Sea-ice CO_2-carbonate chemistry and impact on the underlying water-column

Nicholas R. Bates

Bermuda Institute of Ocean Sciences (BIOS), Bermuda

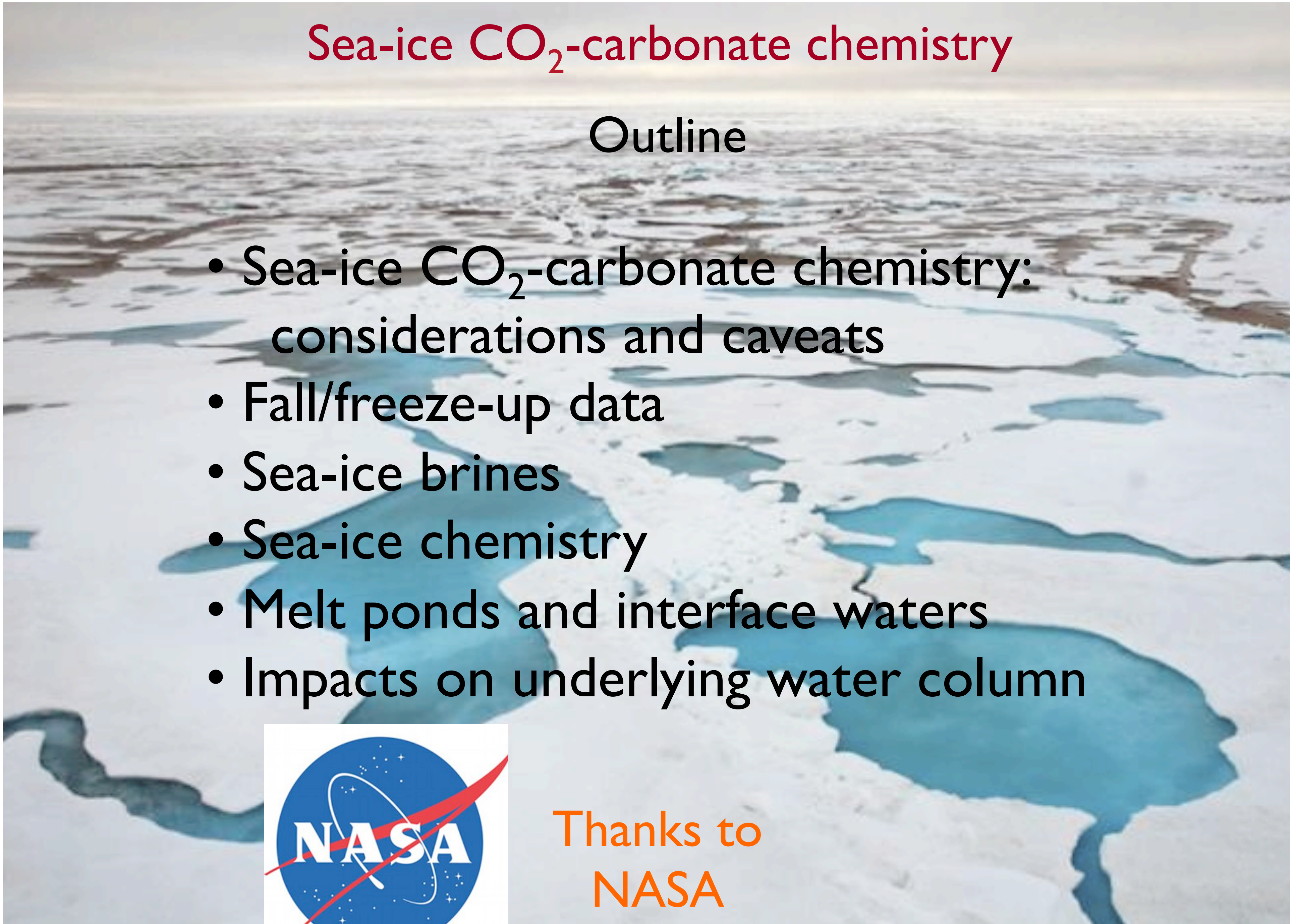
Senior Scientist and Director of Research

Nicholas R. Bates[1,5], Rebecca Garley[1], Karen E Frey[2], Kristen L. Shake[2], Jeremy T. Mathis[3,4]

1. Bermuda Institute of Ocean Sciences (BIOS), St. Georges, Bermuda
2. Graduate School of Geography, Clark University, 950 Main Street, Worcester, MA 01610
3. NOAA-Pacific Marine Environmental Lab, Seattle, WA USA
4. Ocean Acidification Research Center, University of Alaska Fairbanks, Fairbanks, AK, USA
5. Professor of Ocean Biogeochemistry, University of Southampton, UK

Also thanks to: Jessica Cross, Bruno Delille, Soren Rysgaard

Karen Frey photo



Sea-ice CO_2-carbonate chemistry

Outline

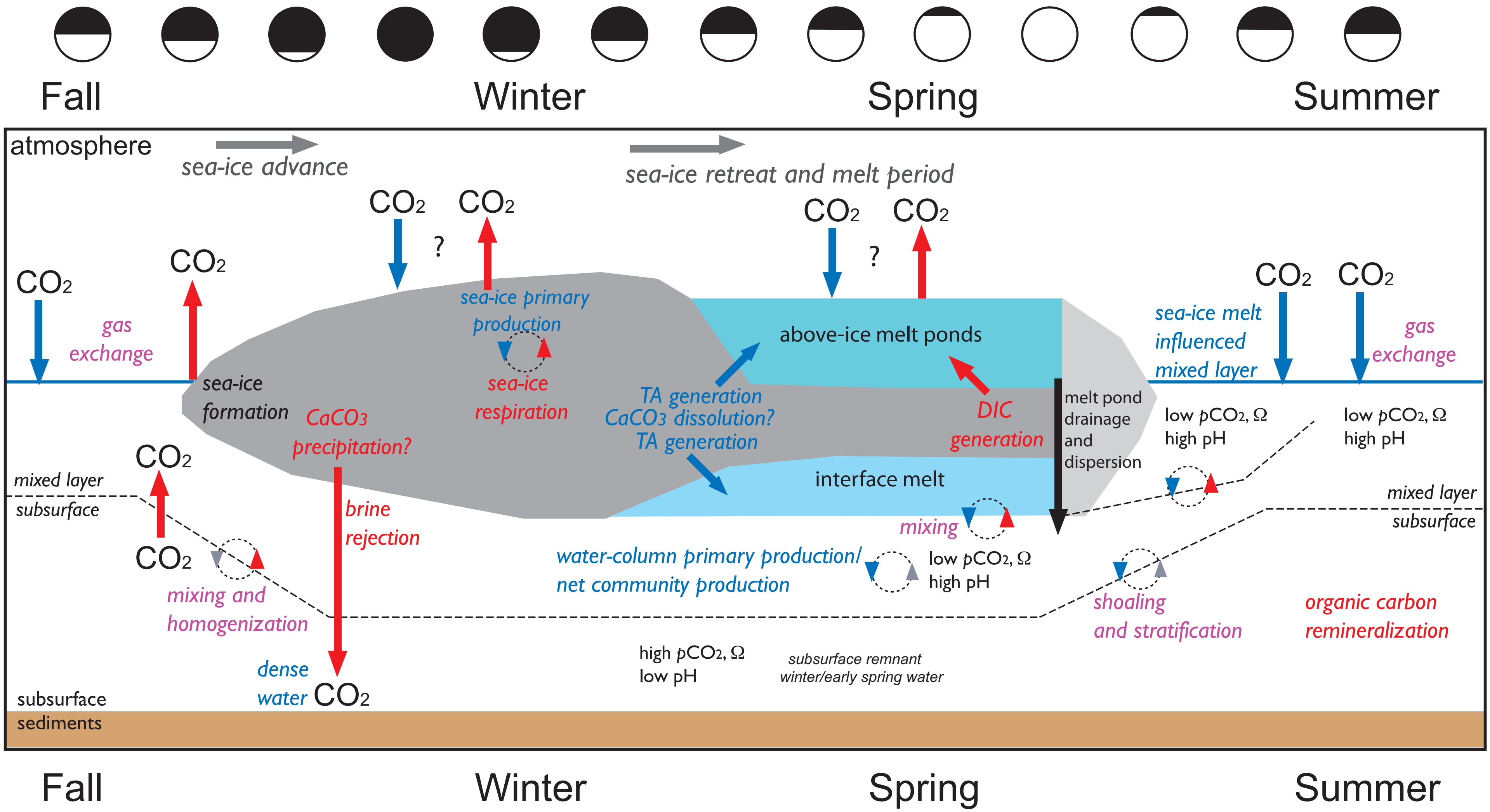
- Sea-ice CO_2-carbonate chemistry: considerations and caveats
- Fall/freeze-up data
- Sea-ice brines
- Sea-ice chemistry
- Melt ponds and interface waters
- Impacts on underlying water column

Thanks to NASA

Karen Frey photo

Sea-ice CO_2-carbonate chemistry

Seasonal changes in generic sea-ice impacted shelf



Bates et al., 2014

Bates et al, OCB Meeting 2014

Sea-ice CO_2-carbonate chemistry

CO_2-carbonate chemistry considerations

$$CO_{2atm} + H_2O = [CO_2^*]_{sea} = HCO_3^-] + [H^+] = [CO_3^{2-}] + [H^+] \qquad (1)$$

Observed or calculated seawater CO_2-carbonate chemistry

Dissolved inorganic carbon (DIC)
- $DIC = [HCO_3^-] + [CO_3^{2-}] + [CO_2$

Total Alkalinity (TA)
- $TA = [HCO_3^-] + 2[CO_3^{2-}] + [B(OH)^-] + [OH^-] – [H^-]$

Partial pressure of CO_2
- pCO_2 or fCO_2

pH
- $-\log_{10} [H^+]$

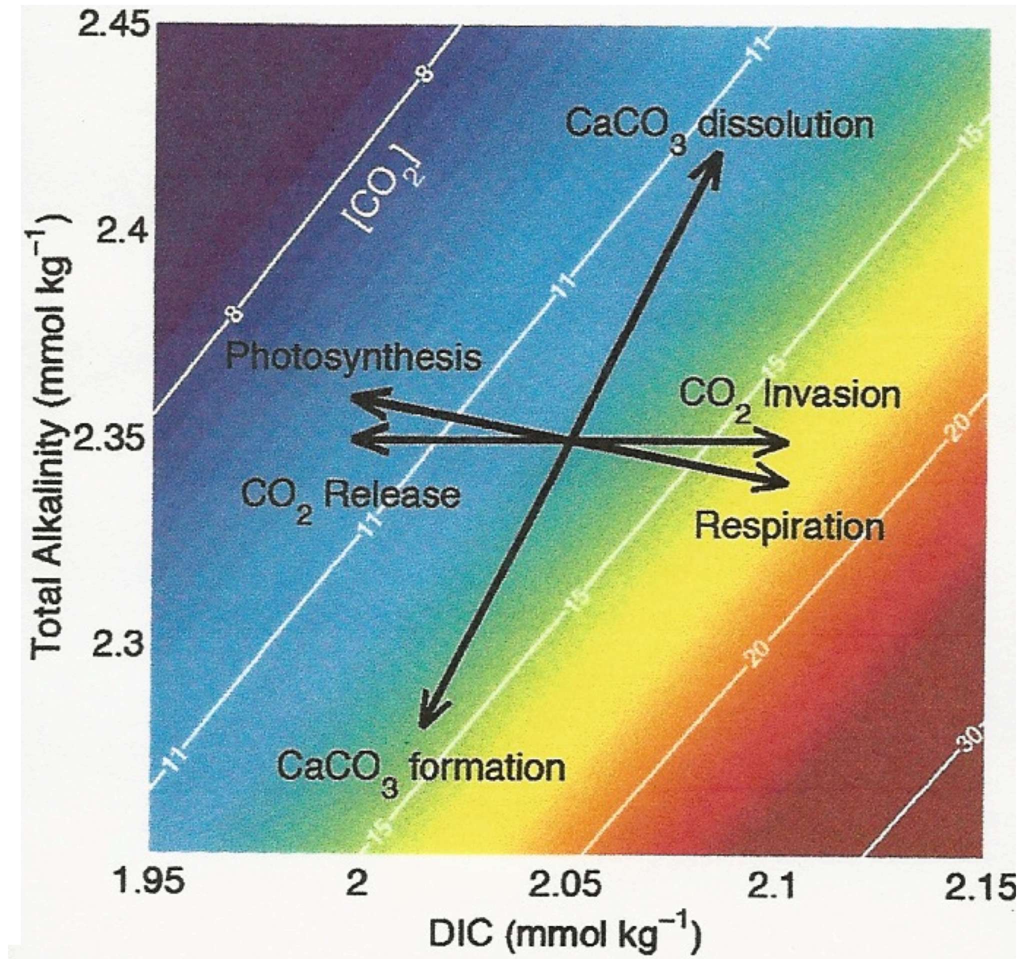


Image: Zeebe and Wolf-Gladrow 2001

Bates et al, OCB Meeting 2014

Sea-ice CO_2-carbonate chemistry

Caveats associated with sea-ice CO_2 carbonate chemistry

Thermodynamic Issues

1. Uncertainty with dissociation constants for waters less than 1°C and salinity of 25
2. Low ionic strength of sea-ice meltwaters
3. High ionic strength of sea-ice brines

Measurement Issues

4. Higher salinity, open ocean seawater certified reference materials
5. Calibration to low salinity waters

Calculation Issues

6. What is the inaccuracy of computing pCO_2, pH, etc in sea-ice?

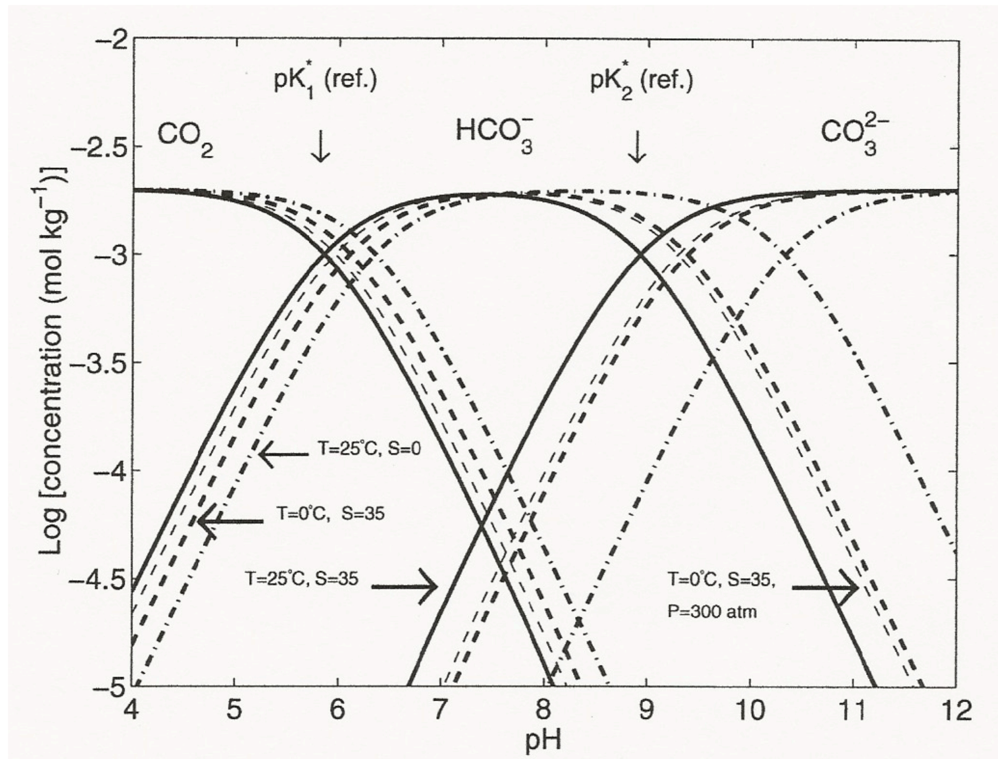


Image: Zeebe and Wolf-Gladrow 2001

Bates et al, OCB Meeting 2014

Sea-ice CO_2-carbonate chemistry

Caveats associated with sea-ice carbonate chemistry

Thermodynamic Issues

1. Uncertainty with dissociation constants for waters less than 1°C and salinity of 25
2. Low ionic strength of sea-ice meltwaters
3. High ionic strength of sea-ice brines

Measurement Issues

4. Higher salinity, open ocean seawater certified reference materials
5. Calibration to low salinity waters

Calculation Issues

6. What is the inaccuracy of computing pCO_2, pH, etc in sea-ice?

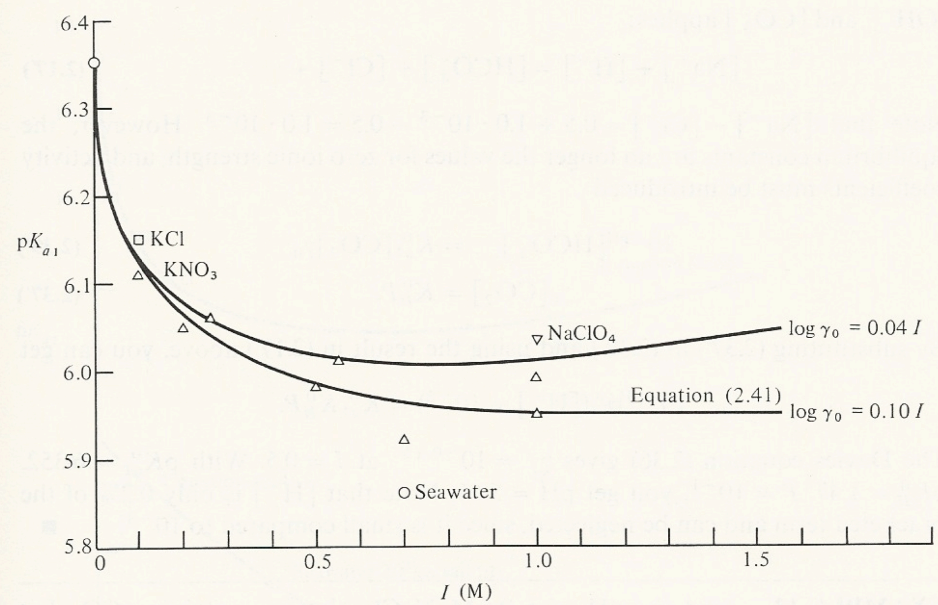


Fig. 2.6. First acidity constant of CO_2, pK_{a1}, as a function of ionic strength. Note that seawater falls well below the data for $NaClO_4$ and KNO_3 media, and that $b = 0.04$ or $b = 0.10$ give equally good fits to the data for $I \leq 1$ M.

Butler 1982

Bates et al, OCB Meeting 2014

Sea-ice CO_2-carbonate chemistry

pCO_2 observed and calculated comparison

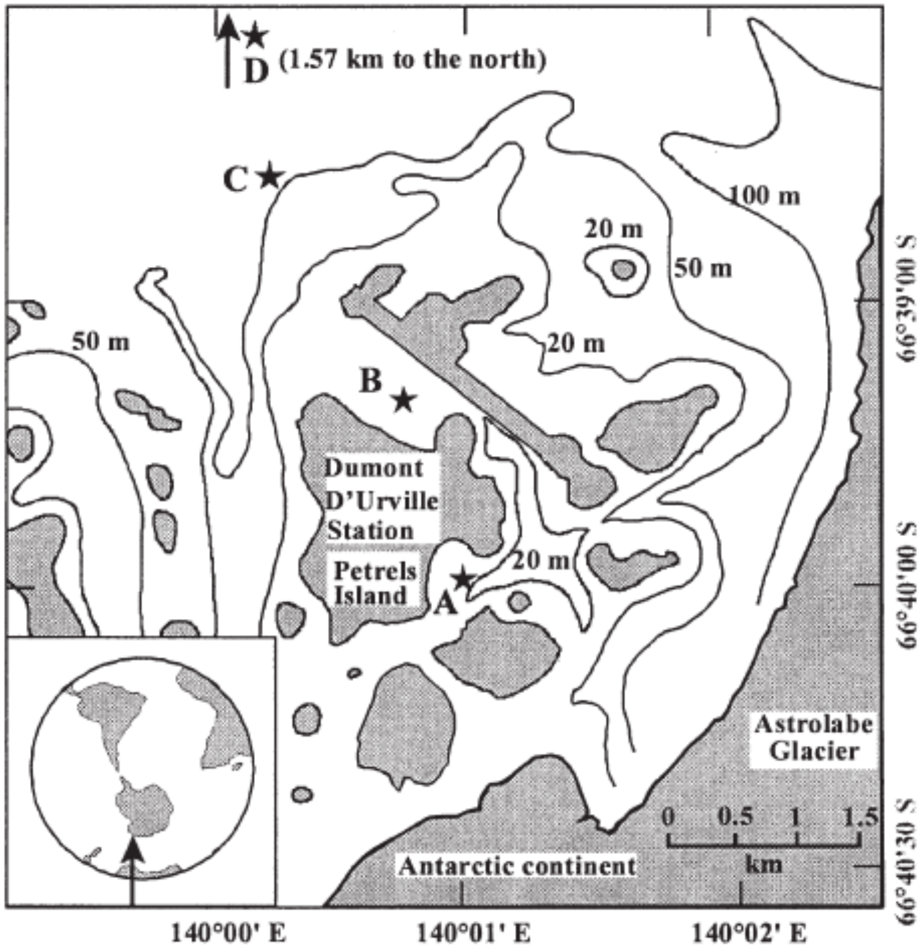


Fig. 1. Location of the stations and bottom topography in the vicinity of the French research station of Dumont D'Urville, located on Petrels Island, Adélie Land, Antarctica.

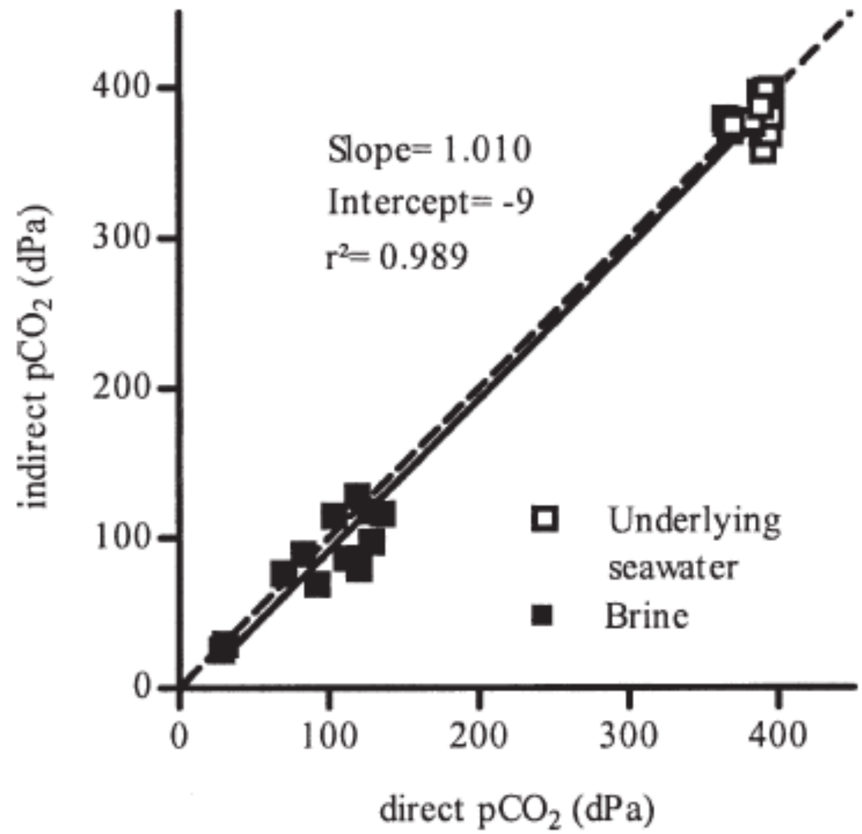


Fig. 2. Comparison of direct partial pressure of CO_2 (pCO_2) measurements and pCO_2 computed from pH and total alkalinity measurements (indirect pCO_2) carried out during the ISPOL cruise in the western Weddell Sea between Nov 2005 and Jan 2006. Open and filled squares correspond to underlying water and brine, respectively, while solid and dashed lines correspond to linear regression and 1 : 1 lines, respectively.

Delille et al., 2007

Bates et al, OCB Meeting 2014

Physical and Biological Processes in Sea-Ice

Primary drivers of sea-ice CO_2

Physical Processes

1. Brine rejection
2. Sea-ice gas exchange with air and seawater (after ice formation)
3. Precipitation/oblation
4. Sea-ice melting (end of season)

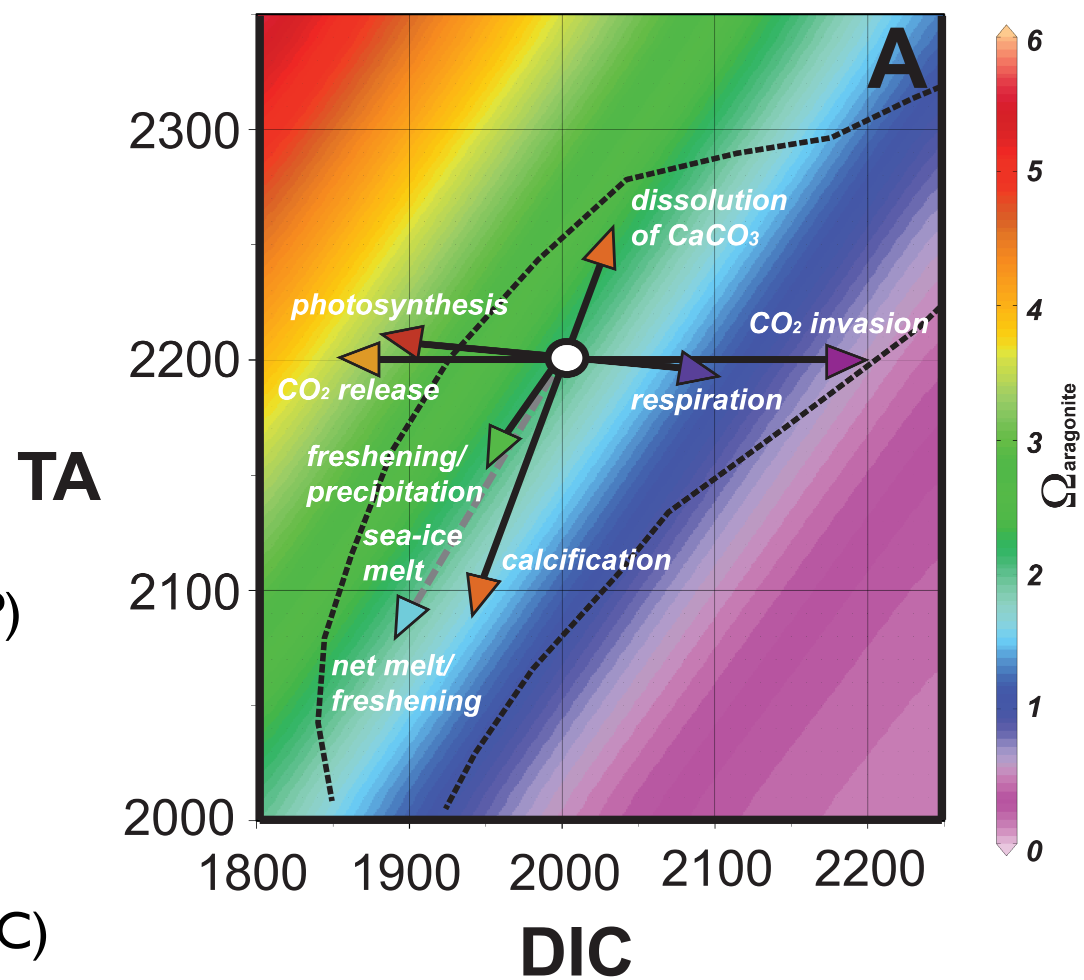
Biological/biogeochemical processes

5. Primary production
6. Respiration

   Net Ecosystem Metabolism (NEP)

7. $CaCO_3$ formation (e.g., Ikaite formation)
8. $CaCO_3$ dissolution

   Net Ecosystem Calcification (NEC)



Bates et al., 2013

Bates et al, OCB Meeting 2014

Physical and Biological Processes in Sea-Ice

Physical Processes

1. Brine rejection
2. Sea-ice gas exchange with air and seawater (after ice formation)
3. Precipitation/oblation
4. Sea-ice melting (end of season)

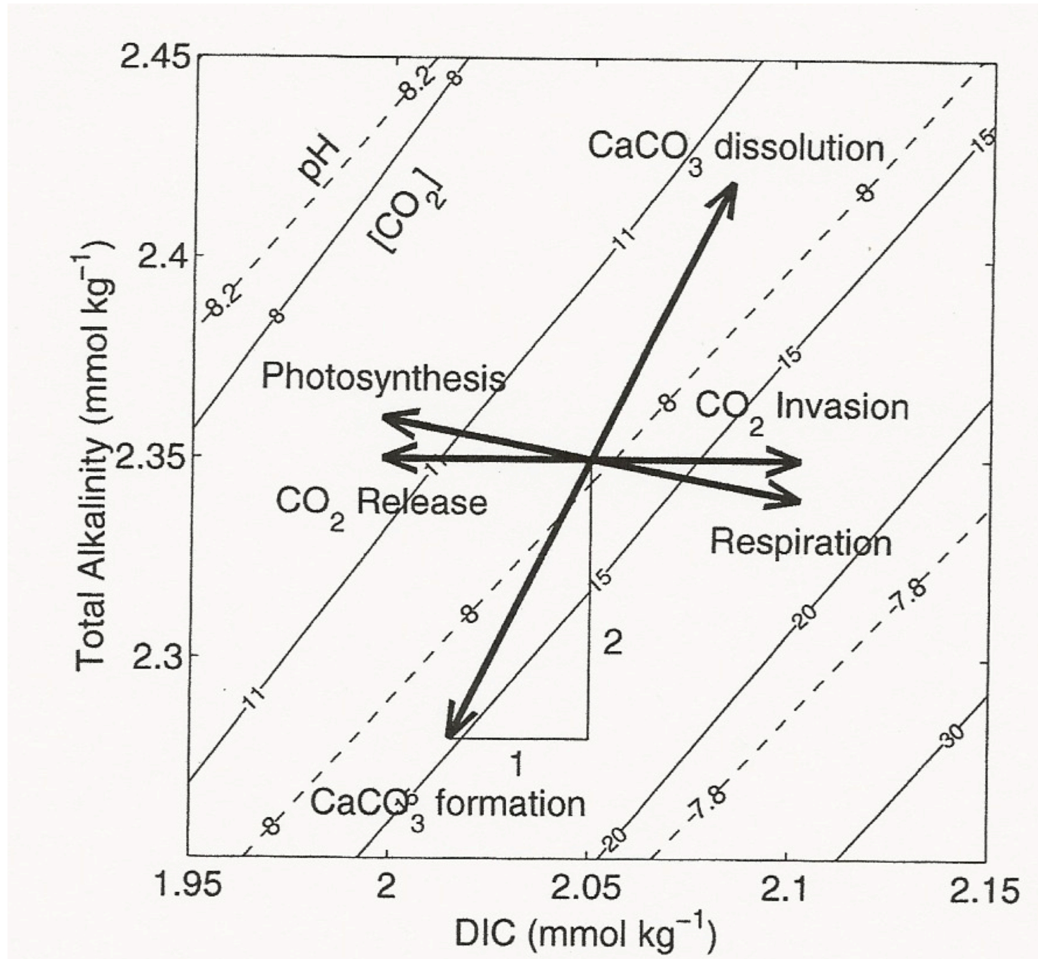
Biological/biogeochemical processes

5. Primary production
6. Respiration

   Net Ecosystem Metabolism (NEP)

7. $CaCO_3$ formation (e.g., Ikaite formation)
8. $CaCO_3$ dissolution

   Net Ecosystem Calcification (NEC)



