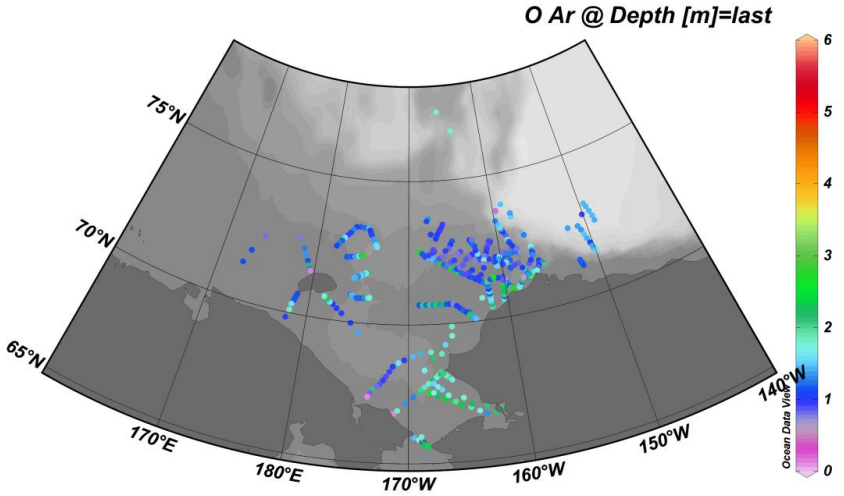
Summer Conditions (sea-ice free period)





Winter Conditions (sea-ice cover period)

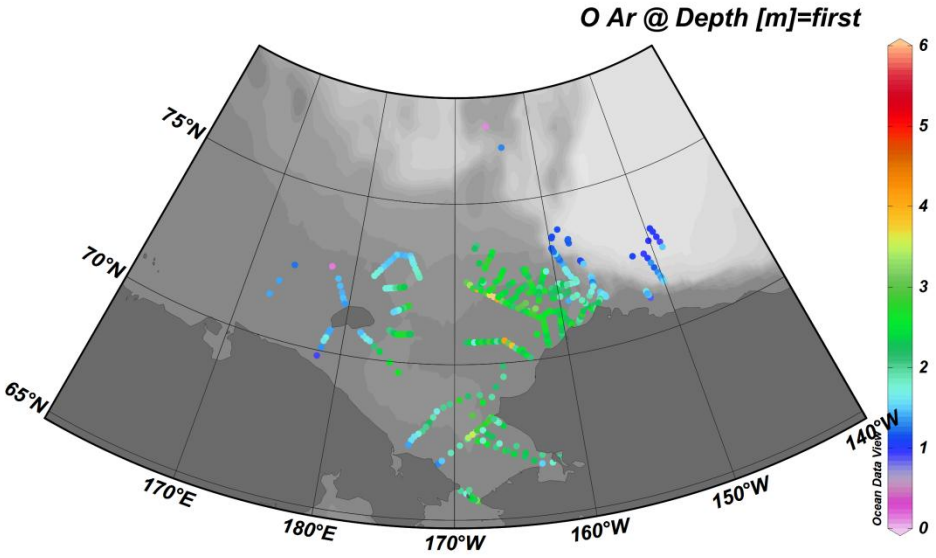




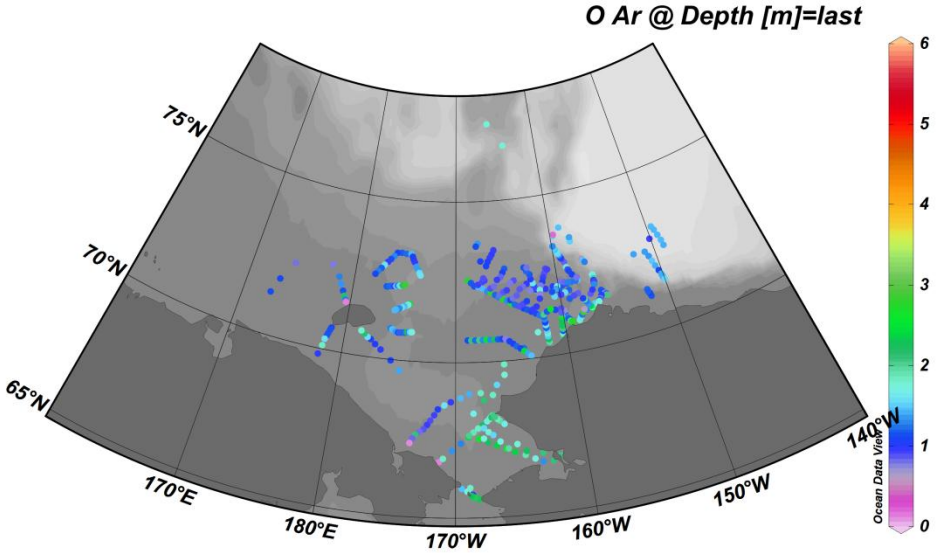
Bates *et al*., 2011

Surface and Nearest to Seafloor aragonite saturation state

Surface



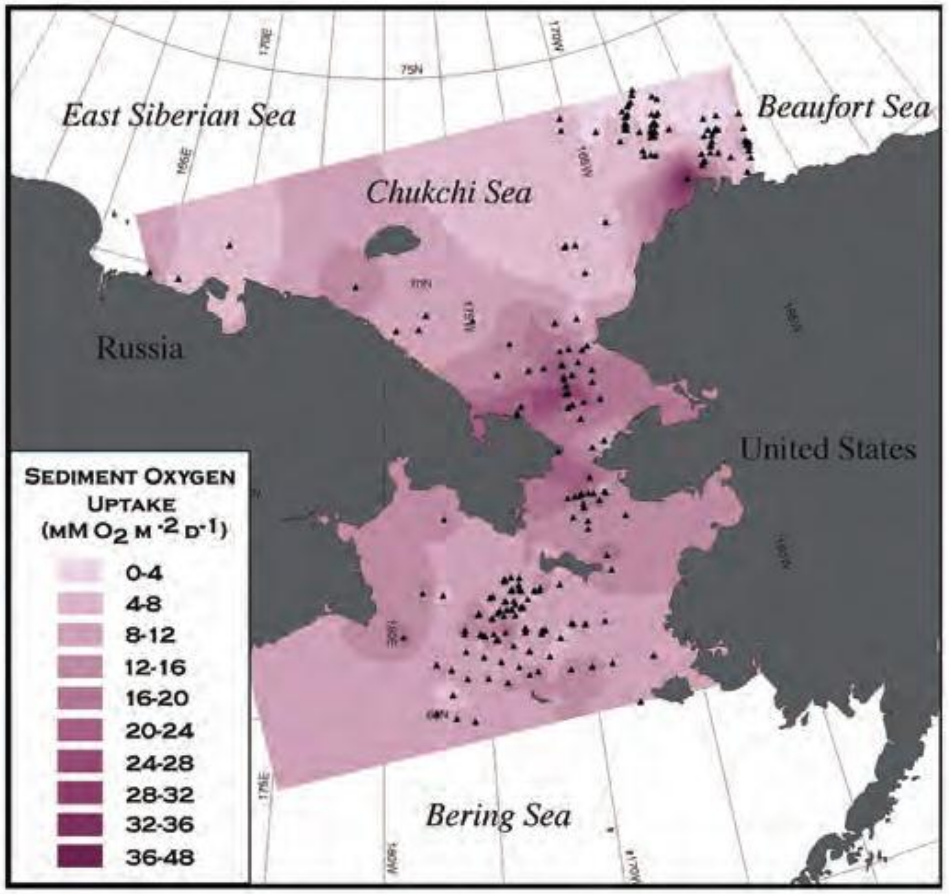
Next to seafloor

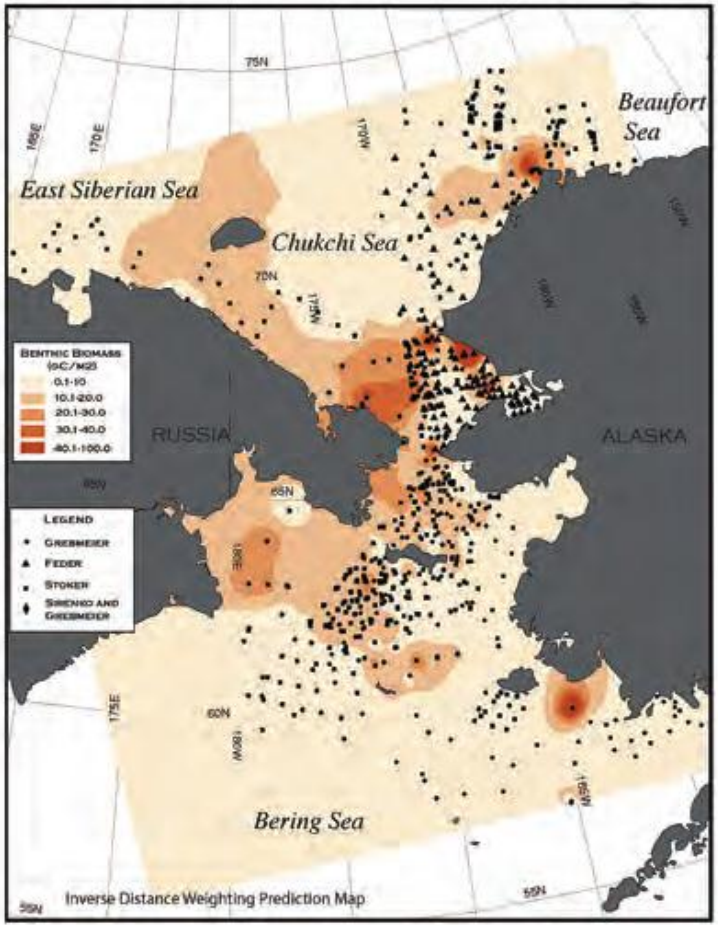


Bates, Orchowska, Garley, Mathis *et al*., 2011

Chukchi and Bering Sea seafloor benthos

Figure 6.7. Distribution of a) benthic O_2 consumption rates, and b) benthic biomass in the Bering and Chukchi shelves. High export productivity and shallow water columns result in tight coupling between surface waters and benthos. From Grebmeier et al. (2006a).

