CO_2 fluxes across the air-ice interface

Delille B.

Champenois W., Heinesch B., Zhou J., Schoemann V., Carnat G., N.-X. Geilfus, D. Delille, Moreau S., Vancoppenolle M., and Tison J.-L.

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Outlines

- Sea ice permeability
- Spring and summer budgets of air-ice CO_2 fluxes
- Gaps in current knowledge
    - Fall and winter release of CO_2
    - Discrepancy between eddy-covariance and chamber measurements

A long lived dogma…

Weiss et al 1979, Gordon et al 1984, Poisson and Chen 1987

- « Weddel Sea pack ice effectively blocks the air-sea exchange of gases »
- No evidence of marked ventilation is found in deep waters of the Weddel Sea. Thus sea ice appears to prevent air-sea exchange.

Weiss et al 1979

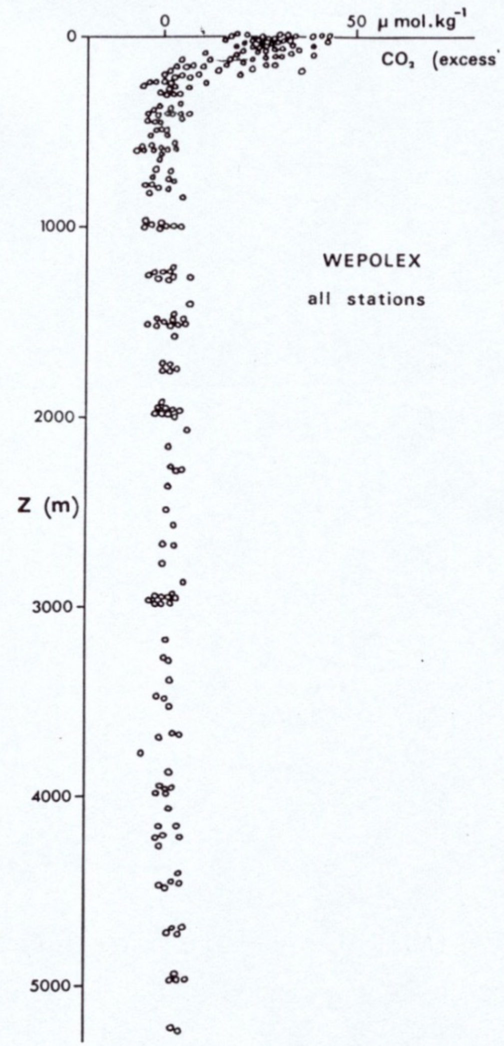


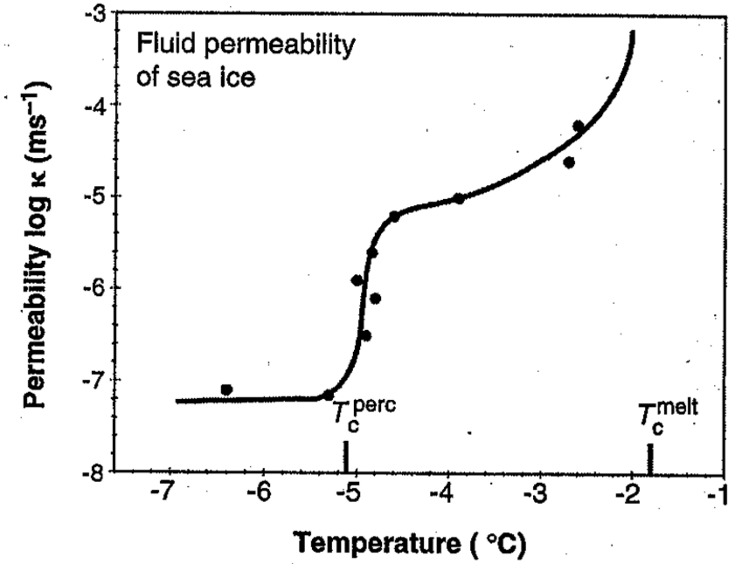
Fig. 11. Excess CO_2 vs depth (Z) for all the WEPOLEX stations.

Outlines

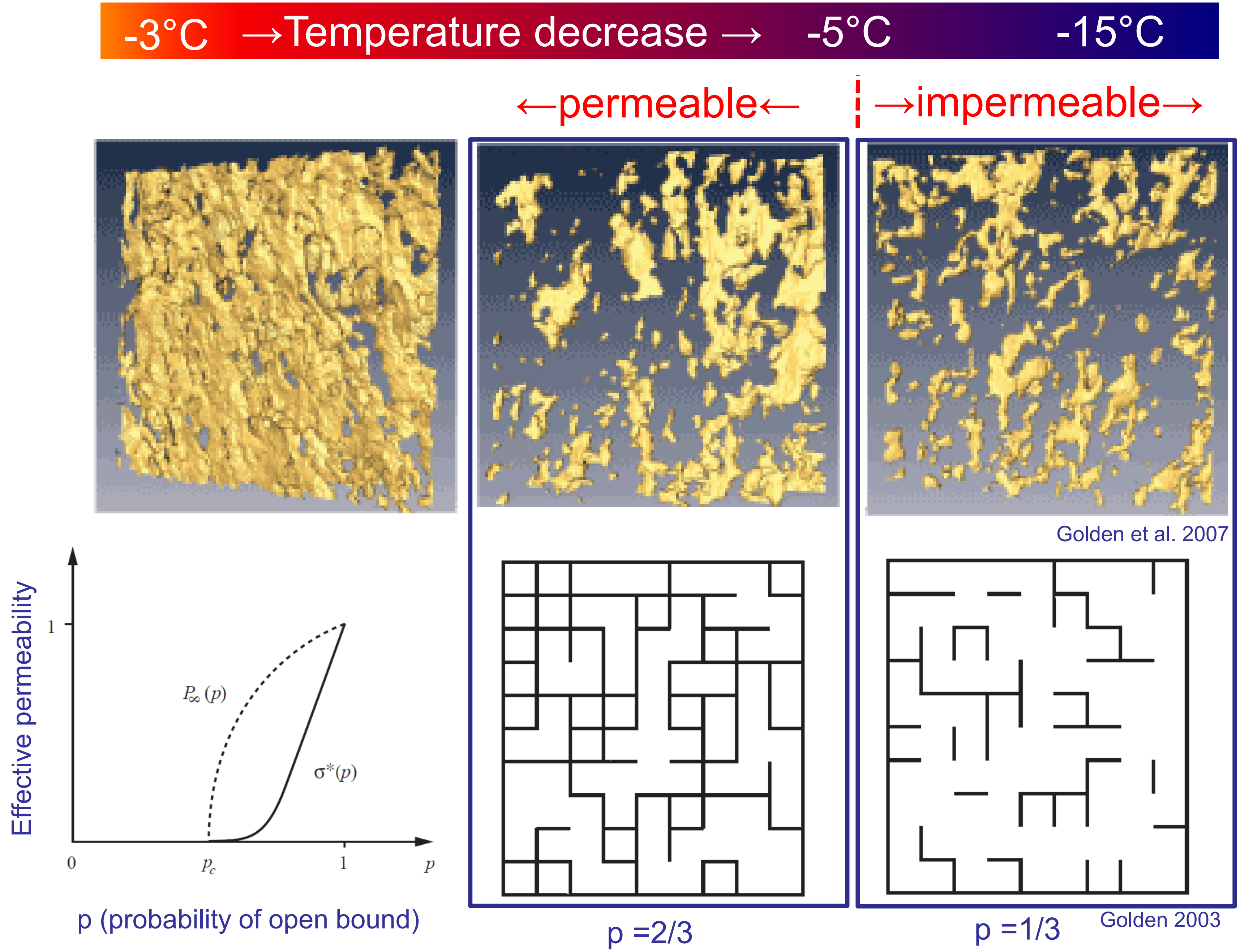
- Kelley & Gosink 1970s-80s
  - « unlike ices from pure freshwater, sea ice is a highly permeable medium for gases »
  - They found rate of CO_2 penetration about 60 cm h^{-1} at -7°C
  - « gas migration through sea ice is an important factor in ocean-atmosphere winter communication particularly when the surface temperature is > -10° » (Gosink et al., 1976. Nature 263: 41)

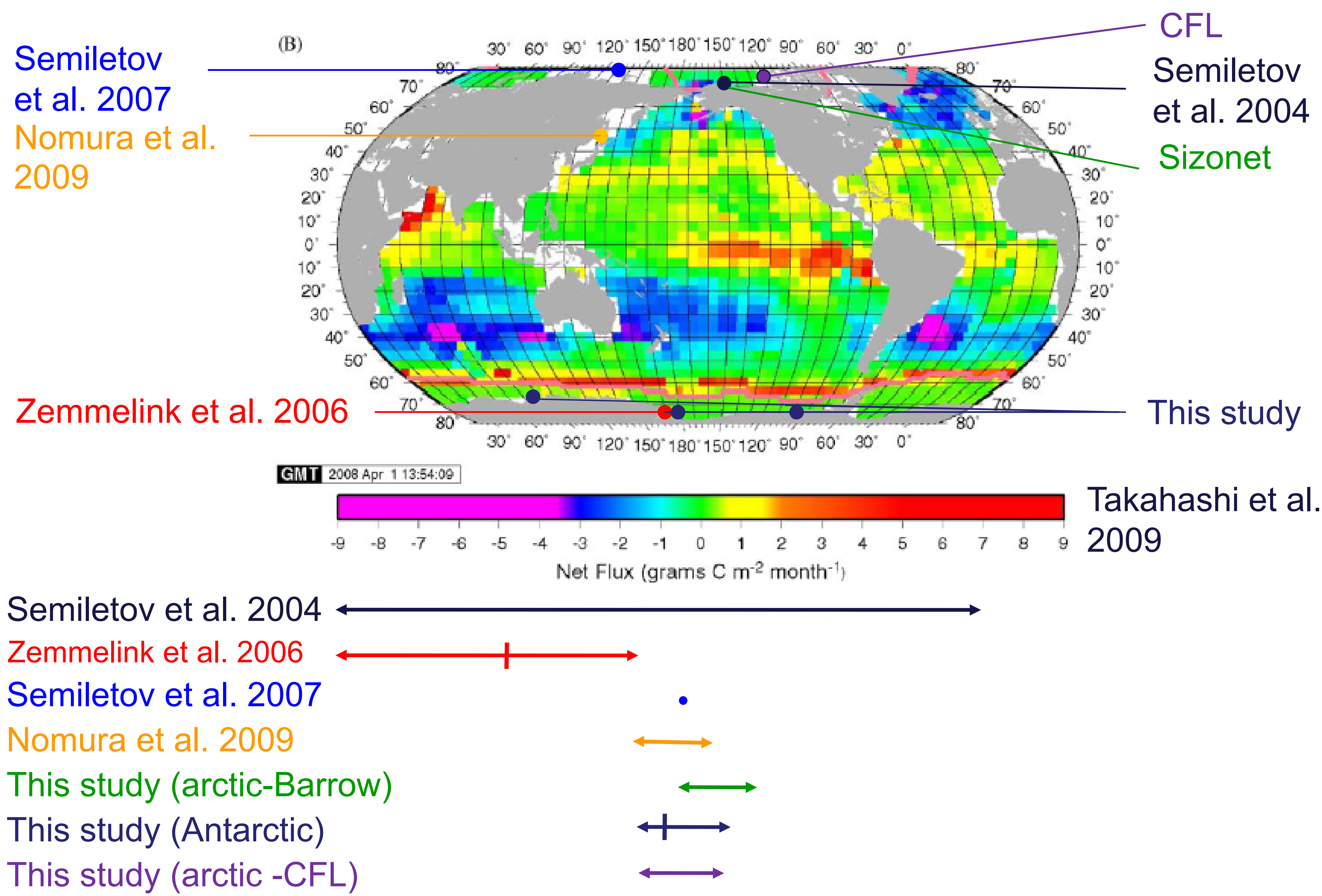
Golden et al., 1998

- Theoretical and experimental evidence that sea ice permeability increases considerably above -5°C, the so-called "law of fives" (Golden et al., 1998. Science 282: 2238)