NEM = NEP + NEP

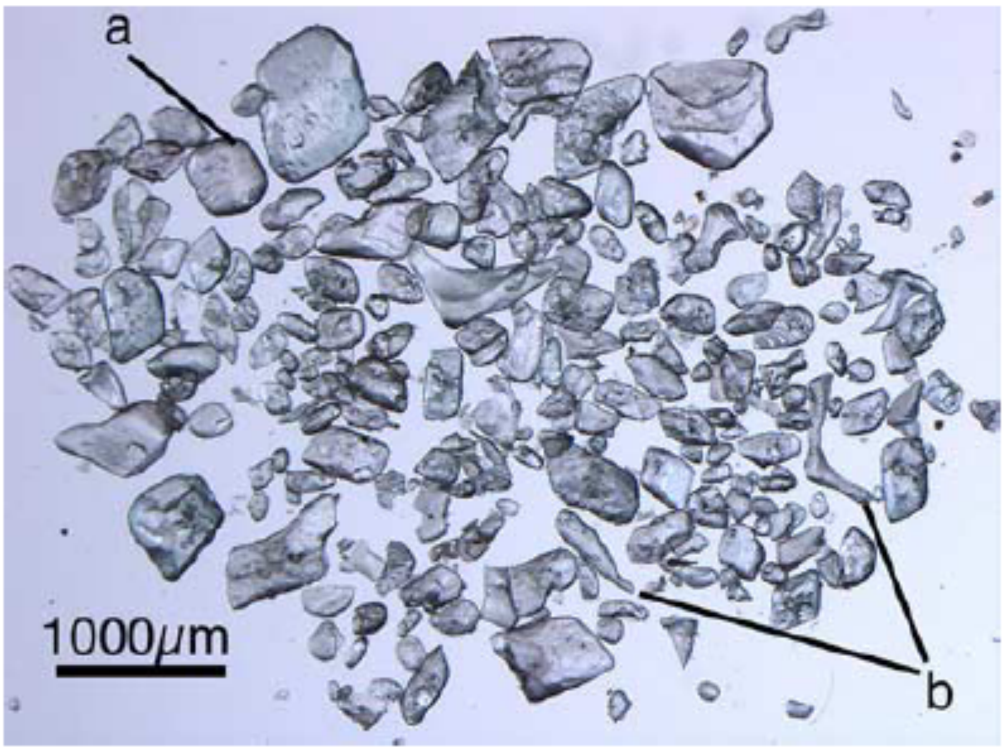
Image: Zeebe and Wolf-Gladrow 2001

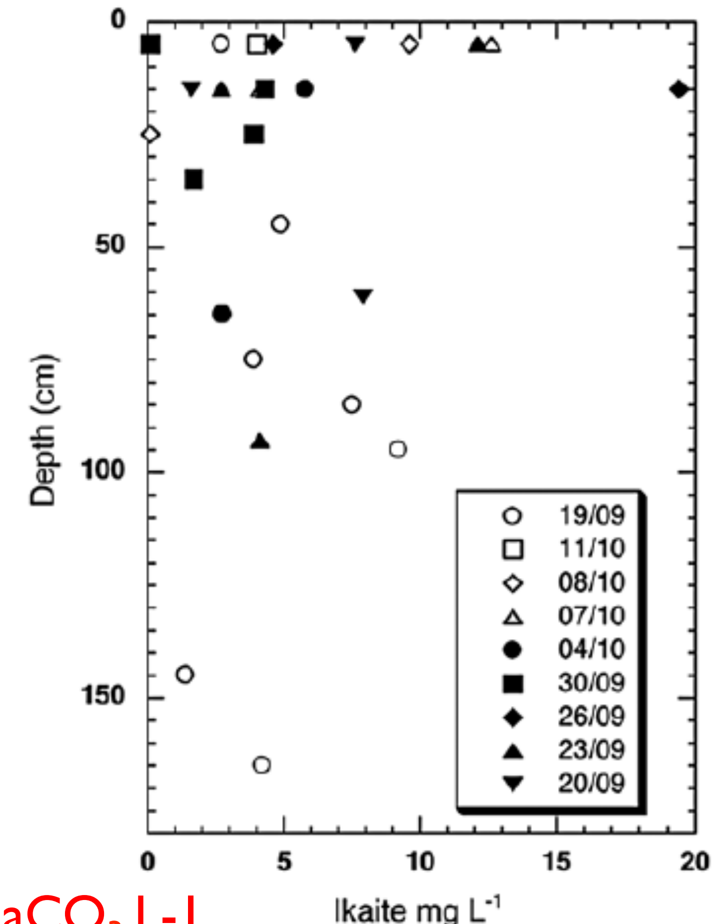
Bates et al, OCB Meeting 2014

Physical and Biological Processes in Sea-Ice

Ikaite formation

Formation of $CaCO_3$
e.g., Killawee et al., 1998; Tisone et al., 2002; Papadimitriou et al., 2004; Dieckmann et al., 2008; Thomas et al., 2013





~0.5 to 19 mg $CaCO_3$ L-1

Dieckmann et al., 2008

Bates et al, OCB Meeting 2014

Physical and Biological Processes in Sea-Ice

$CaCO_3$ formation

Formation of $CaCO_3$

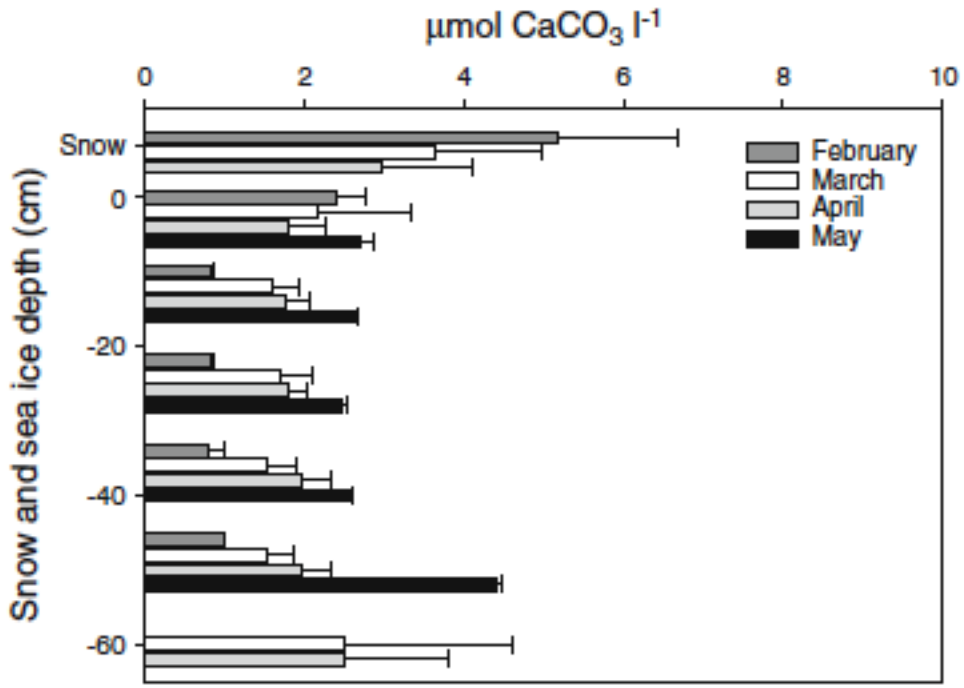


Fig. 5 Temporal development of the $CaCO_3$ concentration [µmol $CaCO_3$ l^{-1}] in bulk sea ice and snow in February, March, April, and May 2010

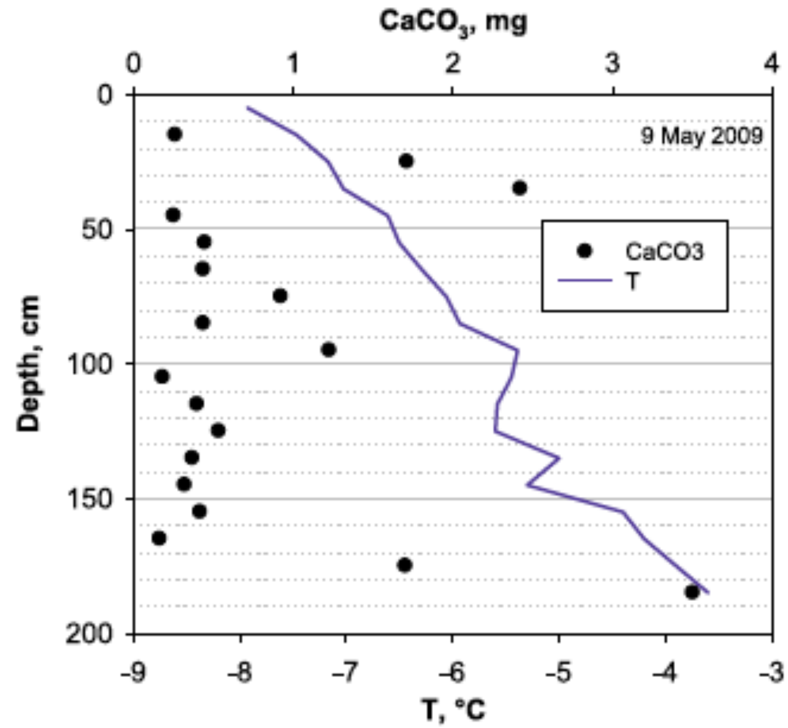


Figure 8. Calcium carbonate and in situ temperature from an ice core collected on 9 May 2004 and stored at −20°C for 5 years.

~0.1 to 0.8 mg $CaCO_3$ L-1

~0.2 to 2.5 mg $CaCO_3$ L-1

Sogaard et al., 2013

Miller et al., 2011b

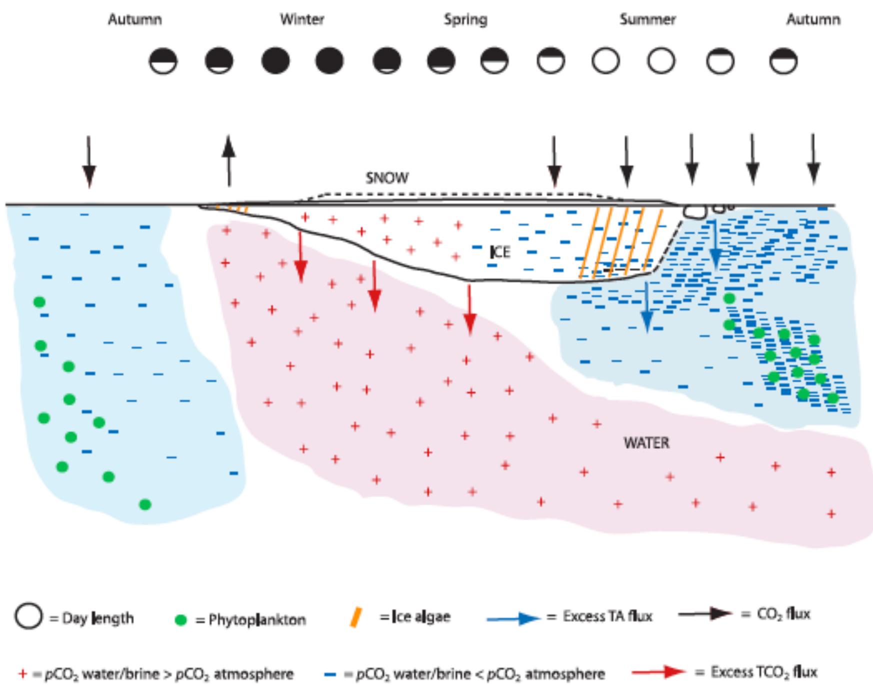
Bates et al, OCB Meeting 2014

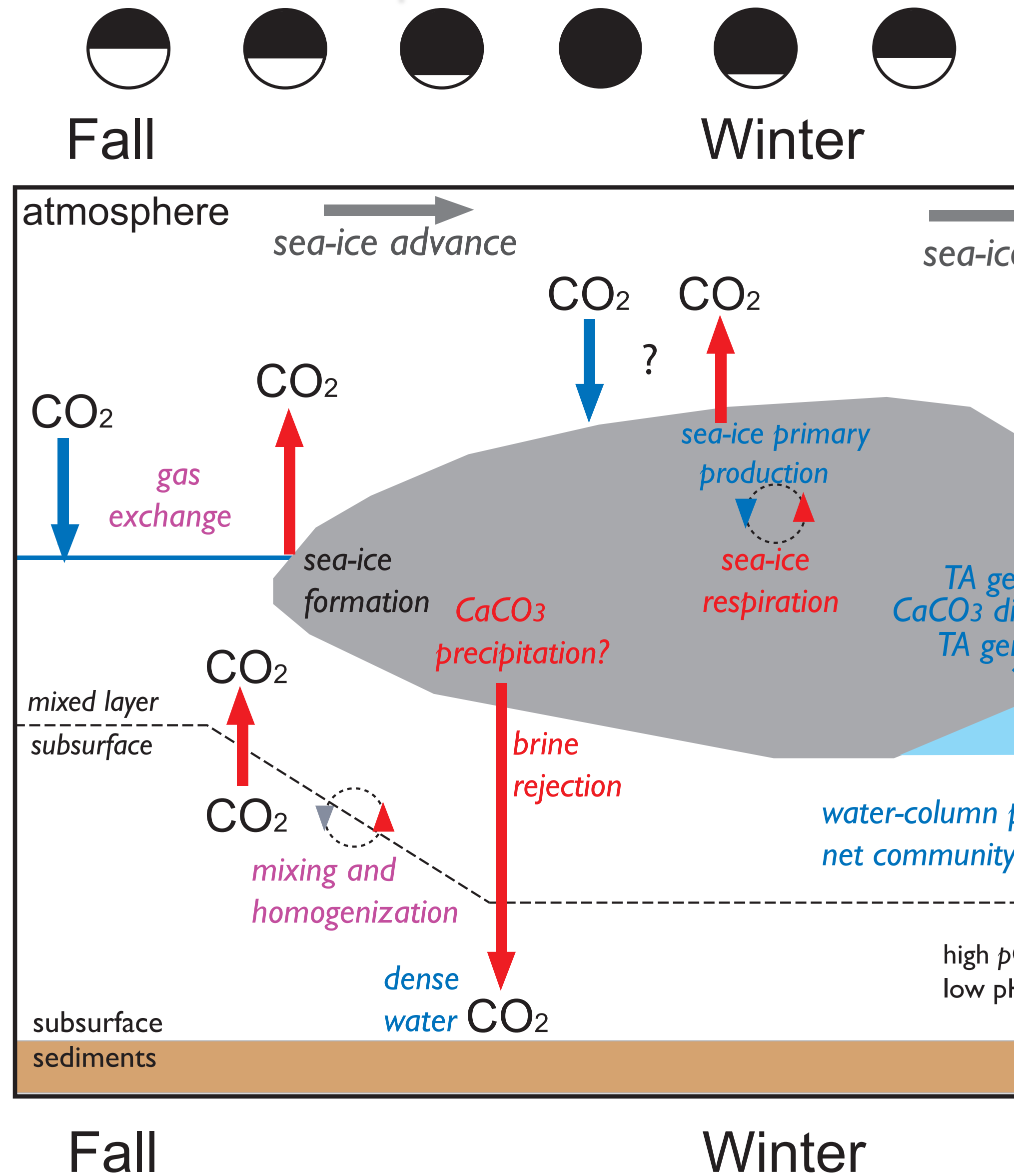
Sea-ice CO_2-carbonate chemistry

Sea-ice formation/freeze-up

Physical Processes

1. Brine rejection





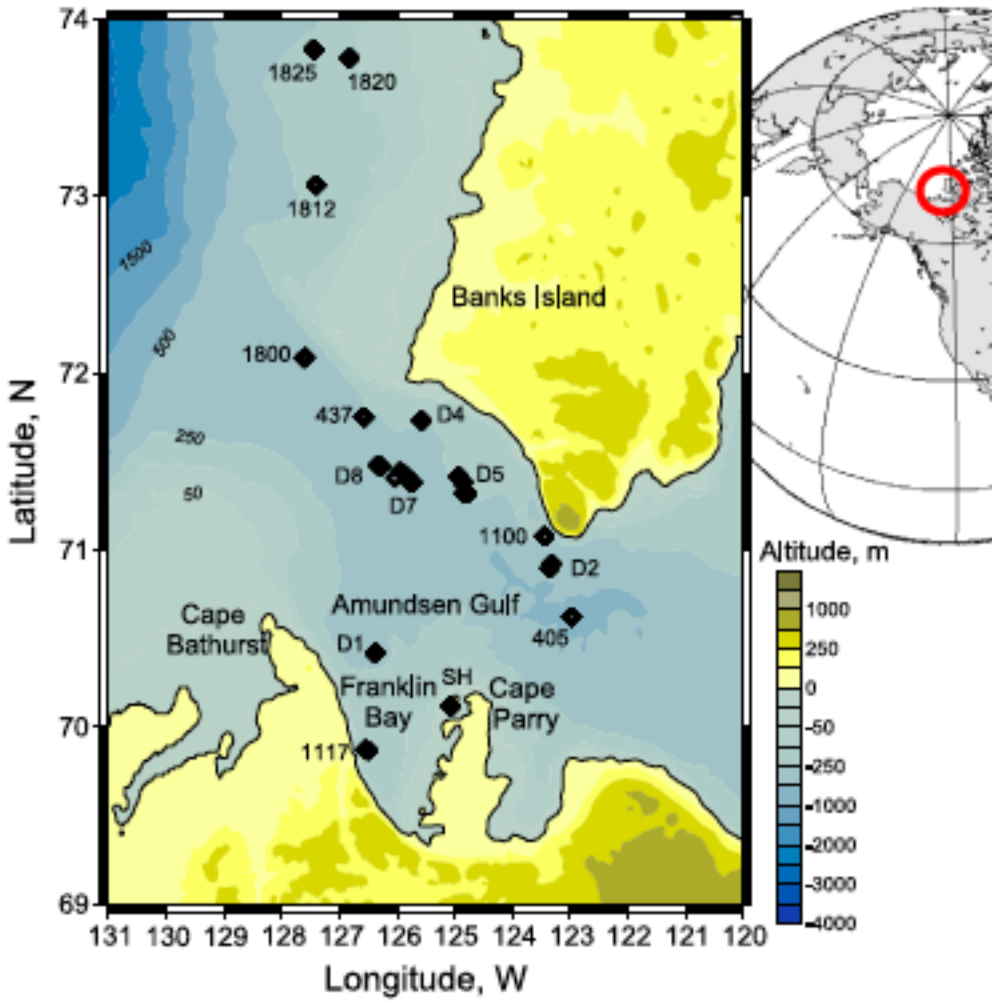
Rysgaard et al., 2007; Bates et al., 2014

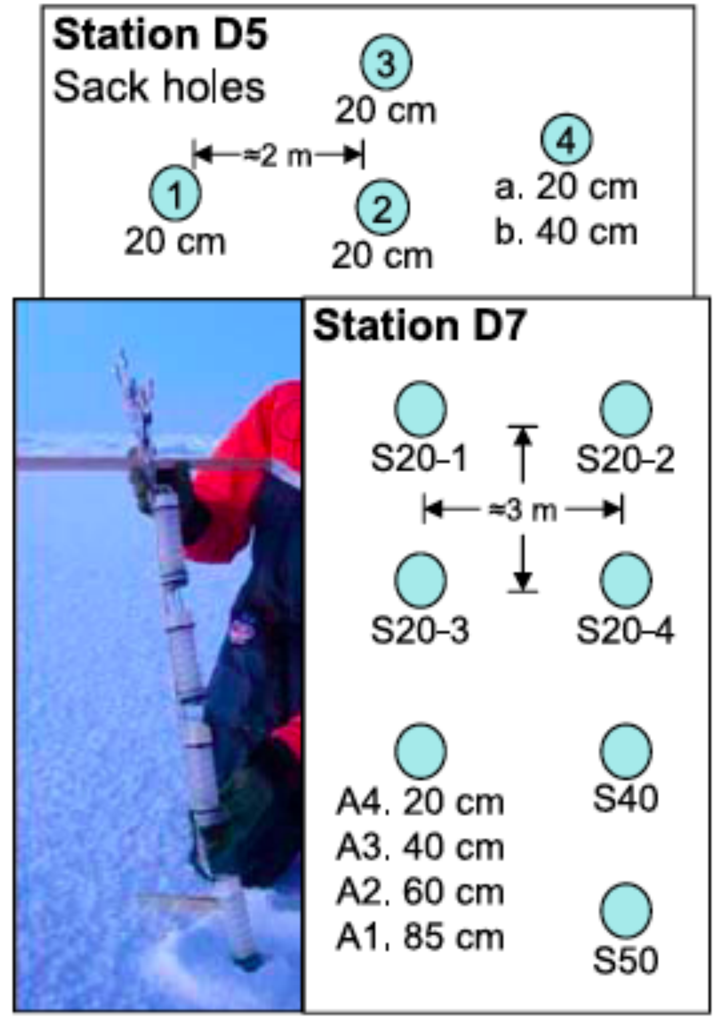
Bates et al, OCB Meeting 2014

Sea-ice CO_2-carbonate chemistry

Sea-ice formation/freeze-up

Brines





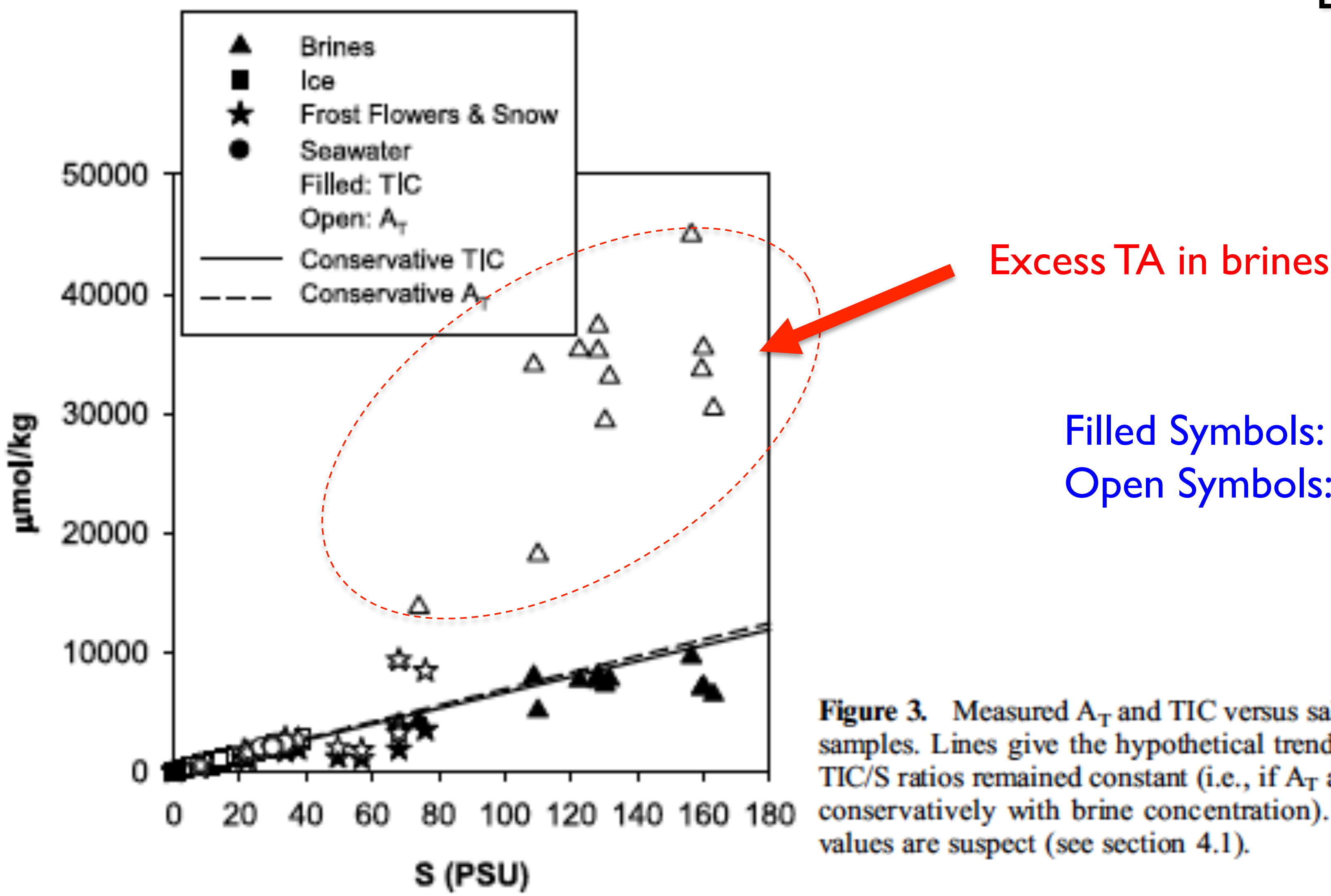
Miller et al., 2011b

Bates et al, OCB Meeting 2014

Sea-ice CO_2-carbonate chemistry

Sea-ice formation/freeze-up

Brines



Filled Symbols: DIC
Open Symbols: TA

Figure 3. Measured A_T and TIC versus salinity for discrete samples. Lines give the hypothetical trend if the A_T/S and TIC/S ratios remained constant (i.e., if A_T and TIC behaved conservatively with brine concentration). Brine alkalinity values are suspect (see section 4.1).

Miller et al., 2011b

Bates et al, OCB Meeting 2014

Sea-ice CO_2-carbonate chemistry

Sea-ice formation/freeze-up

Brine rejection

Miller et al., 2011b

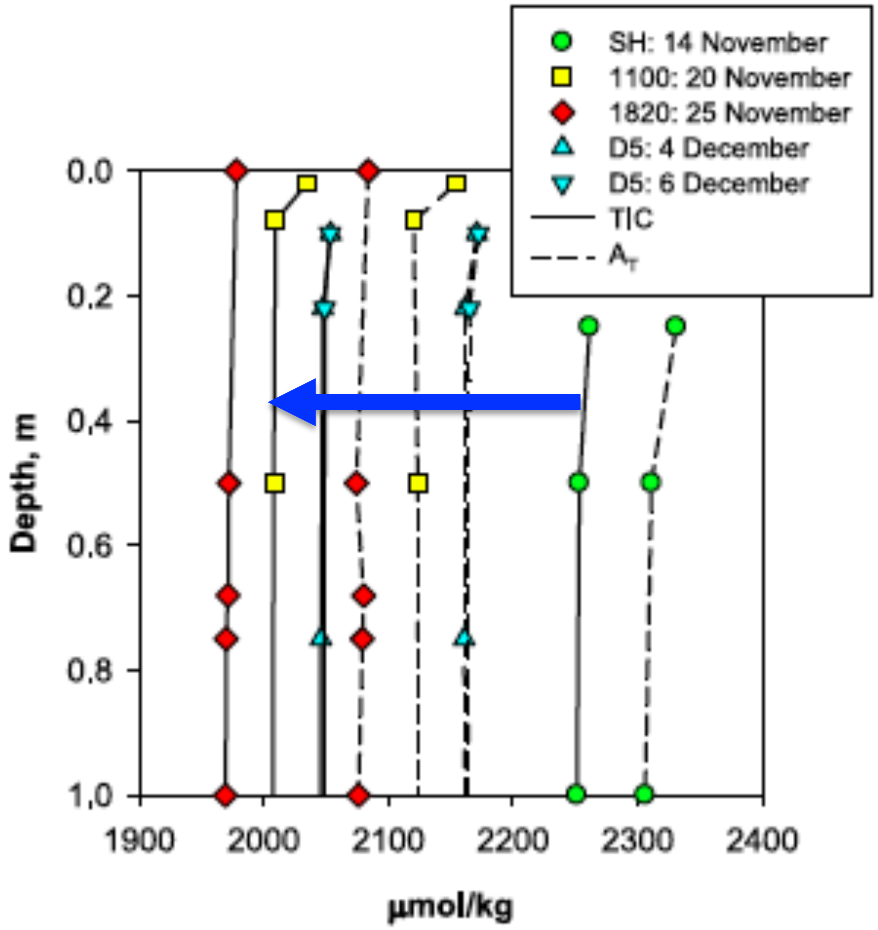


Figure 8. Total inorganic carbon and alkalinity in seawater over the top 1 m under the sea ice at selected stations showing evidence of carbon rejection with brine from the ice. See Figure 1 for station locations.

Removal of DIC and TA from brines

Miller et al., 2011b

Bates et al, OCB Meeting 2014

Sea-ice CO_2-carbonate chemistry

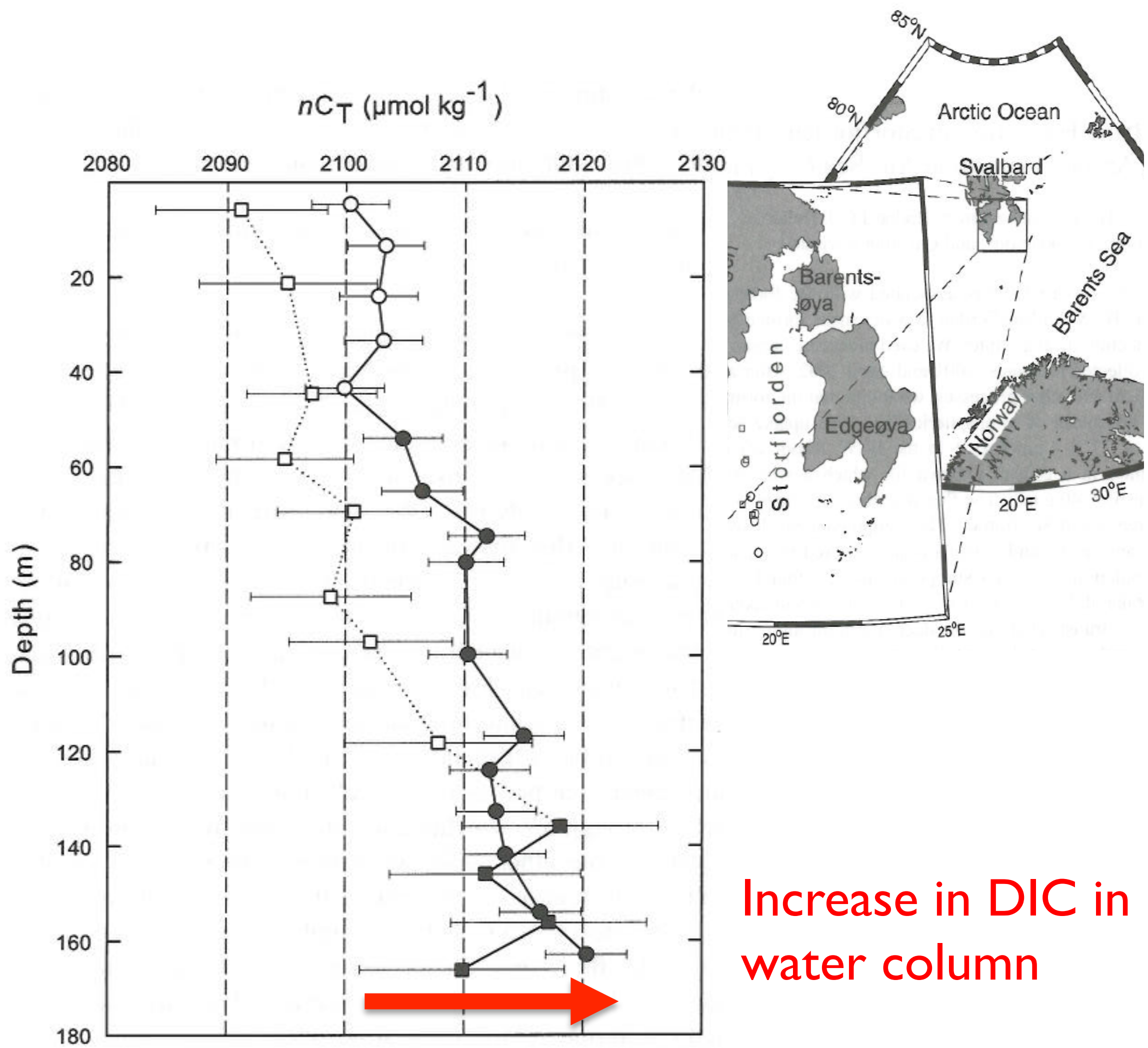
Brine rejection

Omar et al 2005

Physical Processes

1. Brine rejection

2. During freeze-up, the formation of high salinity brines appears to drive a large uptake of CO_2 from the atmosphere and downward flux of dissolved inorganic carbon (DIC) with cold dense waters formed during brine rejection (e.g., Anderson *et al.*, 2004; Omar *et al.*, 2005; Rysgaard *et al.*, 2007).