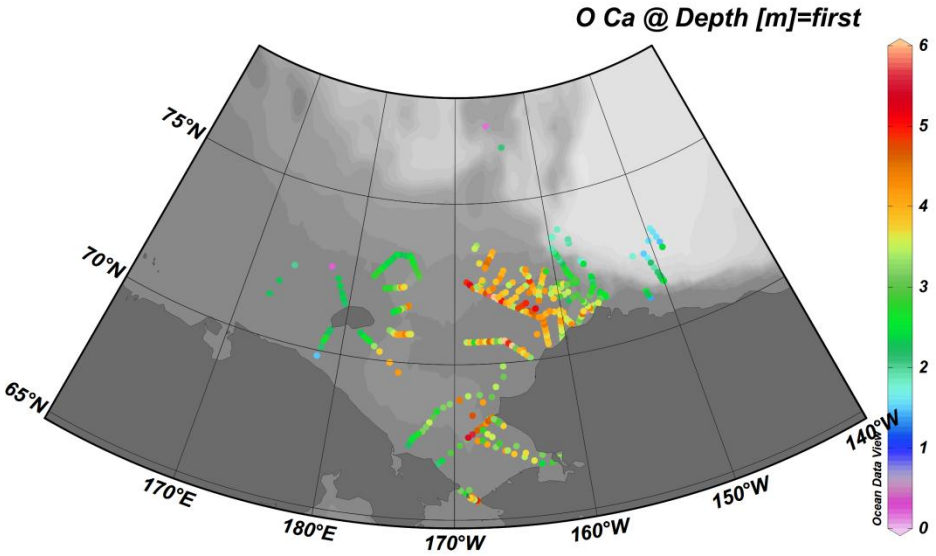




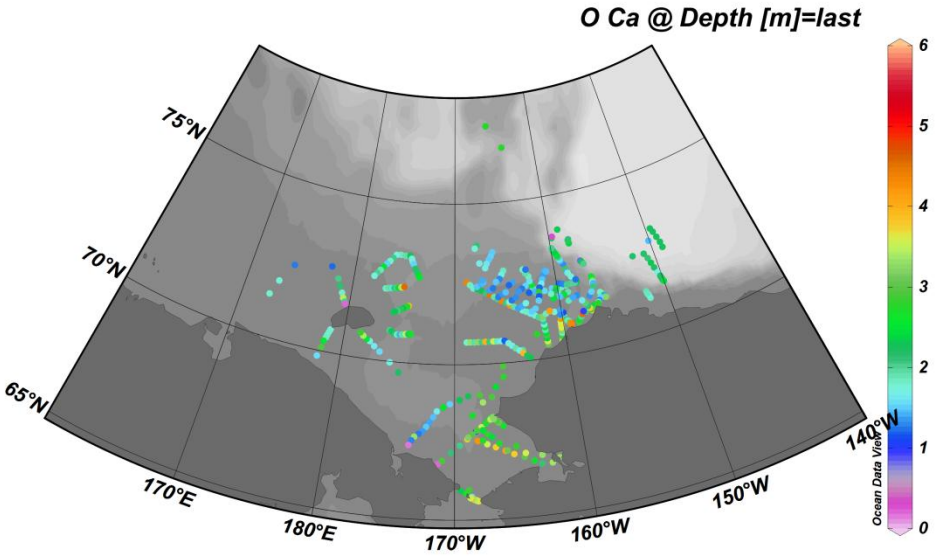
Grebmeier *et al.*, 2008

Surface and Nearest to Seafloor calcite saturation state

Surface

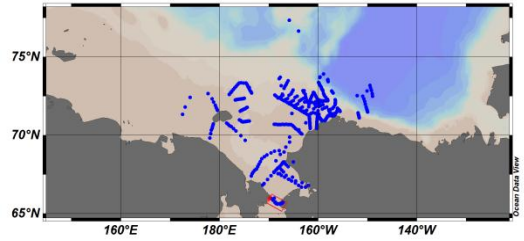


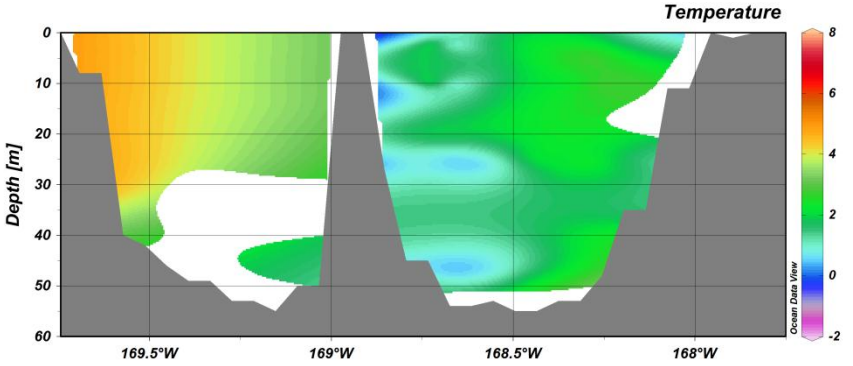
Next to seafloor

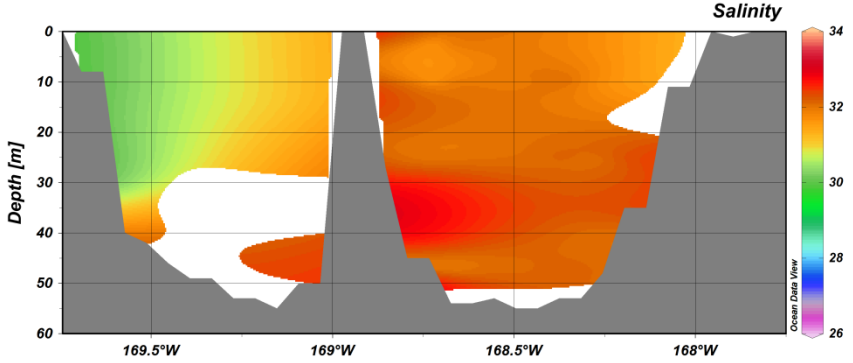


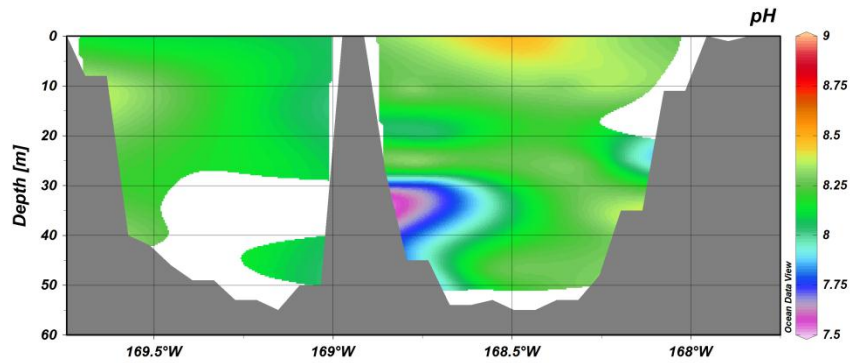
Bates, Orchowska, Garley, Mathis *et al*., 2011