- *Science* 282: 2238


-3°C →Temperature decrease → -5°C -15°C
←permeable←
→impermeable→
Golden et al. 2007
Effective permeability
1
$P_\infty(p)$
$\sigma^*(p)$
0
p_c
1
p
p (probability of open bound)
p =2/3
p =1/3
Golden 2003

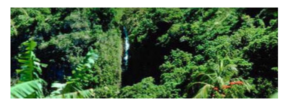
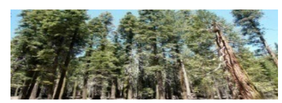
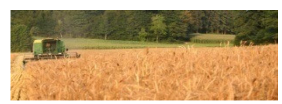


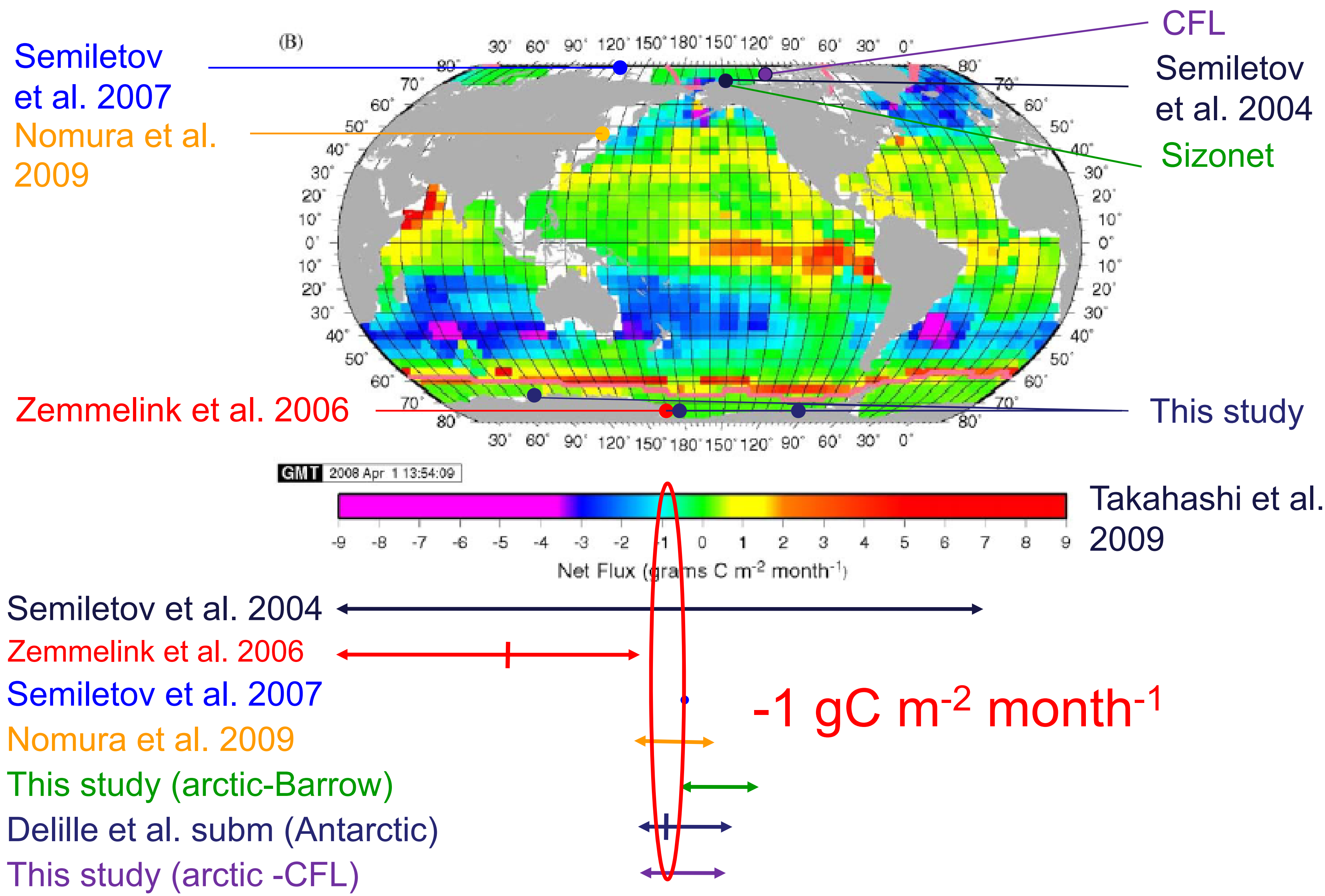
Semiletov et al. 2007
Nomura et al. 2009
Zemmelink et al. 2006
(B)
CFL
Semiletov et al. 2004
Sizonet
This study
GMT 2008 Apr 1 13:54:09
Takahashi et al. 2009
-9 -8 -7 -6 -5 -4 -3 -2 -1 0 1 2 3 4 5 6 7 8 9
Net Flux (grams C m-2 month-1)
Semiletov et al. 2004
Zemmelink et al. 2006
Semiletov et al. 2007
Nomura et al. 2009
This study (arctic-Barrow)
This study (Antarctic)
This study (arctic -CFL)

Sept.
(28 = 8+20)

Sea ice

Feb.
(18 = 14+4)

		10^6 km2 (IPCC, 2001)
	DESERT, SEMI DESERT	27.7
	TROPICAL SAVANNAS, GRASSLANDS	27.6
	COASTAL OCEAN	26.0
	TEMPERATE GRASSLANDS, SHRUBLANDS	17.8
	RAINFOREST	17.5
	CONTINENTAL ICE	15.5
	TAÏGA	13.7
	CROPLANDS	13.5
	TEMPERATE FOREST	10.4
	TUNDRA	5.6