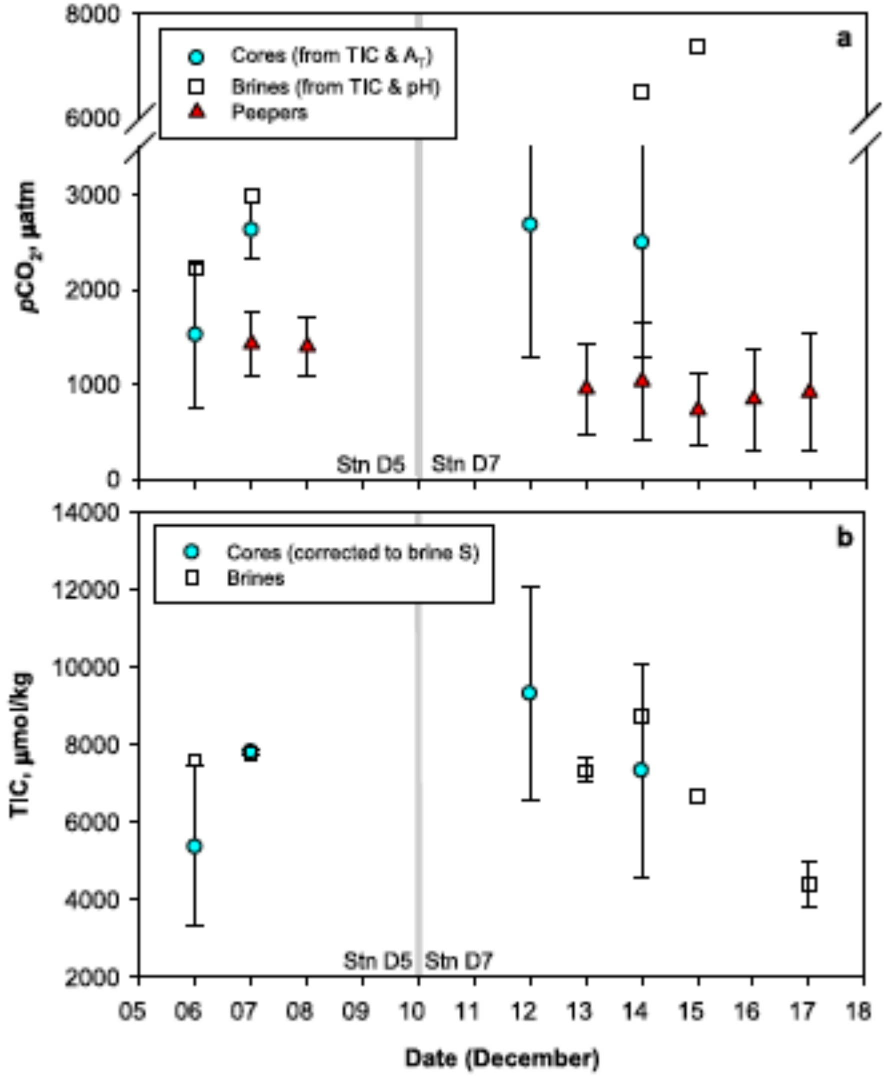


Omar et al., 2005

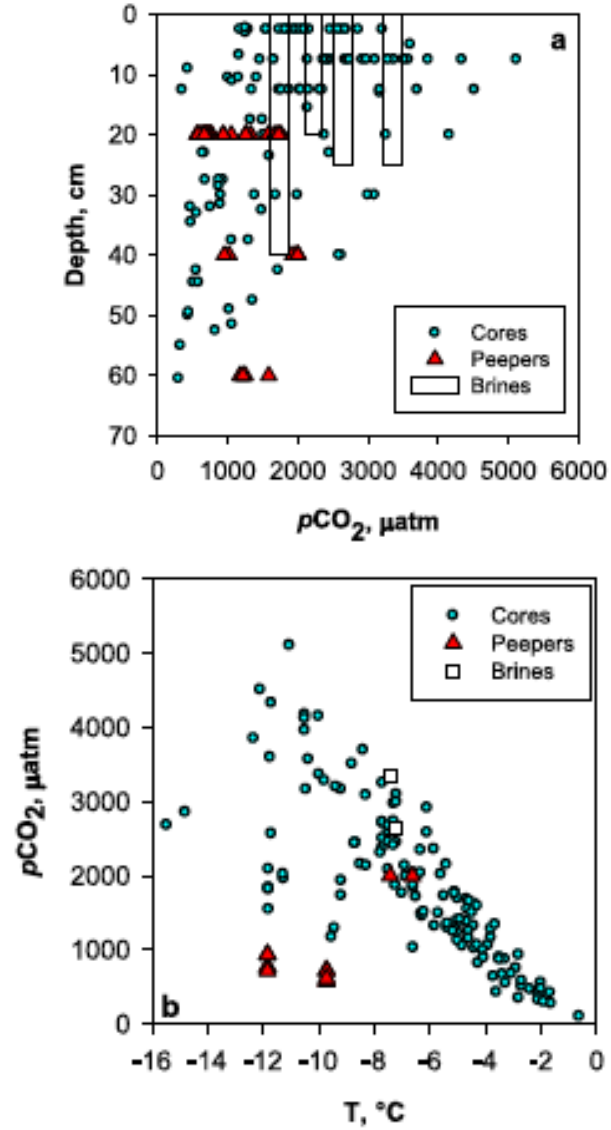
Bates et al, OCB Meeting 2014

Sea-ice CO_2-carbonate chemistry

Sea-ice formation/freeze-up



Brines



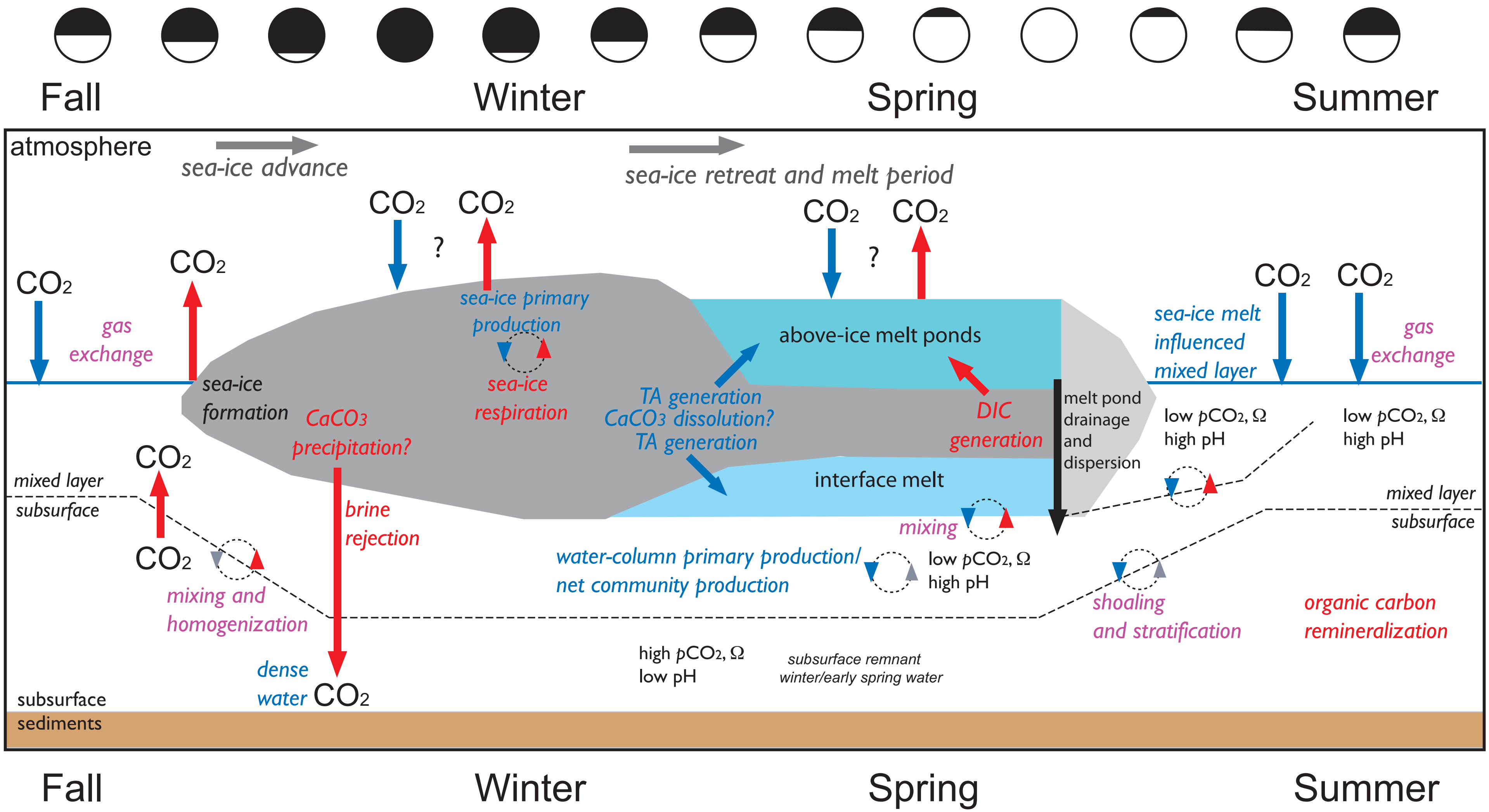
~500 to 8000 µatm

Miller et al., 2011b

Bates et al, OCB Meeting 2014

Sea-ice CO_2-carbonate chemistry

Winter Observations



Bates et al., 2014

Bates et al, OCB Meeting 2014

Sea-ice CO_2-carbonate chemistry

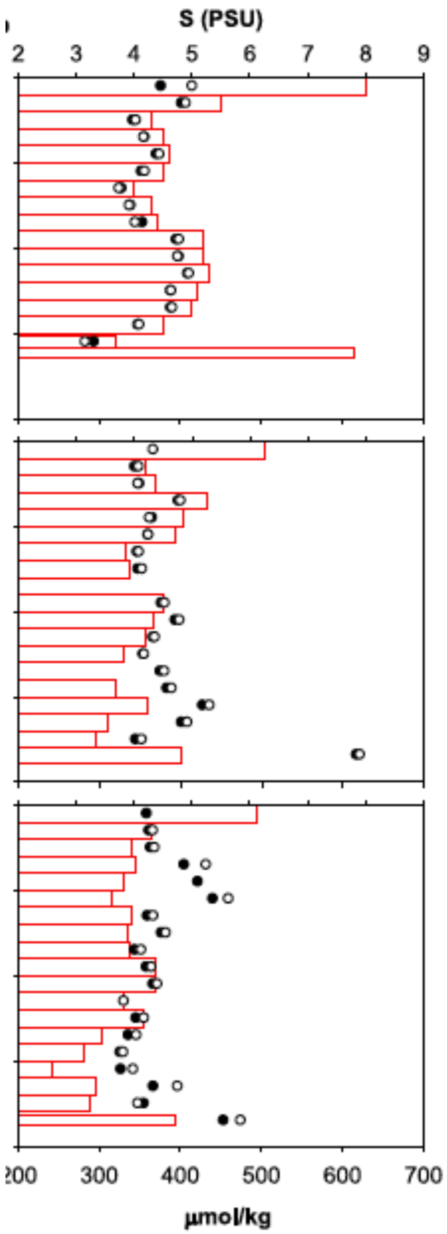
Sea-ice Brines

Study	Location	Period	Season	pCO_2 (μatm)	pH	$\Omega_{calcite}$	$\Omega_{aragonite}$
Brine							
Miller et al., 2011a	Arctic	Nov. to Dec	Fall	<1	12.4	22.5	4.6
Miller et al., 2011b	Arctic	Dec to Mar	Winter	~800 to 12,000	8.2 to 7.1	11.9-1.3	0.8-7.4
Miller et al., 2011b	Arctic	April to June	Spring	~800 to 12,000	8.2 to 7.1	1.3-11.9	0.8-7.4
Geilfus et al. 2012a	Arctic	April	Spring	465 to 1834	8.0	3.0	1.6
Geilfus et al. 2012a	Arctic	May	Spring	147 to 888	8.2	1.5	<0.1
Delille et al., 2007	Antarctic	November	Spring	~100	9.42	>20	>6
Delille et al., 2007	Antarctic	December	Spring	~420	8.38	3.4	1.8
Geilfus et al. 2012a	Arctic	June	Spring	0 to 180	8.3	0.1	<0.1
Geilfus et al. 2014	Arctic	June	Spring	20 to 389			
Fransson et al 2011	Antarctic	Dec. to Jan	Spring	9 to 210	9.3-8.3	3.7-14.8	2.3-9.3

Table 1. Summary of measured and calculated pCO_2 values reported in sea-ice brine, sea-ice and melt ponds. The studies are arranged in seasonal order from fall to spring observations where possible. In most cases, pCO_2, pH, $\Omega_{calcite}$, and $\Omega_{aragonite}$ were calculated from TA and DIC, or from pCO_2 and pH. In the cases where values were reported in the original study, salinity and temperature values of 4 and 0°C were used in the calculations. (from Bates et al., 2014).

Bates et al., 2014

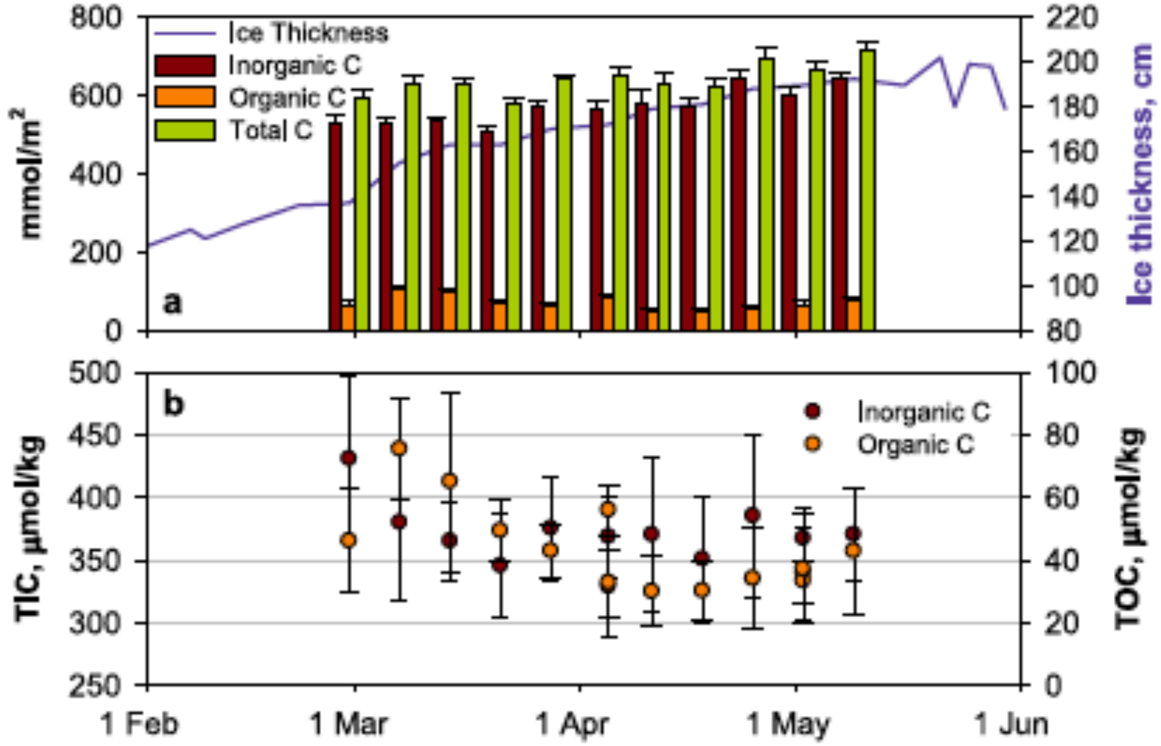
Sea-ice CO_2-carbonate chemistry



Miller et al., 2011a

Winter Observations

Sea-ice



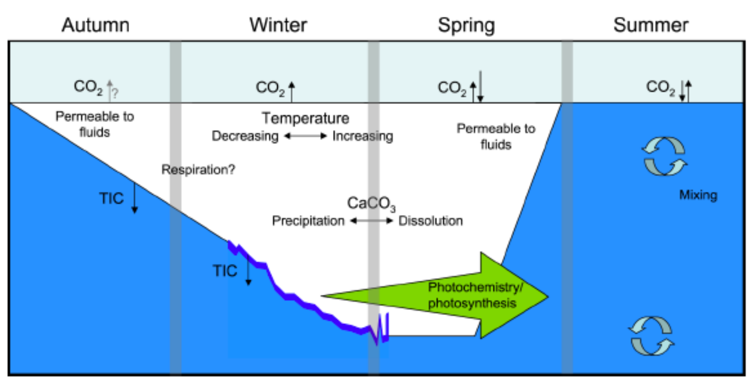
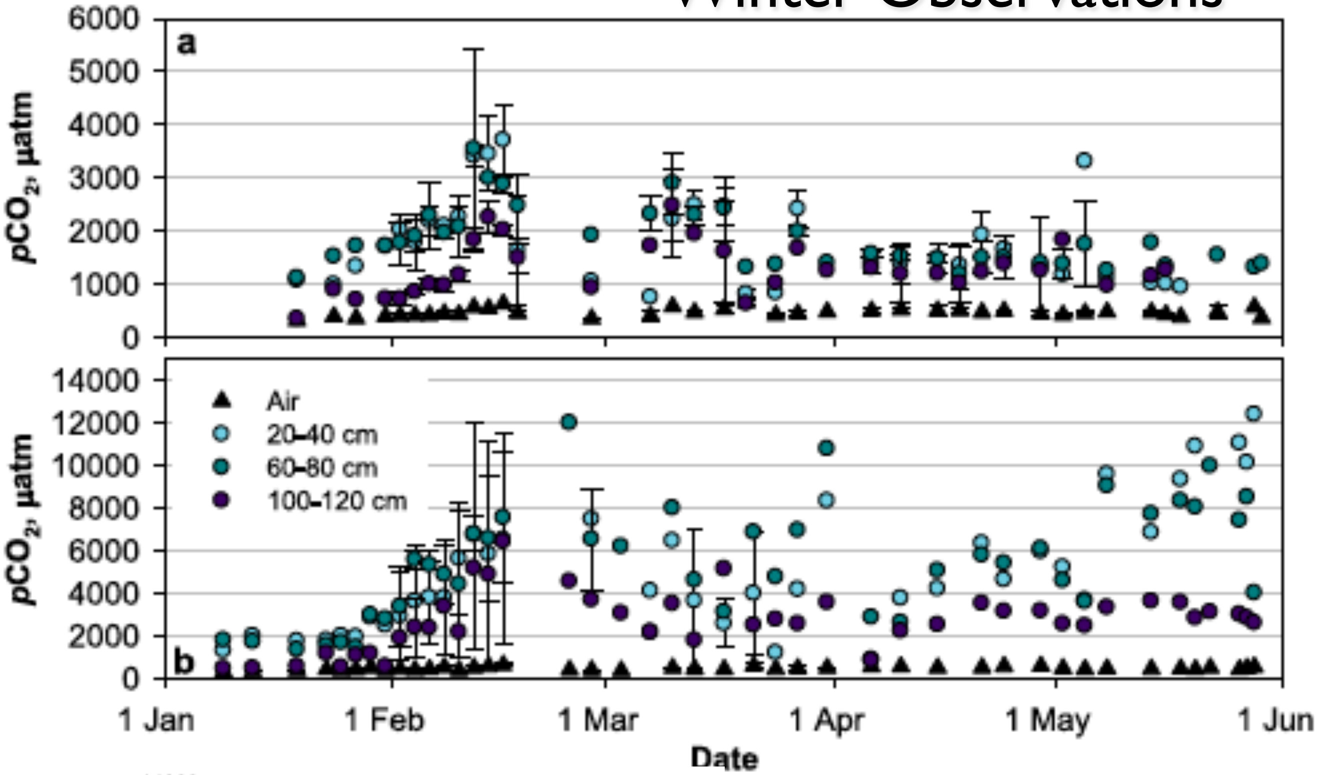


Figure 16. Summary of processes controlling sea ice inorganic carbon dynamics. The dark blue line represents the relative ice thickness during our study (Figure 6a).

Bates et al, OCB Meeting 2014

Sea-ice CO_2-carbonate chemistry

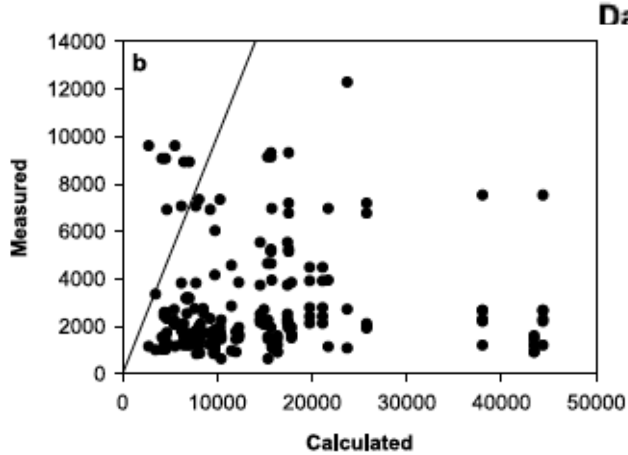
Winter Observations



Brines

Miller et al 2011a

~500 to 14,000 µatm



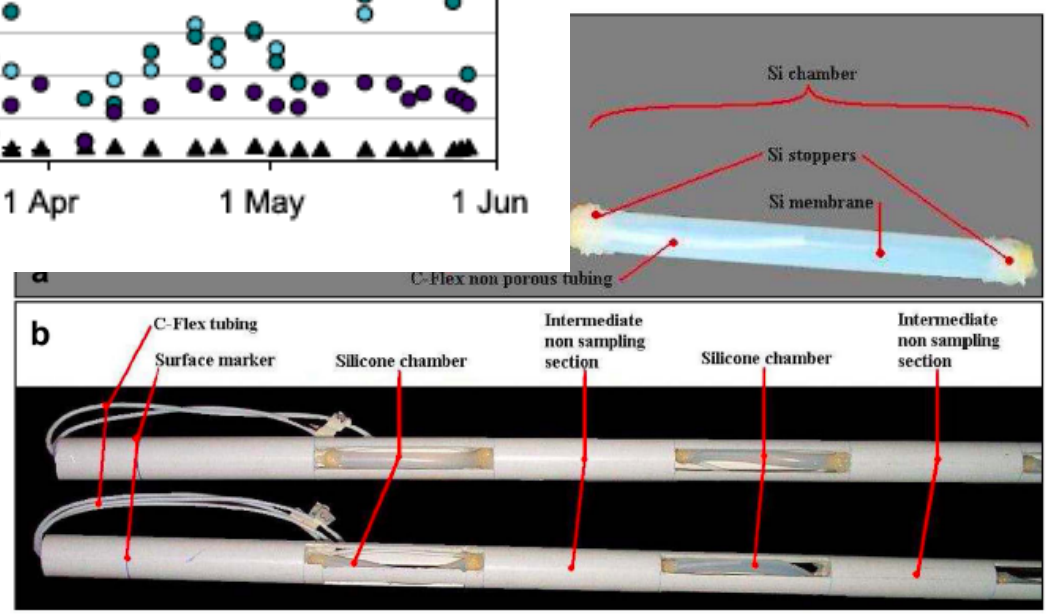


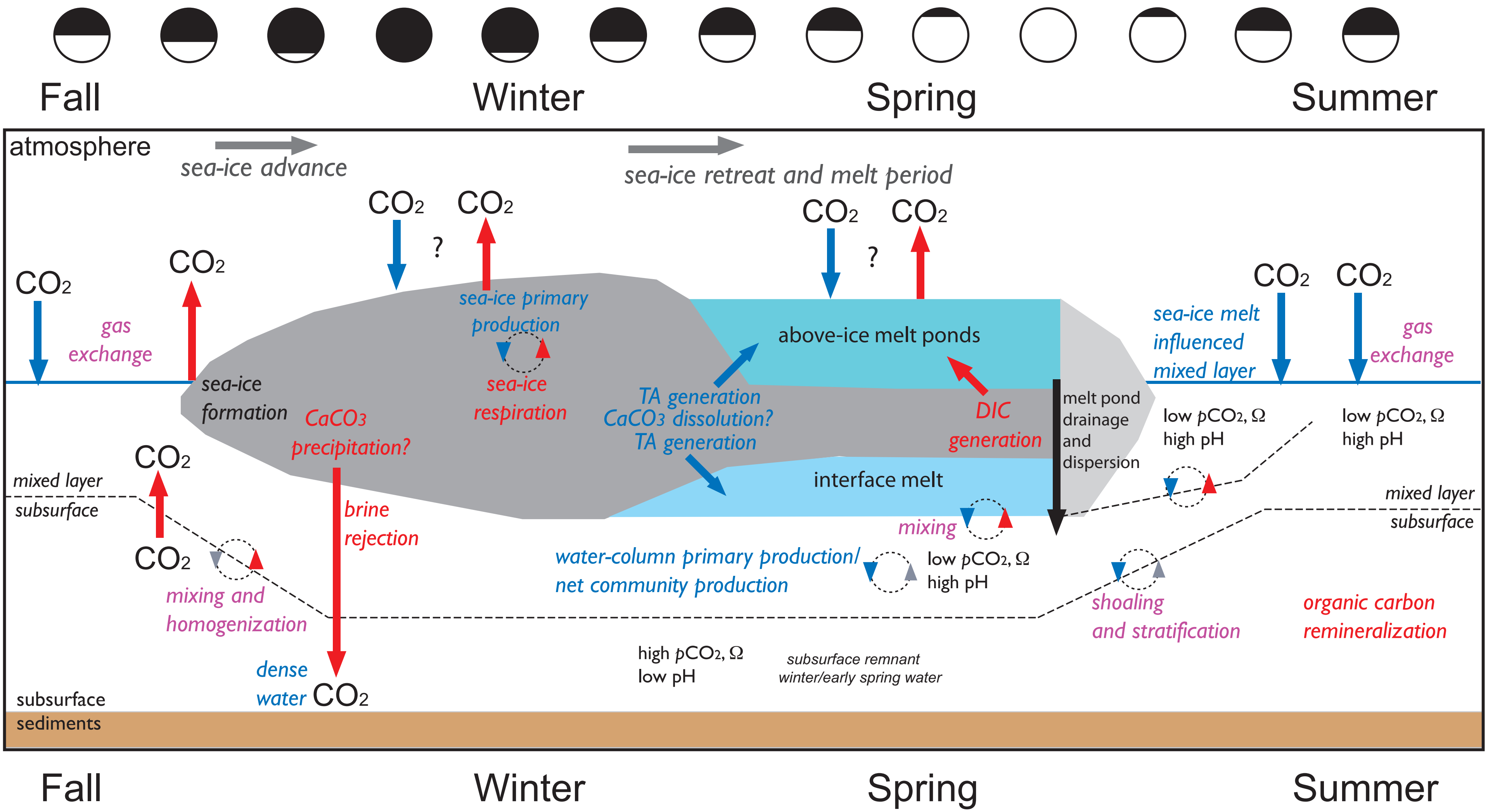
Figure 2. Peepers used for in situ pCO_2 sampling in sea ice. (a) Individual silicone chamber peeper. (b) Two three-peeper arrays for vertical profile sampling. From *Owens* [2008].

Miller et al., 2011a

Bates et al, OCB Meeting 2014

Sea-ice CO_2-carbonate chemistry

Spring Observations



Bates et al., 2014

Bates et al, OCB Meeting 2014

Sea-ice CO_2-carbonate chemistry

Sea-ice

Table 1. Summary of measured and calculated pCO_2 values reported in sea-ice brine, sea-ice and melt ponds. The studies are arranged in seasonal order from fall to spring observations where possible (from Bates et al., 2014).

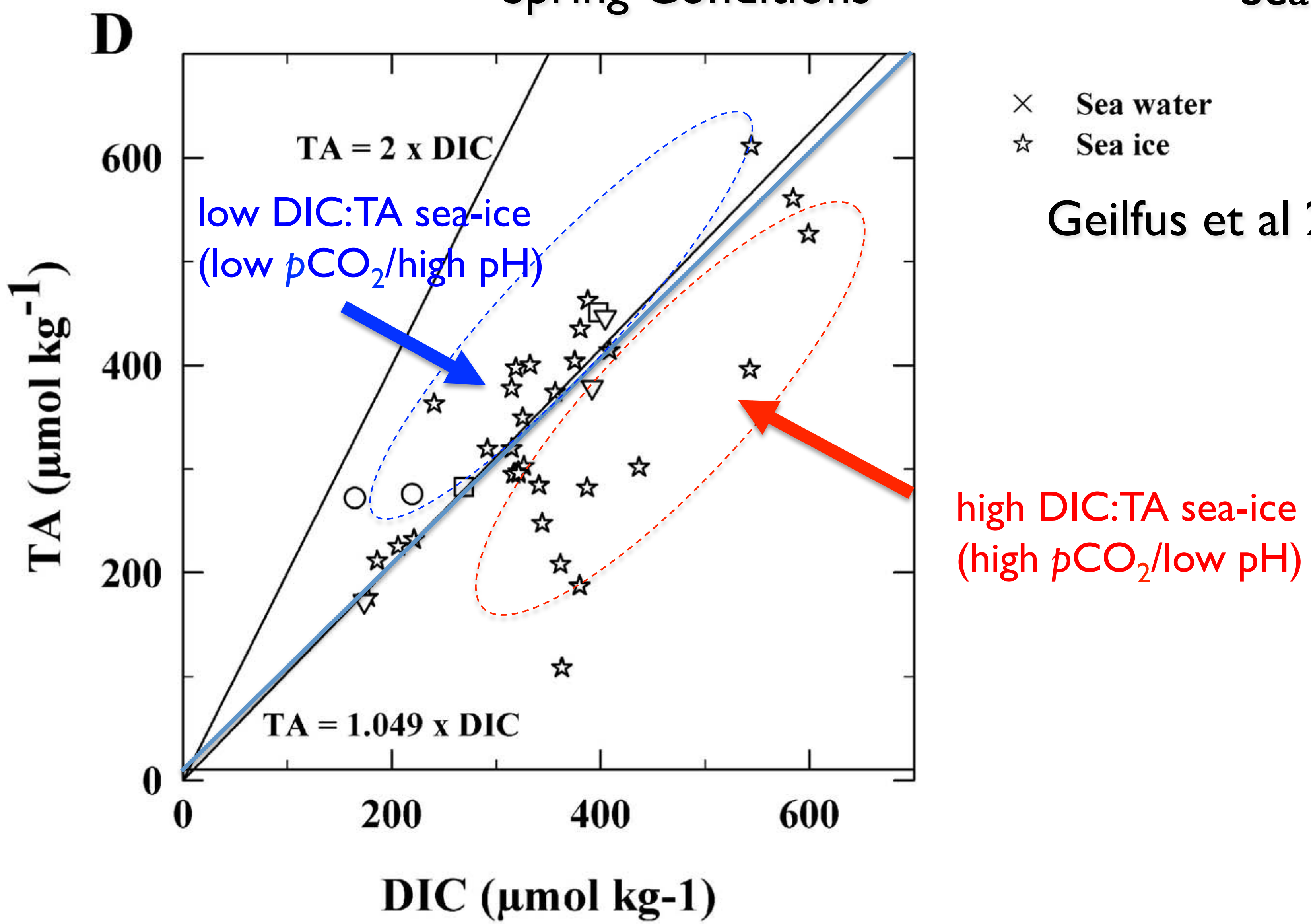
Study	Location	Period	Season	pCO_2 (µatm)	pH	$\Omega_{calcite}$	$\Omega_{aragonite}$
Sea-Ice							
Miller et al., 2011a	Arctic	Nov. to Dec	Fall	<1	8.20	0.42	0.25
Miller et al., 2011a	Arctic	Nov. to Dec	Fall	<1	8.97	1.75	0.96
Rysgaard et al. 2007	Arctic	March	Spring	<1 to 6	9.1-10.4	1.6-5.5	0.86-3.0
Crabeck et al. 2014	Arctic	March	Spring	60 to 330 (1)			
Miller et al., 2011b	Arctic	April to June	Spring	103 to 197	7.7-7.97	<0.1	<0.1
Sejr et al. 2011	Greenland	March/April	Spring	165 and 195			
Rysgaard et al. 2007	Arctic	April	Spring	204 to 522	7.36-7.8	<0.05	<0.05
Delille et al., 2007	Antarctic	Nov. to Dec	Spring	<10 to 420	8.0-8.7	0.5	0.3-0.19
Sogaard et al., 2013	Arctic	April	Spring	<2 to ~10			
Sogaard et al., 2013	Arctic	May	Spring	~5 to ~145			
Geilfus et al. 2012a	Arctic	June	Spring	50 to 1800	8.4-6.2	0.56-<0.1	0.3-<0.1
Fransson et al 2011	Antarctic	Dec. to Jan	Spring	<10	9.3	14.8	9.3
Rysgaard et al. 2011	Arctic	not given	Spring	< 1	10.0	<0.1	<0.1
Rysgaard et al. 2011	Antarctic	not given	Spring	< 1	10.0	<0.1	<0.1

Bates et al., 2014

Sea-ice CO_2-carbonate chemistry

Spring Conditions

Sea-ice



Geilfus et al 2012

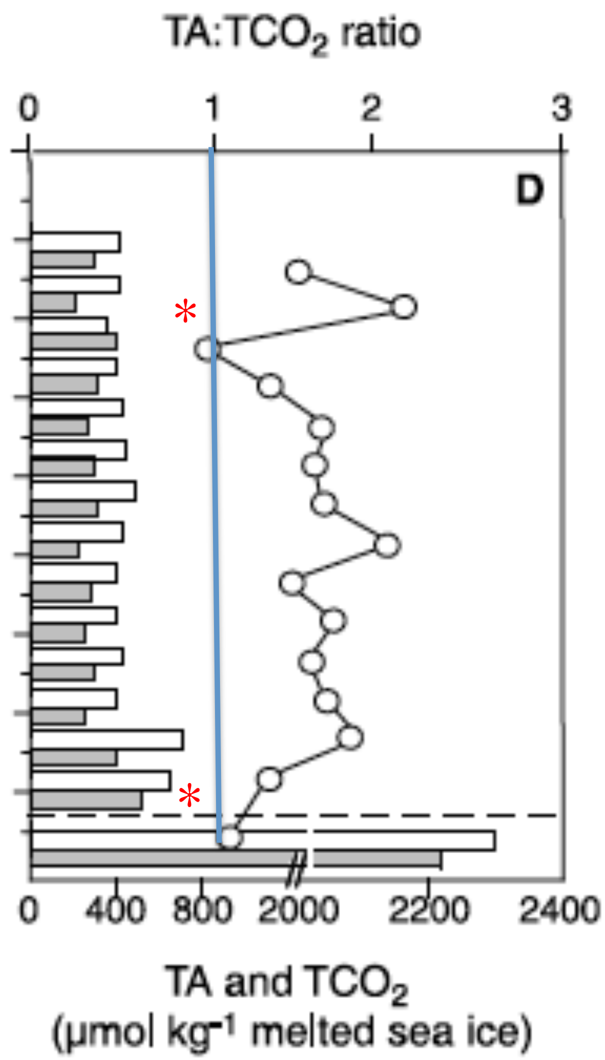
Geilfus et al., 2012

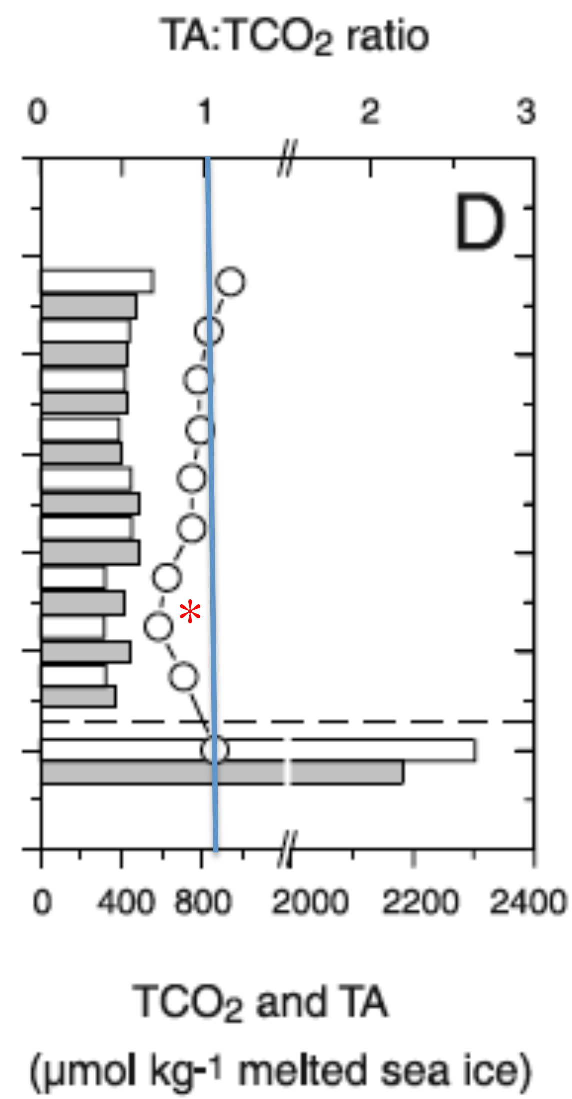
Bates et al, OCB Meeting 2014

Sea-ice CO_2-carbonate chemistry

Spring Conditions

Sea-ice





Geilfus et al 2012

DIC>TA in sea-ice
(high $p CO_2$/low pH)