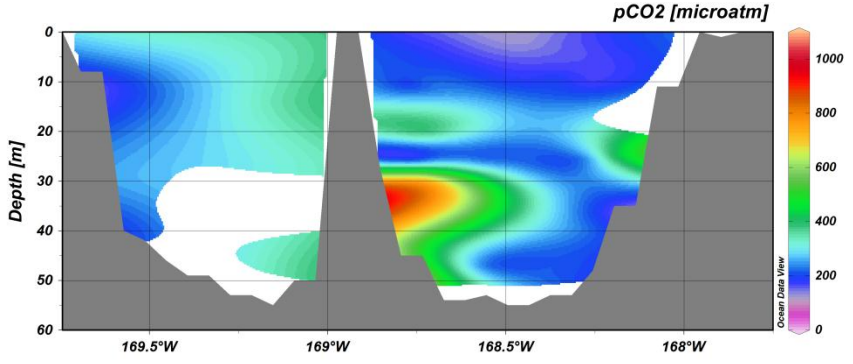
Bering Strait

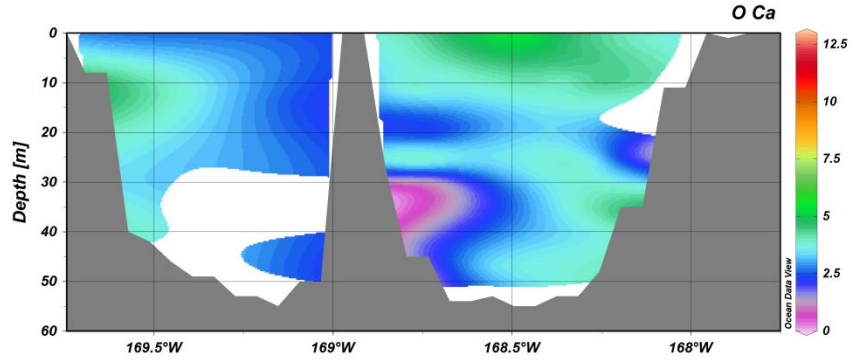


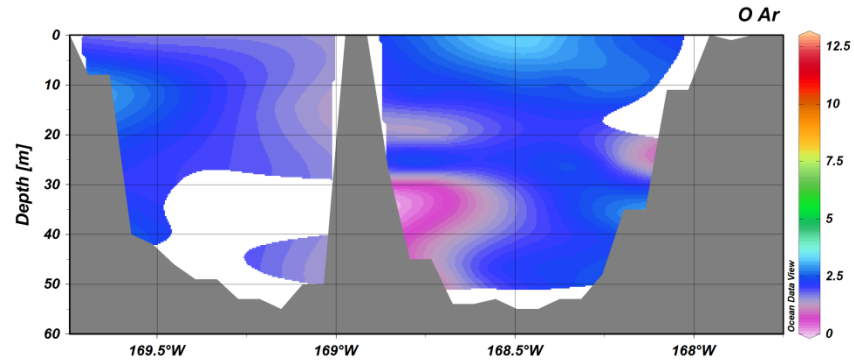






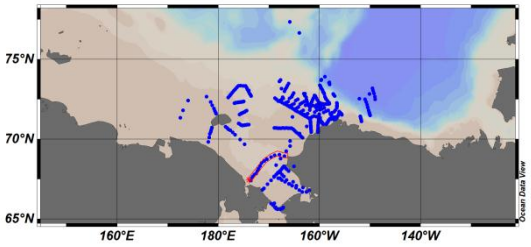


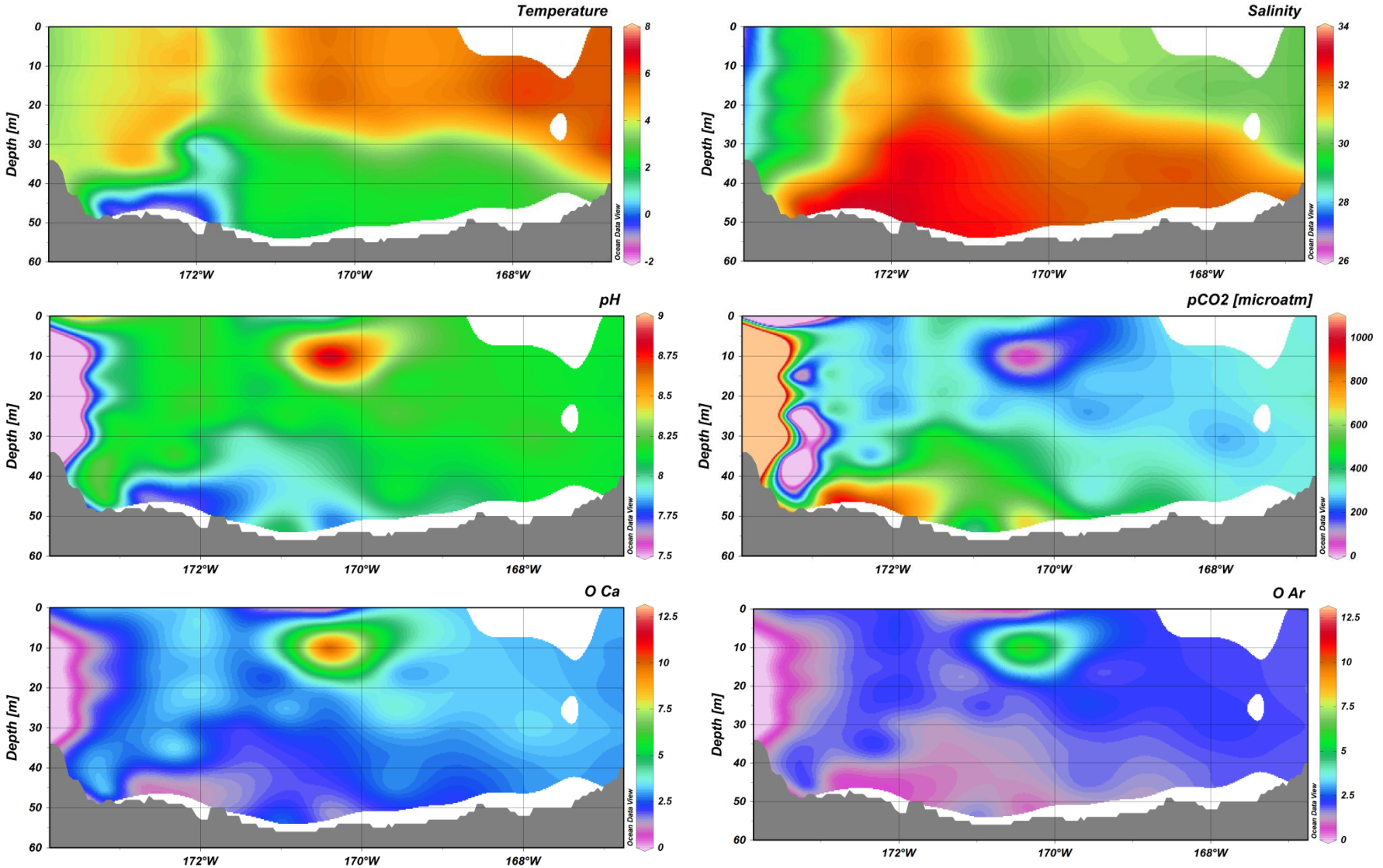




Bates, Orchowska, Garley, Mathis *et al*., 2011

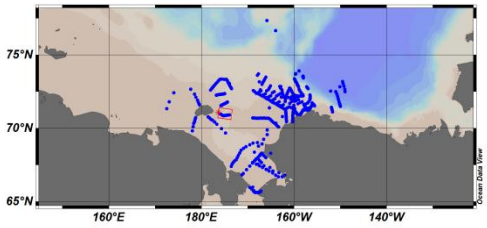
Alyatki to Cape Lisburne

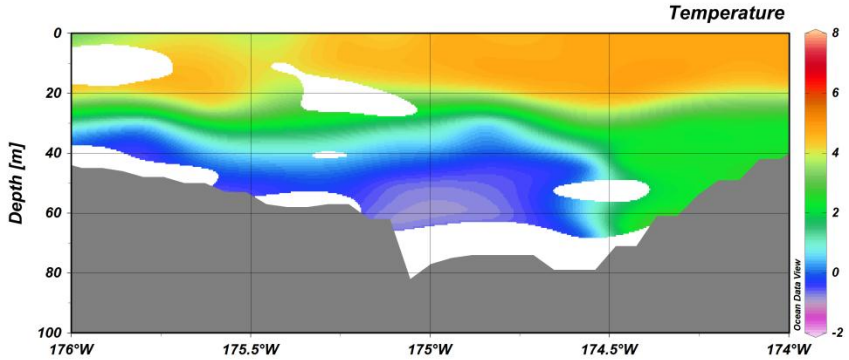


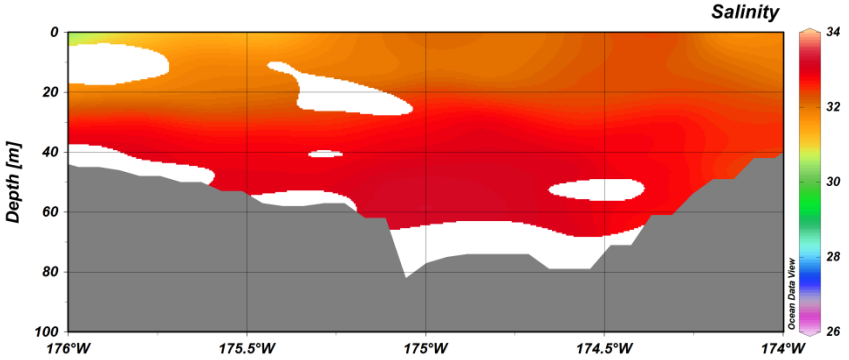


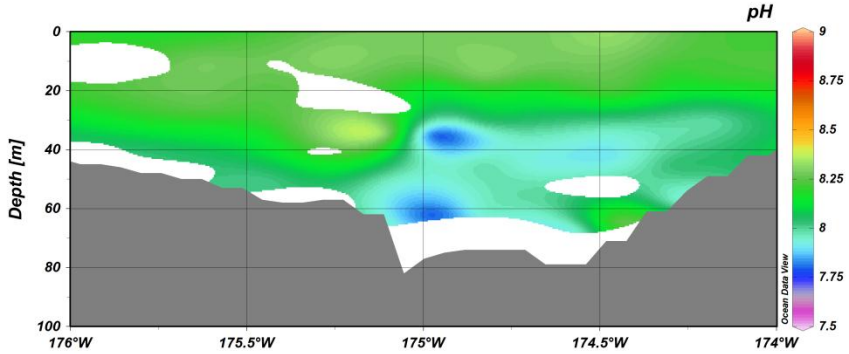
Bates, Orchowska, Garley, Mathis *et al*., 2011

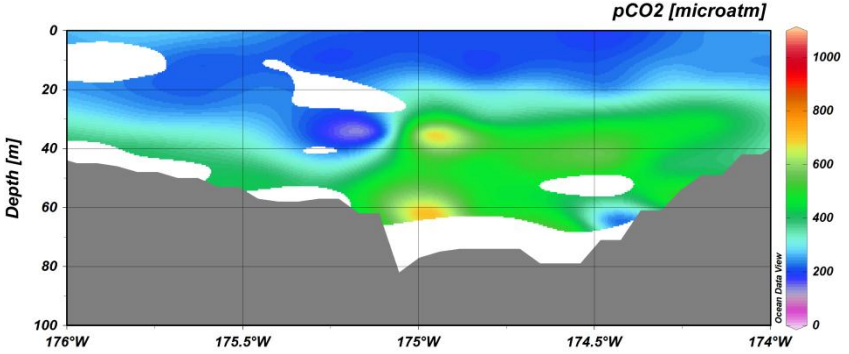
Herald Valley

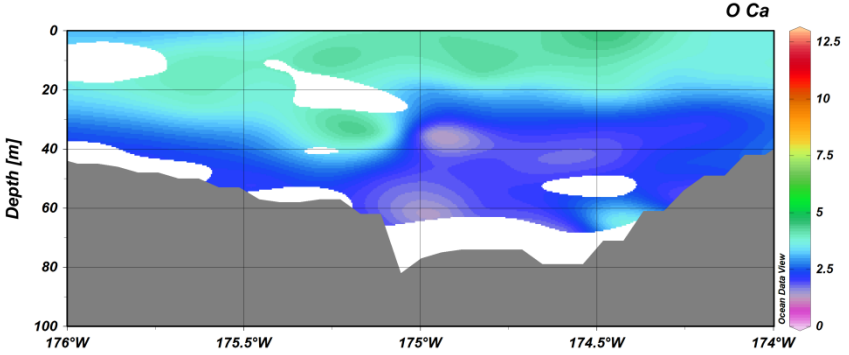


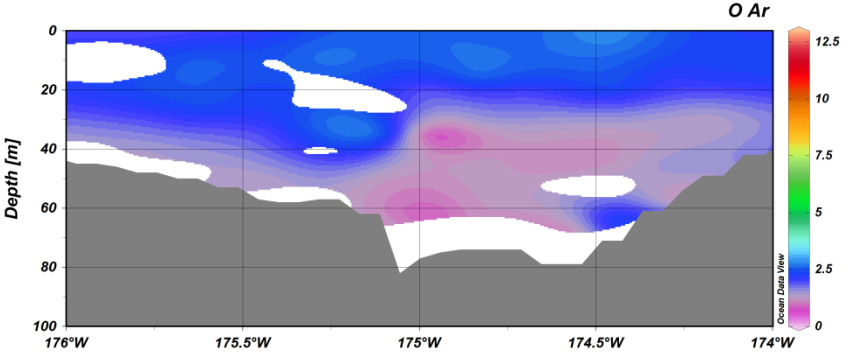






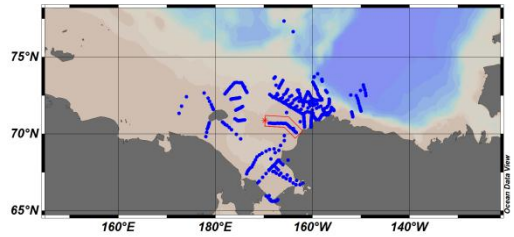


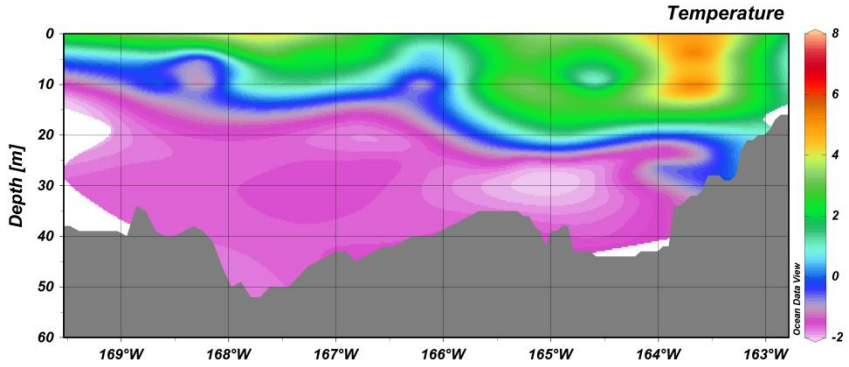


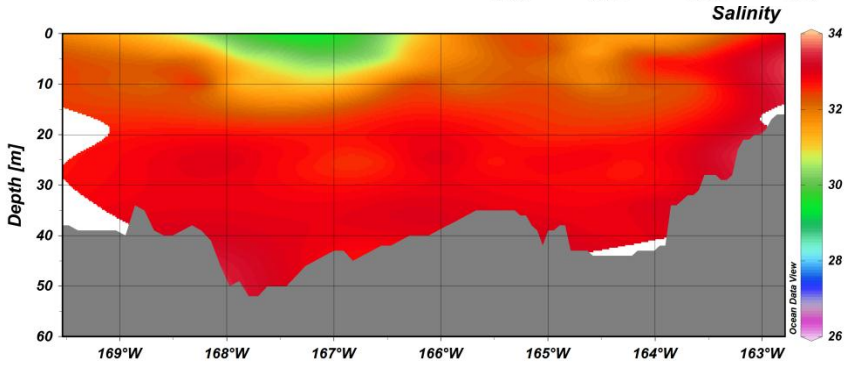


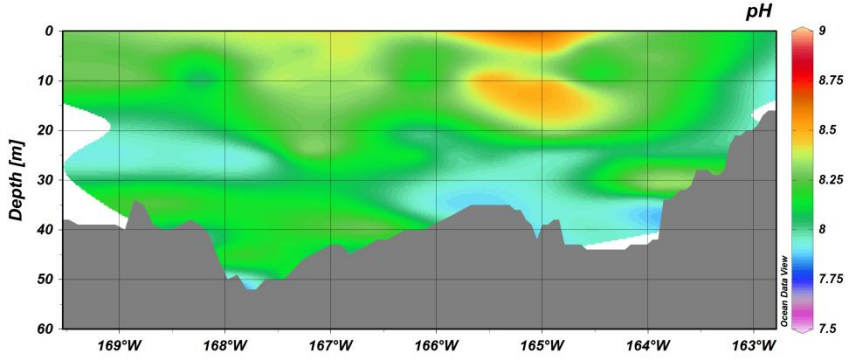
Bates, Orchowska, Garley, Mathis *et al*., 2011