Semiletov et al. 2007
Nomura et al. 2009
CFL
Semiletov et al. 2004
Sizonet
(B)
Zemmelink et al. 2006
This study
GMT 2008 Apr 1 13:54:09
Takahashi et al. 2009
-9 -8 -7 -6 -5 -4 -3 -2 -1 0 1 2 3 4 5 6 7 8 9
Net Flux (grams C m-2 month-1)
Semiletov et al. 2004
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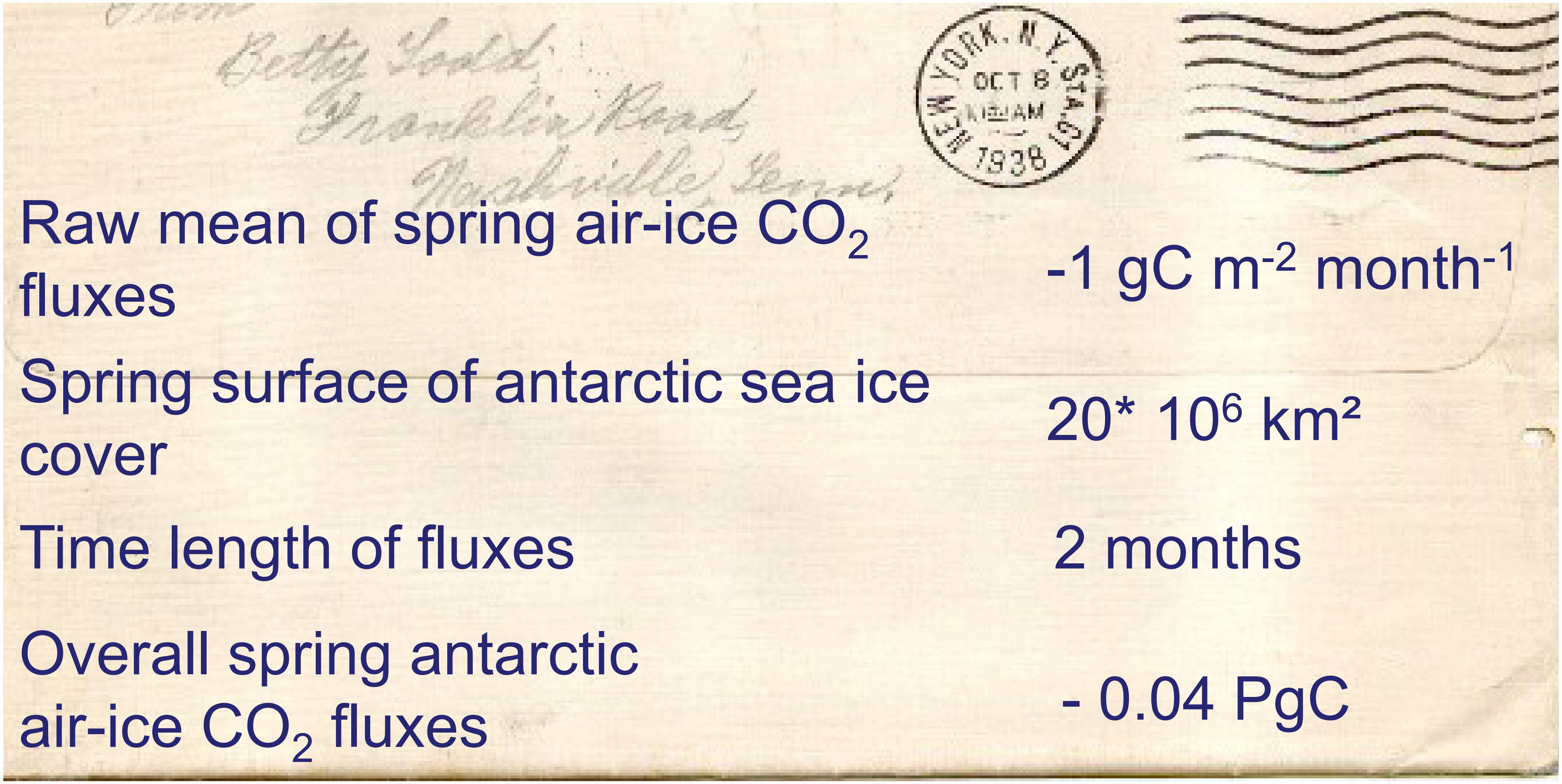
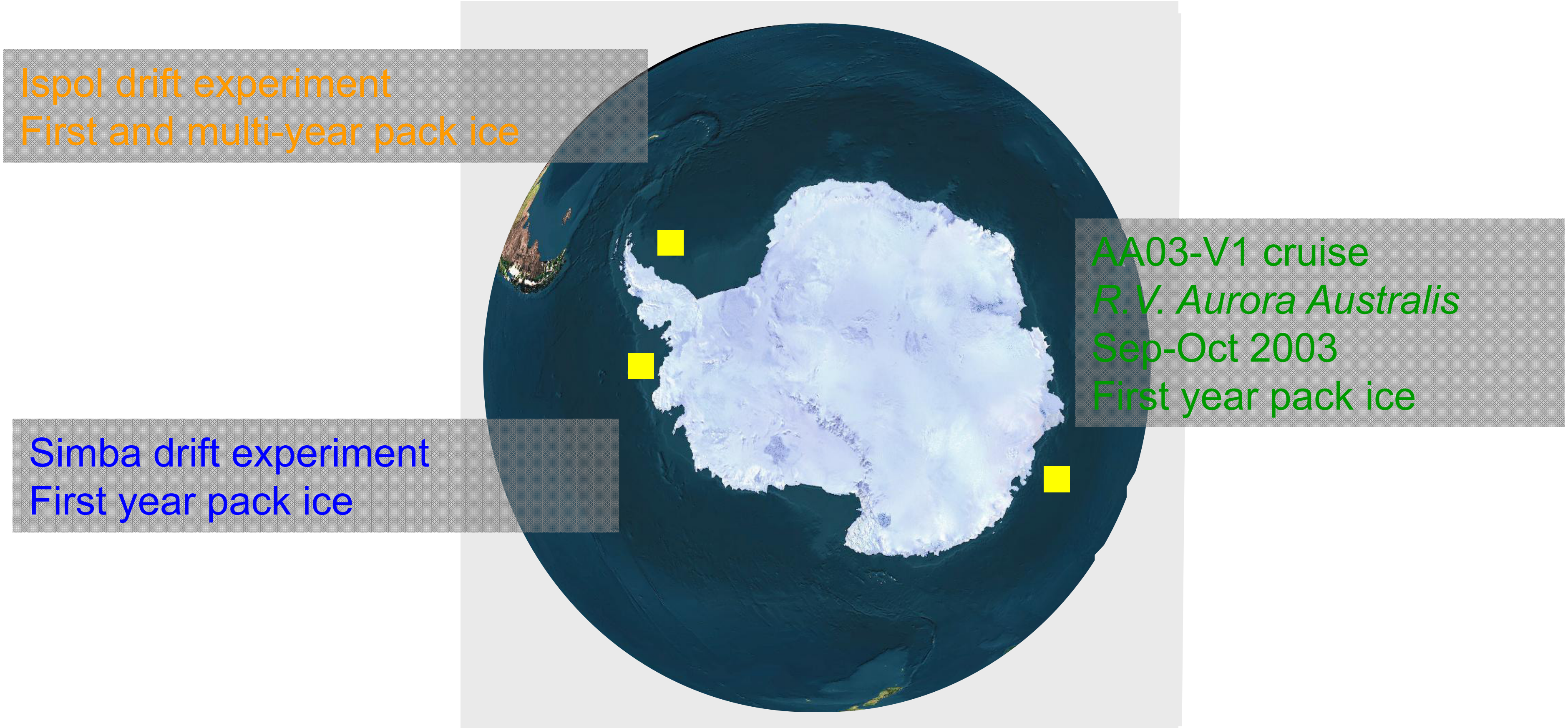
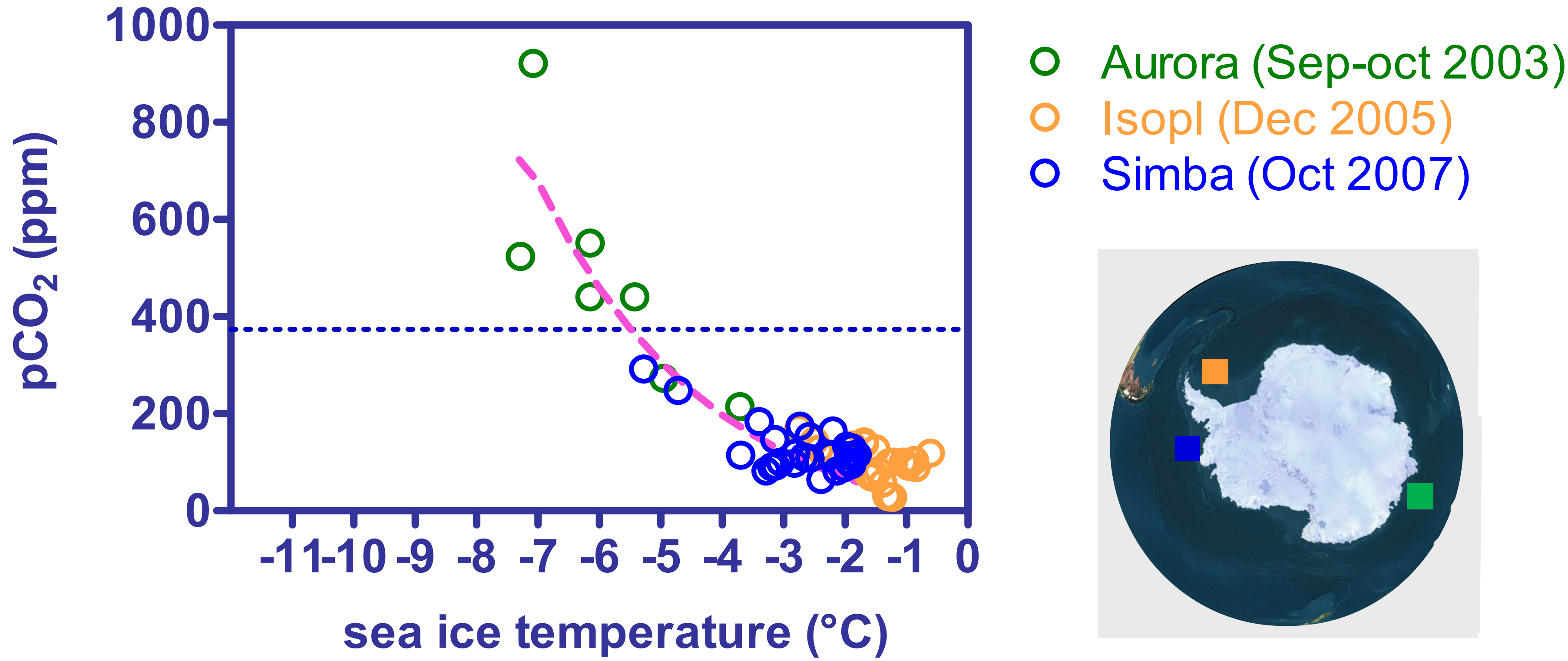
Semiletov et al. 2007
Nomura et al. 2009
This study (arctic-Barrow)
Delille et al. subm (Antarctic)
This study (arctic -CFL)
-1 gC m-2 month-1

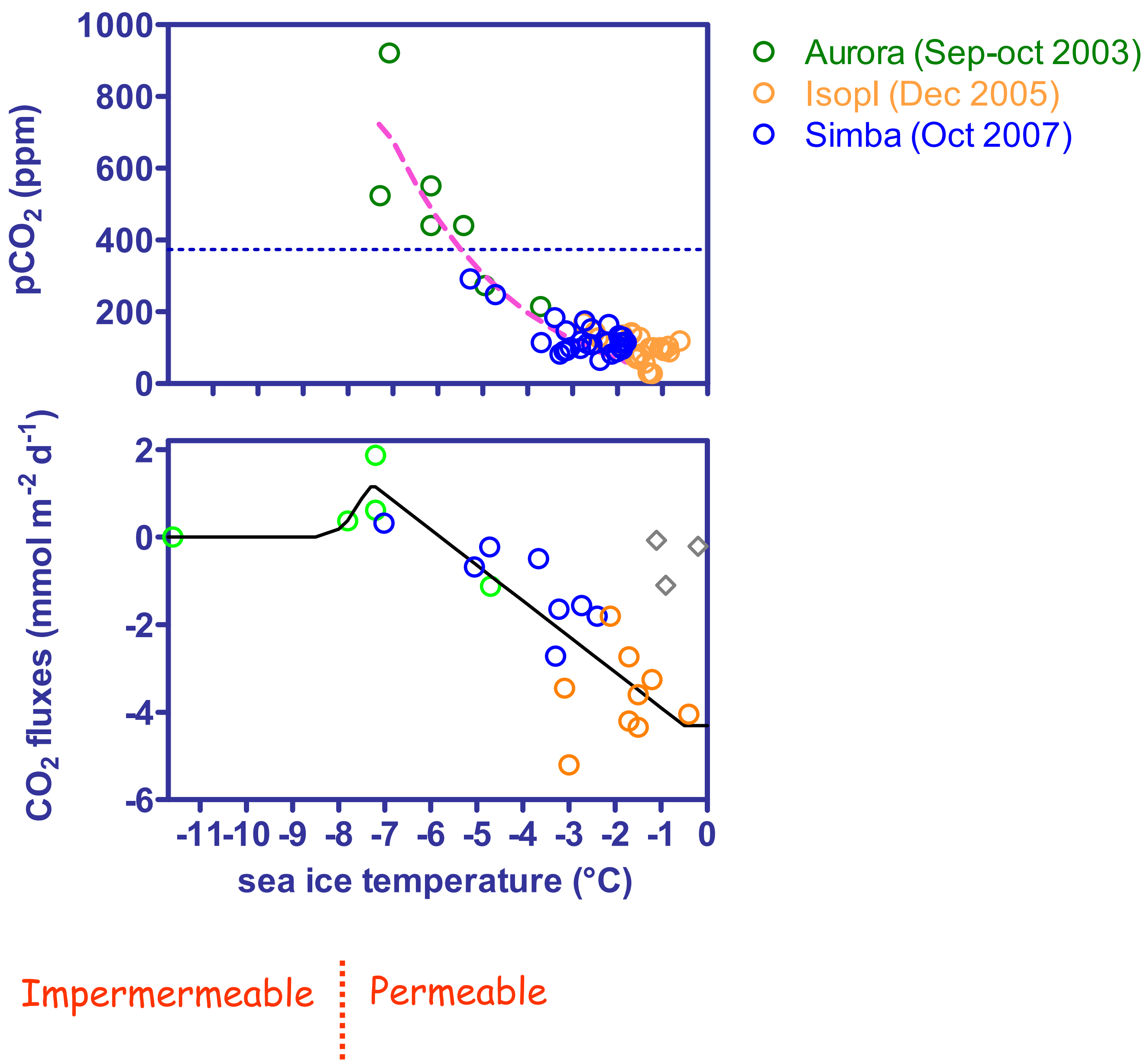


Raw mean of spring air-ice CO_2 fluxes	-1 gC m^{-2} $month^{-1}$
Spring surface of antarctic sea ice cover	20* 10^6 km^2
Time length of fluxes	2 months
Overall spring antarctic air-ice CO_2 fluxes	- 0.04 PgC
Overall S.O. open water fluxes (Takahashi et al. 2009)	- 0.04 PgC yr^{-1}


Ispol drift experiment
First and multi-year pack ice
AA03-V1 cruise
R.V. Aurora Australis
Sep-Oct 2003
First year pack ice
Simba drift experiment
First year pack ice