TA, µmol kg^{-1} Melted Sea Ice	TCO_2, µmol kg^{-1} Melted Sea Ice	TA:TCO_2, mol mol^{-1}
426 ± 15	320 ± 18	1.33 ± 0.05
403 ± 20	278 ± 16	1.45 ± 0.06
457 ± 19	369 ± 7	1.24 ± 0.06
425 ± 26	285 ± 21	1.49 ± 0.08
573 ± 25	258 ± 19	2.22 ± 0.19
424 ± 24	463 ± 15	0.92 ± 0.03
414 ± 11	425 ± 23	0.97 ± 0.03
406 ± 26	439 ± 13	0.93 ± 0.03
541 ± 34	465 ± 27	1.16 ± 0.01

ice as in Figure 1. YS represents Young Sound, and FB

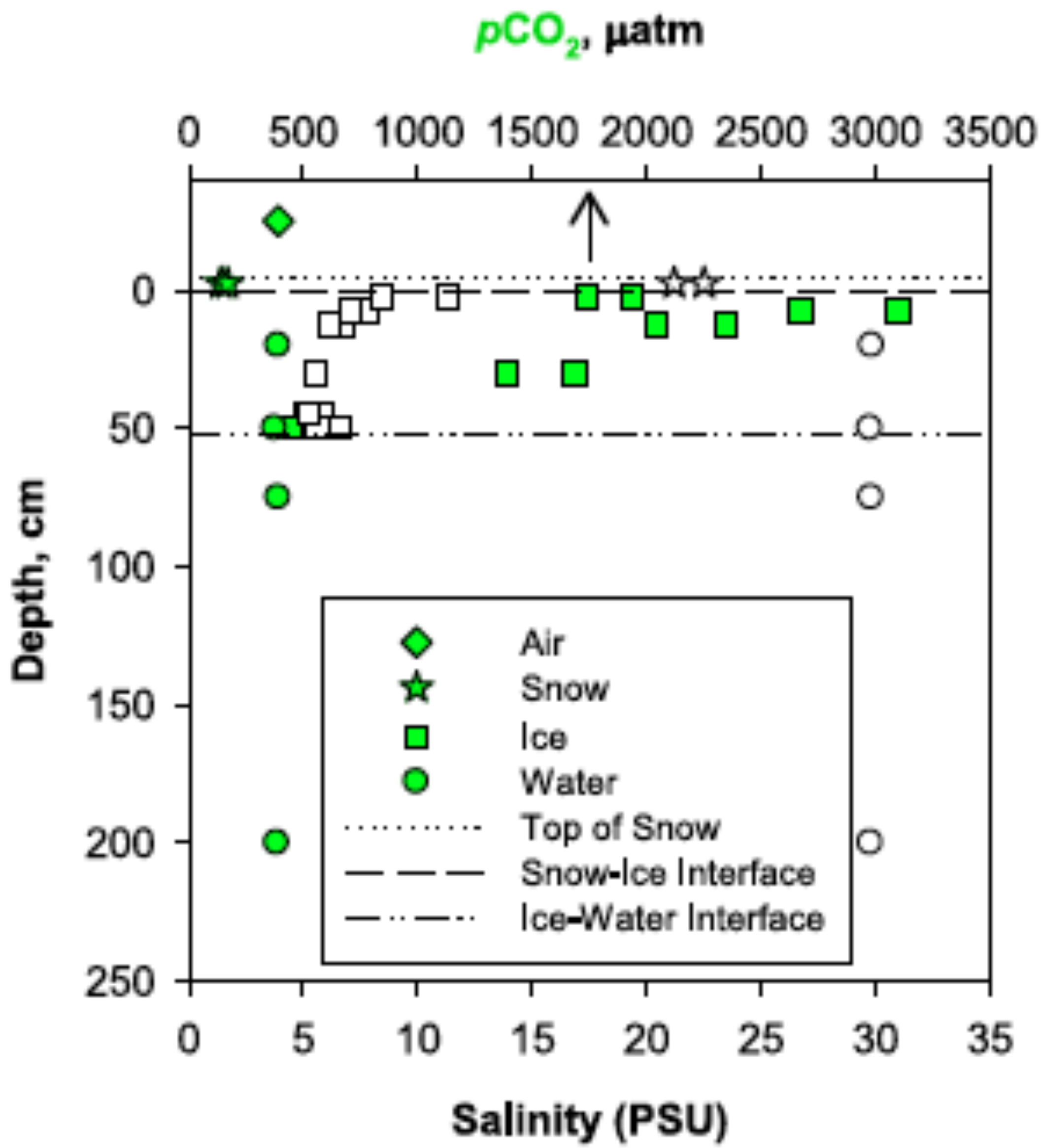
Geilfus et al., 2012

Bates et al, OCB Meeting 2014

Sea-ice CO_2-carbonate chemistry

Sea-ice formation/freeze-up

Sea-ice

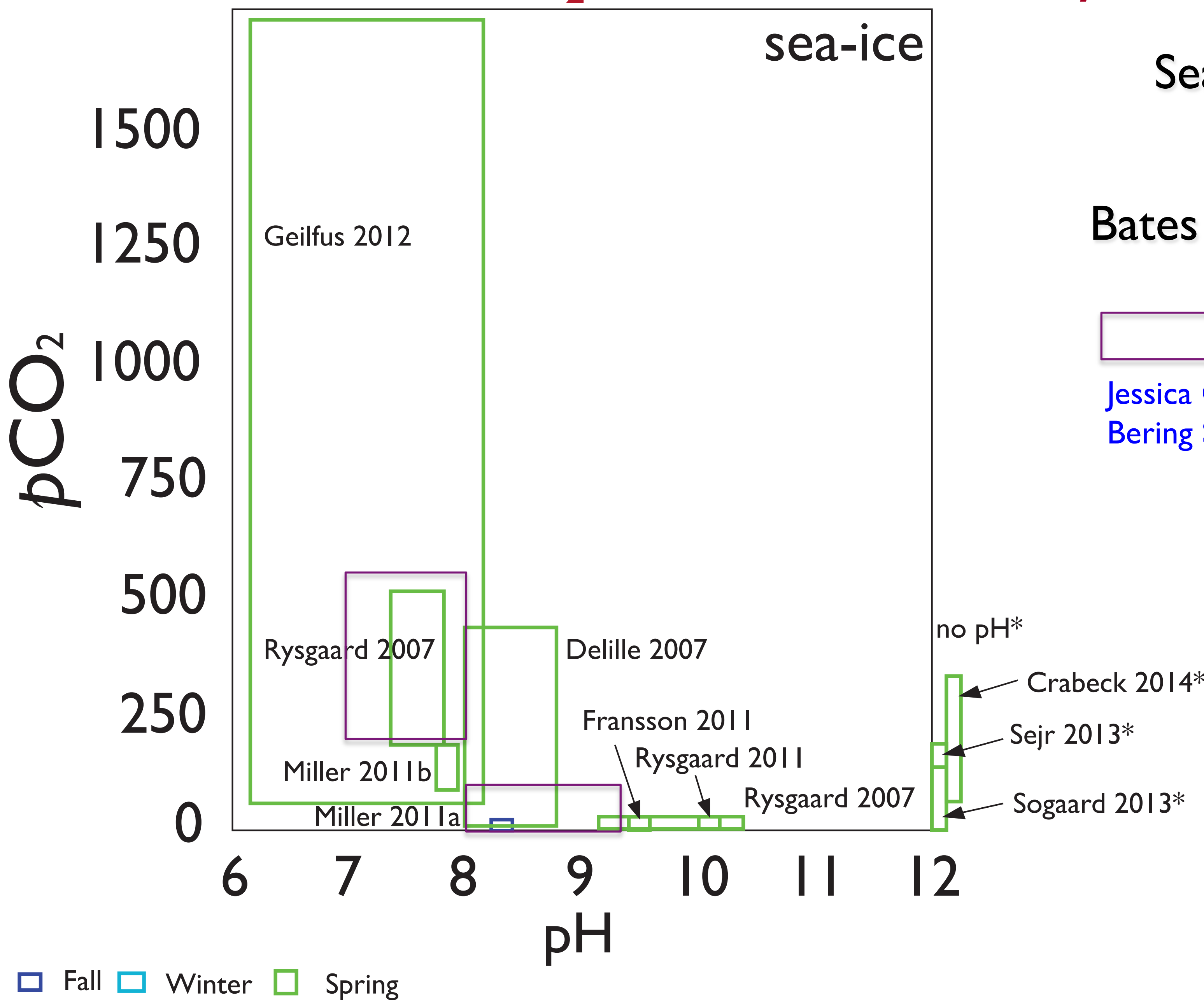


Miller et al 2011b

Miller et al., 2011b

Bates et al, OCB Meeting 2014

Sea-ice CO_2-carbonate chemistry



Sea-ice

Bates et al 2014

Jessica Cross, 2014
Bering Sea data

Bates et al., 2014

Bates et al, OCB Meeting 2014

Sea-ice CO_2-carbonate chemistry

Sea-ice

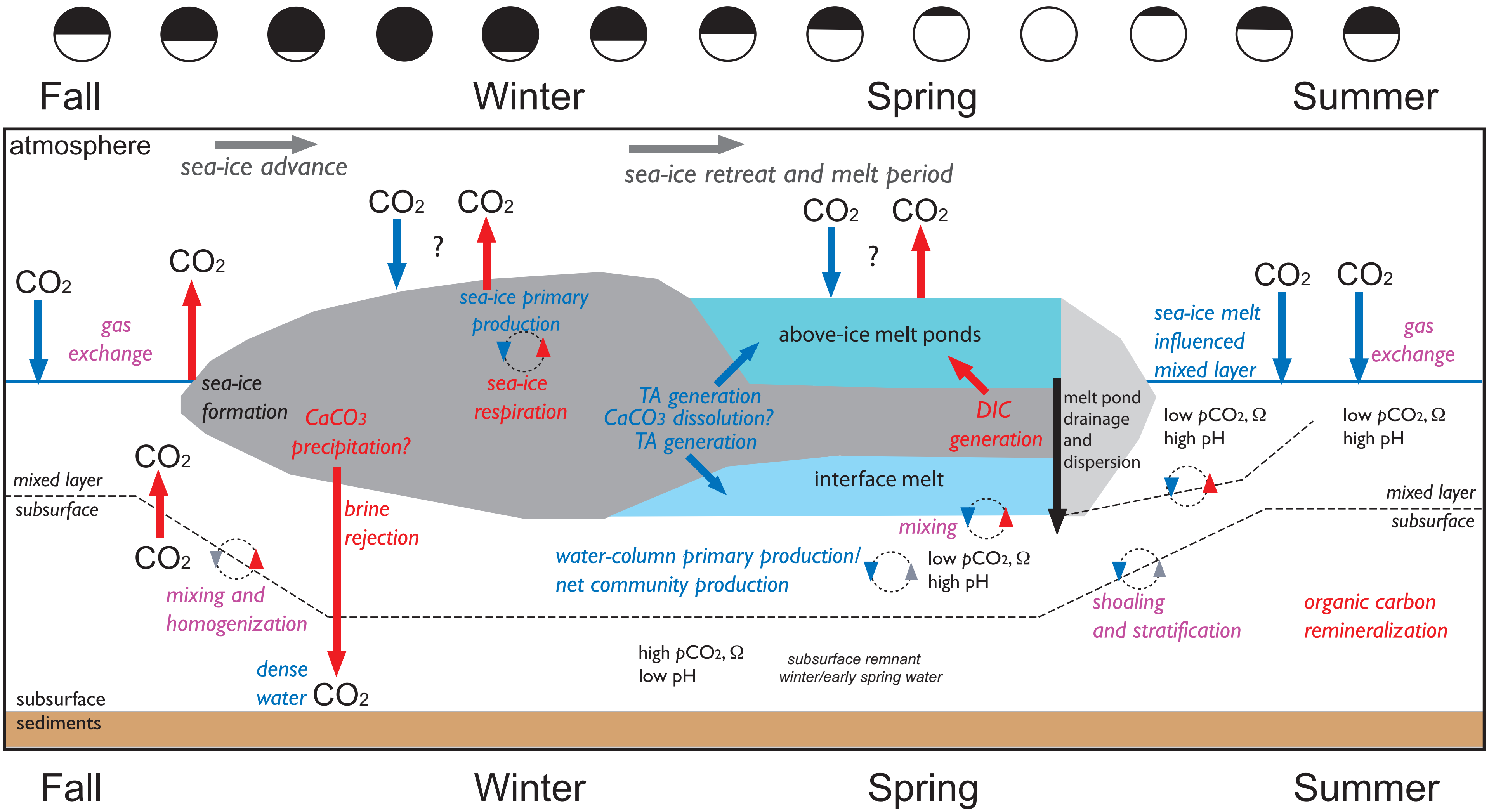
Table 1. Summary of measured and calculated pCO_2 values reported in sea-ice brine, sea-ice and melt ponds. The studies are arranged in seasonal order from fall to spring observations where possible (from Bates et al., 2014).

Study	Location	Period	Season	pCO_2 (µatm)	pH	$\Omega_{calcite}$	$\Omega_{aragonite}$
Sea-Ice							
Miller et al., 2011a	Arctic	Nov. to Dec	Fall	<1	8.20	0.42	0.25
Miller et al., 2011a	Arctic	Nov. to Dec	Fall	<1	8.97	1.75	0.96
Rysgaard et al. 2007	Arctic	March	Spring	<1 to 6	9.1-10.4	1.6-5.5	0.86-3.0
Crabeck et al. 2014	Arctic	March	Spring	60 to 330 (1)			
Miller et al., 2011b	Arctic	April to June	Spring	103 to 197	7.7-7.97	<0.1	<0.1
Sejr et al. 2011	Greenland	March/April	Spring	165 and 195			
Rysgaard et al. 2007	Arctic	April	Spring	204 to 522	7.36-7.8	<0.05	<0.05
Delille et al., 2007	Antarctic	Nov. to Dec	Spring	<10 to 420	8.0-8.7	0.5	0.3-0.19
Sogaard et al., 2013	Arctic	April	Spring	<2 to ~10			
Sogaard et al., 2013	Arctic	May	Spring	~5 to ~145			
Geilfus et al. 2012a	Arctic	June	Spring	50 to 1800	8.4-6.2	0.56-<0.1	0.3-<0.1
Fransson et al 2011	Antarctic	Dec. to Jan	Spring	<10	9.3	14.8	9.3
Rysgaard et al. 2011	Arctic	not given	Spring	< 1	10.0	<0.1	<0.1
Rysgaard et al. 2011	Antarctic	not given	Spring	< 1	10.0	<0.1	<0.1

Bates et al., 2014

Sea-ice CO_2-carbonate chemistry

Seasonal changes in generic sea-ice impacted shelf

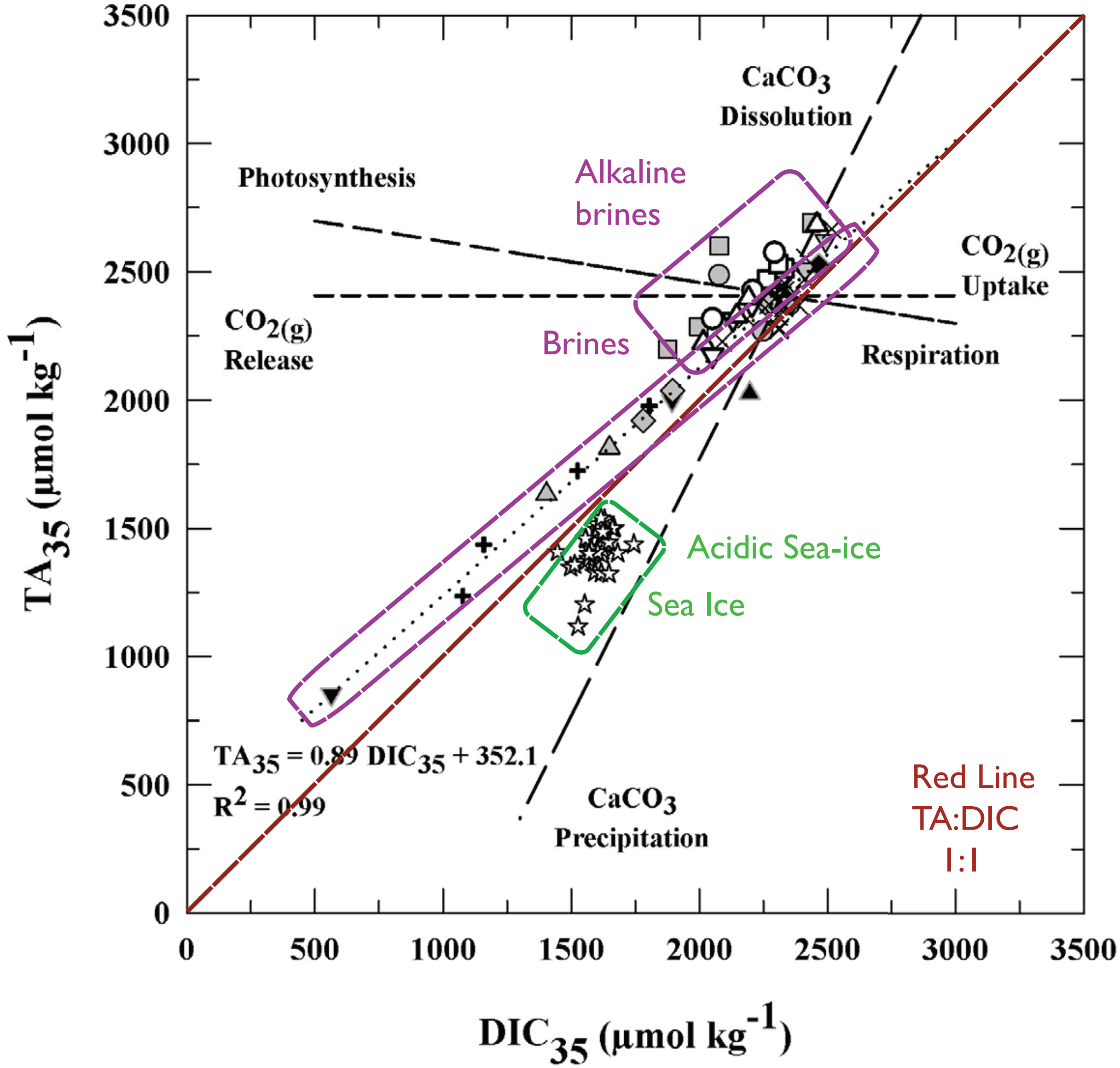


Bates et al., 2014

Bates et al, OCB Meeting 2014

Sea-ice CO_2-carbonate chemistry

Spring Conditions



Brines

Geilfus et al 2012

- Alkaline brines
- Acidic sea-ice (melted)