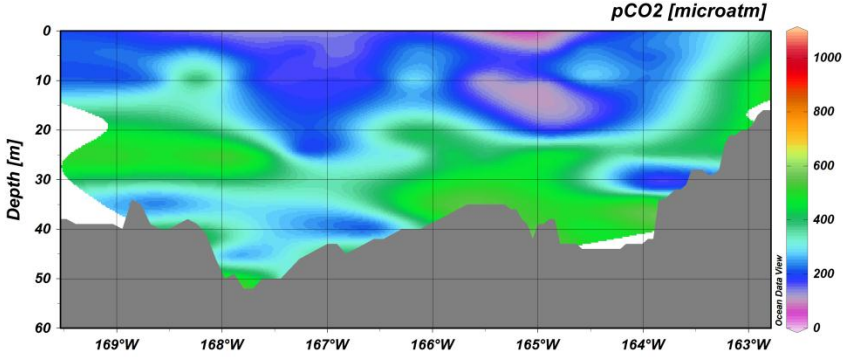
Central Channel

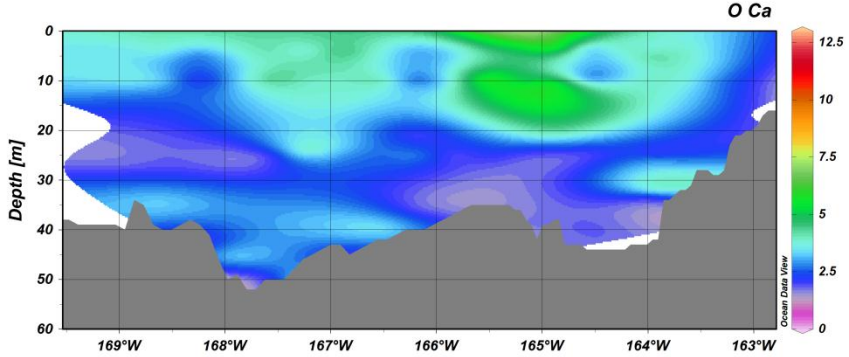


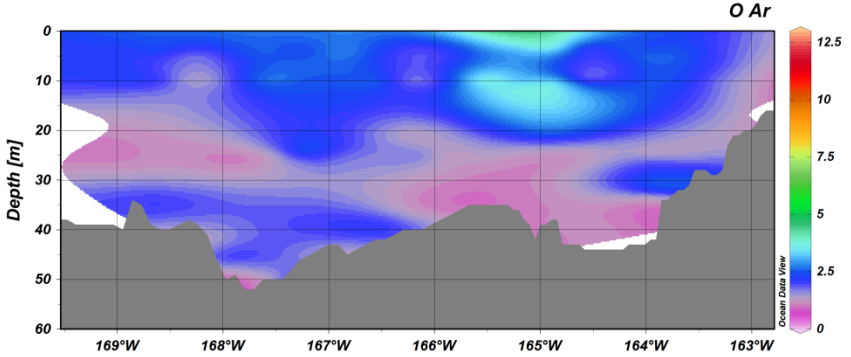






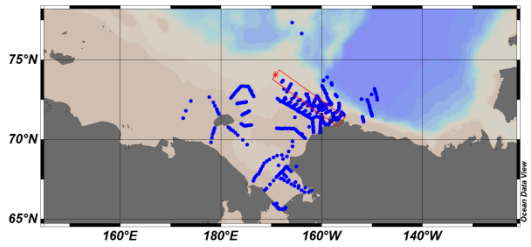


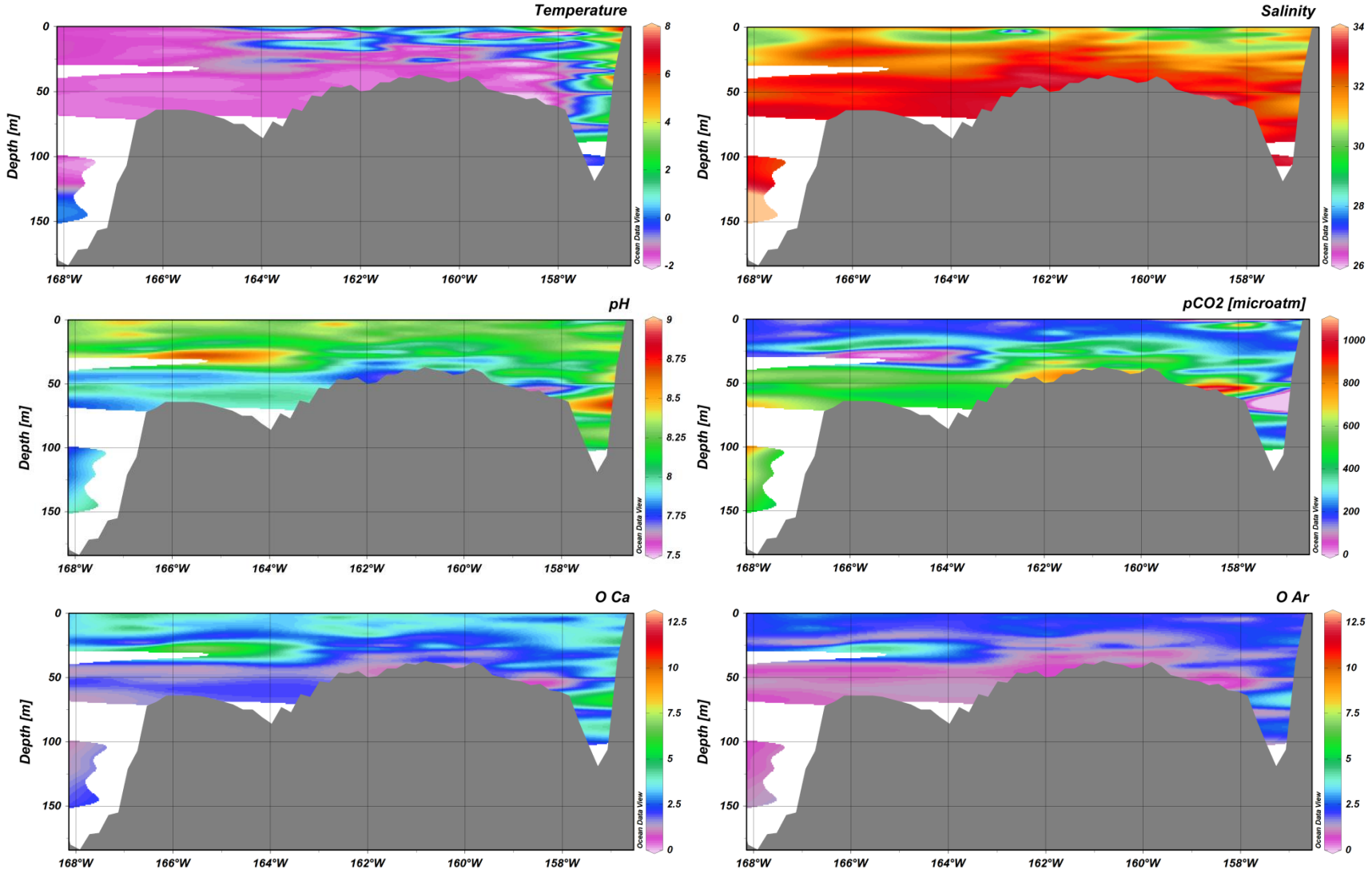




Bates, Orchowska, Garley, Mathis *et al*., 2011

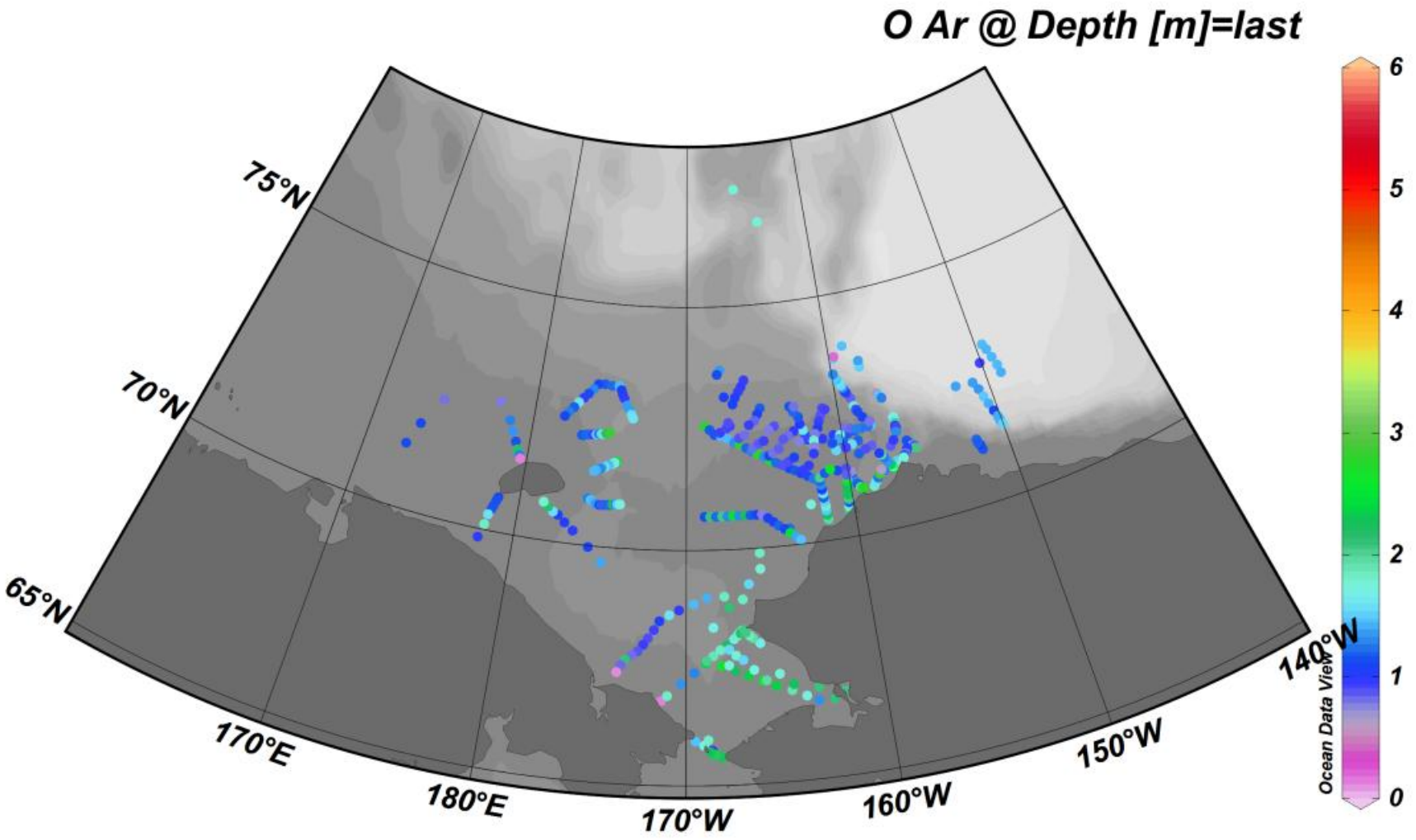
170° W to Point Narrow





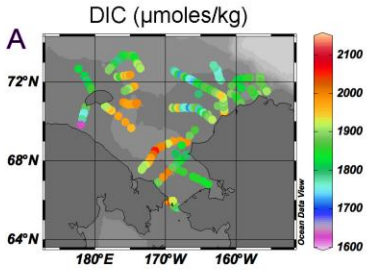
Bates, Orchowska, Garley, Mathis *et al*., 2011