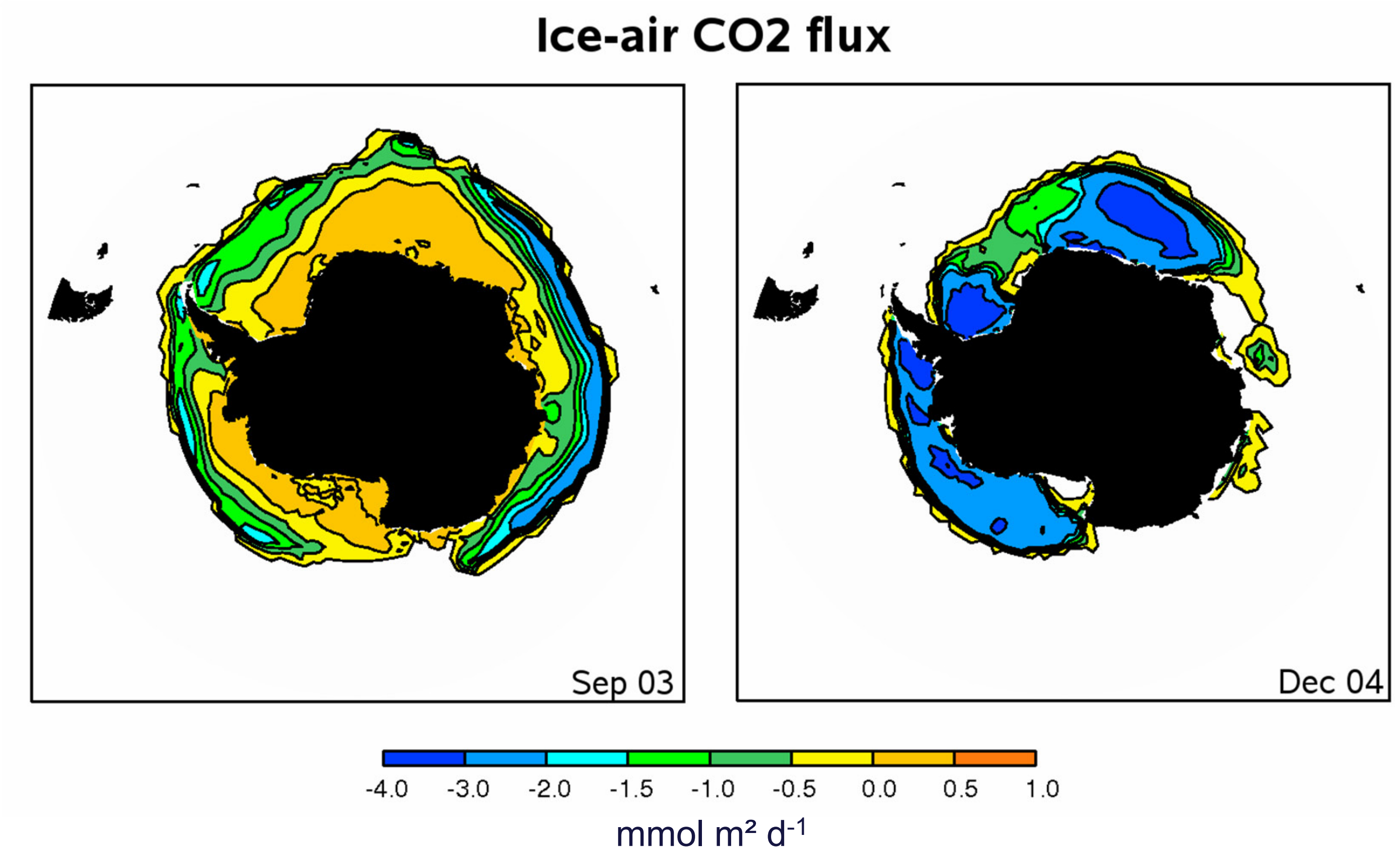


1000
800
600
400
200
0
pCO$_2$ (ppm)
-11 -10 -9 -8 -7 -6 -5 -4 -3 -2 -1 0
sea ice temperature (°C)
Aurora (Sep-oct 2003)
Isopl (Dec 2005)
Simba (Oct 2007)



Aurora (Sep-oct 2003)
Isopl (Dec 2005)
Simba (Oct 2007)
pCO2 (ppm)
1000
800
600
400
200
0
CO2 fluxes (mmol m-2 d-1)
2
0
-2
-4
-6
-11 -10 -9 -8 -7 -6 -5 -4 -3 -2 -1 0
sea ice temperature (°C)
Impermermeable
Permeable

Scaled using sea ice temperature from NEMO-LIM3 model

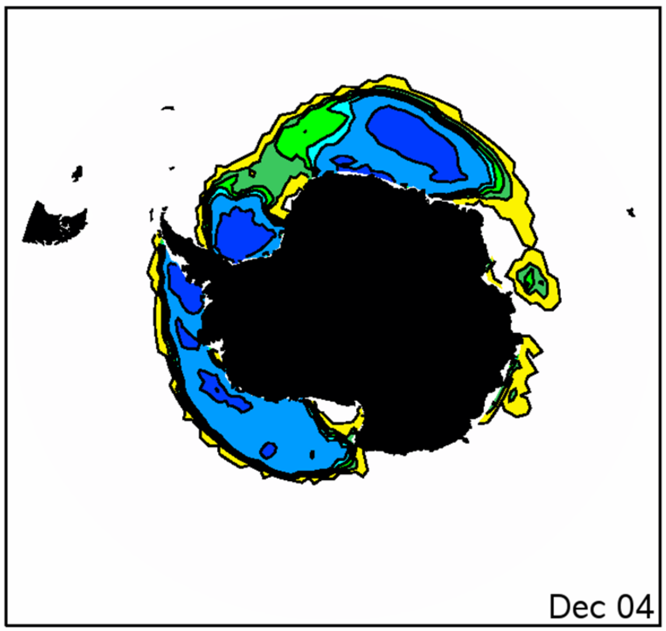


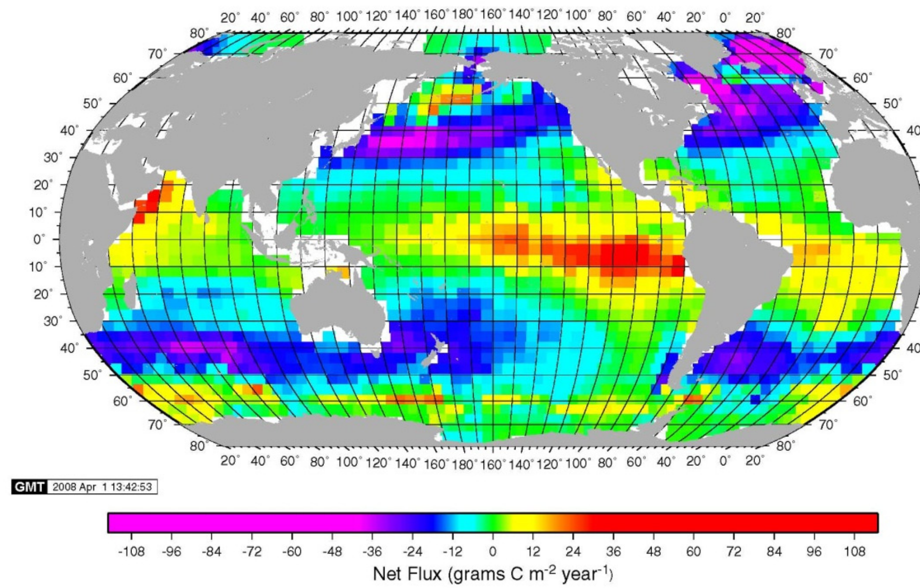
Spring air-ice fluxes of CO_2 for the Antarctic sea ice cover is assessed to -0.029 PgC from October to December

Scaled using sea ice temperature derived the NEMO-LIM3 model

Air-ice fluxes:
-0.029 Pg

Air-sea fluxes south of 50°S:
-0.04 Pg yr-1





Spring/early summer antarctic sea ice cover would represent an additional sink of about 70% of the overall CO_2 sink of the Southern Ocean.
We only consider areas with ice concentration over 65 % and we did not accounted flooded areas.

Is it realistic ?

Independent assessment

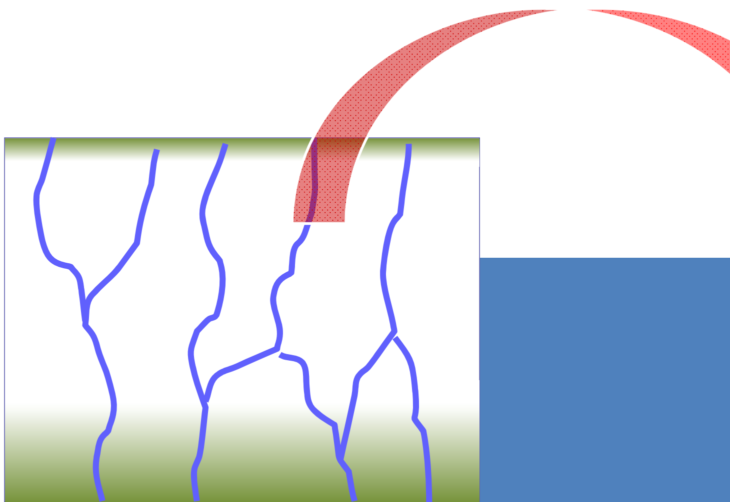
	related CO_2 transfer from the atmosphere (mmol m^{-2})
temperature increase and related dilution	-60
Primary production	-25
$CaCO_3$ dissolution	-57

Estimates of potential air-ice CO_2 fluxes related to spring and summer physical and biogeochemical processes observed during the 2003/V1 and ISPOL cruises. Flux representative of a 4 months period.

The overall CO_2 fluxes reach 142 mmol m^{-2}.
Taking into account a mean value for the Antarctic sea ice edge surface area of 16×10^6 km^2, the corresponding overall CO_2 fluxes account for 0.029 PgC.

This compares favourably with our previous estimate of an additional sink of 0.025 PgC.