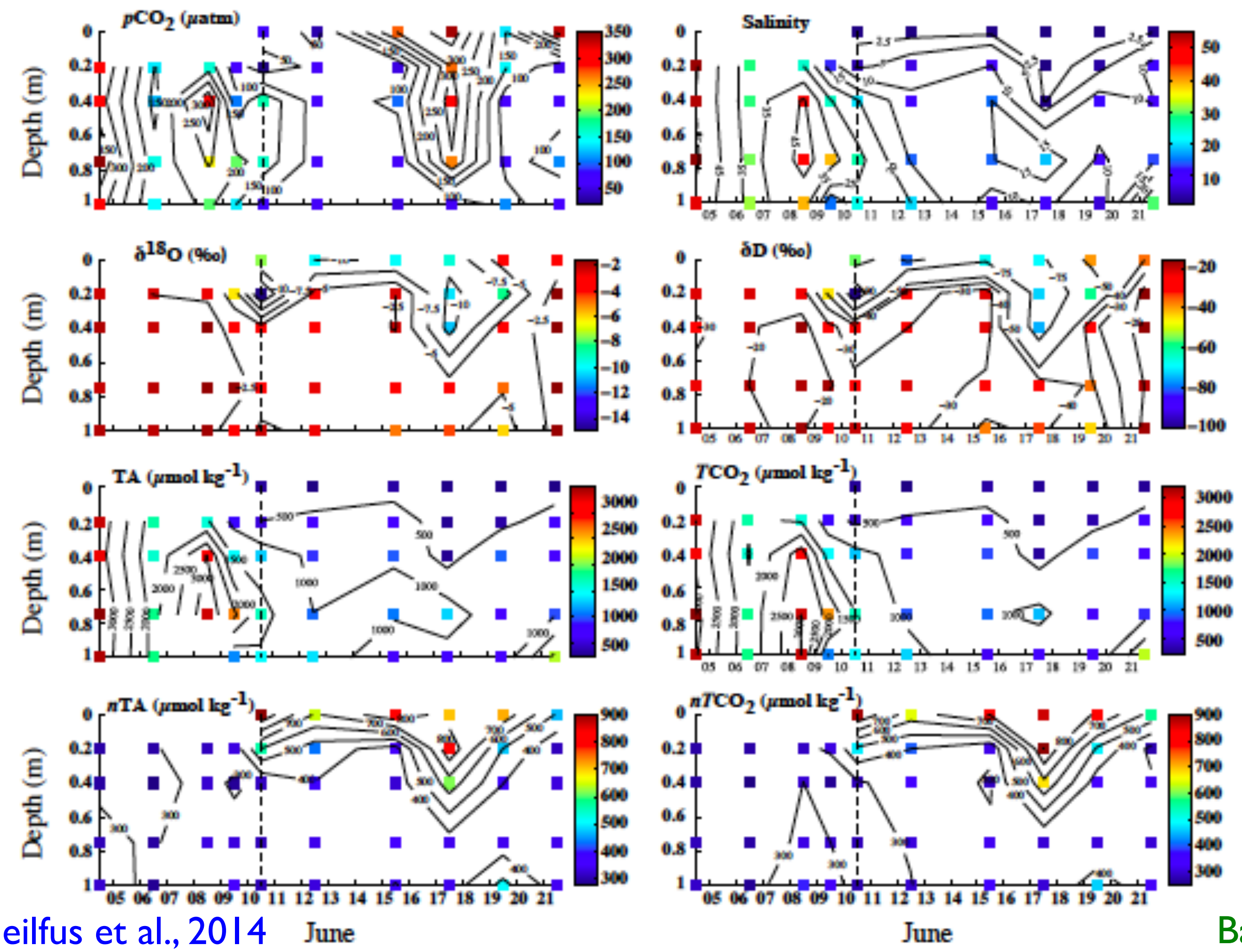
Geilfus et al., 2012

Bates et al, OCB Meeting 2014

Sea-ice CO_2-carbonate chemistry

Spring Conditions

Sea-ice Brines



Decrease in pCO_2

Geilfus et al 2014

Decrease in DIC and TA

June

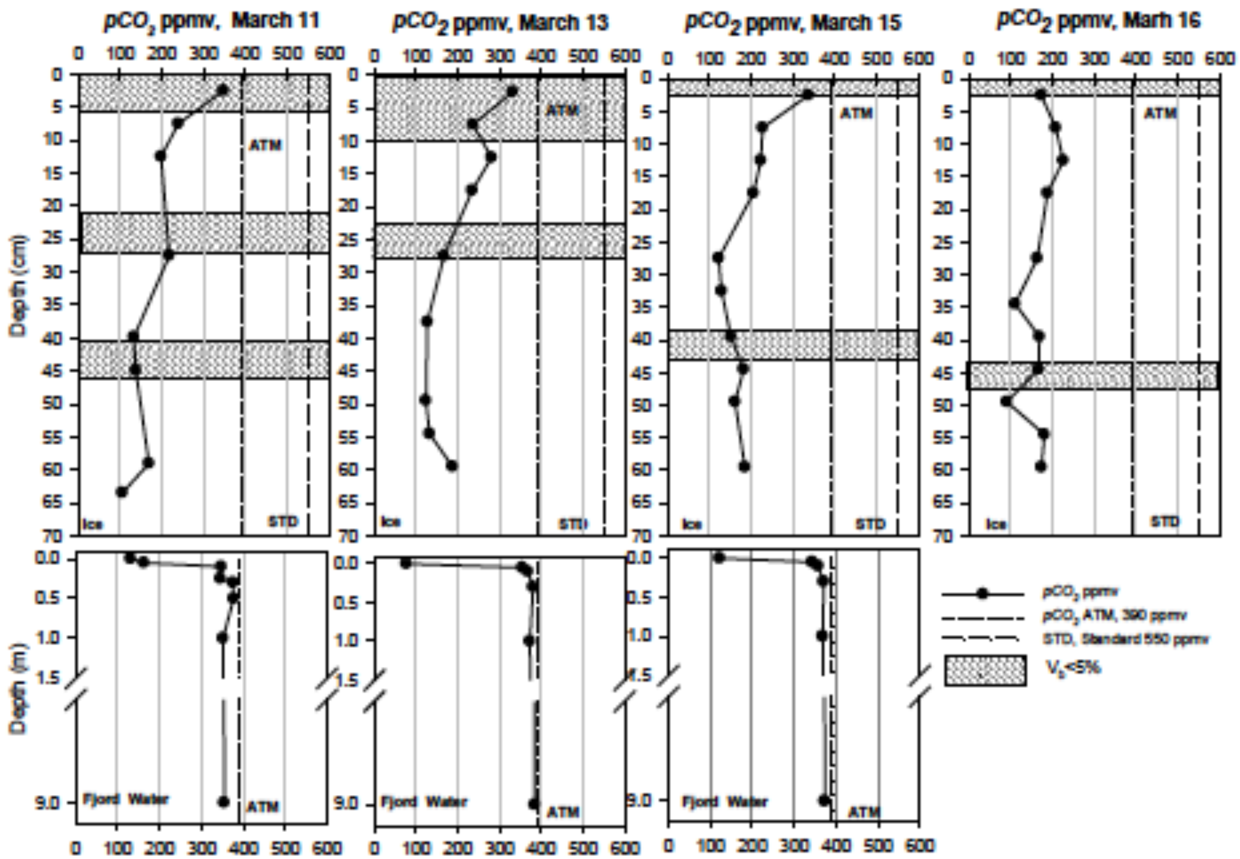
Geilfus et al., 2014

Bates et al, OCB Meeting 2014

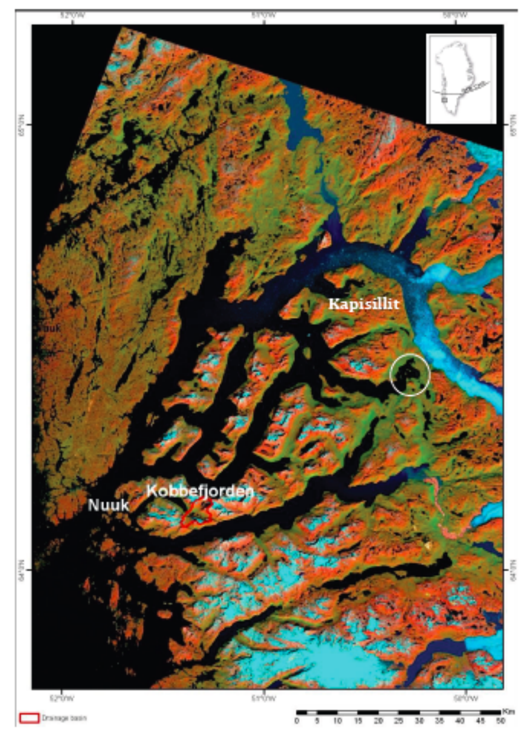
Sea-ice CO_2-carbonate chemistry

Spring Conditions

March



Crabeck et al., 2014



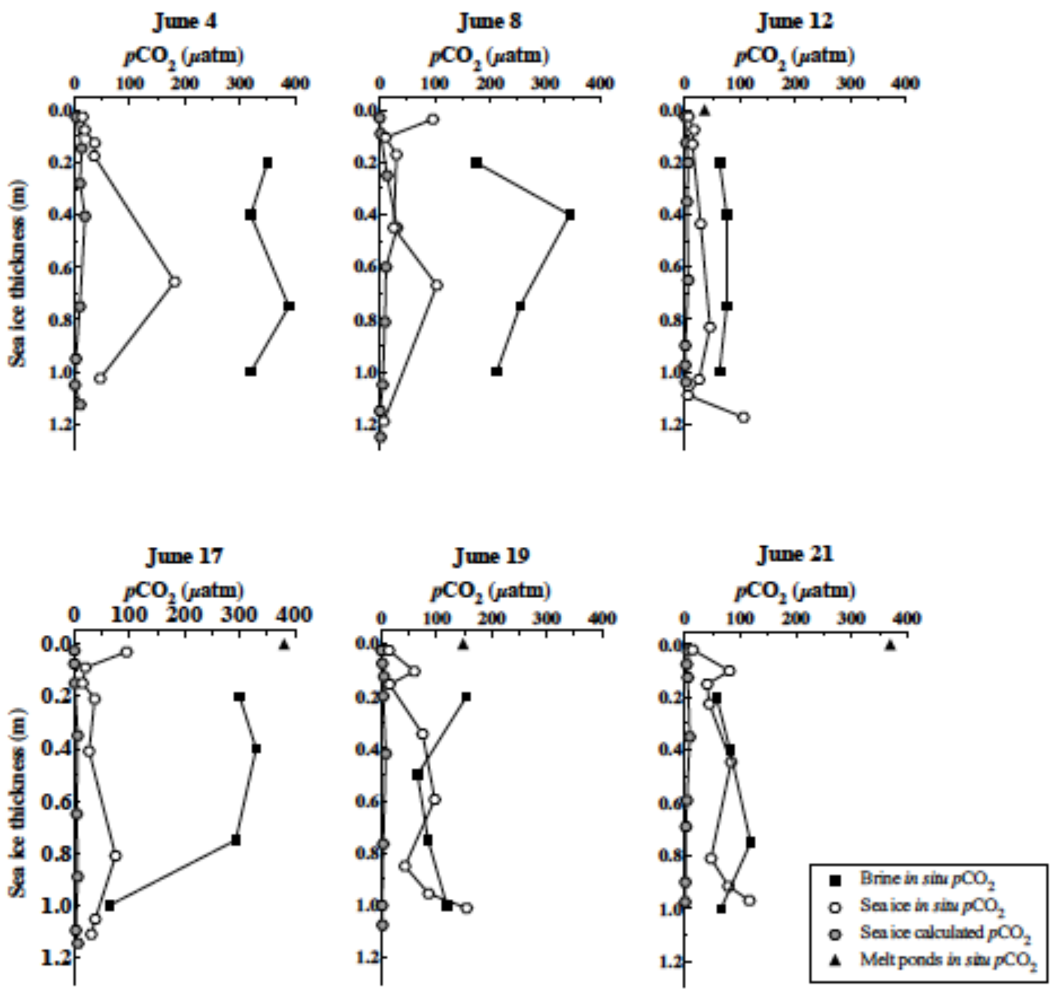
Crabeck et al., 2014

Bates et al, OCB Meeting 2014

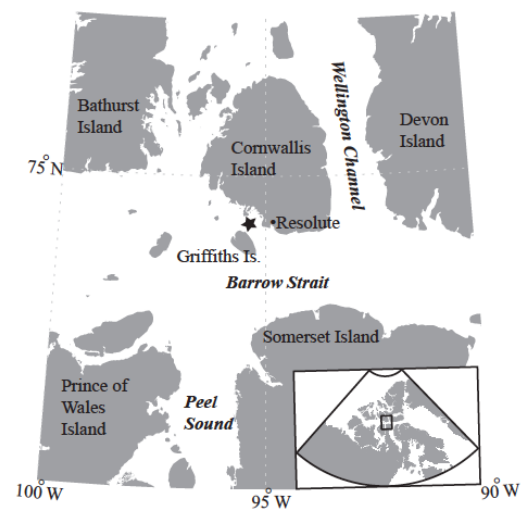
Sea-ice CO_2-carbonate chemistry

Spring Conditions

Sea-ice Brines



June



Geilfus et al., 2014

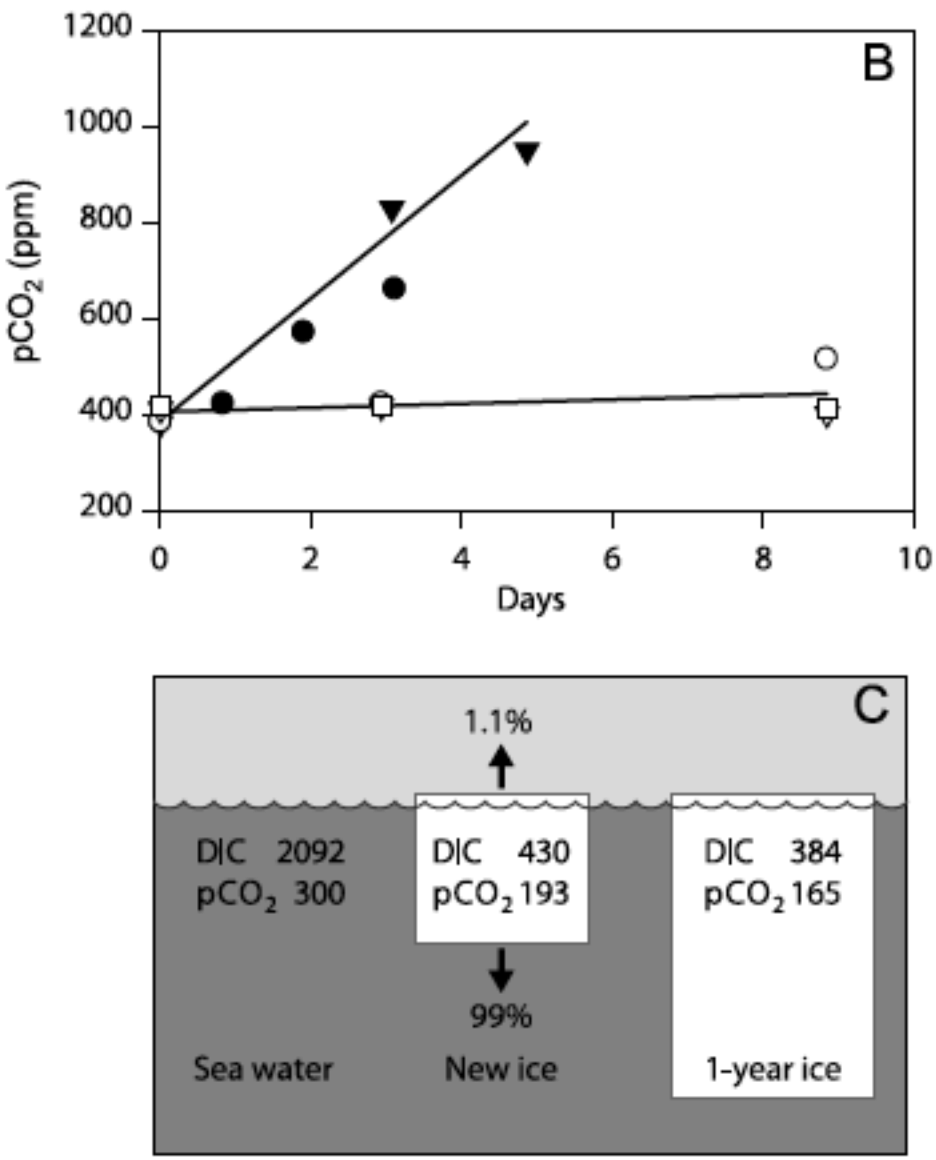
Geilfus et al., 2014

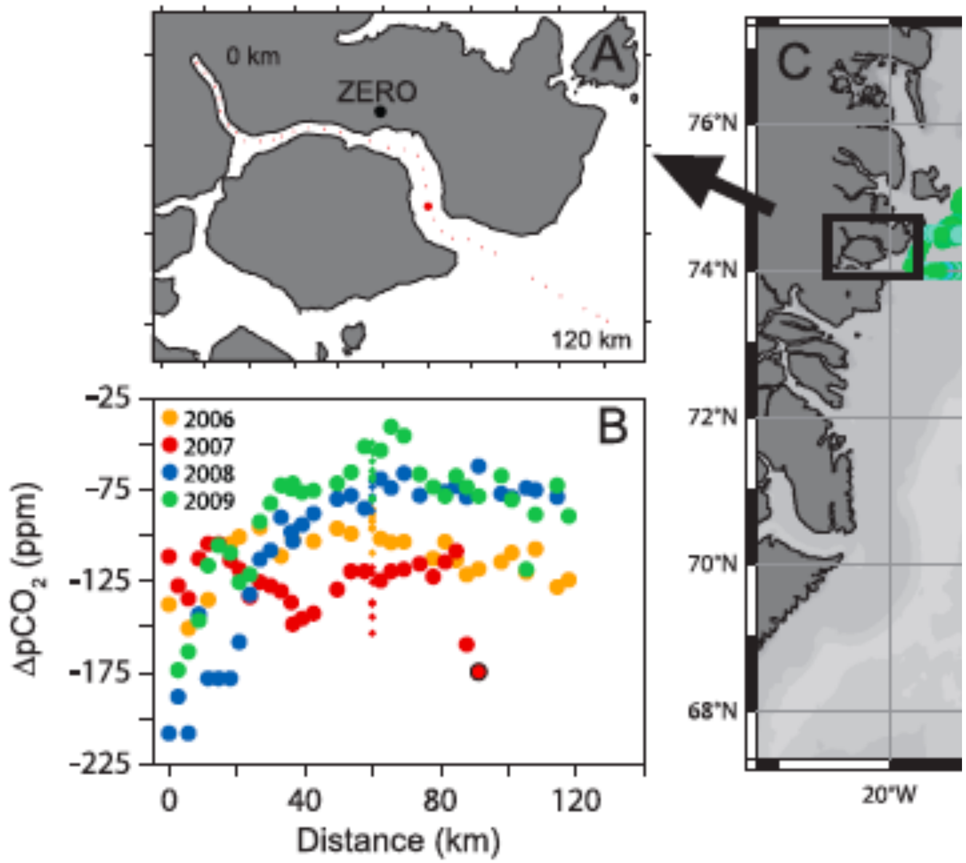
Bates et al, OCB Meeting 2014

Sea-ice CO_2-carbonate chemistry

Brines

Sejr et al 2012





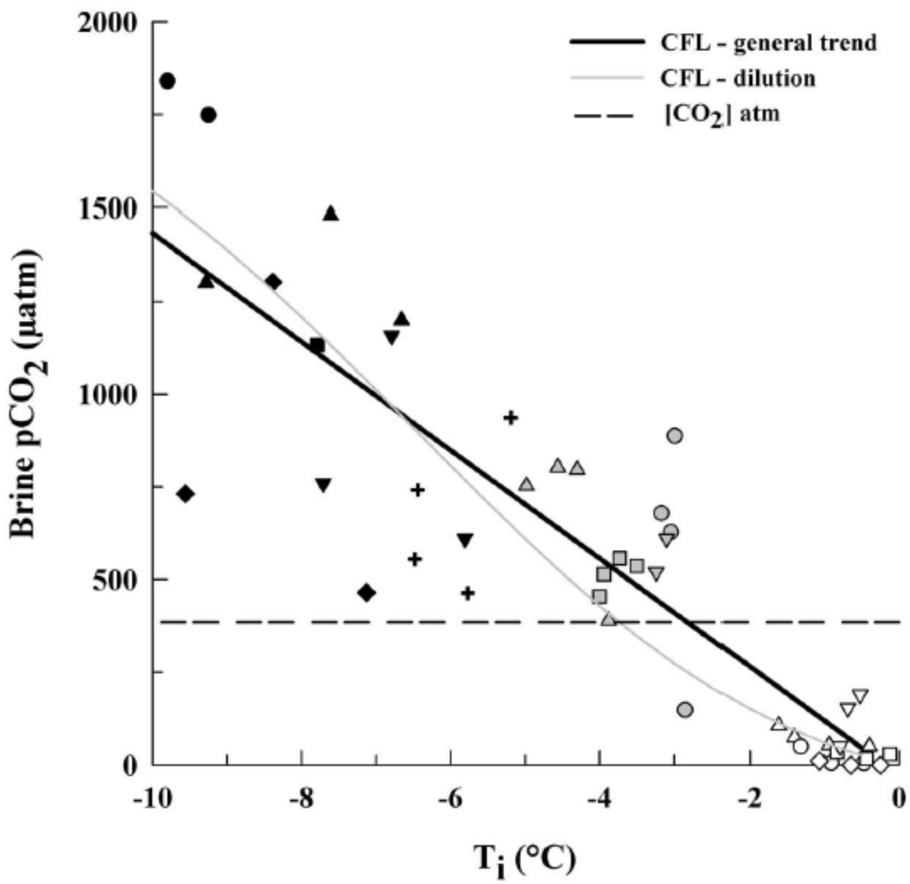
Sejr et al., 2012

Bates et al, OCB Meeting 2014

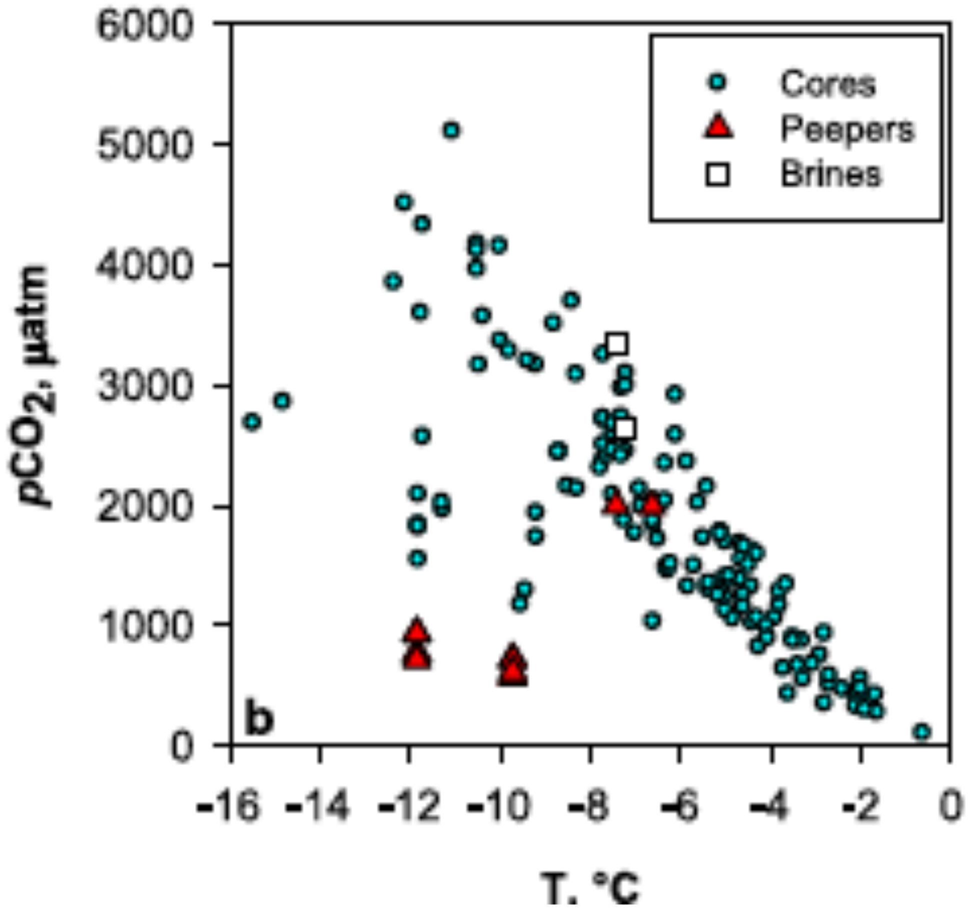
Sea-ice CO_2-carbonate chemistry

Spring Conditions

Brines/
Sea ice



Geilfus et al., 2012

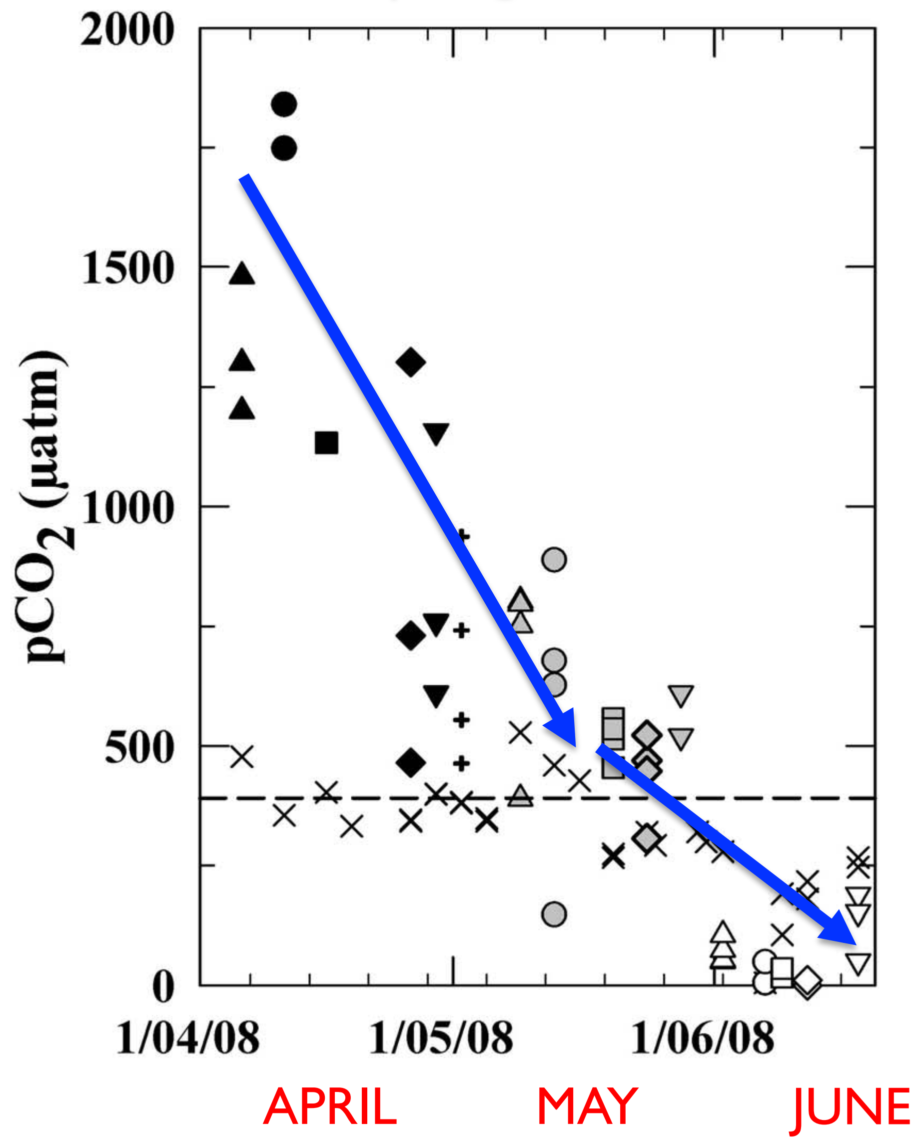


Miller et al., 2011b

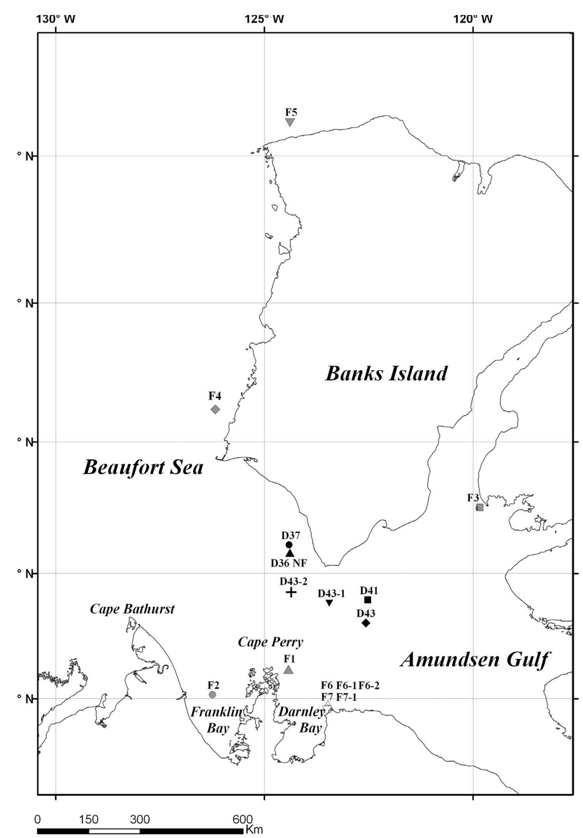
Sea-ice CO_2-carbonate chemistry

Spring Conditions: Seasonal Changes

Brines



seasonal decrease of
pCO_2 in brines



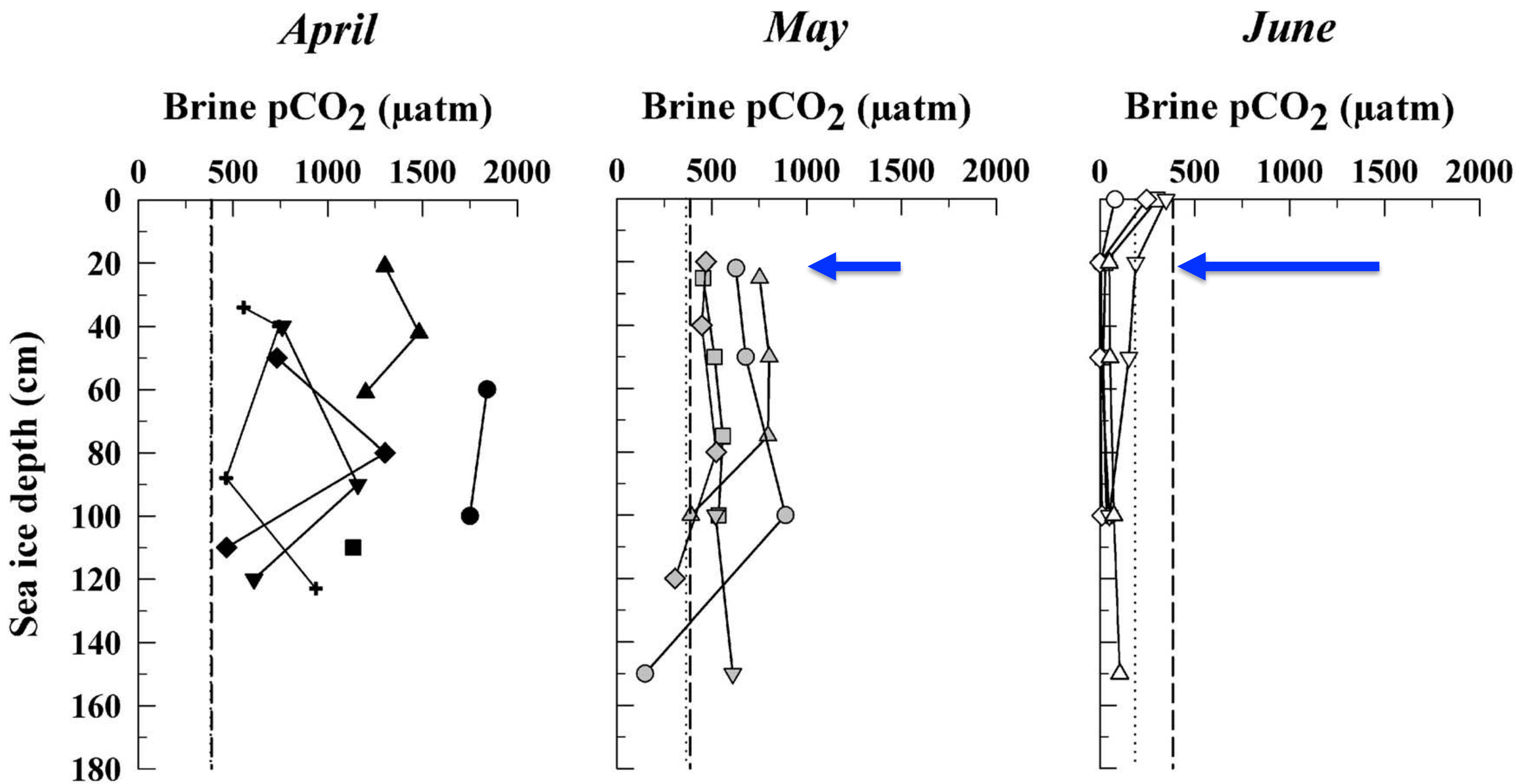
Geilfus et al., 2012

Bates et al, OCB Meeting 2014

Sea-ice CO_2-carbonate chemistry

Geilfus et al., 2012

Brines

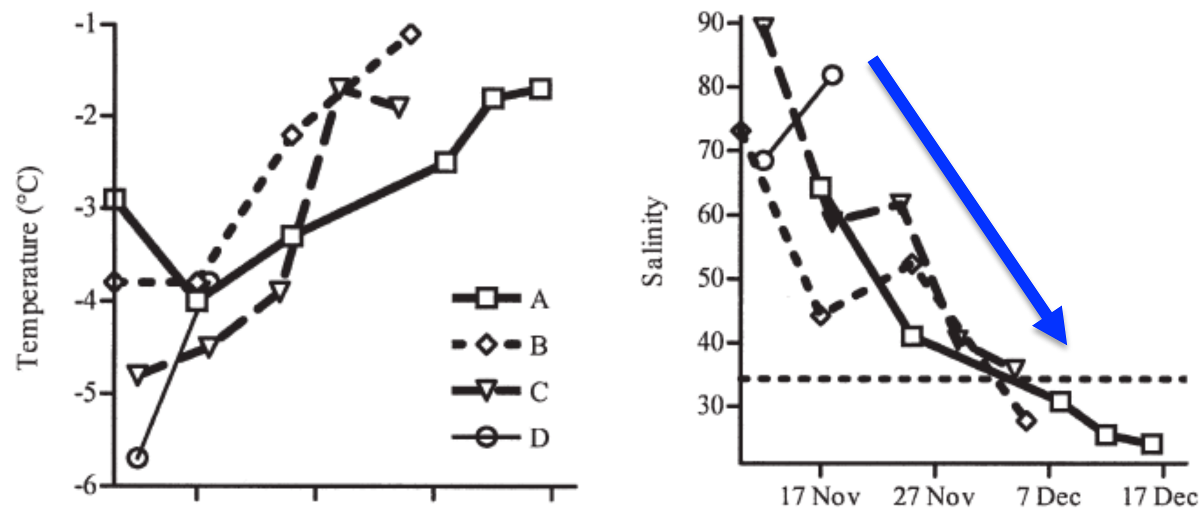


seasonal decrease of $p$$CO_2$ in brines

Geilfus et al., 2012

Bates et al, OCB Meeting 2014

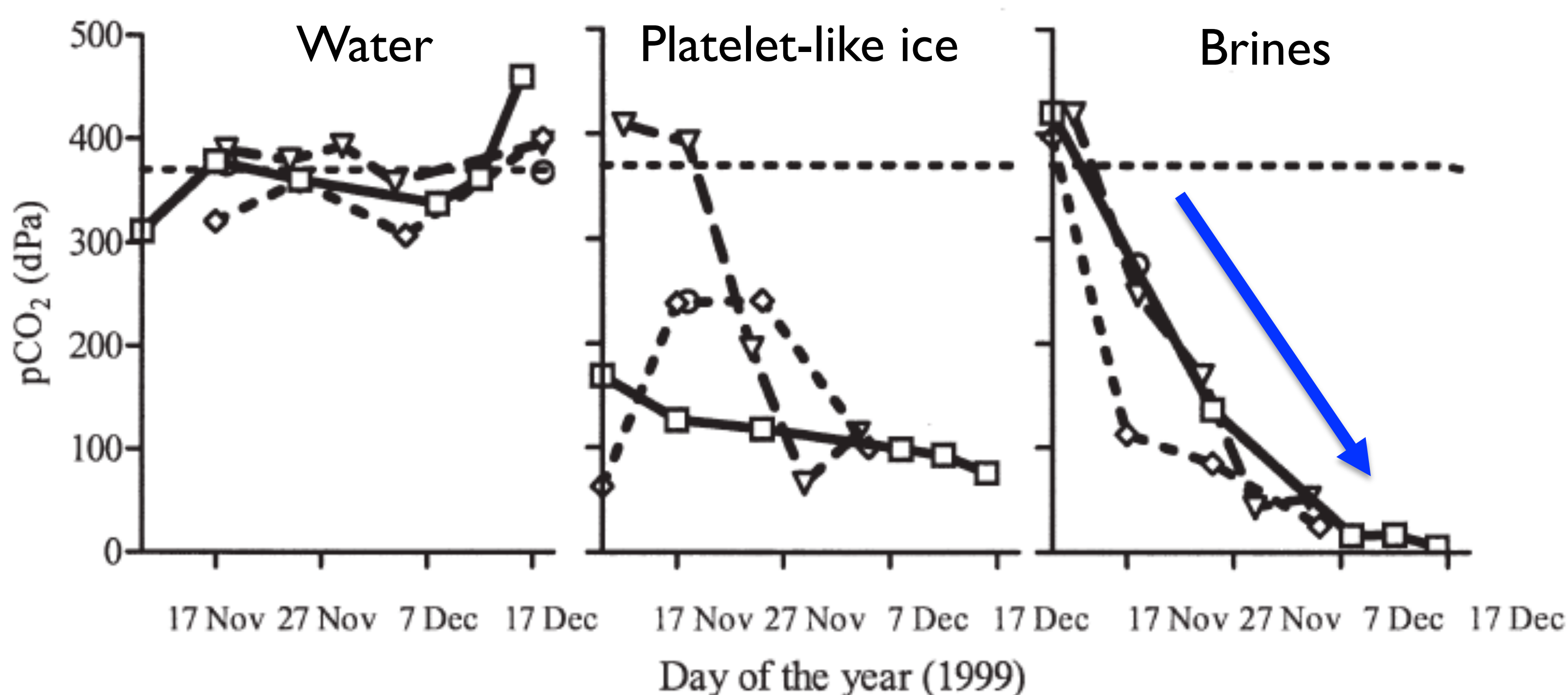
Sea-ice CO_2-carbonate chemistry



Brines

seasonal decrease of pCO_2 in brines

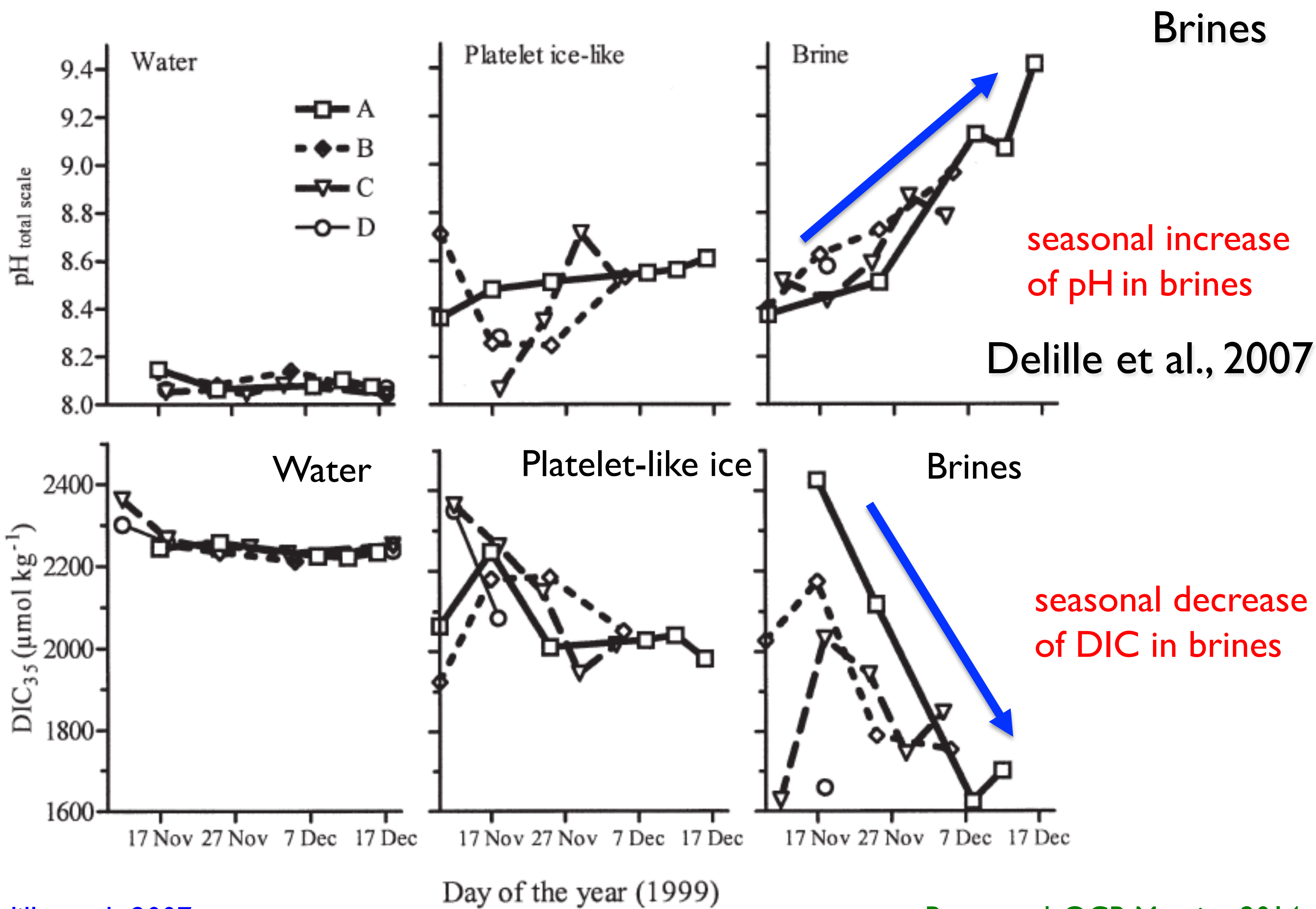
Delille et al., 2007



Delille et al., 2007

Bates et al, OCB Meeting 2014

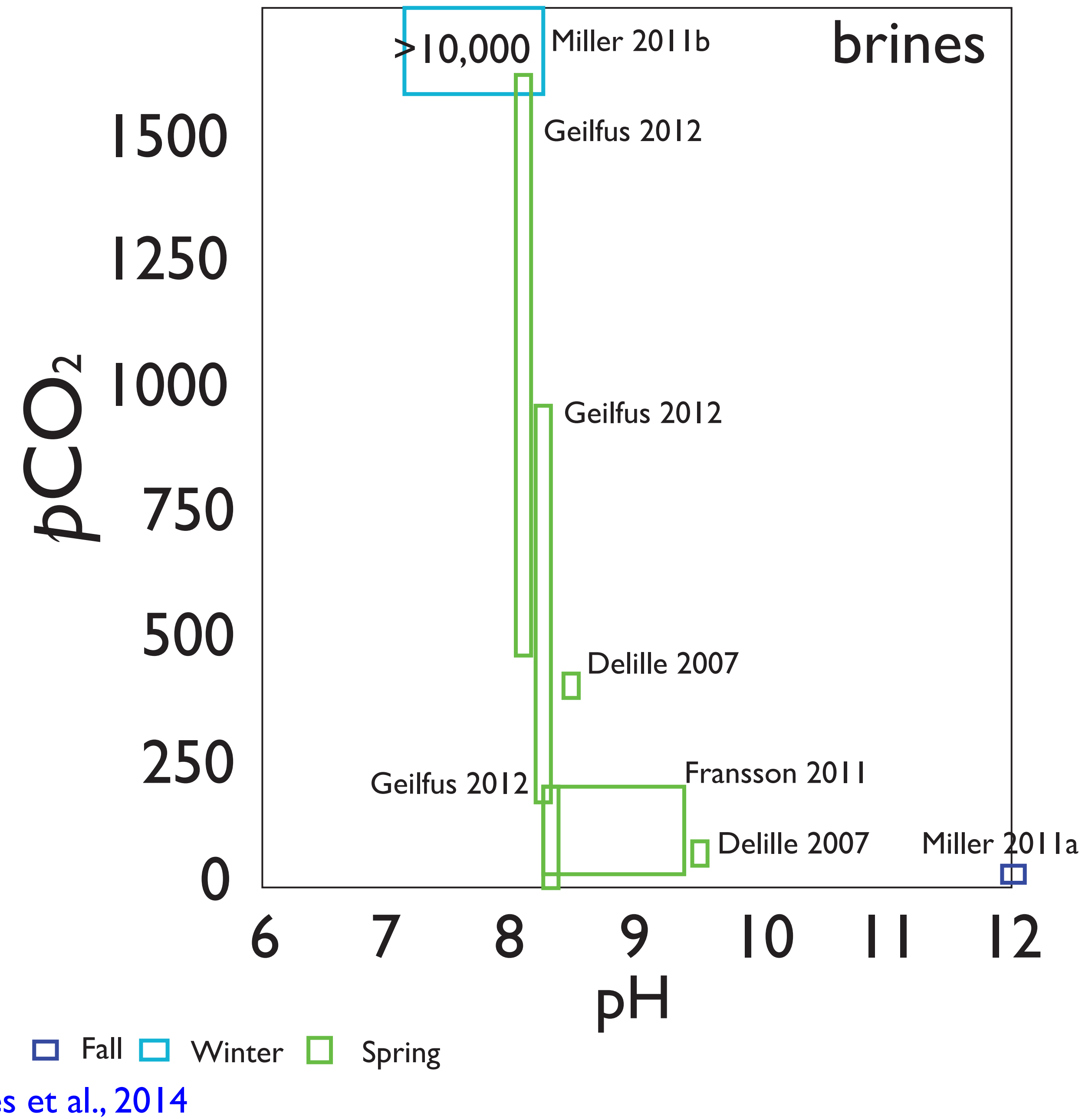
Sea-ice CO_2-carbonate chemistry



Delille et al., 2007

Bates et al, OCB Meeting 2014

Sea-ice CO_2-carbonate chemistry



Brines in sea-ice

Bates et al., 2014

Bates et al, 2014

Sea-ice CO_2-carbonate chemistry

Sea-ice Brines

Study	Location	Period	Season	pCO_2 (μatm)	pH	$\Omega_{calcite}$	$\Omega_{aragonite}$
Brine							
Miller et al., 2011a	Arctic	Nov. to Dec	Fall	<1	12.4	22.5	4.6
Miller et al., 2011b	Arctic	Dec to Mar	Winter	~800 to 12,000	8.2 to 7.1	11.9-1.3	0.8-7.4
Miller et al., 2011b	Arctic	April to June	Spring	~800 to 12,000	8.2 to 7.1	1.3-11.9	0.8-7.4
Geilfus et al. 2012a	Arctic	April	Spring	465 to 1834	8.0	3.0	1.6
Geilfus et al. 2012a	Arctic	May	Spring	147 to 888	8.2	1.5	<0.1
Delille et al., 2007	Antarctic	November	Spring	~100	9.42	>20	>6
Delille et al., 2007	Antarctic	December	Spring	~420	8.38	3.4	1.8
Geilfus et al. 2012a	Arctic	June	Spring	0 to 180	8.3	0.1	<0.1
Geilfus et al. 2014	Arctic	June	Spring	20 to 389			
Fransson et al 2011	Antarctic	Dec. to Jan	Spring	9 to 210	9.3-8.3	3.7-14.8	2.3-9.3

Table 1. Summary of measured and calculated pCO_2 values reported in sea-ice brine, sea-ice and melt ponds. The studies are arranged in seasonal order from fall to spring observations where possible. In most cases, pCO_2, pH, $\Omega_{calcite}$, and $\Omega_{aragonite}$ were calculated from TA and DIC, or from pCO_2 and pH. In the cases where values were reported in the original study, salinity and temperature values of 4 and 0°C were used in the calculations. (from Bates et al., 2014).