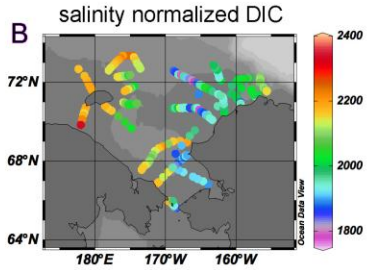
Ocean Acidification vulnerability

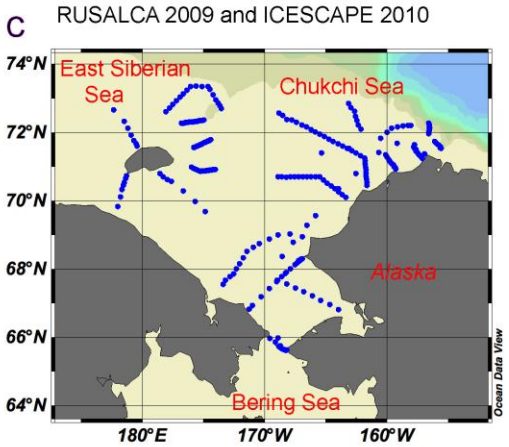


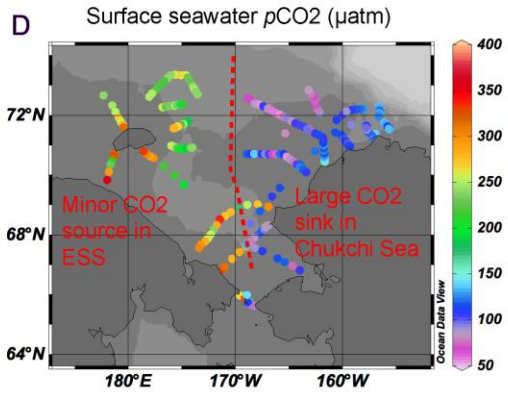
Bates, Orchowska, Garley, Mathis *et al*., 2011

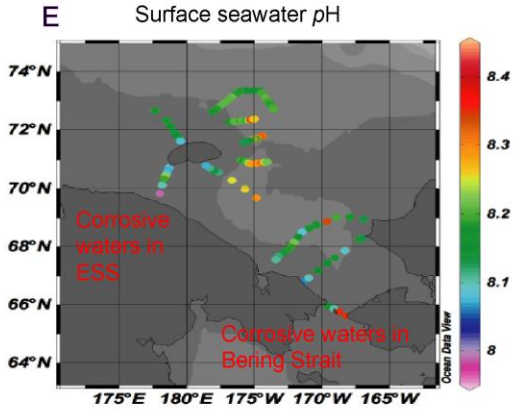
Arctic Ocean CO_2 sinks and sources: RUSALCA and ICESCAPE

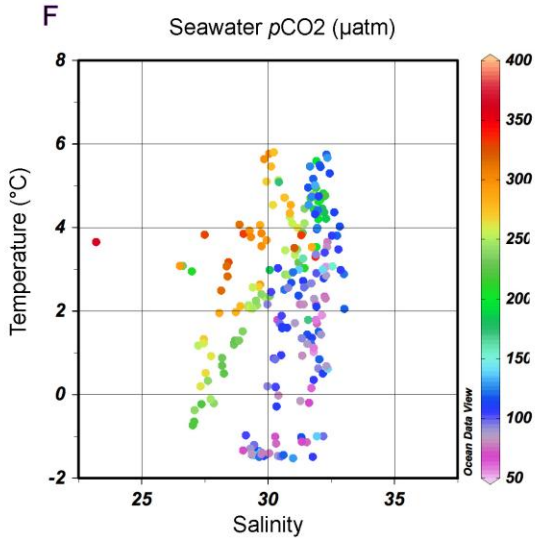


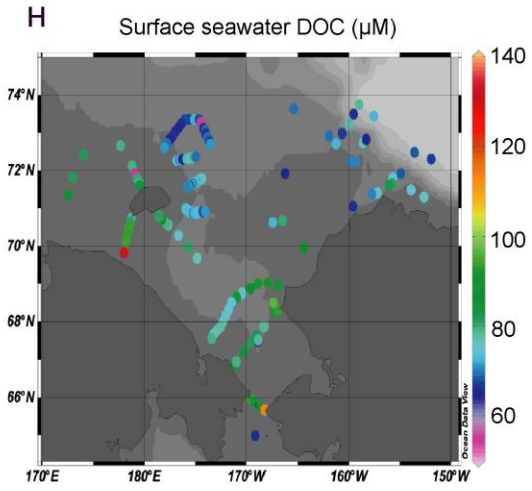










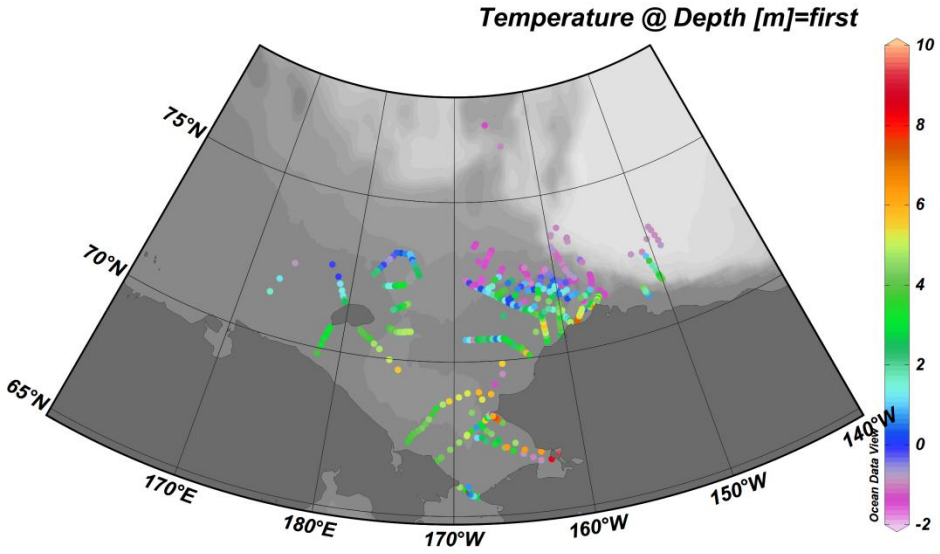


RUSALCA: Russian-American Long-term Census of the Arctic

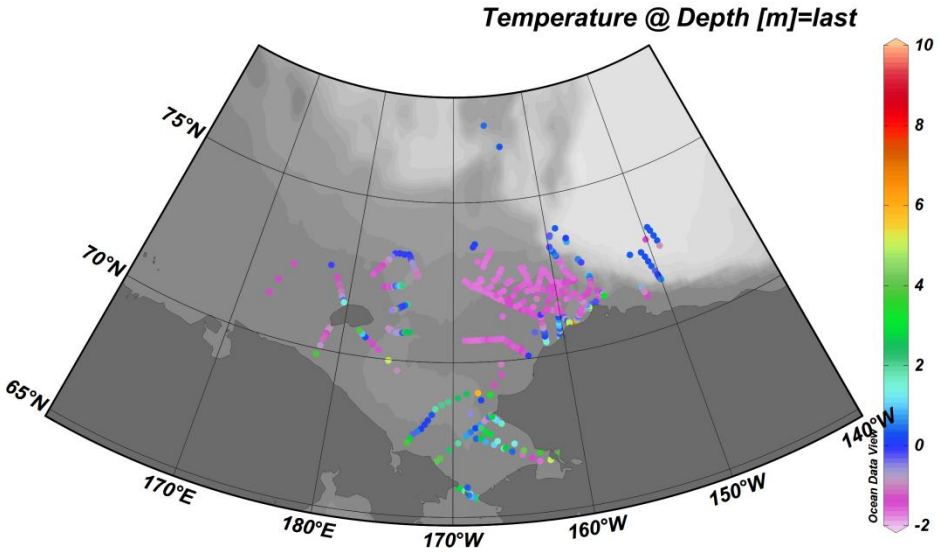
Nicholas Bates, BIOS; Bates and Mathis, 2009; Bates et al., 2011

Surface and Nearest to Seafloor Temperature

Surface



Next to seafloor

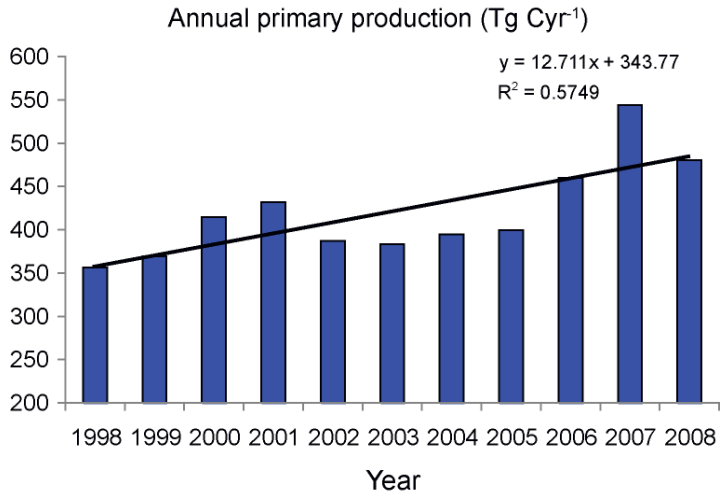


Bates, Orchowska, Garley, Mathis *et al*., 2011

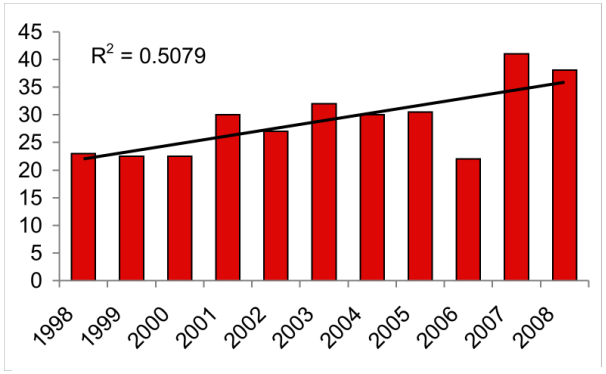
Arctic Ocean Productivity

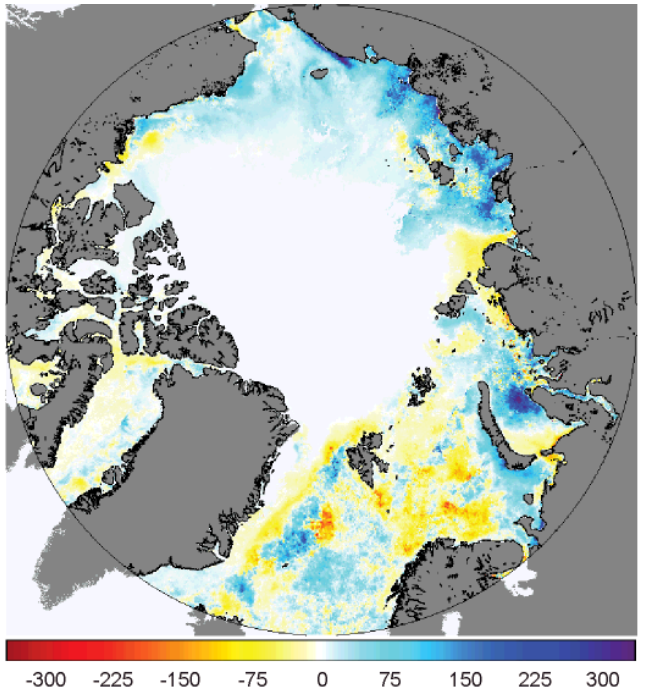
Changes in Arctic Productivity

- Annual primary production increased by 140 Tg C yr^{-1} between 1998 and 2008 (statistically significant trend)
- A 40% increase over the last decade
- Unexpected given presumed nutrient limitation
- Largest increases on continental shelf