What happens when ice melts ?



knowing DIC and TA of ice, it is possible to derive the decrease of pCO_2 of surface water related to melting of the ice then to compute related uptake of atmospheric CO_2

Net CO_2 fluxes	without ikaite formation	-0.033 PgC yr^{-1}
	including ikaite formation	-0.083 PgC yr^{-1}
To be compared to fluxes of polar open oceans		-0.199 PgC yr^{-1}

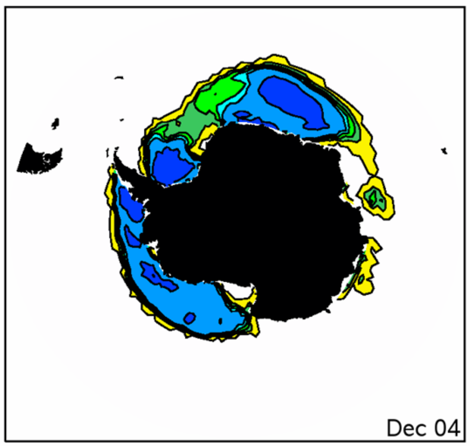
Sea ice accounts for 17 to 42 % of CO_2 uptake of the polar oceans

Rysgaard et al. 2012

Sea ice

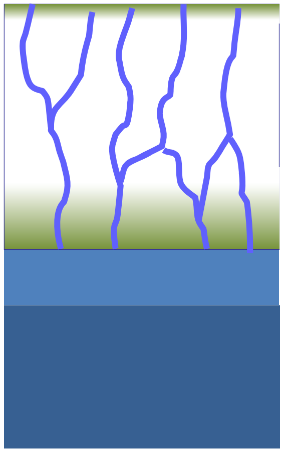
Open ocean

Direct air measurement of air-ice CO_2 fluxes, scaled using sea ice temperature derived the NEMO-LIM3 model



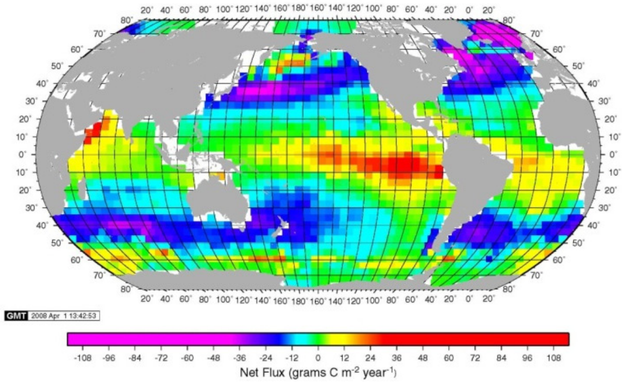
Air-ice fluxes:
-0.029 Pg

Simple box model approach
Rysgaard et al. 2012



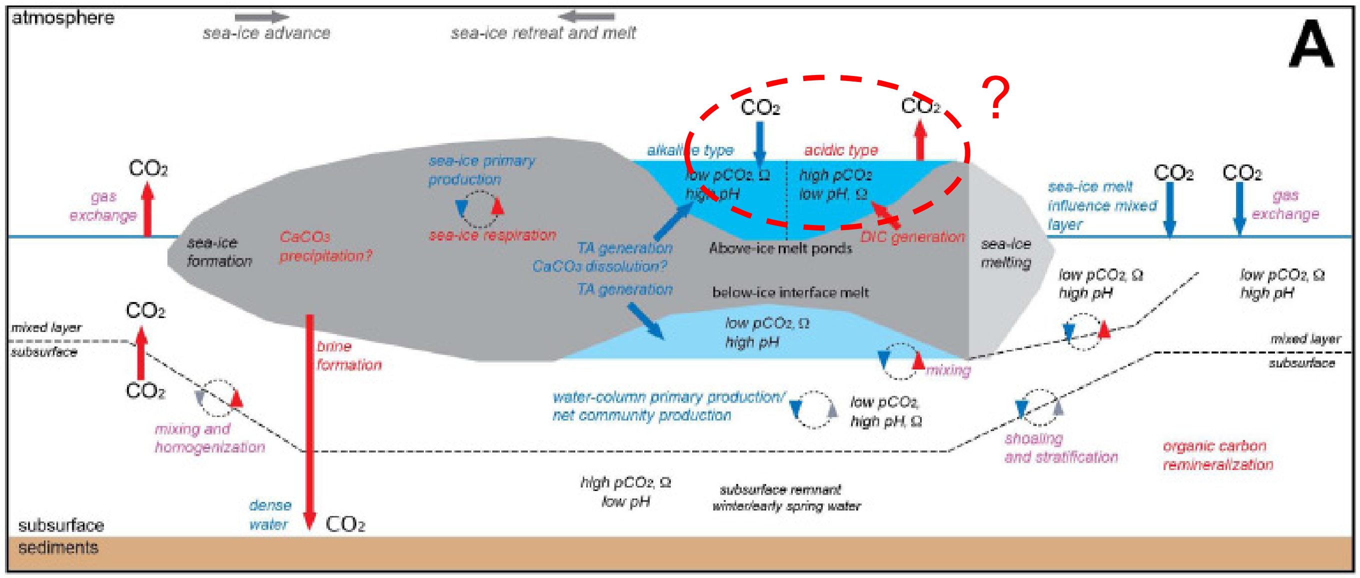
Air-ice fluxes:
-0.019 to -0.052 Pg

Takahashi et al. 2009 climatology



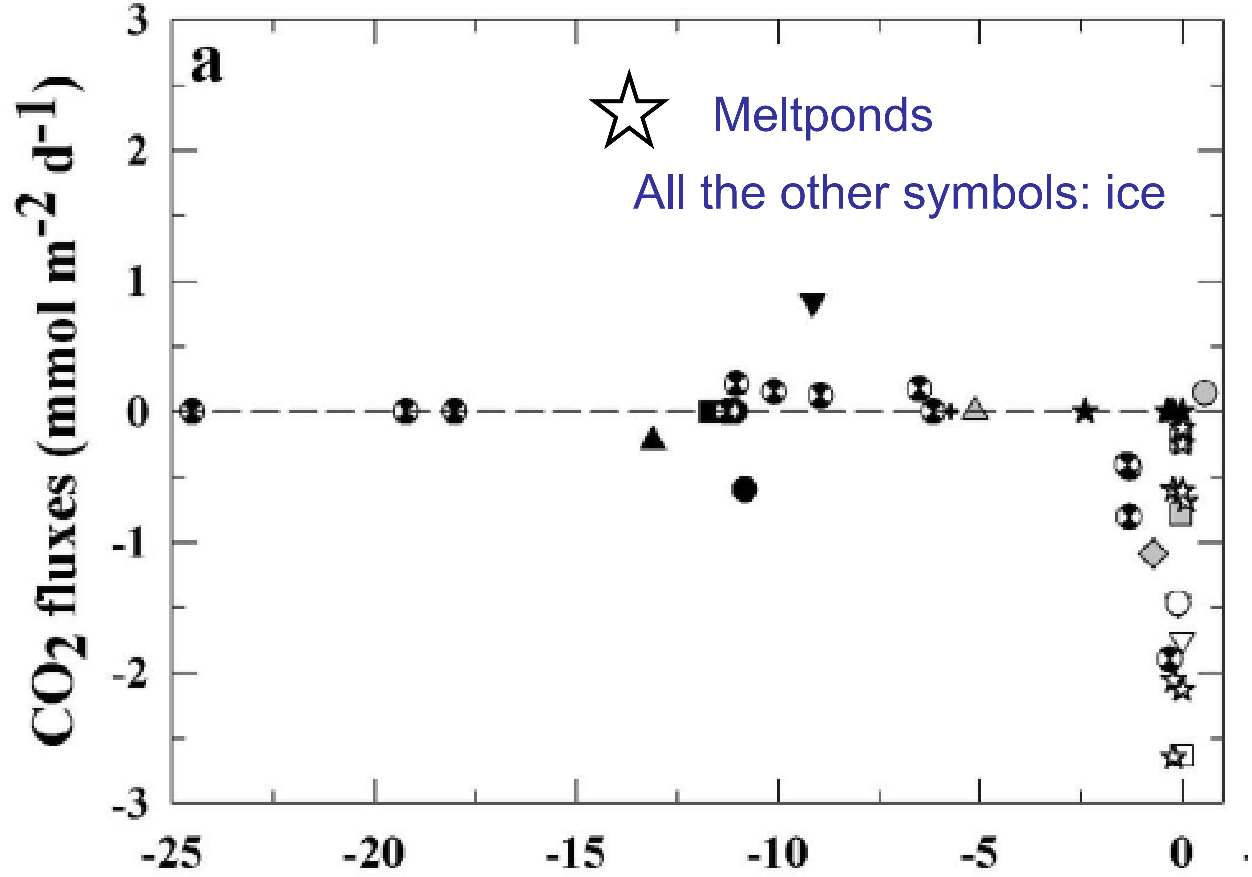
Air-sea fluxes south of 50°S:
-0.04 Pg yr-1