Bates et al., 2014

Sea-ice CO_2-carbonate chemistry

Sea-ice

Study	Location	Period	Season	pCO_2 (µatm)	pH	$\Omega_{calcite}$	$\Omega_{aragonite}$
Sea-Ice							
Miller et al., 2011a	Arctic	Nov. to Dec	Fall	<1	8.20	0.42	0.25
Miller et al., 2011a	Arctic	Nov. to Dec	Fall	<1	8.97	1.75	0.96
Rysgaard et al. 2007	Arctic	March	Spring	<1 to 6	9.1-10.4	1.6-5.5	0.86-3.0
Crabeck et al. 2014	Arctic	March	Spring	60 to 330 (1)			
Miller et al., 2011b	Arctic	April to June	Spring	103 to 197	7.7-7.97	<0.1	<0.1
Sejr et al. 2011	Greenland	March/April	Spring	165 and 195			
Rysgaard et al. 2007	Arctic	April	Spring	204 to 522	7.36-7.8	<0.05	<0.05
Delille et al., 2007	Antarctic	Nov. to Dec	Spring	<10 to 420	8.0-8.7	0.5	0.3-0.19
Sogaard et al., 2013	Arctic	April	Spring	<2 to ~10			
Sogaard et al., 2013	Arctic	May	Spring	~5 to ~145			
Geilfus et al. 2012a	Arctic	June	Spring	50 to 1800	8.4-6.2	0.56-<0.1	0.3-<0.1
Fransson et al 2011	Antarctic	Dec. to Jan	Spring	<10	9.3	14.8	9.3
Rysgaard et al. 2011	Arctic	not given	Spring	< 1	10.0	<0.1	<0.1
Rysgaard et al. 2011	Antarctic	not given	Spring	< 1	10.0	<0.1	<0.1

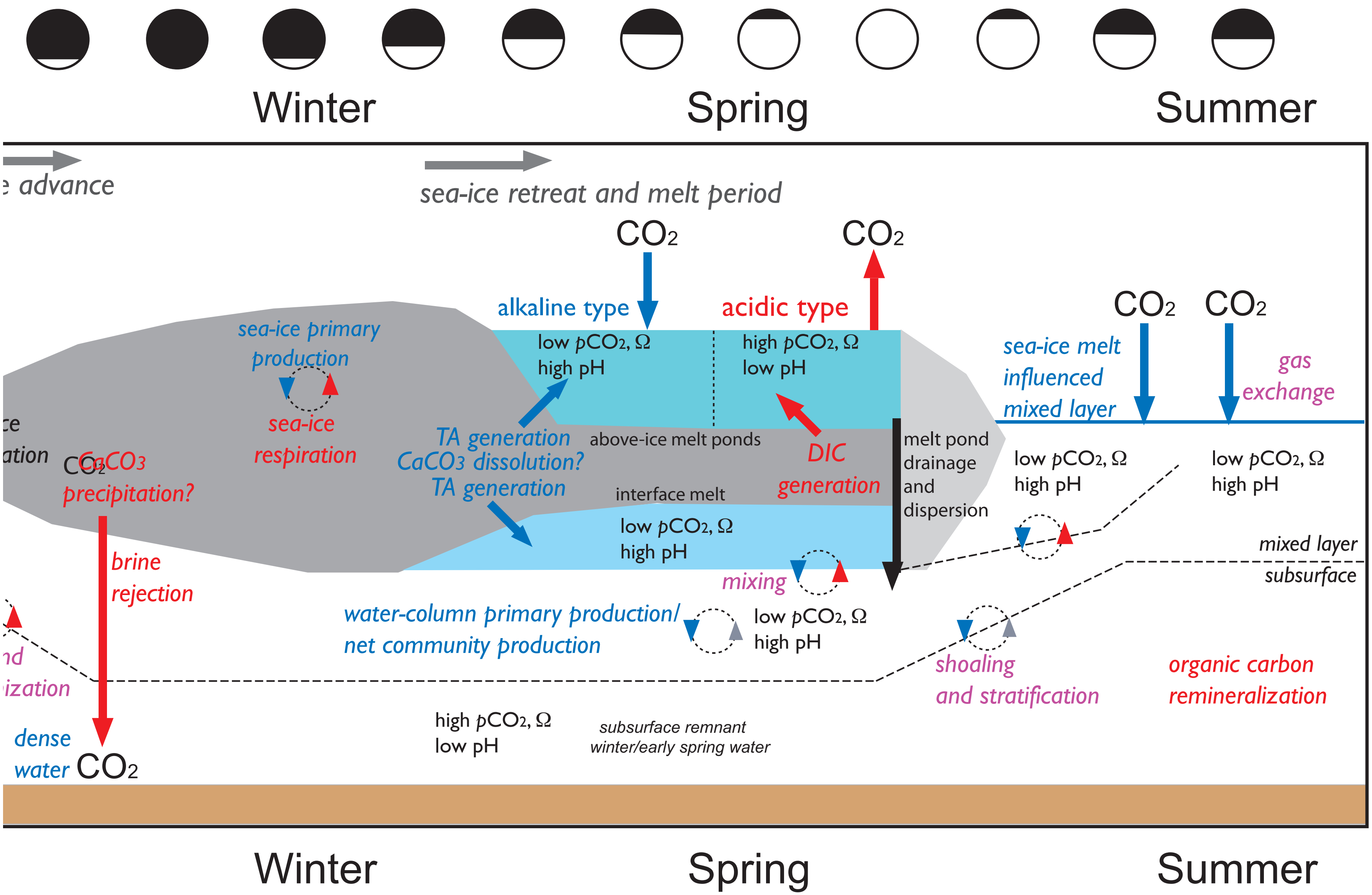
Table 1. Summary of measured and calculated pCO_2 values reported in sea-ice brine, sea-ice and melt ponds. The studies are arranged in seasonal order from fall to spring observations where possible (from Bates et al., 2014).

Bates et al., 2014

Bates et al, OCB Meeting 2014

Sea-ice CO_2-carbonate chemistry

Seasonal sea-ice melt ponds



Bates et al., 2014

Bates et al, OCB Meeting 2014

Sea-ice CO_2-carbonate chemistry

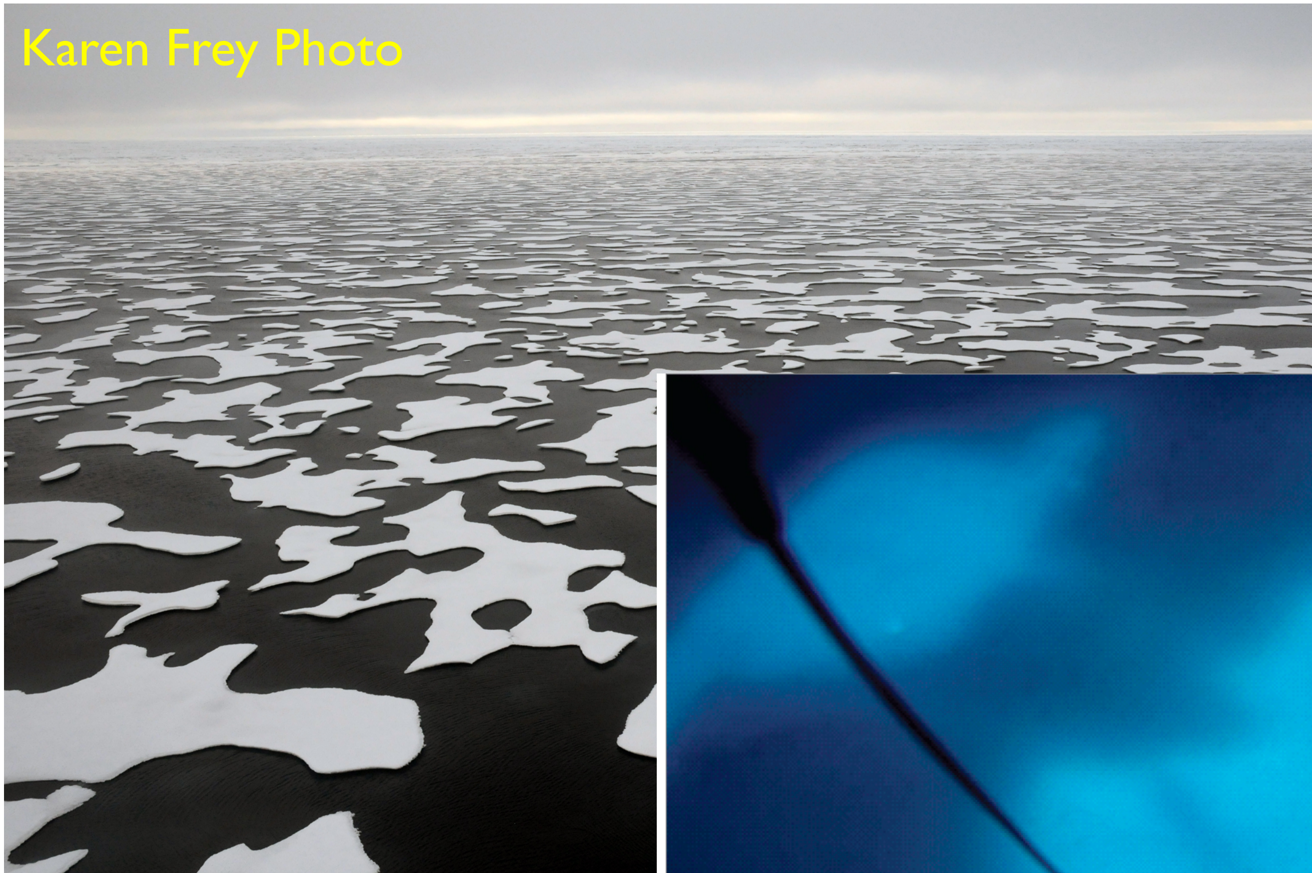
Seasonal sea-ice melt ponds

- 12 million km^2 extent in Arctic at present
- ~20% to 50% cover
- 2 to 4 week duration

Bates et al., 2014

Sea-ice CO_2-carbonate chemistry

Seasonal sea-ice melt ponds



- 12 million km^2 extent in Arctic at present
- ~20% to 50% cover
- 2 to 4 week duration

Bates et al., 2014

Bates et al, OCB Meeting 2014

Sea-ice CO_2-carbonate chemistry

Sea-ice melt ponds

Bates et al., 2014

Study	Location	Period	Season	pCO_2 (µatm)	pH	$\Omega_{calcite}$	$\Omega_{aragonite}$
Ice melt ponds							
Geilfus et al. 2012a	Arctic	June	Spring	79 to 348	n/a	n/a	n/a
this study (acidic type)	Arctic	June/July	Spring	355-1516	7.4 to 6.1	<0.1	<0.1
this study (alkaline)	Arctic	June/July	Spring	<1 to 60	10.8 to 8.6	2.6 to 0.2	1.5 to <0.1

NASA
ICESCAPE
2010 - 2011
Impacts of Climate Change on the EcoSystems and Chemistry of the Arctic Pacific Environment