Chukchi Sea





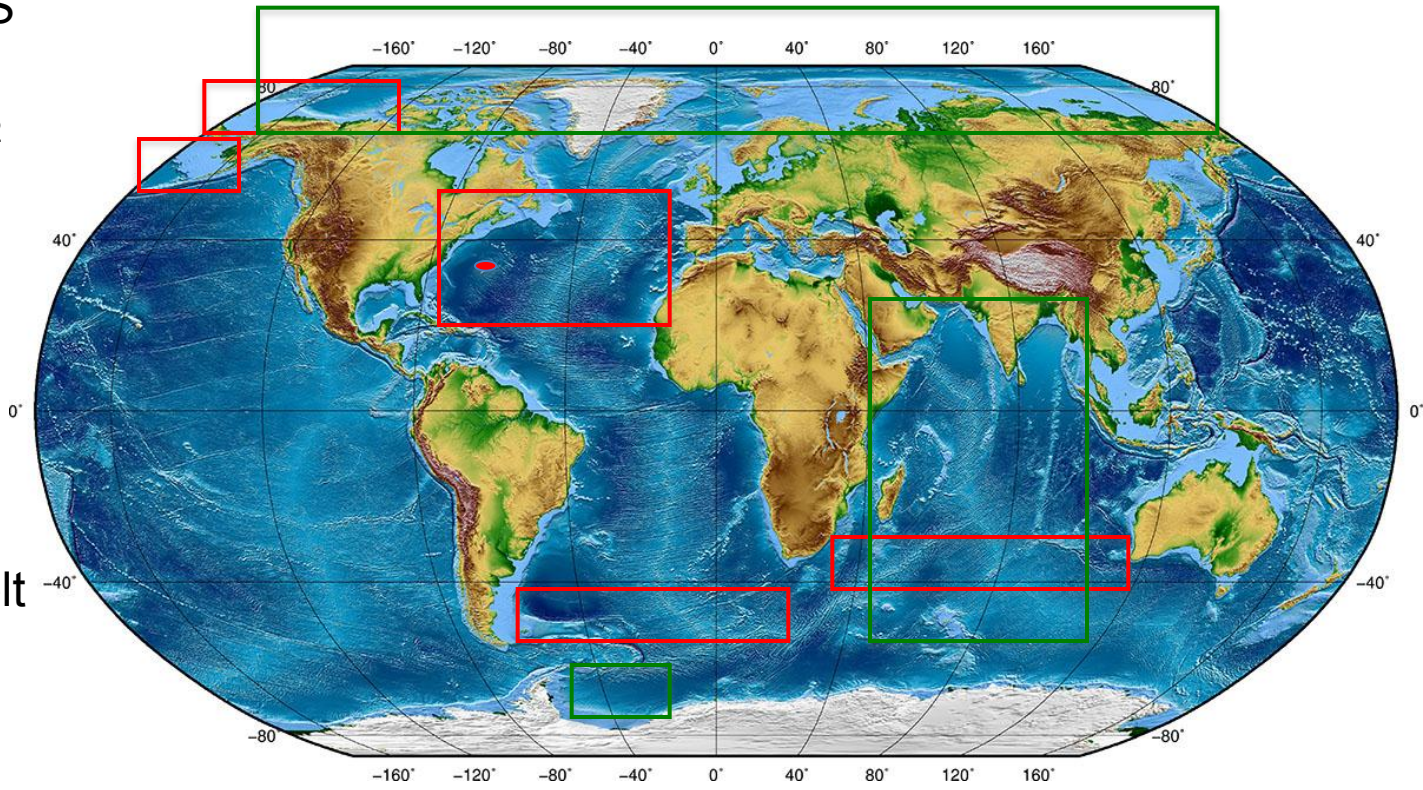
Arrigo *et al*., 2018; 2012

Present and recent research projects

North Atlantic Ocean
- BATS, Hydrostation S
- BEACON (Bermuda)
- CLIMODE, VOS CO_2

Arctic Ocean
- SBI, ICESCAPE
- RUSALCA
- BEST (Bering Sea)

Southern Ocean
- COPAS 08, Great Belt

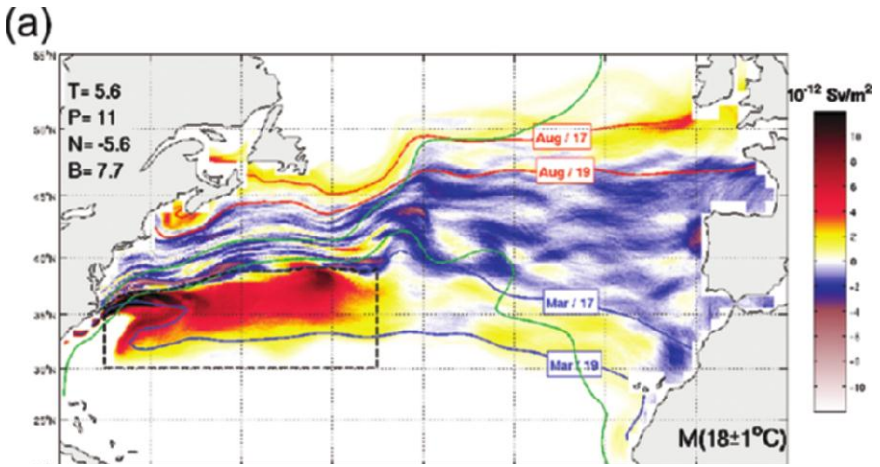


Current projects
Synthesis, reviews and models

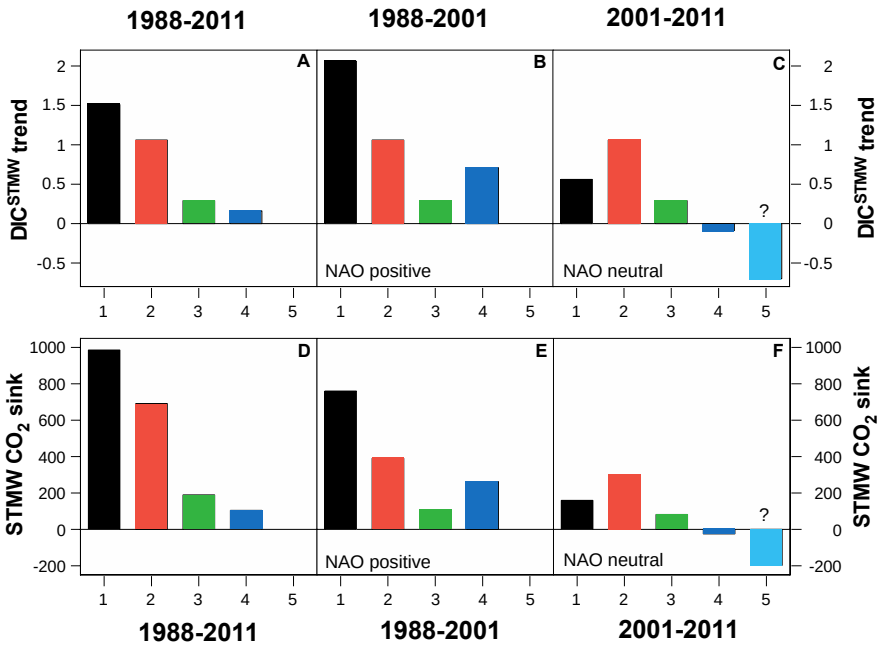
NSF NASA NOAA NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION U.S. DEPARTMENT OF COMMERCE BIOS BERMUDA INSTITUTE OF OCEAN SCIENCES