Meltponds

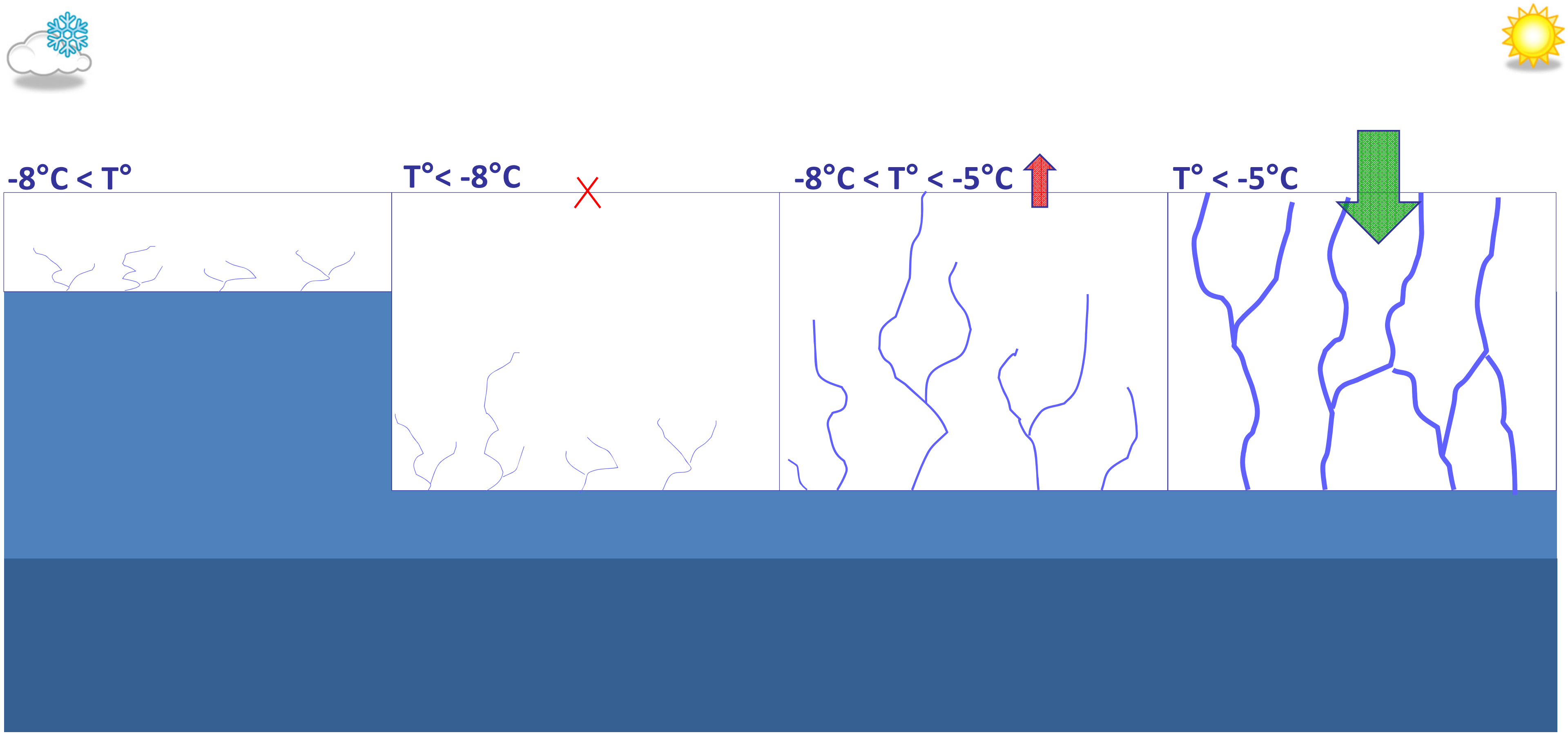


Fall Winter Spring Summer

Bates et al. 2014



Geilfus et al. 2012



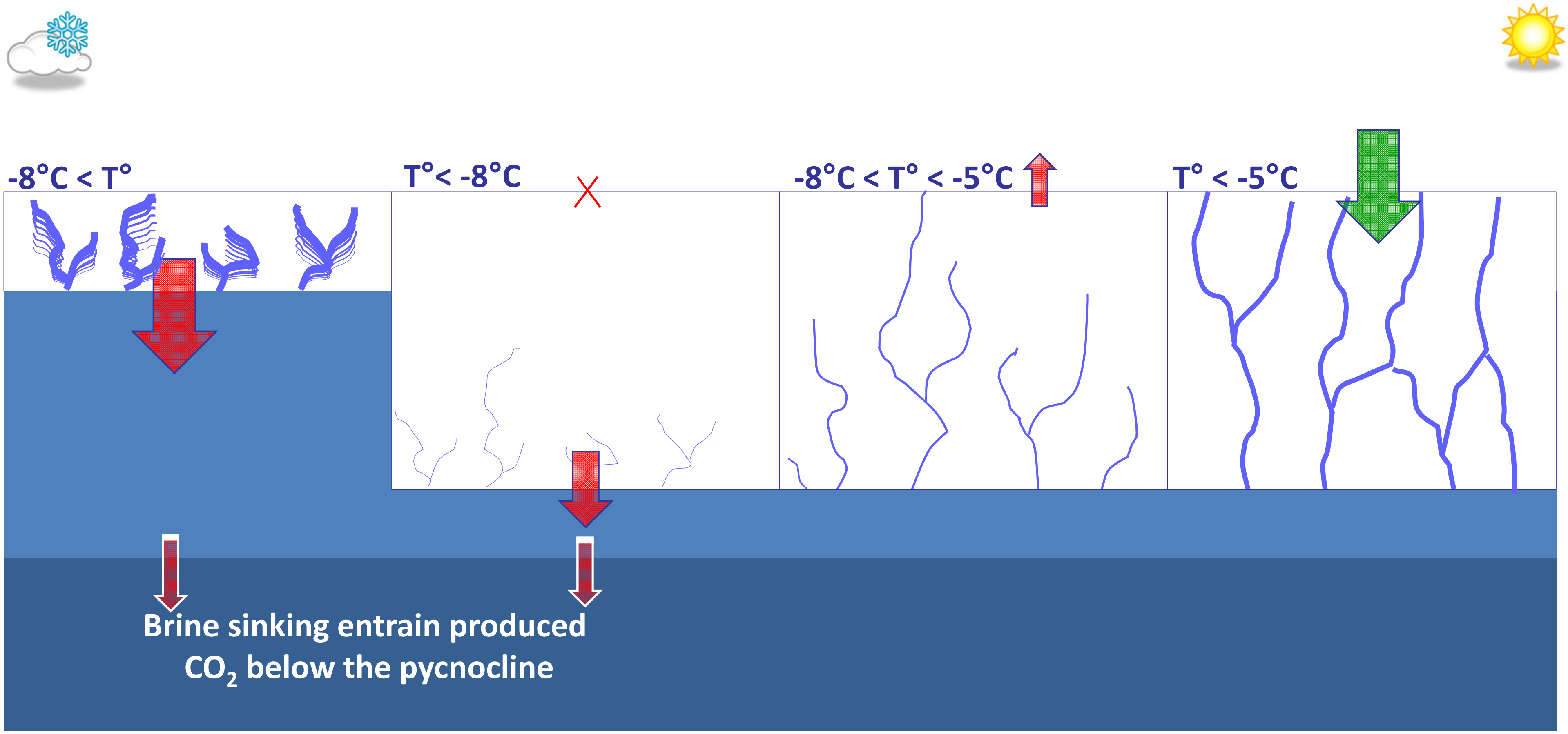
In spring sea ice shift from a transient source of CO_2 to a sink of CO_2 for the atmosphere

Why such fluxes ?

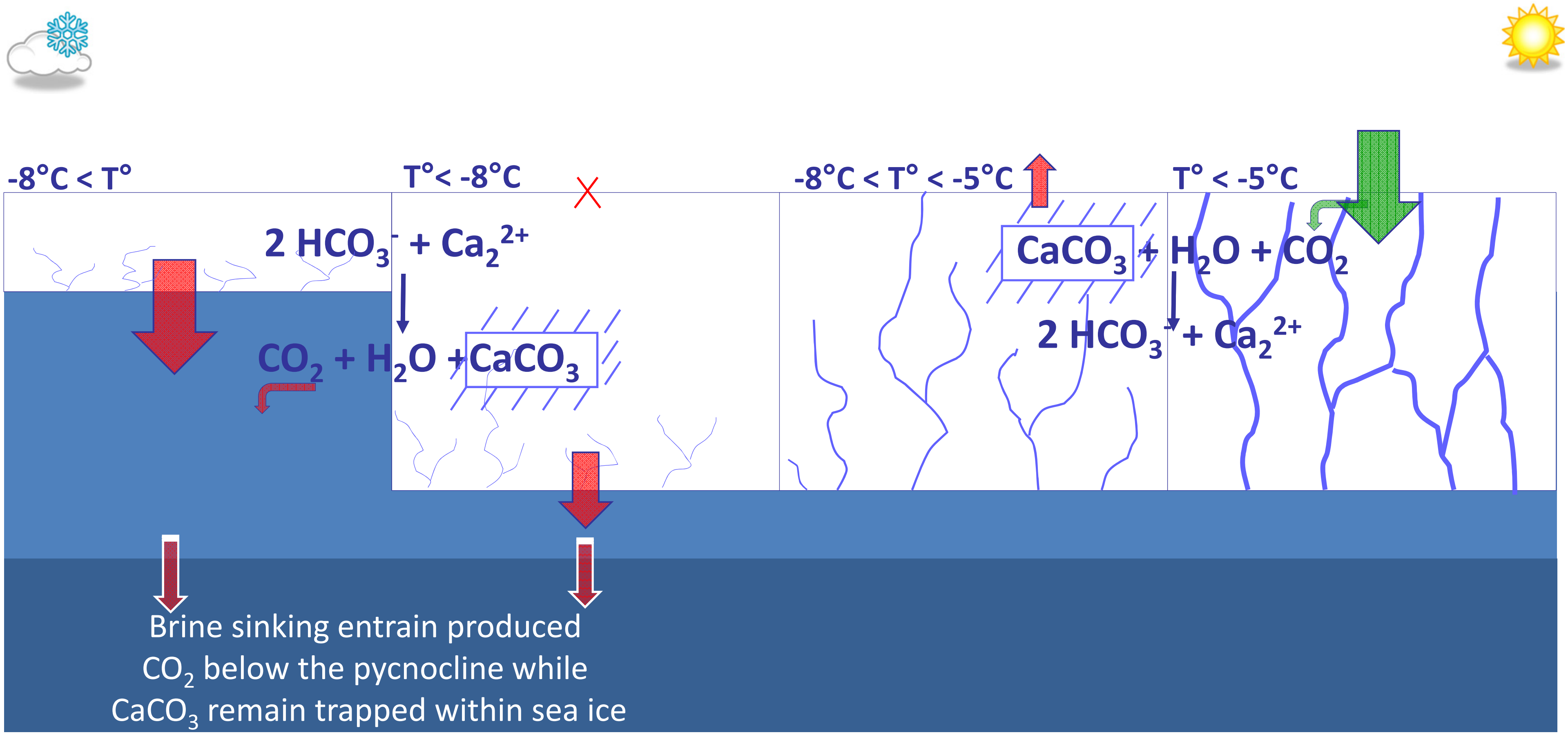
Sea ice appears to be depleted in DIC

Sea ice appears to have high TA:DIC

But why sea ice shows these properties ?

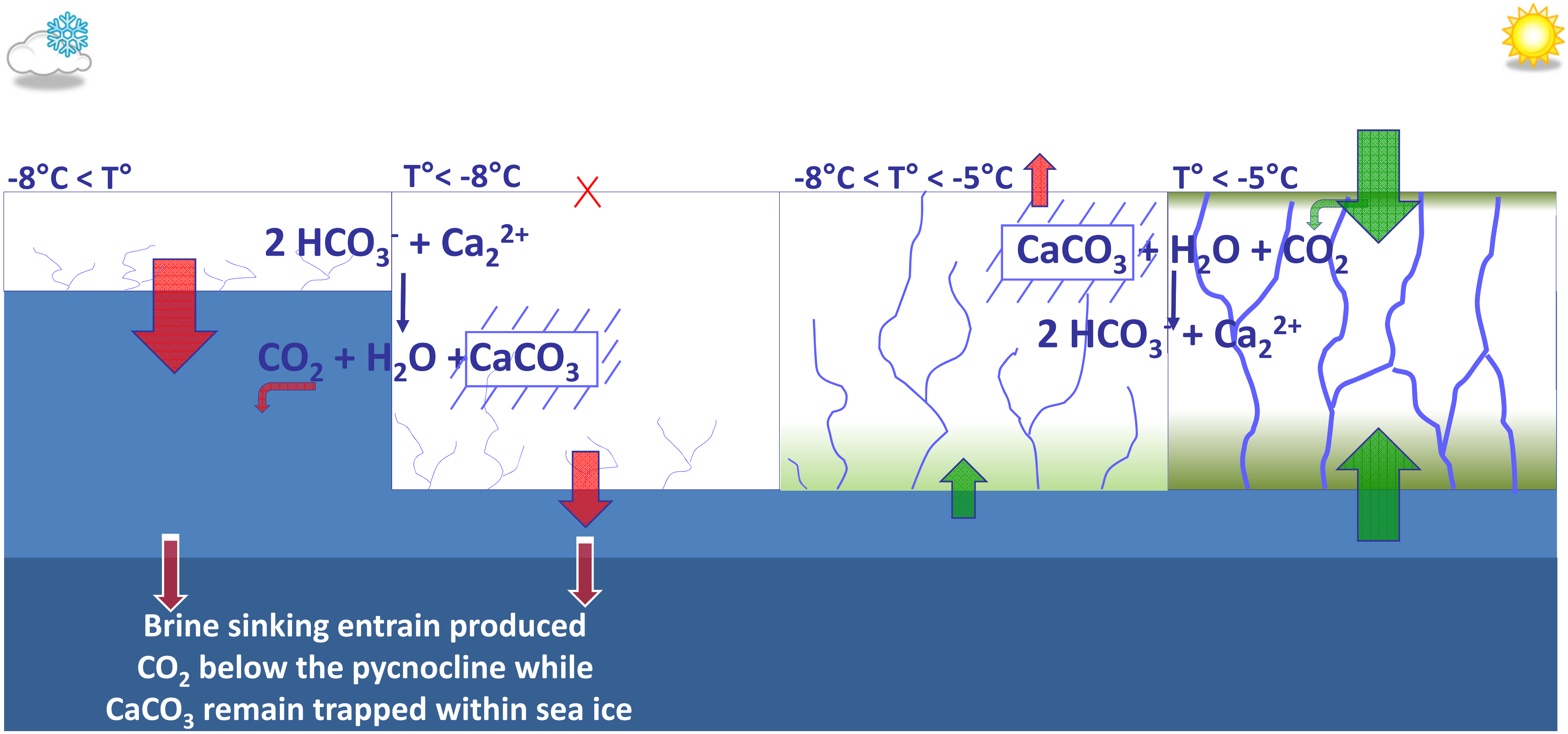


Brine concentration promotes oversaturation of pCO_2.
Brine rejection lead to expulsion of CO_2, mainly below sea ice, as the surface quickly becomes impermeable.
CO_2 rich brines tends to sink below the pycnocline, acting as efficient CO_2 sequestration mechanism