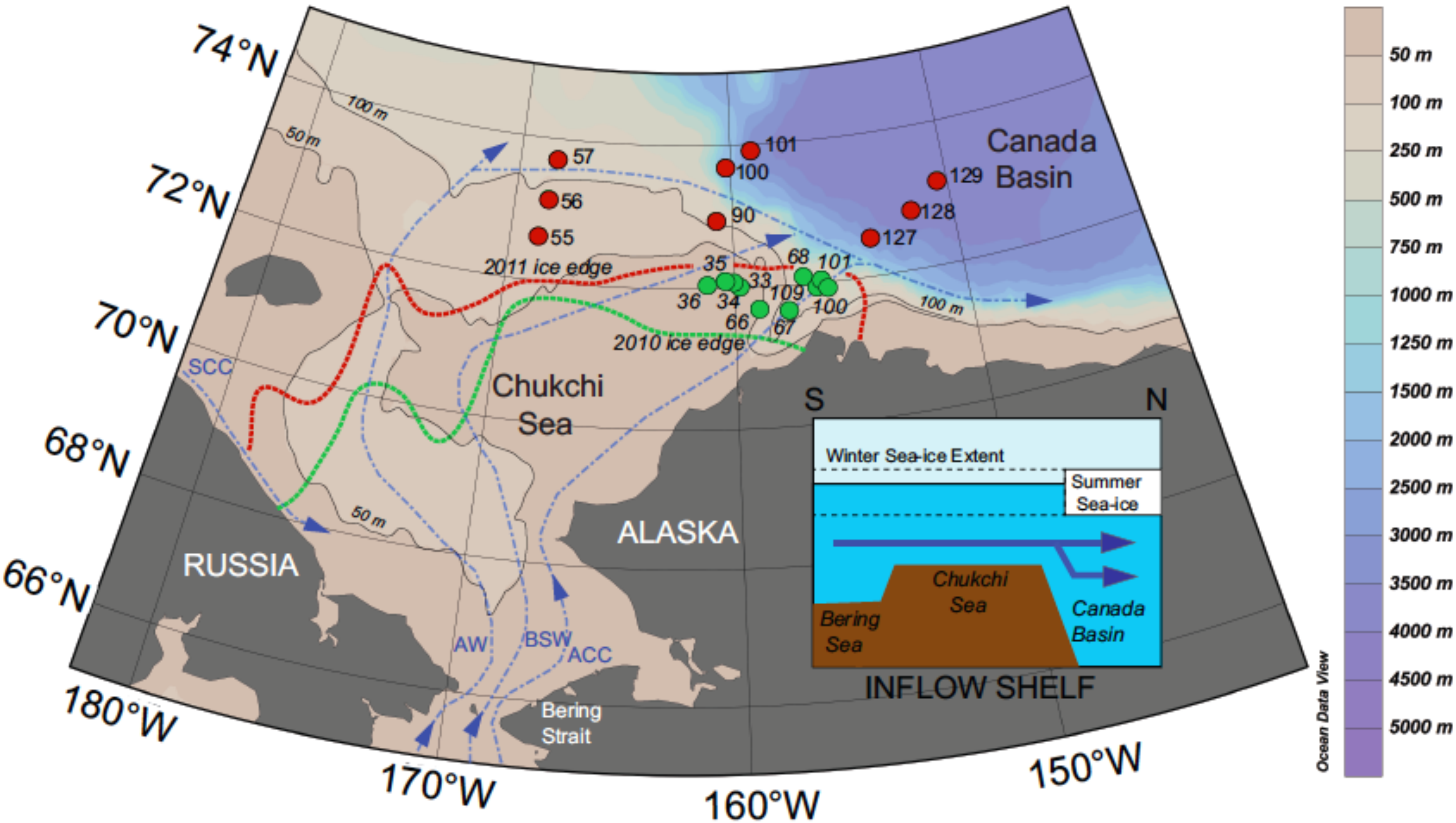
Karen Frey Photo

Bates et al., 2014

Bates et al, OCB Meeting 2014

Sea-ice CO_2-carbonate chemistry

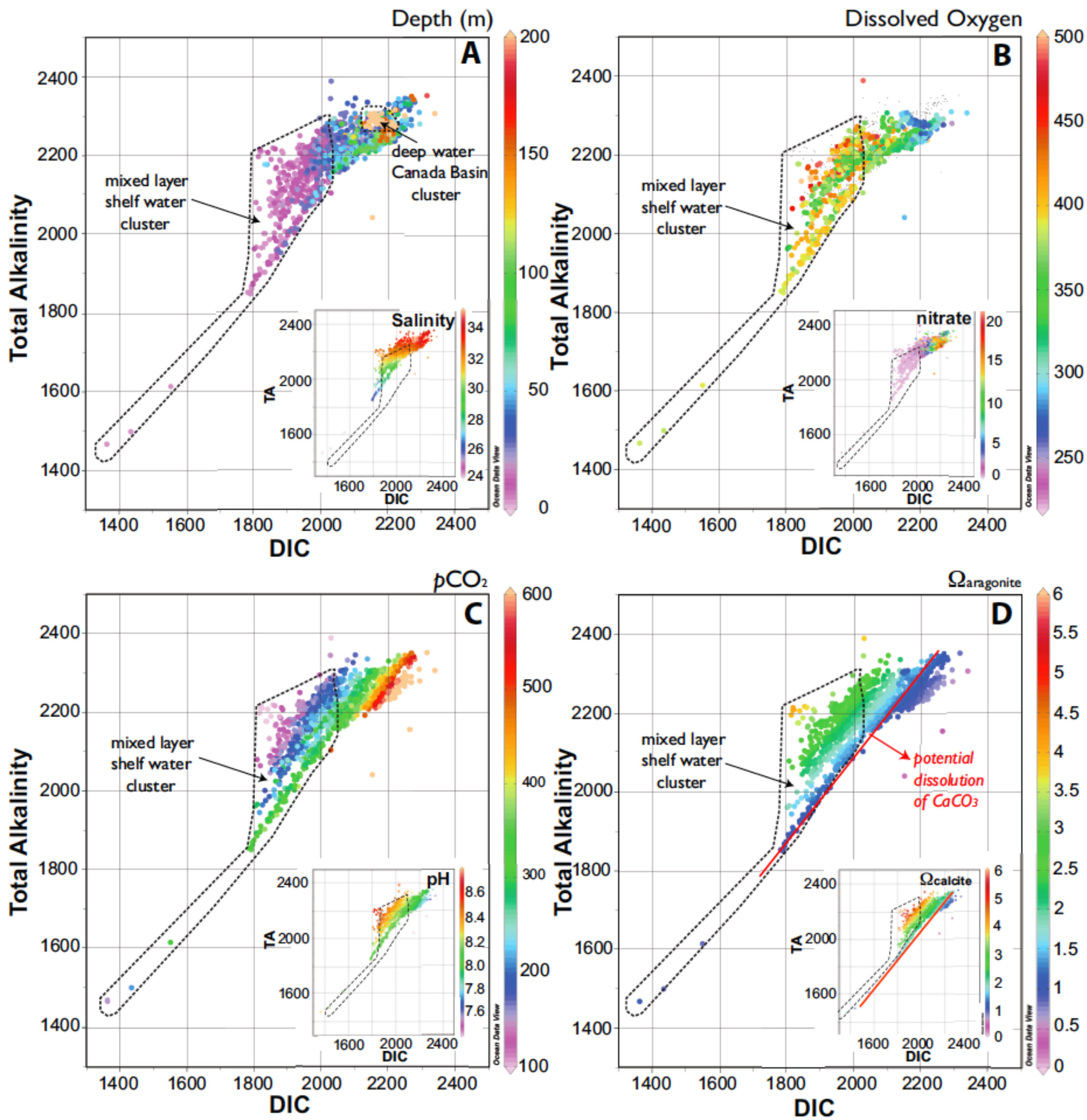
Sea-ice melt ponds



Bates et al., 2014

Bates et al, OCB Meeting 2014

Sea-ice CO_2-carbonate chemistry



Sea-ice melt ponds

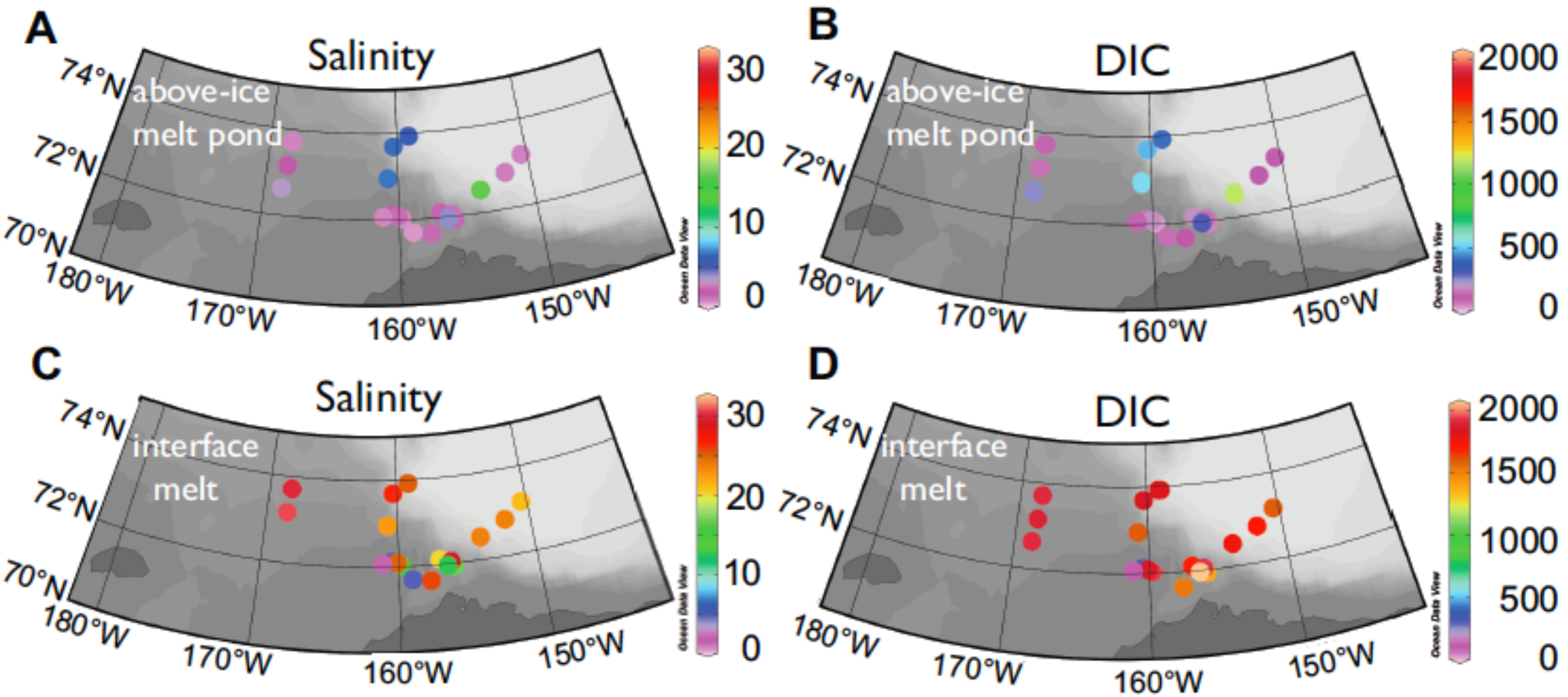
Bates et al., 2014

Bates et al., 2014

Bates et al, OCB Meeting 2014

Sea-ice CO_2-carbonate chemistry

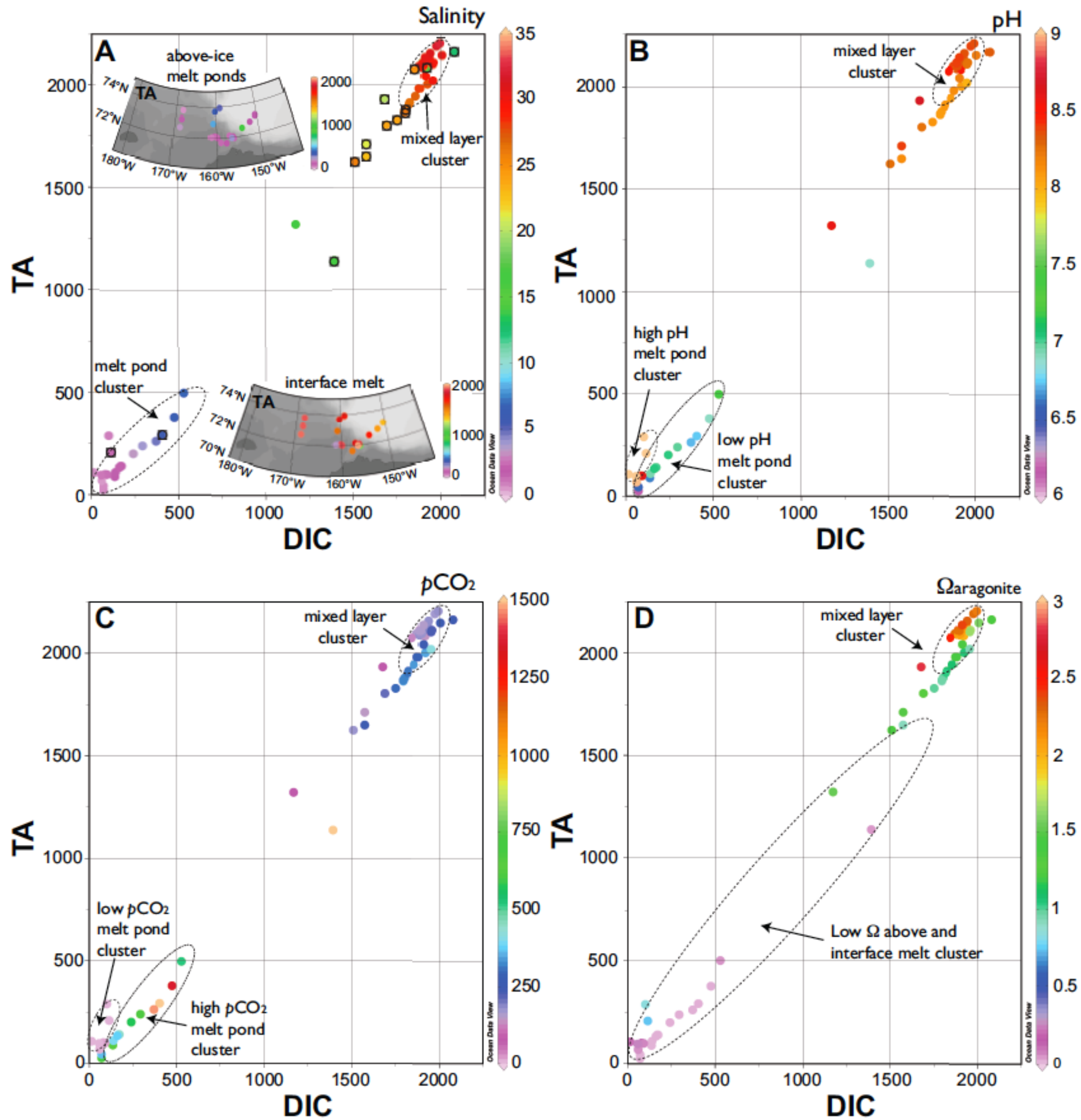
Sea-ice melt ponds



Bates et al., 2014

Bates et al, OCB Meeting 2014

Sea-ice CO_2-carbonate chemistry



Sea-ice melt ponds

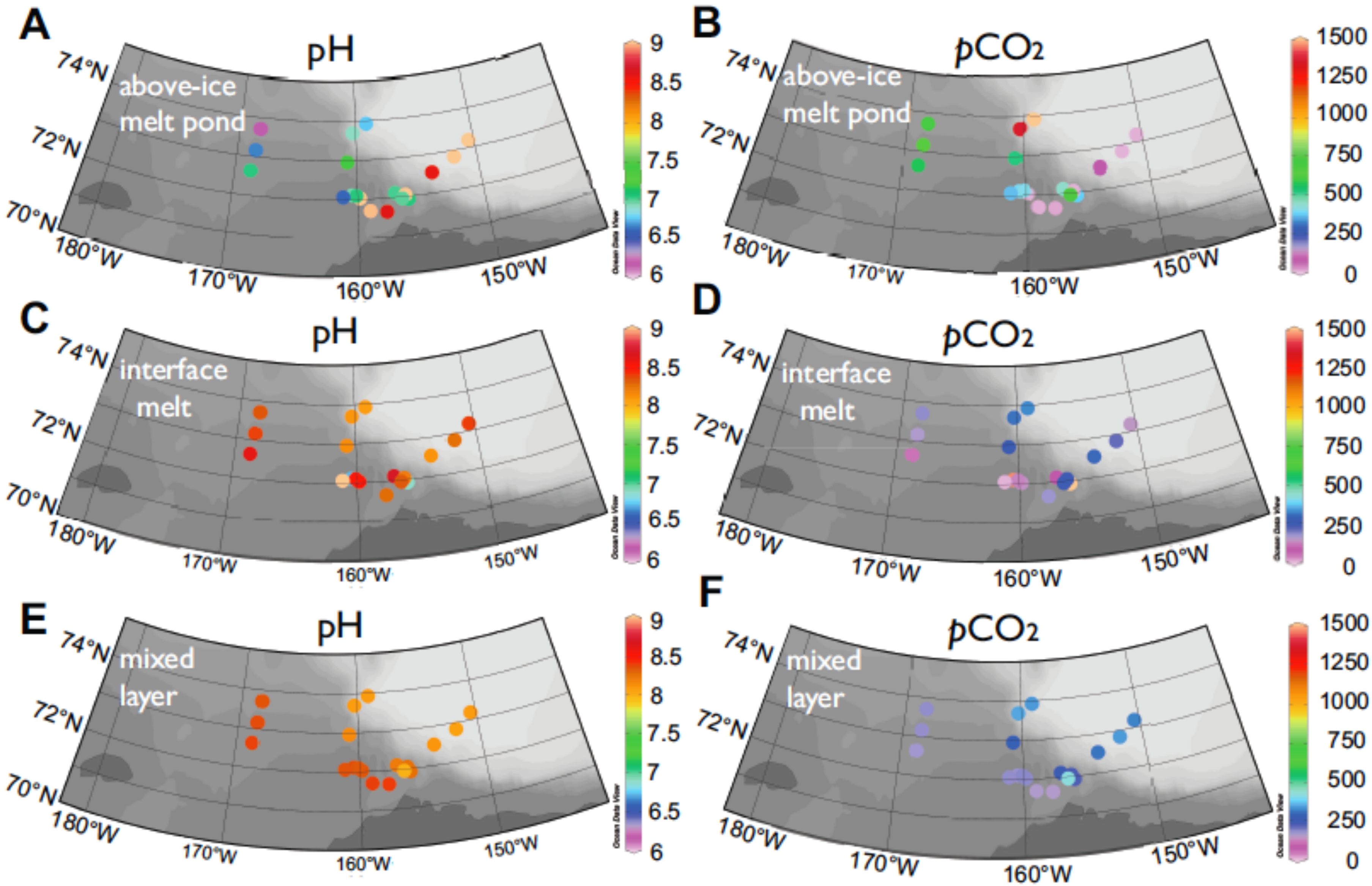
Bates et al., 2014

Bates et al., 2014

Bates et al, OCB Meeting 2014

Sea-ice CO_2-carbonate chemistry

Sea-ice melt ponds

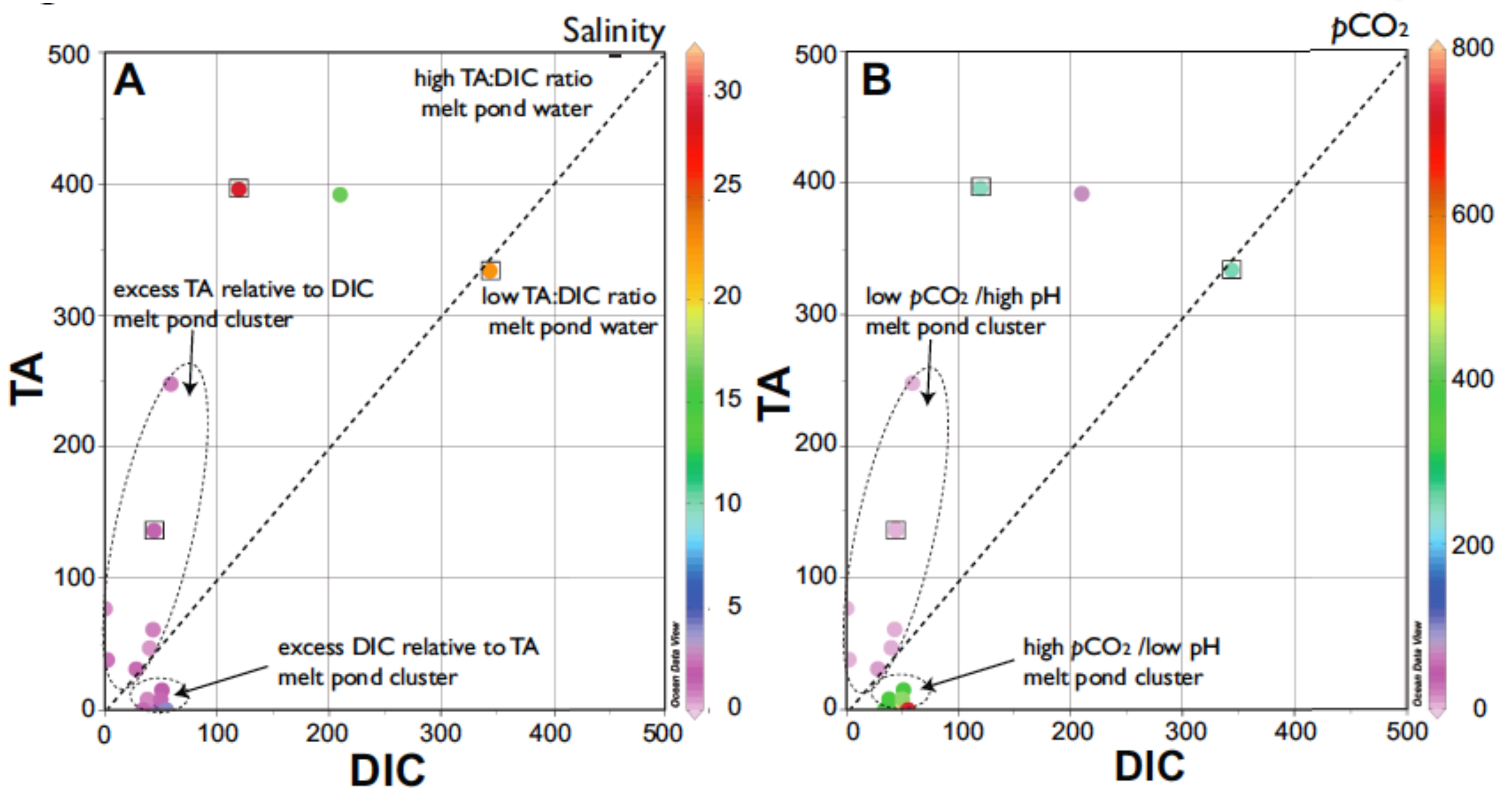


Bates et al., 2014

Bates et al, OCB Meeting 2014

Sea-ice CO_2-carbonate chemistry

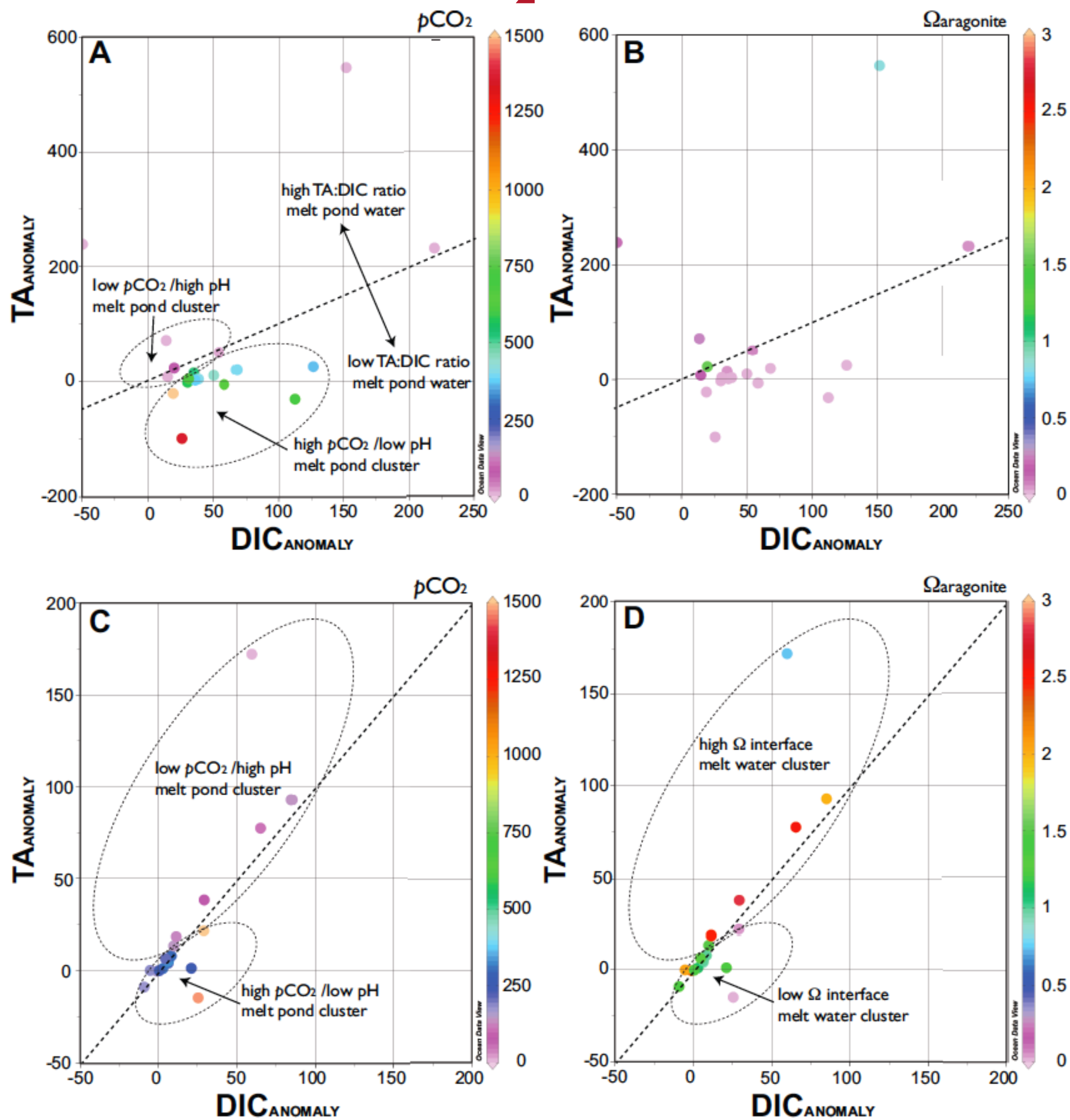
Sea-ice melt ponds



Bates et al., 2014

Bates et al, OCB Meeting 2014

Sea-ice CO_2-carbonate chemistry



Sea-ice
melt ponds

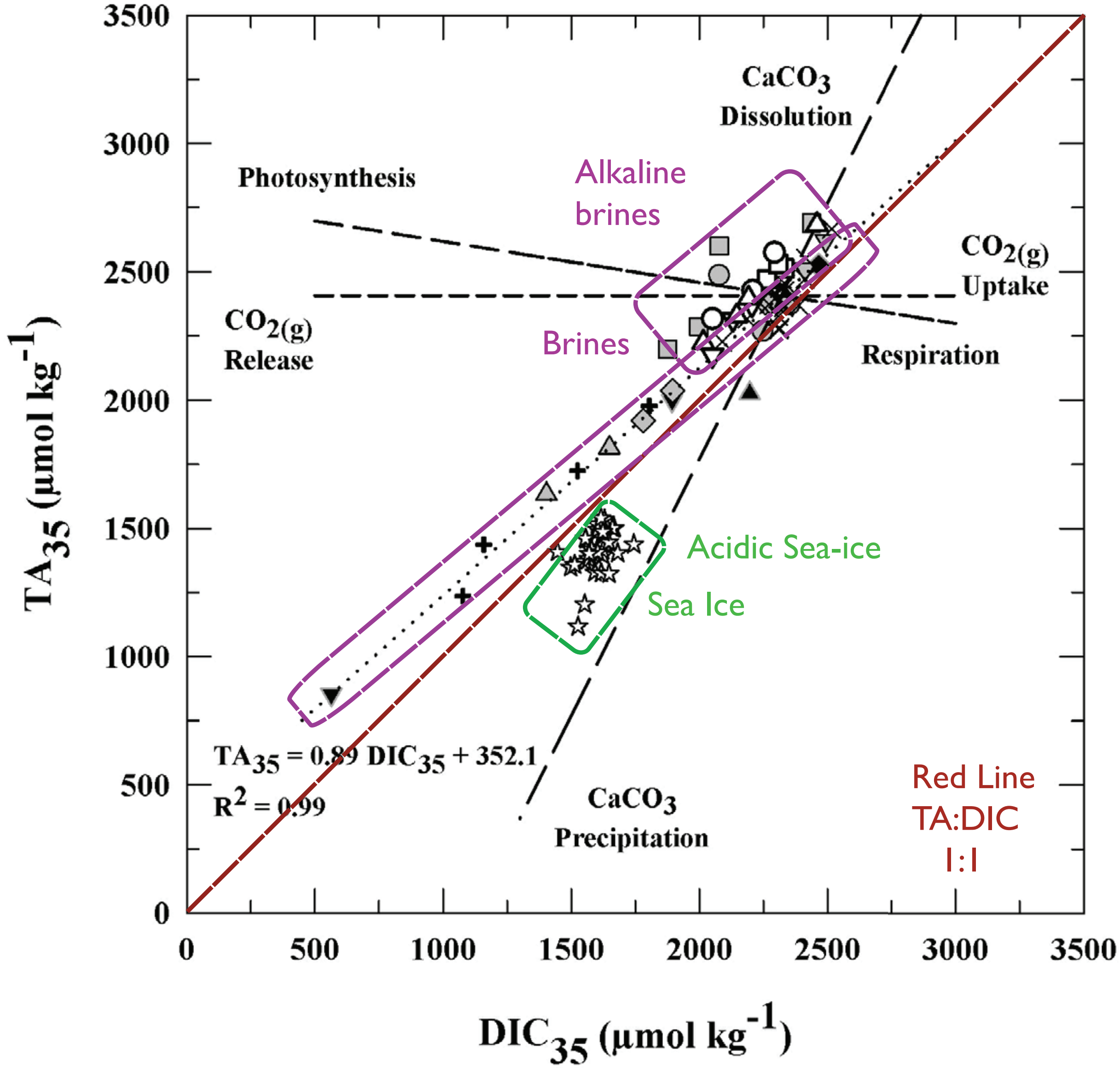
Bates et al

t al, OCB Meeting 2014

Sea-ice CO_2-carbonate chemistry

Spring Conditions

Brines

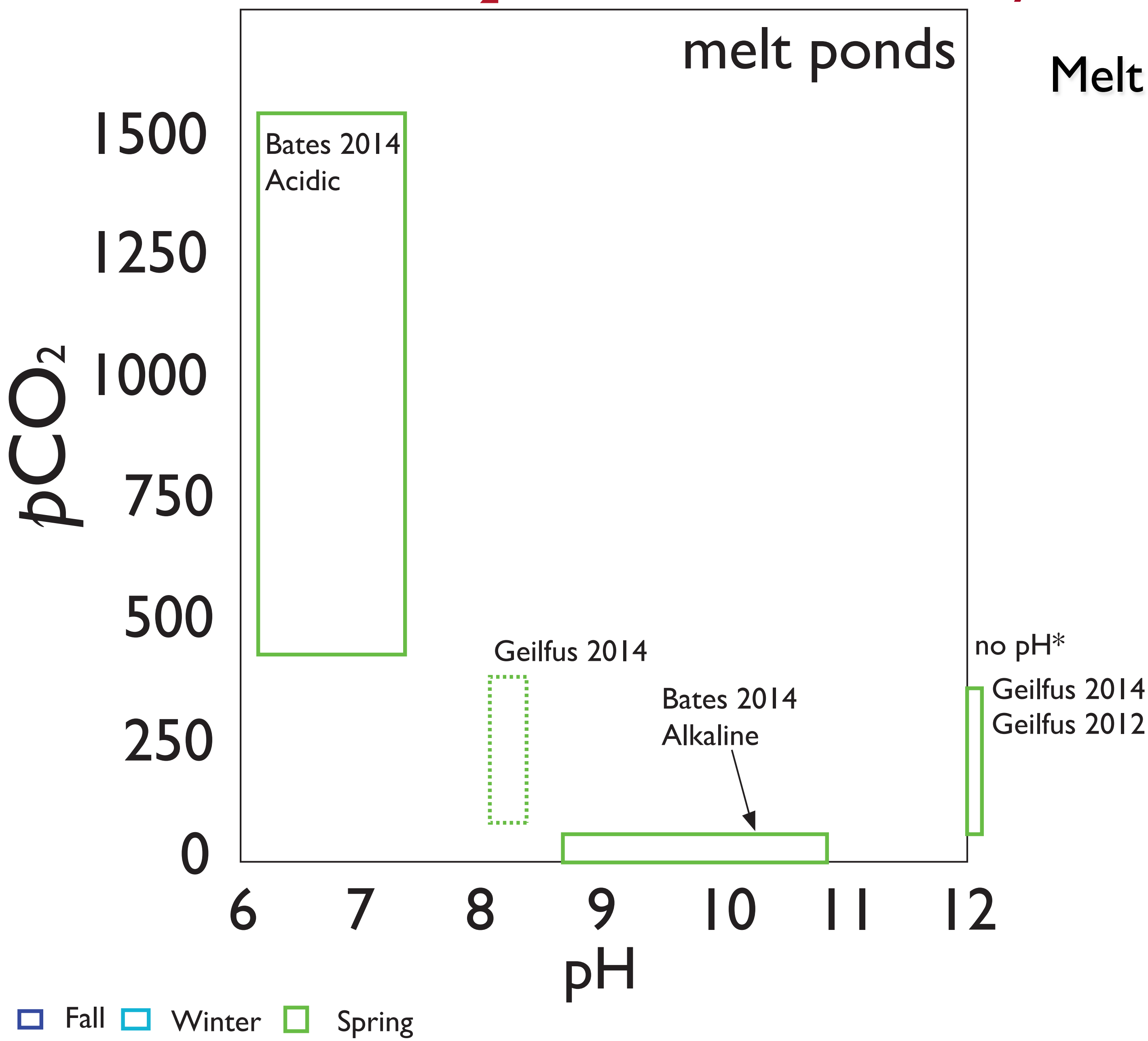


- Alkaline brines
- Acidic sea-ice (melted)