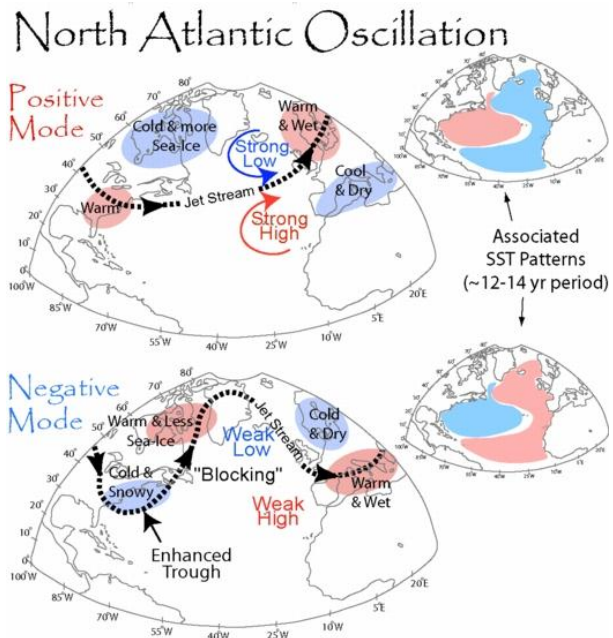
North Atlantic CO_2 Uptake

Less uptake of CO_2 into Sargasso Sea and North Atlantic in the 2000's



Subtropical mode water (STMW) influenced by the state of the NAO

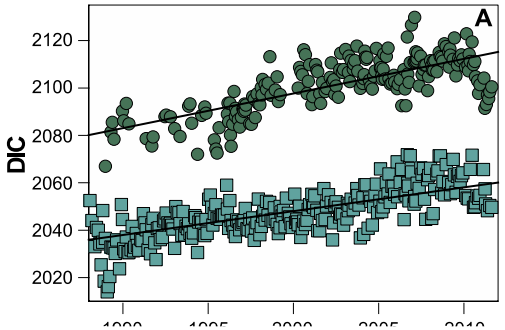


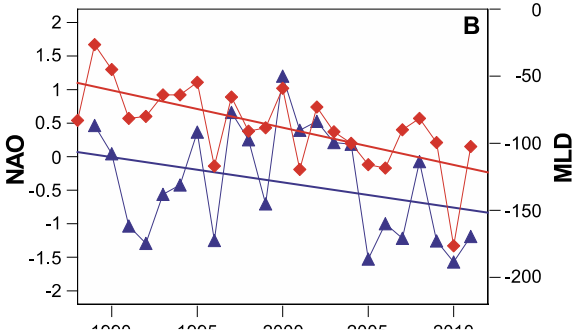


Reduced uptake into STMW by ~1 Pg C

~30-35% of the North Atlantic CO_2 sink in 2000's

~6% decrease in global CO_2 sink





Bates, 2012; Levine et al., 2011

Western Arctic and Arctic Ocean Context

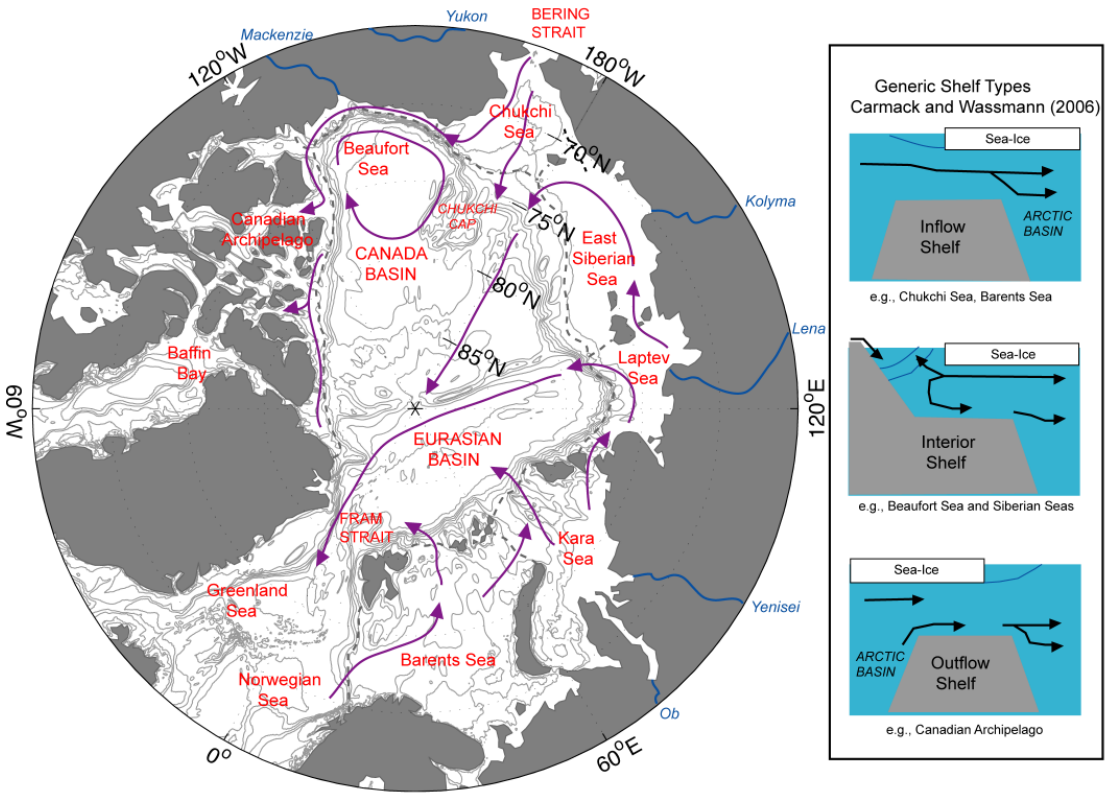
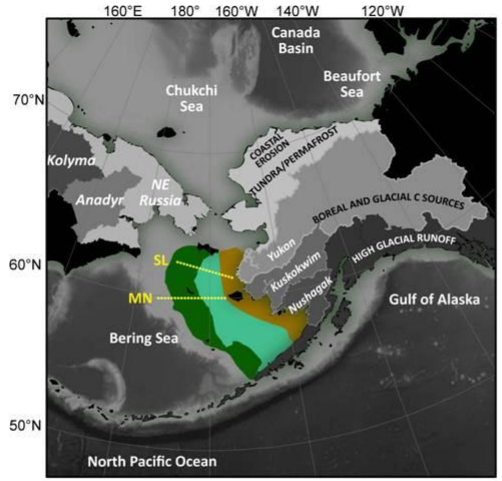


Figure 1. Left Panel. Schematic of the Arctic Ocean, central basin (Canada and Eurasian Basins) and Arctic continental shelves (with approximate boundaries for each Arctic Ocean coastal sea), major rivers draining into the region (Macdonald *et al*., 2009) and adjoining seas that have significant exchanges of water with the Arctic. Right panel. The three generic types of continental shelves are shown (Carmack and Wassman, 2006). This includes: "inflow" shelves such as the Chukchi and Barents Seas, "interior" shelves such as the Siberian and Beaufort Seas, and; "outflow" shelves (i.e., Canadian Archipelago).

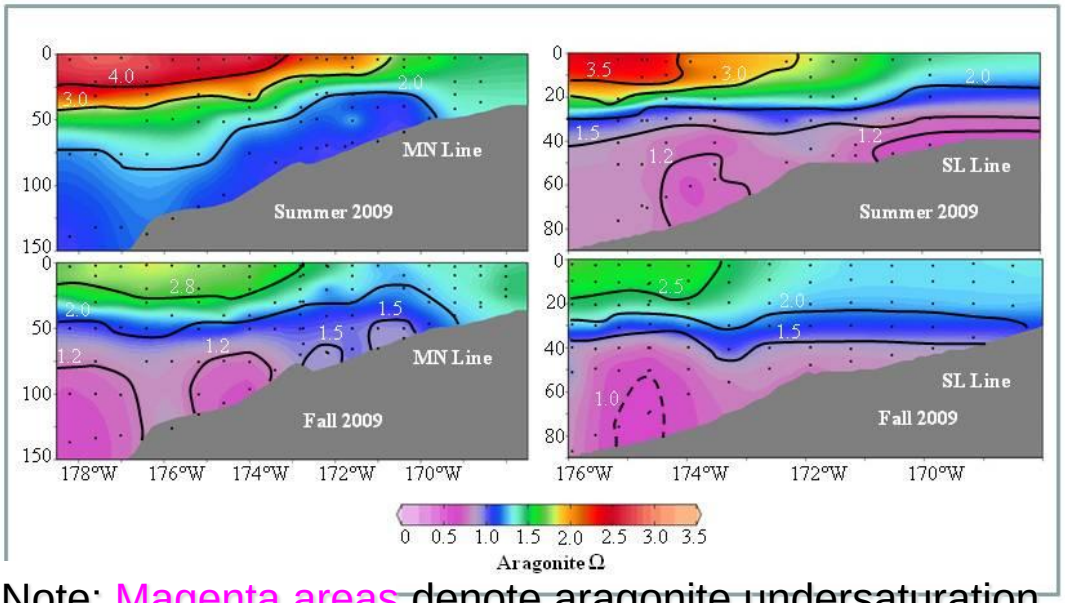
Bates *et al*., 2011

Bering Sea Ocean Acidification

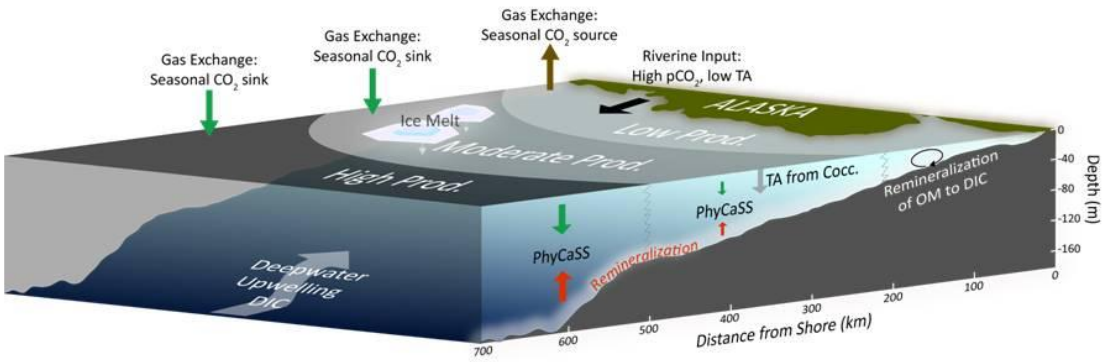
"PhyCASS" and water column aragonite saturation states