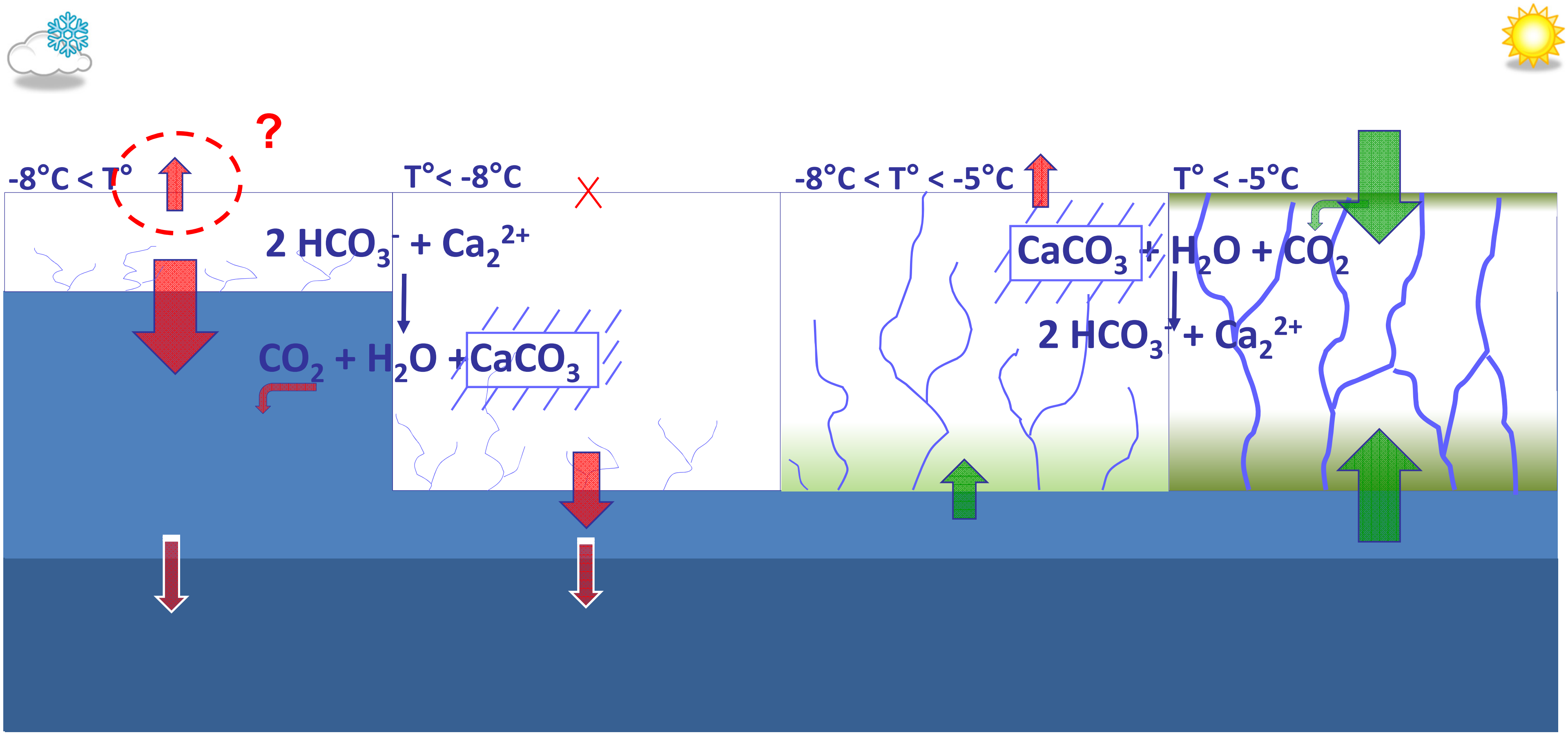


$CaCO_3$ formation and trapping during sea ice growth, can promote the increase of pCO_2 and expulsion of CO_2 .

$CaCO_3$ dissolution in spring consumes CO_2



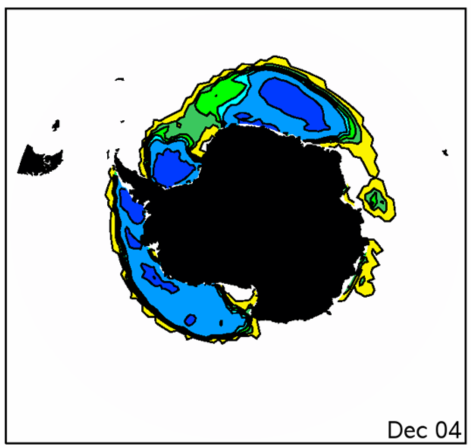
Primary production promotes the uptake of CO_2



Release of CO_2 to the atmosphere during ice growth ?

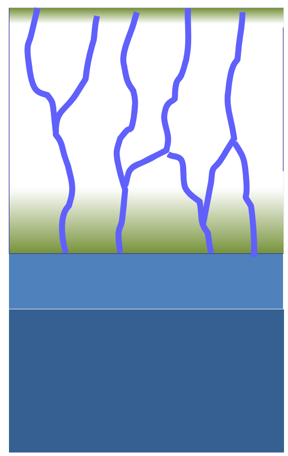
Sea ice

Direct air measurement of air-ice CO_2 fluxes, scaled using sea ice temperature derived the NEMO-LIM3 model



Air-ice fluxes:
-0.029 Pg

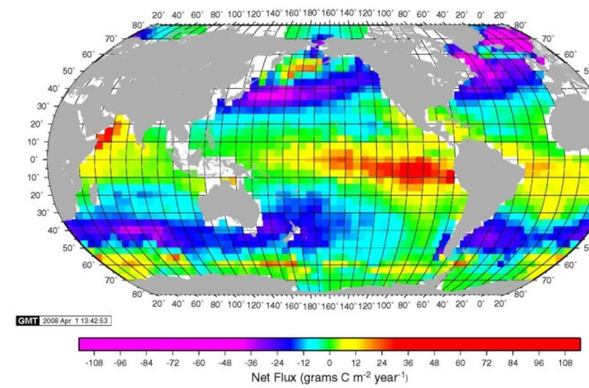
Simple box model approach
Rysgaard et al. 2012