Geilfus et al., 2012

Bates et al, OCB Meeting 2014

Sea-ice CO_2-carbonate chemistry



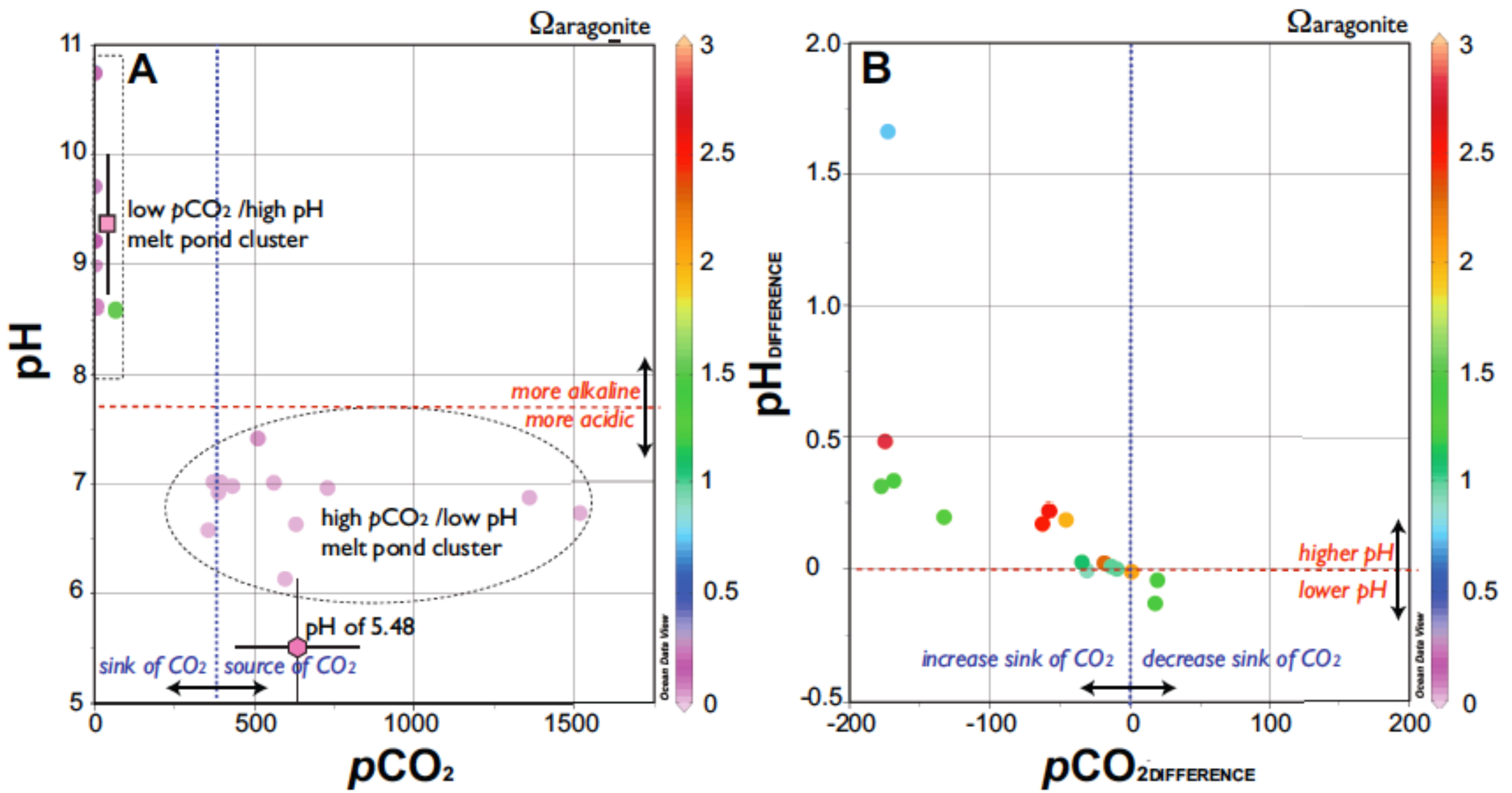
Melt Ponds

Bates et al., 2014

Bates et al, OCB Meeting 2014

Sea-ice CO_2-carbonate chemistry

Sea-ice melt ponds

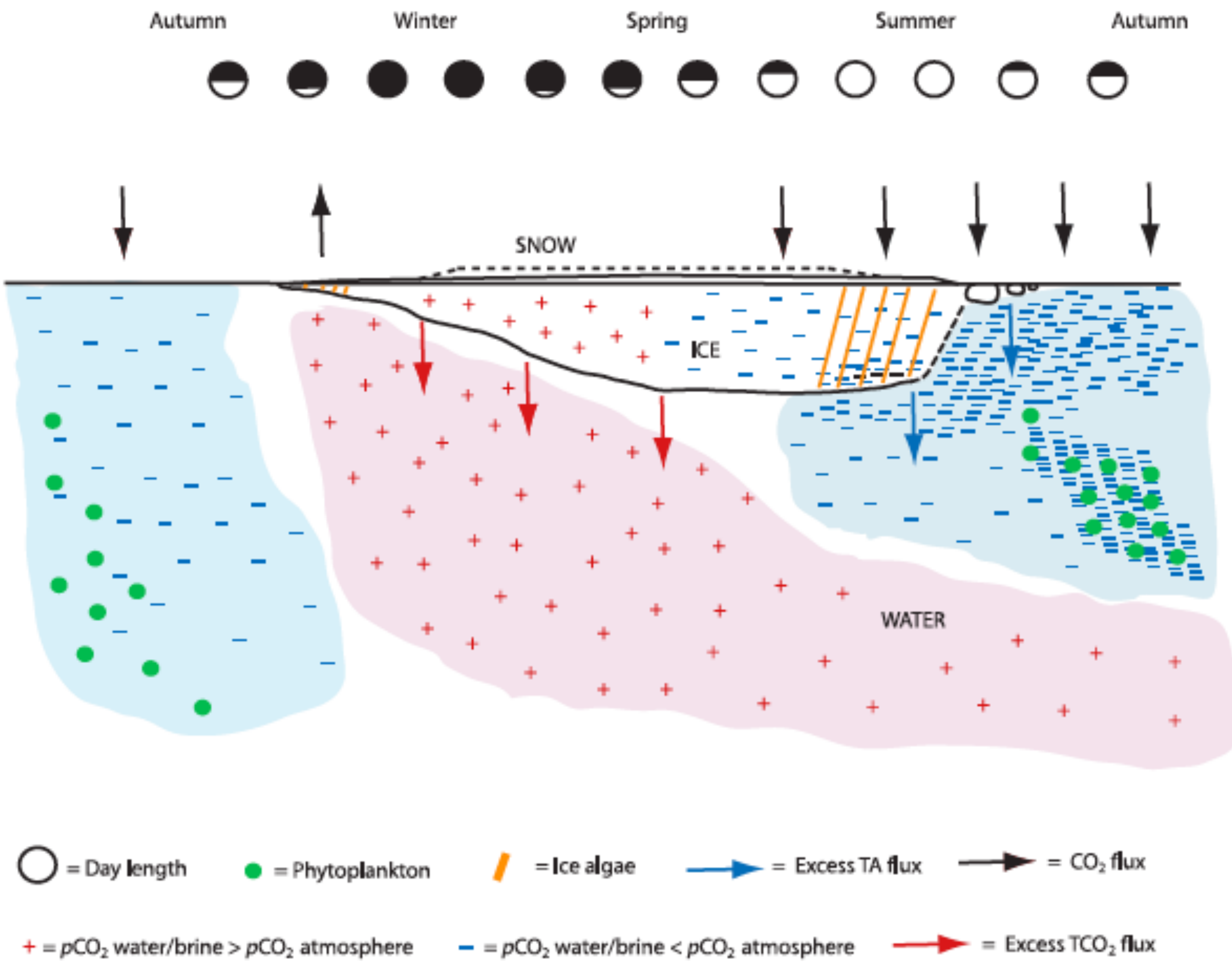


Bates et al., 2014

Bates et al, OCB Meeting 2014

Sea-ice CO_2-carbonate chemistry

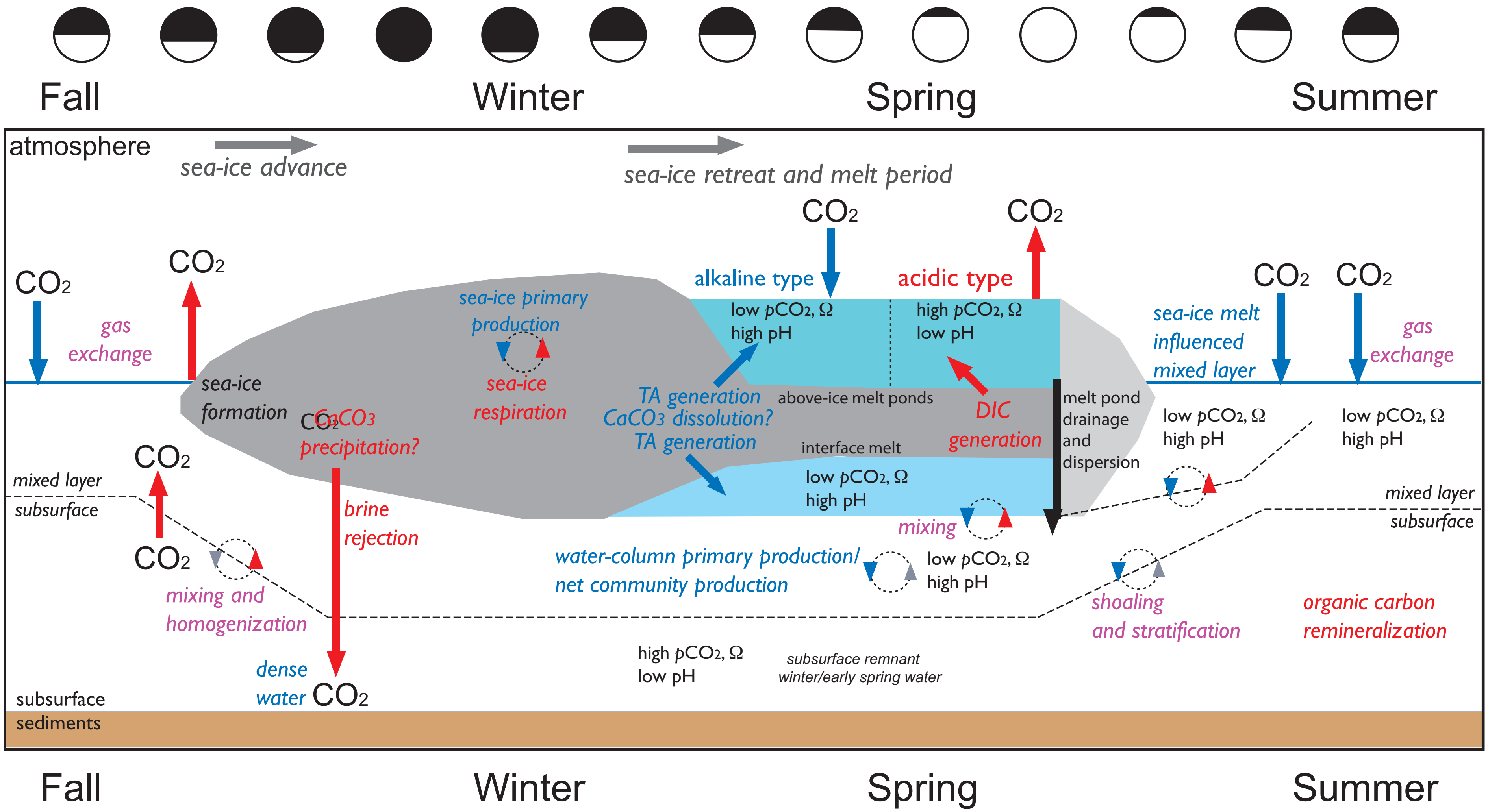
Sea-ice melt ponds



Rysgaard et al., 2011

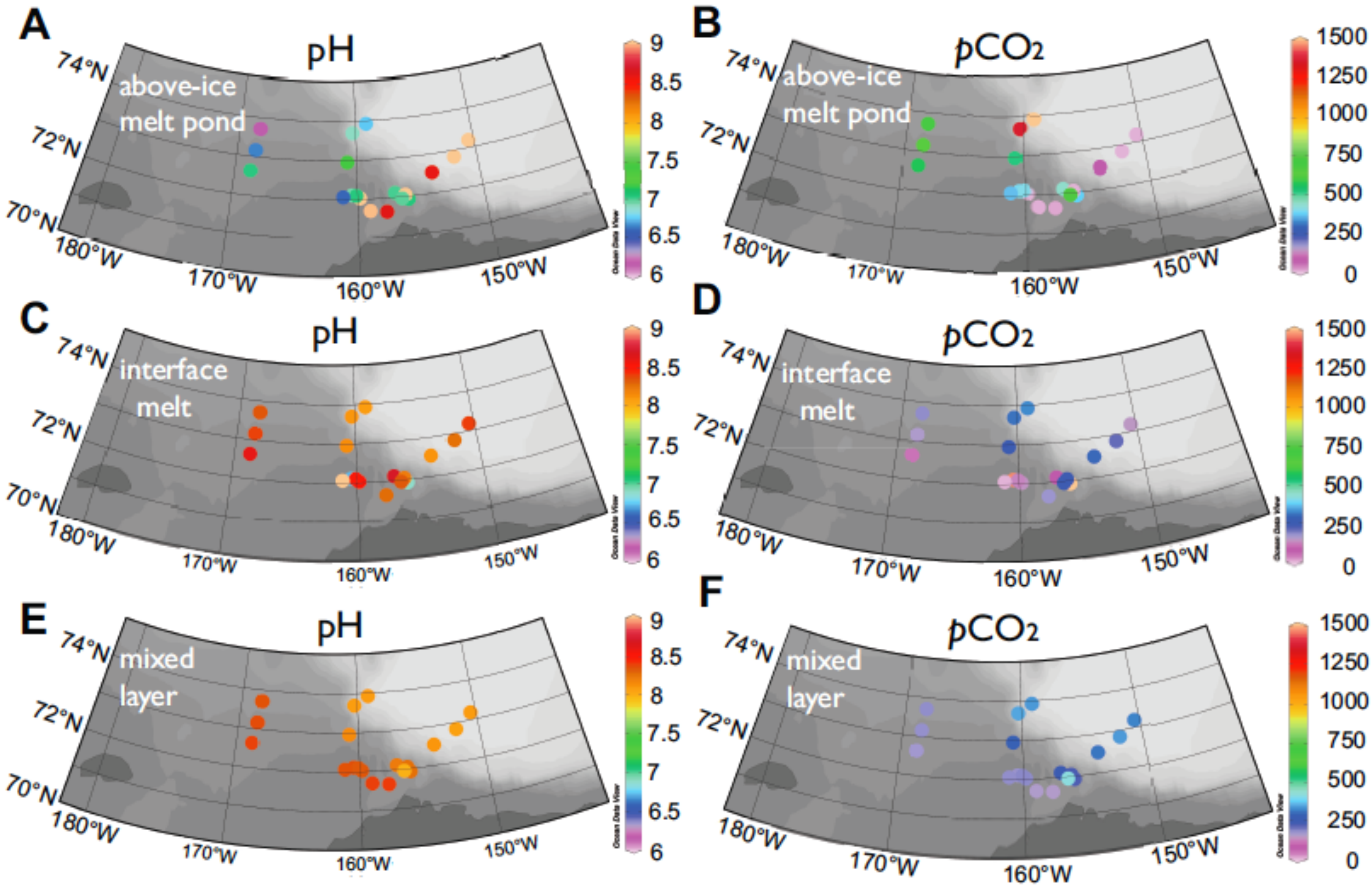
Bates et al, OCB Meeting 2014

Sea-ice CO_2-carbonate chemistry



Sea-ice CO_2-carbonate chemistry

Below-ice interface water

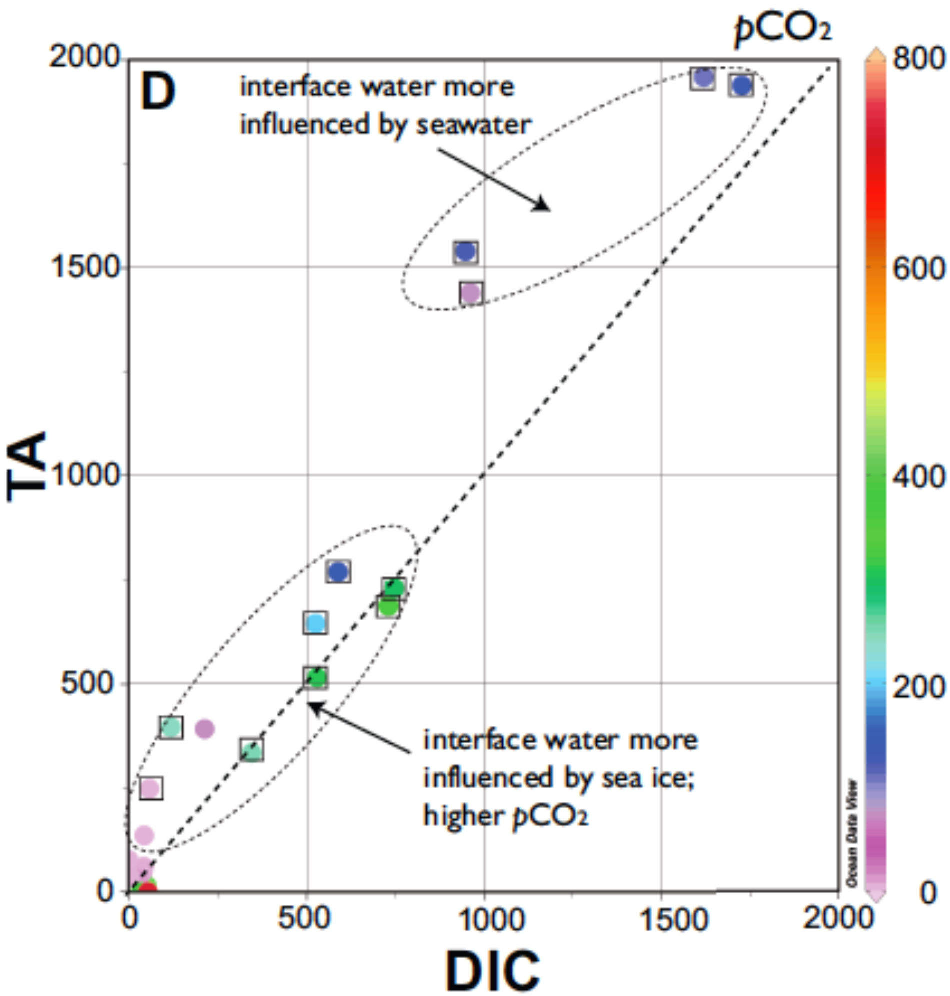


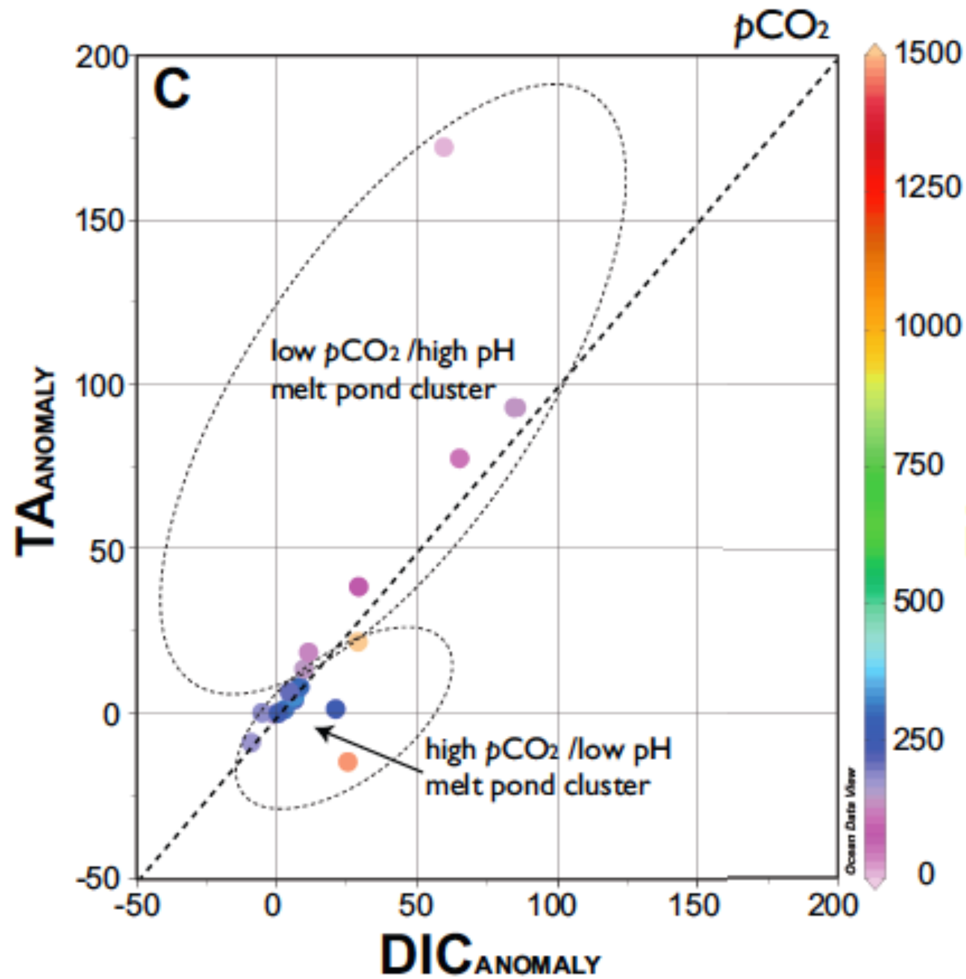
Bates et al., 2014

Bates et al, OCB Meeting 2014

Sea-ice CO_2-carbonate chemistry

Below-ice interface water



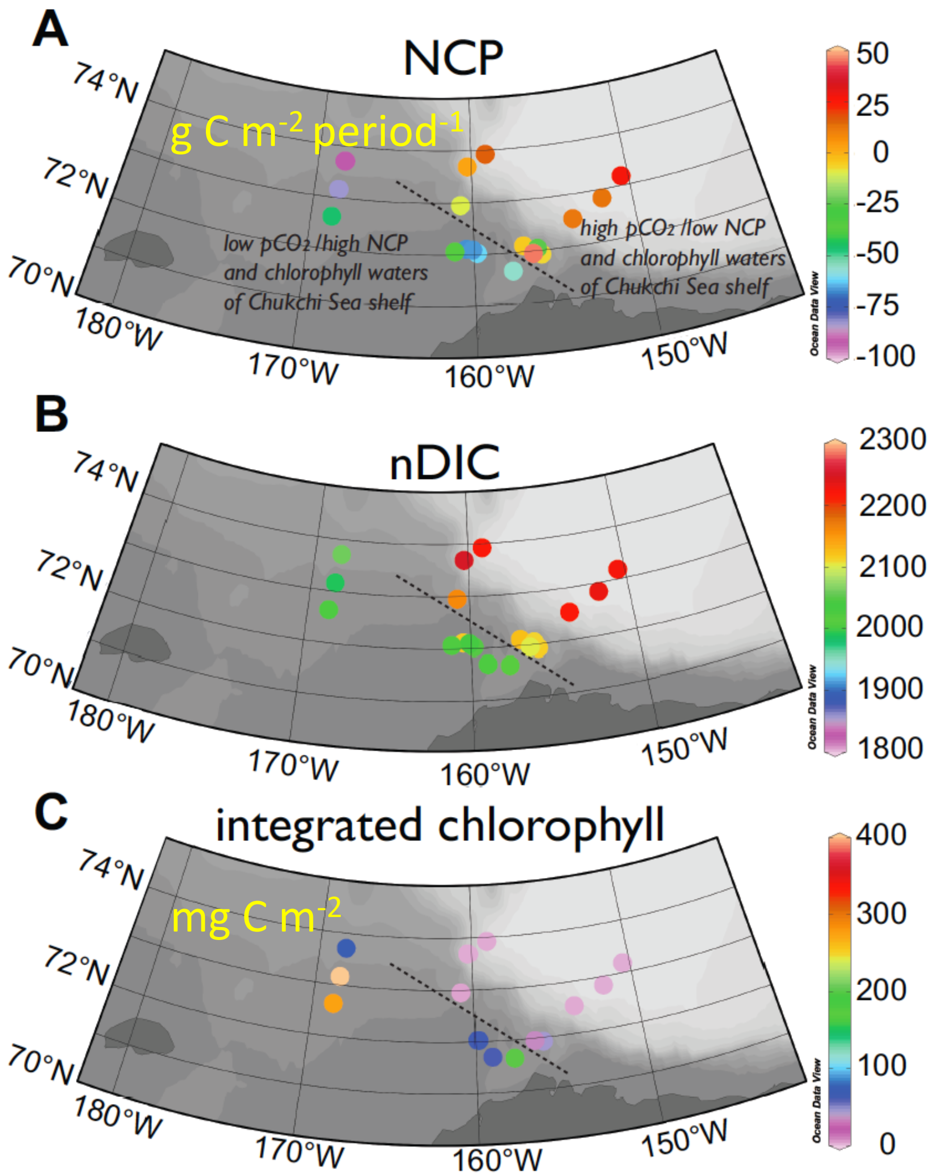


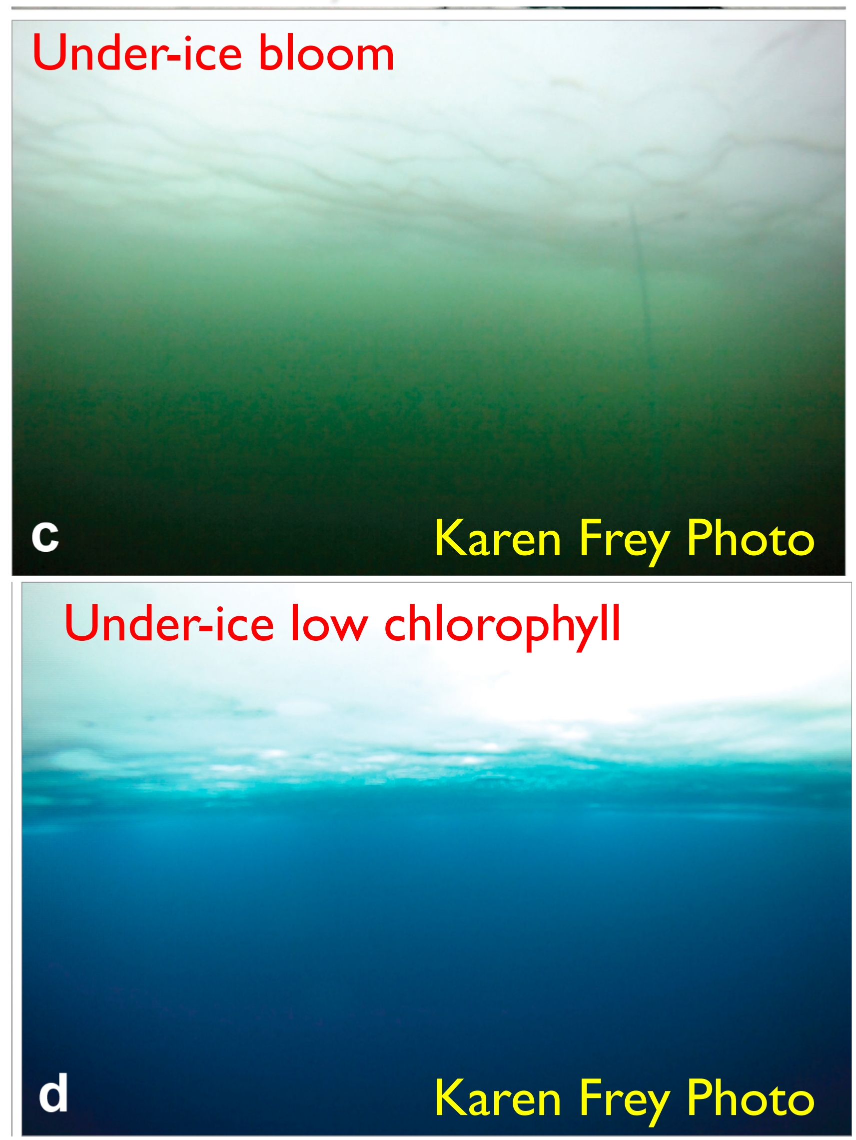
Bates et al., 2014

Bates et al, OCB Meeting 2014

Sea-ice CO_2-carbonate chemistry

Melt water contributions to mixed layer water



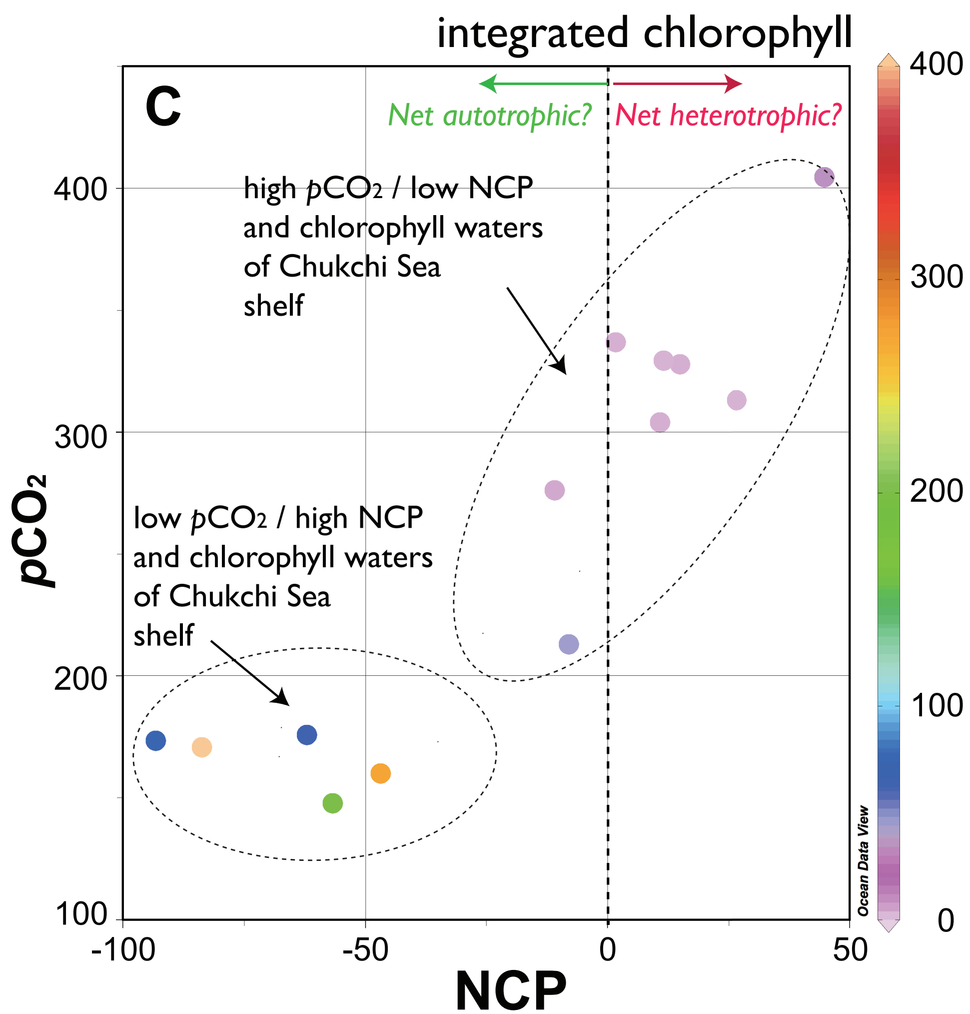


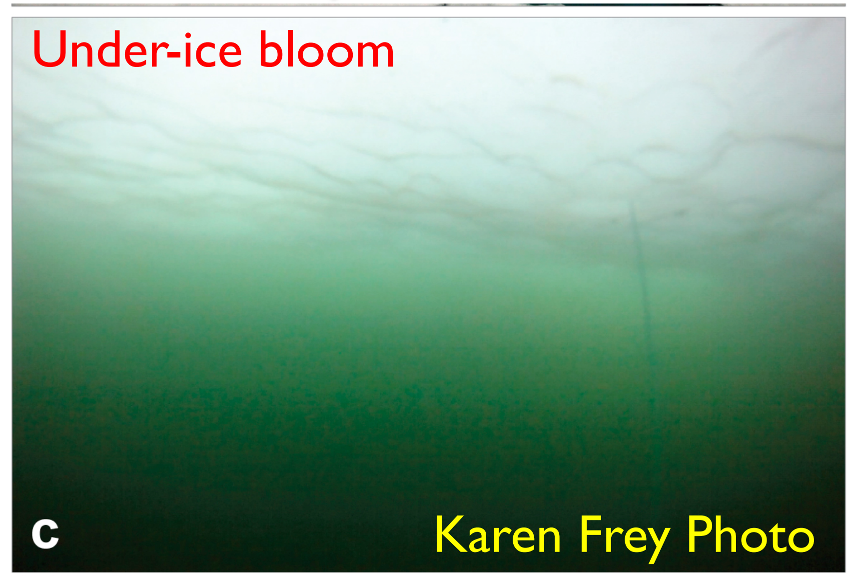
Bates et al., 2014

Bates et al, OCB Meeting 2014

Sea-ice CO_2-carbonate chemistry

Melt water contributions to mixed layer water





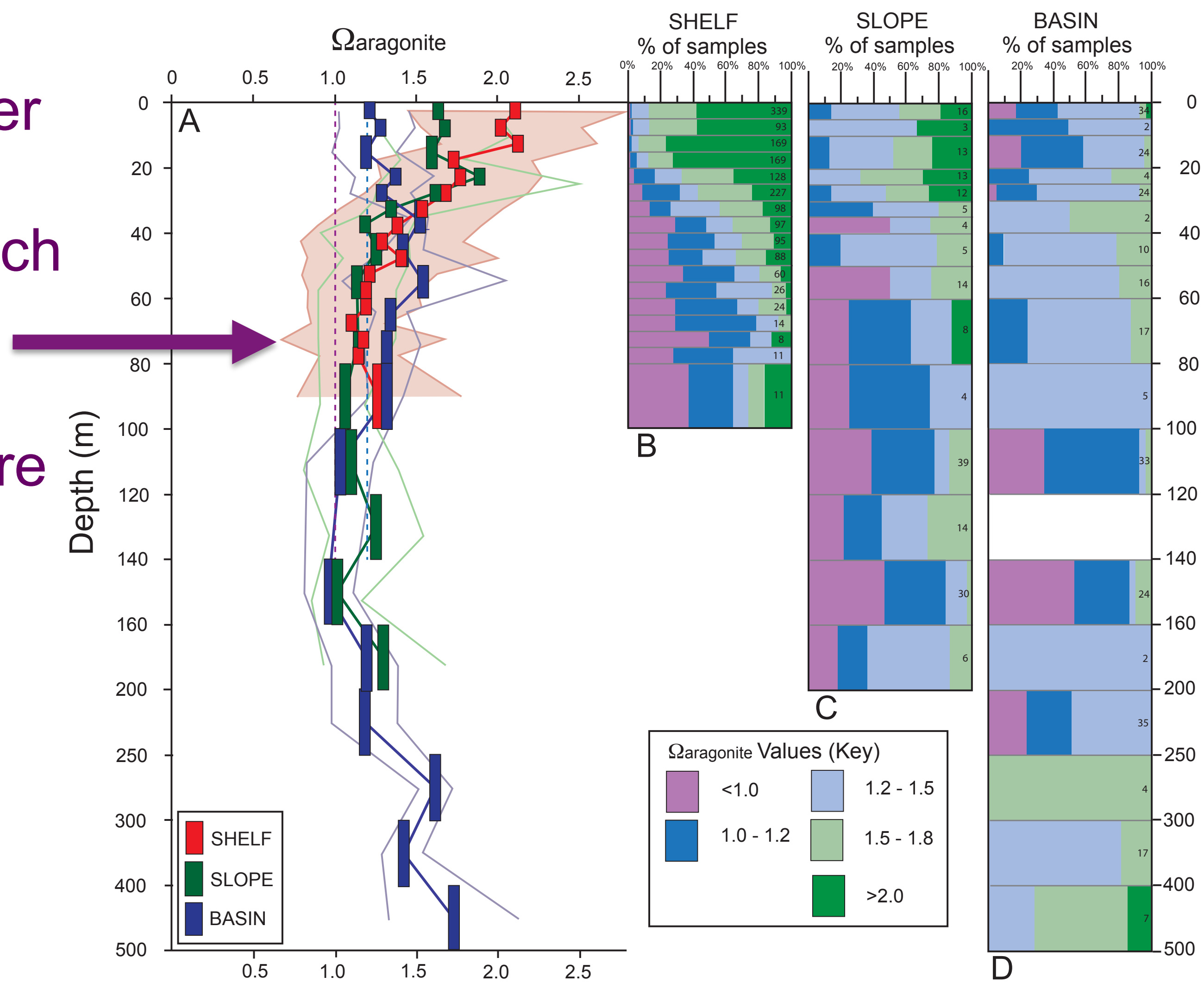
Bates et al., 2014

Bates et al, OCB Meeting 2014

Western Arctic OA vulnerability

Arctic highly vulnerable to OA

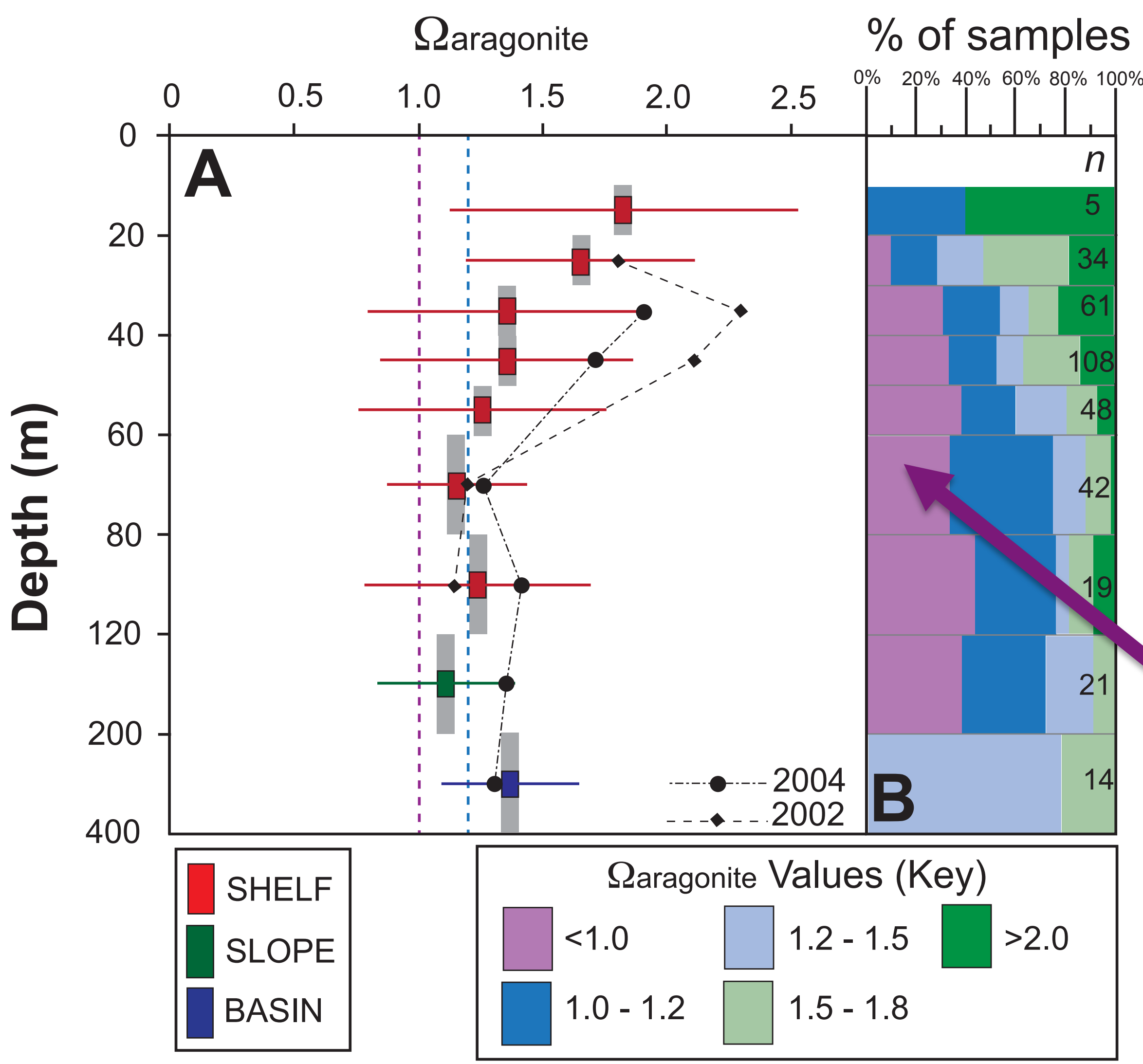
Areas of low seawater saturation state for $CaCO_3$ minerals. Much of the Chukchi Sea benthos exposed to bottom waters that are corrosive to $CaCO_3$ during summertime.



Bates et al., 2013

Bates et al, OCB Meeting 2014

Western Arctic OA vulnerability



Areas of low seawater saturation state for $CaCO_3$ minerals. At least 40% of the Chukchi Sea benthos is exposed to bottom waters that are corrosive to $CaCO_3$ during summertime

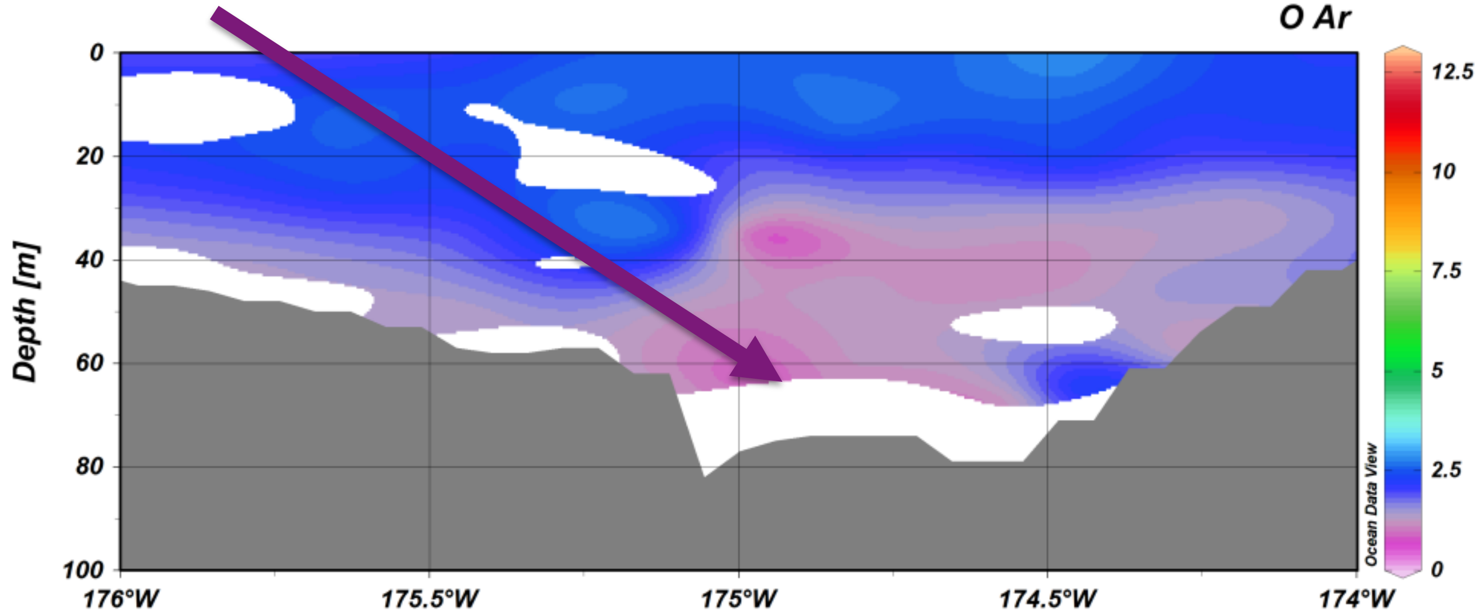
Bates et al., 2013

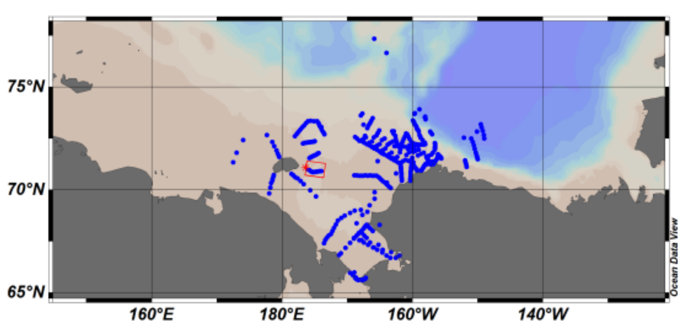
Bates et al, OCB Meeting 2014

Western Arctic OA vulnerability

Outflow of corrosive bottom waters through Herald Valley

Chukchi Sea and ESS highly vulnerable to OA

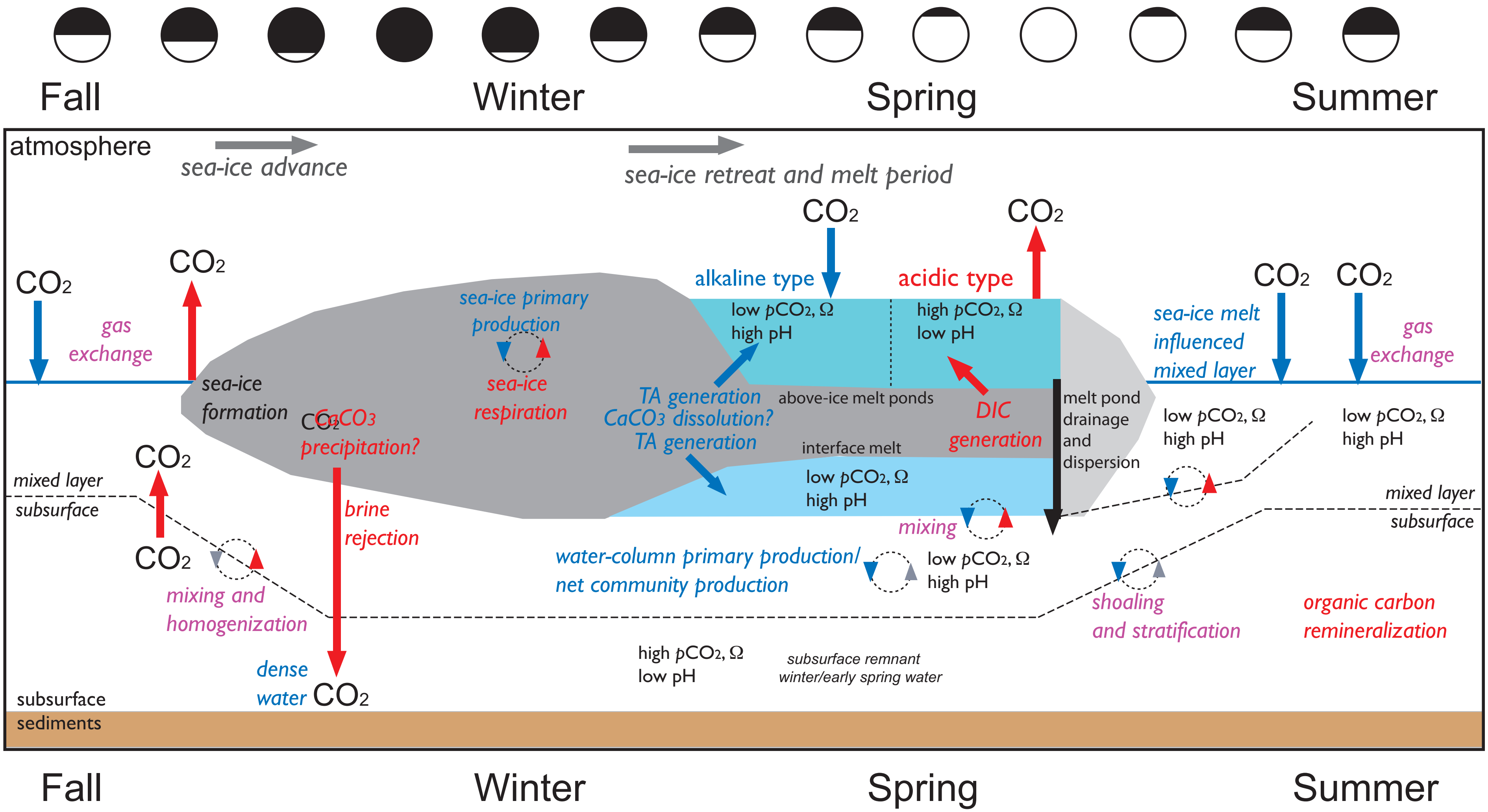




Bates et al., 2013

Bates et al, OCB Meeting 2014

Sea-ice CO_2-carbonate chemistry

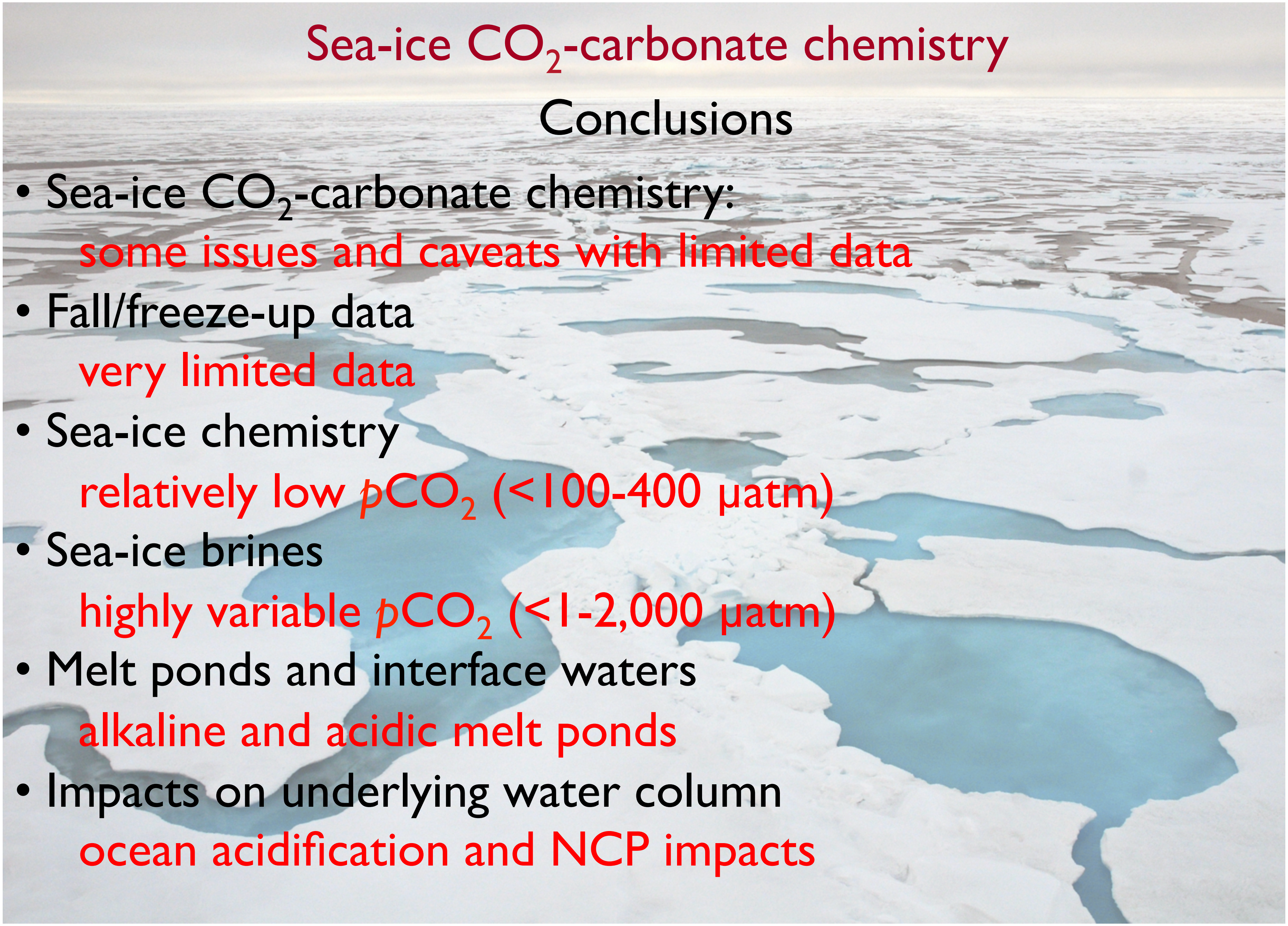


Bates et al., 2014

Bates et al, OCB Meeting 2014

Sea-ice CO_2-carbonate chemistry

Conclusions



- Sea-ice CO_2-carbonate chemistry:
  some issues and caveats with limited data
- Fall/freeze-up data
  very limited data
- Sea-ice chemistry
  relatively low pCO_2 (<100-400 µatm)
- Sea-ice brines
  highly variable pCO_2 (<1-2,000 µatm)
- Melt ponds and interface waters
  alkaline and acidic melt ponds
- Impacts on underlying water column
  ocean acidification and NCP impacts

Karen Frey photo