Ocean acidification already impacts seafloor benthos of the Bering Sea



Note: Magenta areas denote aragonite undersaturation

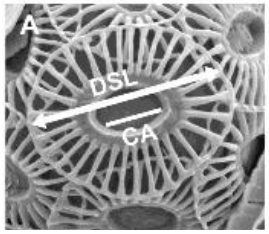


Bates et al., 2009; Mathis et al., 2011

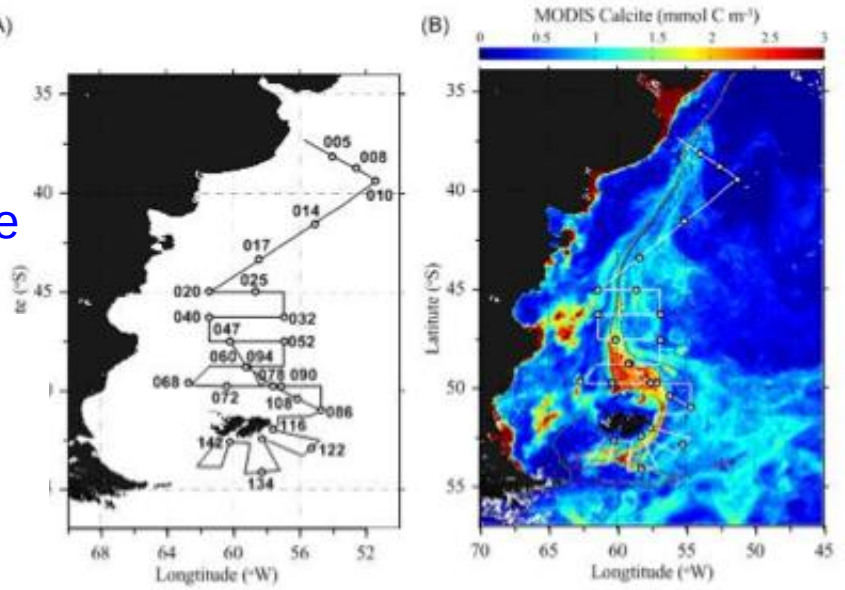
Southern Ocean: COPAS and Great Belt

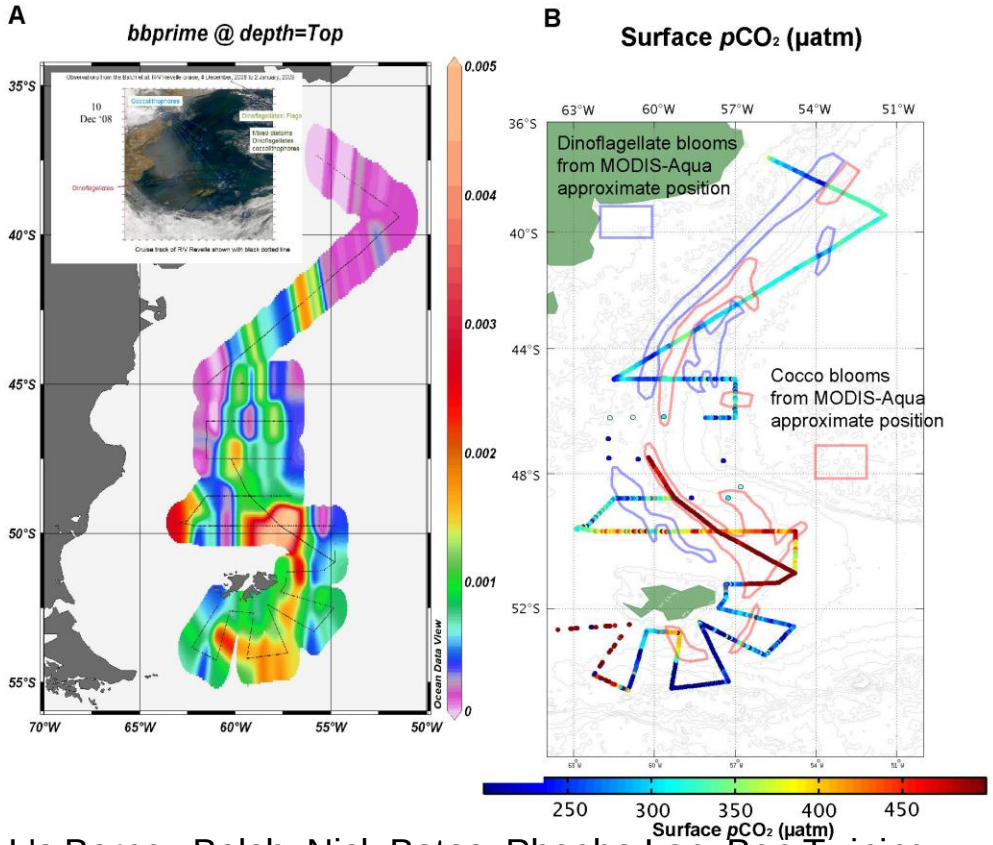
Testing the "CO_2-coccolithophore feedback"

COPAS 2008

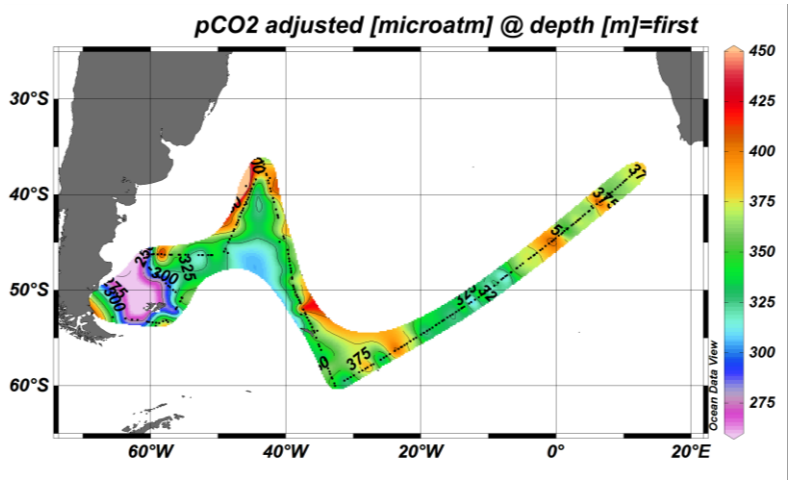


Coccolithophore blooms
add CO_2 back to atmosphere





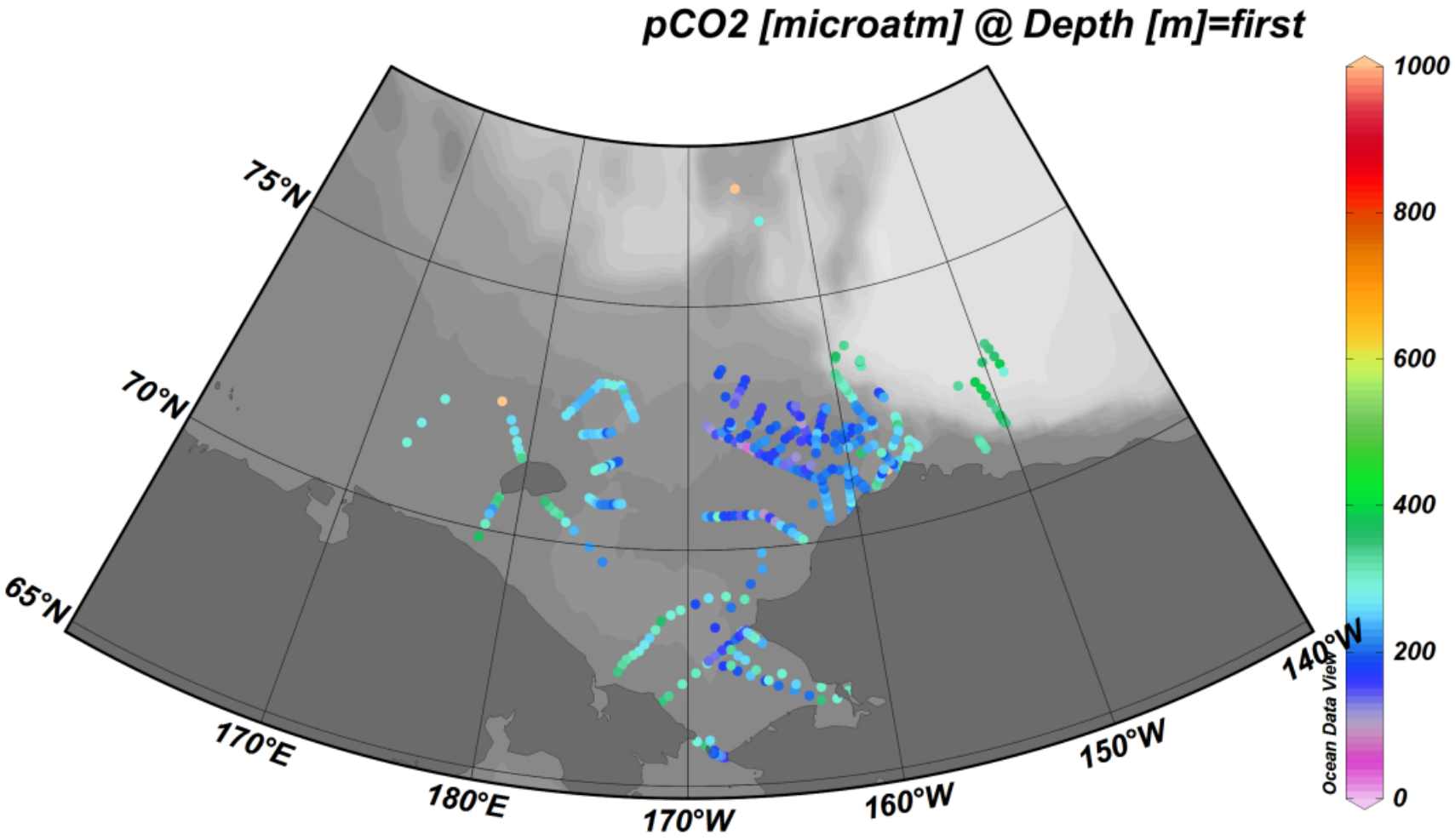
Great Belt 2010-2012



P.I.'s Barney Balch, Nick Bates, Phoebe Lan, Ben Twining

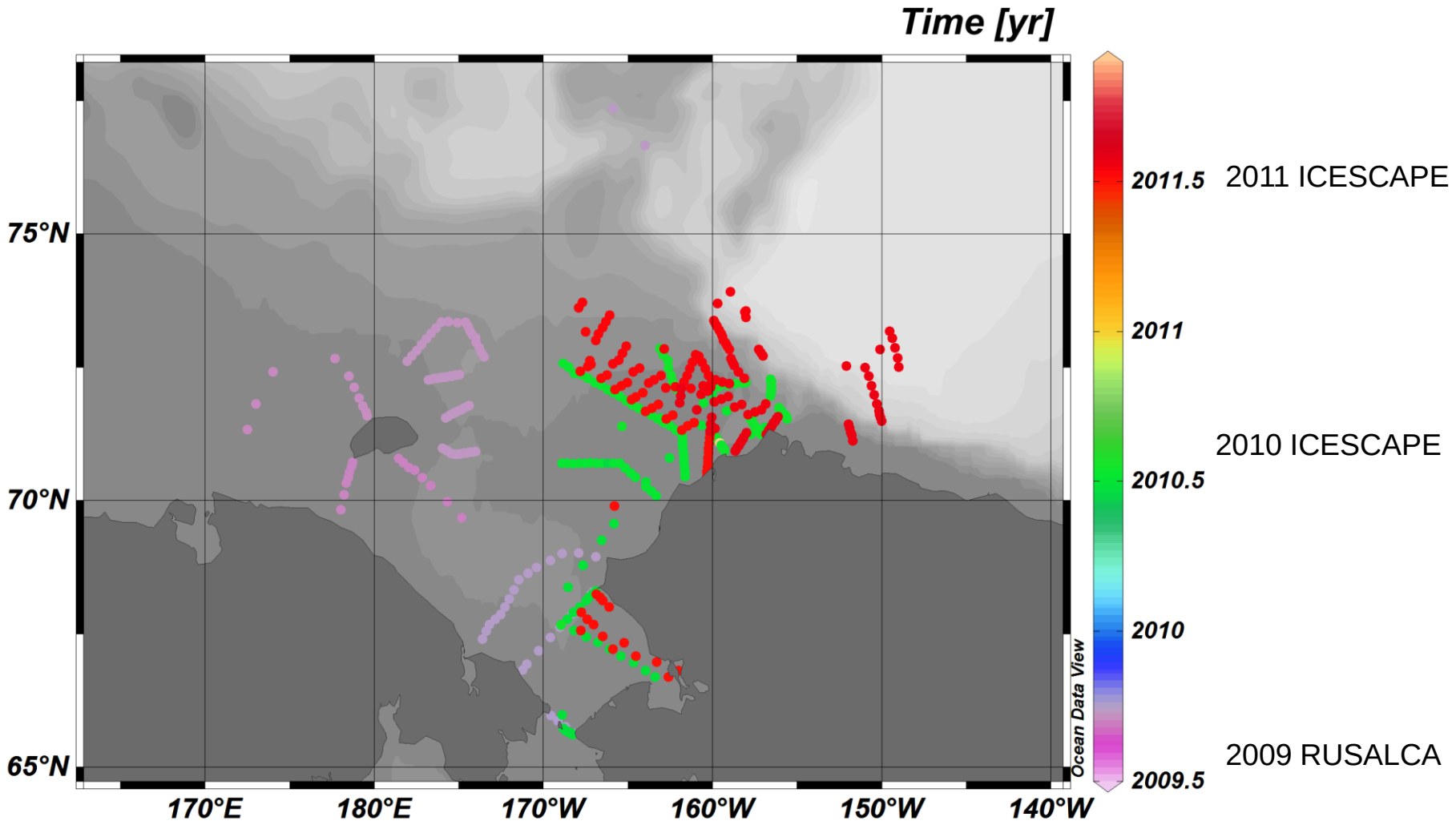
Bates et al., 2011; Poulton et al, 2011

Surface pCO_2 (2011 ICESCAPE)



Bates, Orchowska, Garley, Mathis *et al*., 2011

Composite of RUSALCA and ICESCAPE



Bates, Orchowska, Garley, Mathis *et al*., 2011