Air-ice fluxes:
-0.019 to -0.052 Pg

Open ocean

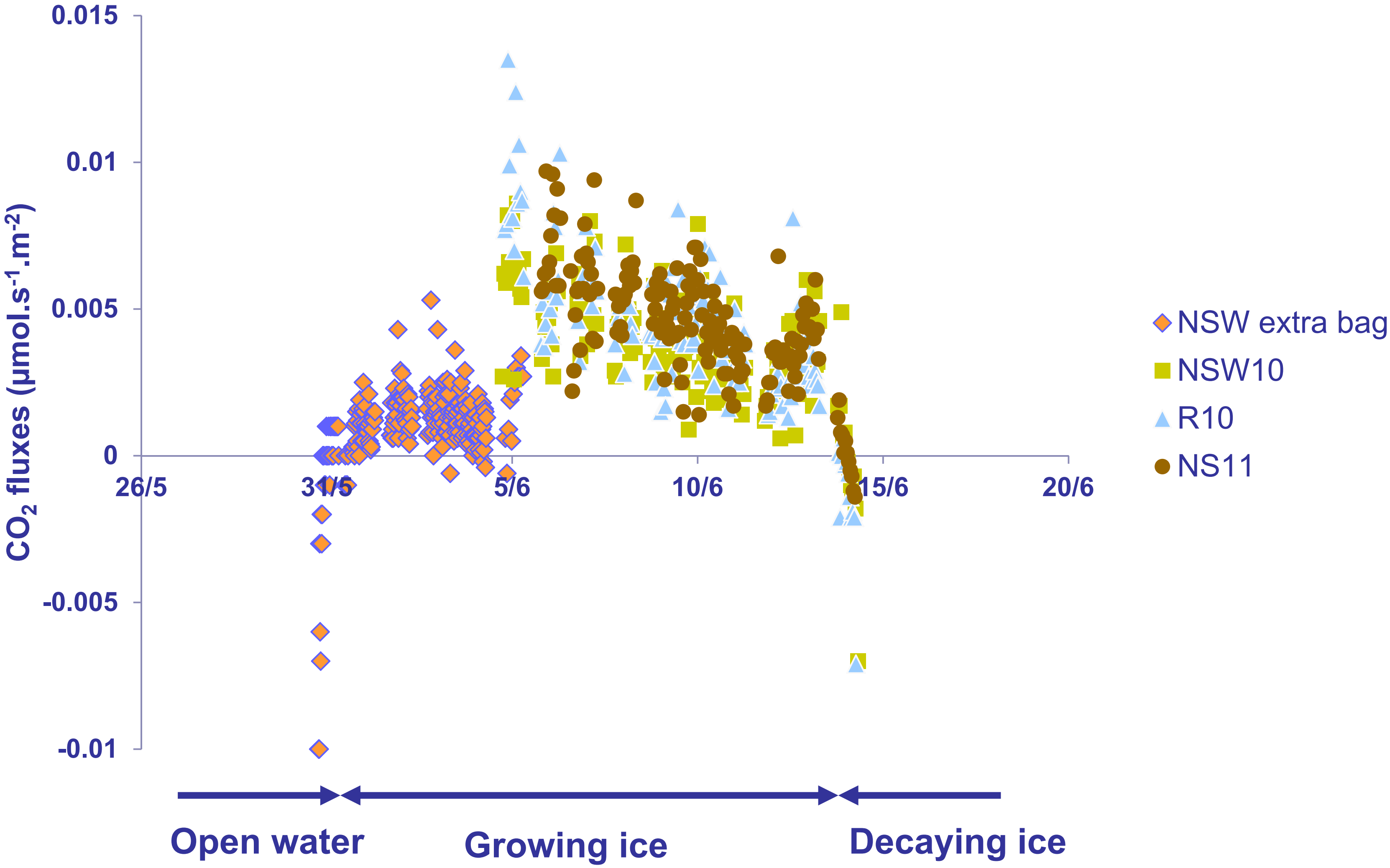
Takahashi et al. 2009 climatology



Air-sea fluxes south of 50°S:
-0.04 Pg yr-1

Artificial ice (growth) – Intreice 5 experiment

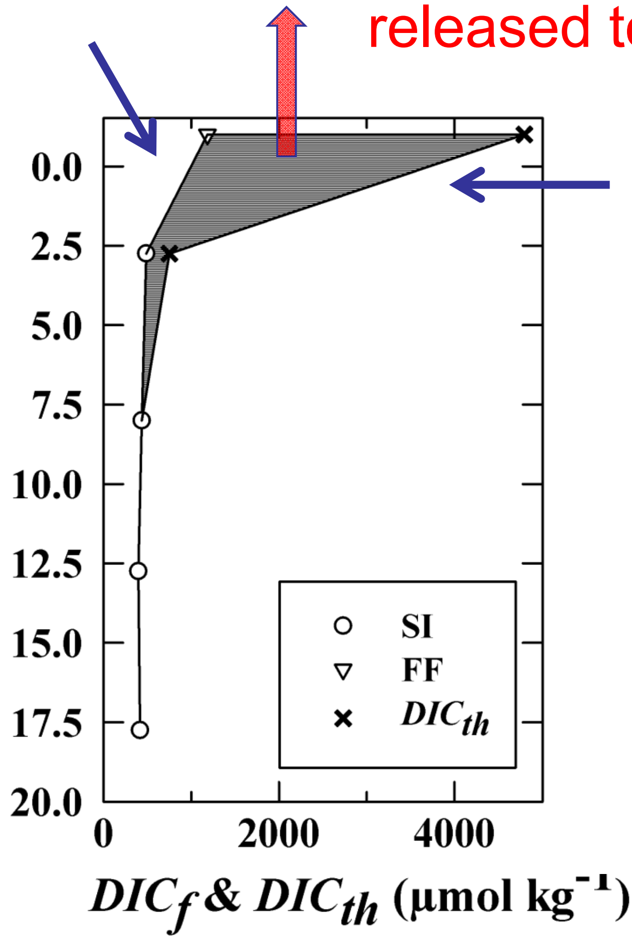
Artificial ice (growth) – Intreice 5 experiment



Barrow – Thin ice

Missing DIC was liekely released to the atmosphere

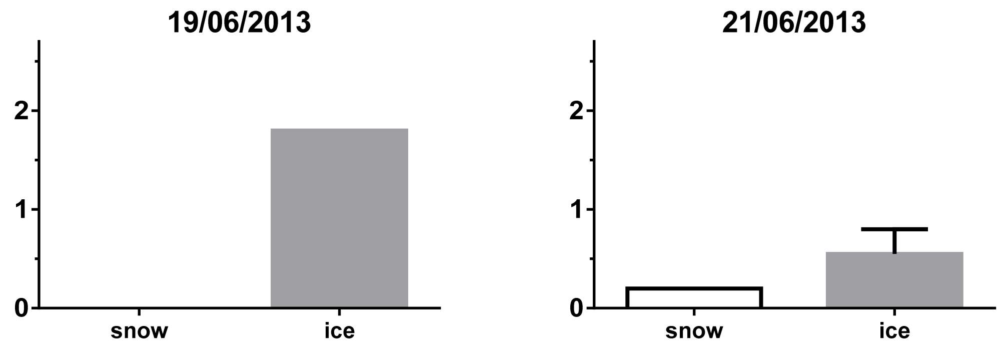
DIC $_f$ observed

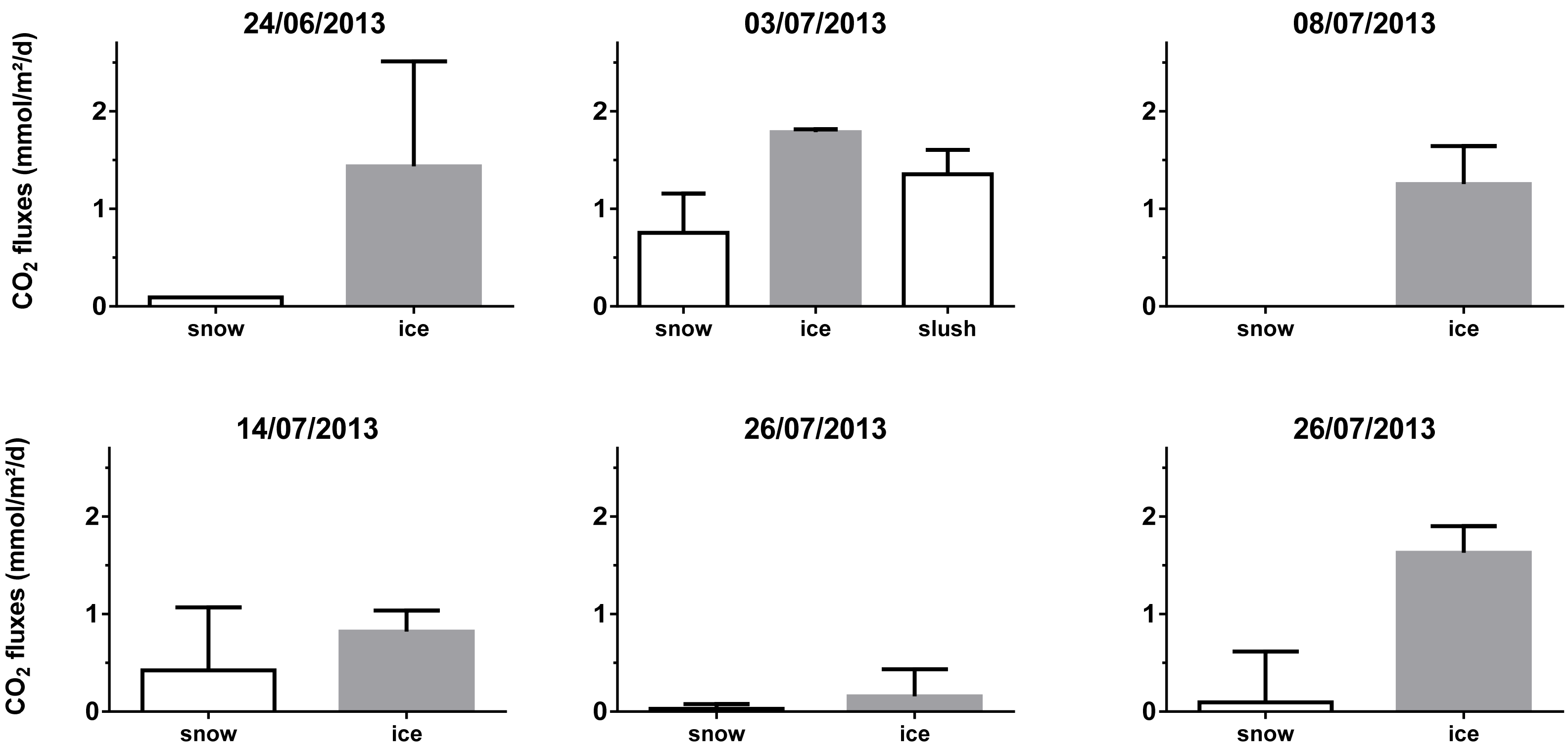


DIC $_{th}$ that we should observe if DIC is conservative (derived from salinity)

Geilfus et al. 2013

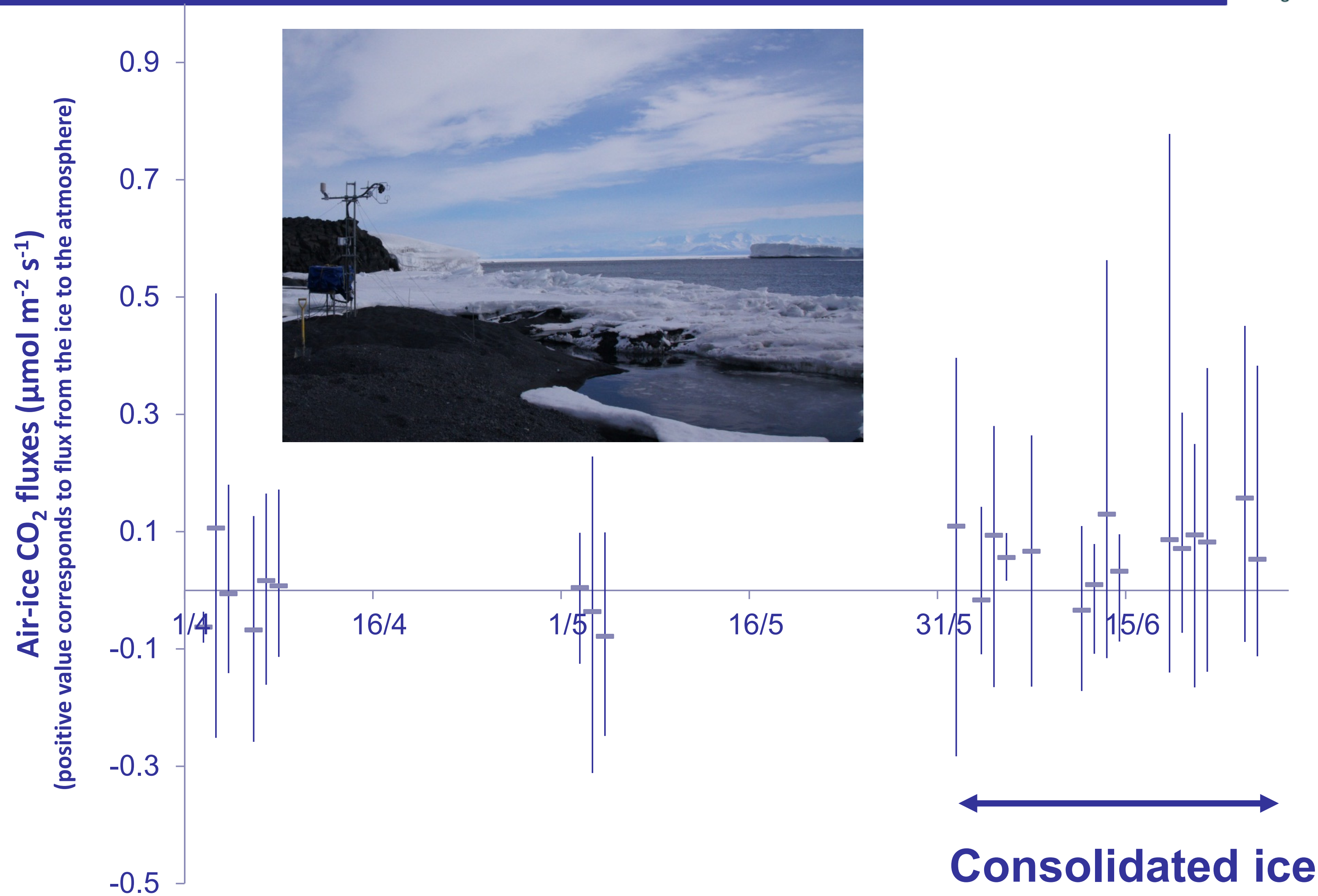
AWECS - Winter Weddell Sea 2013





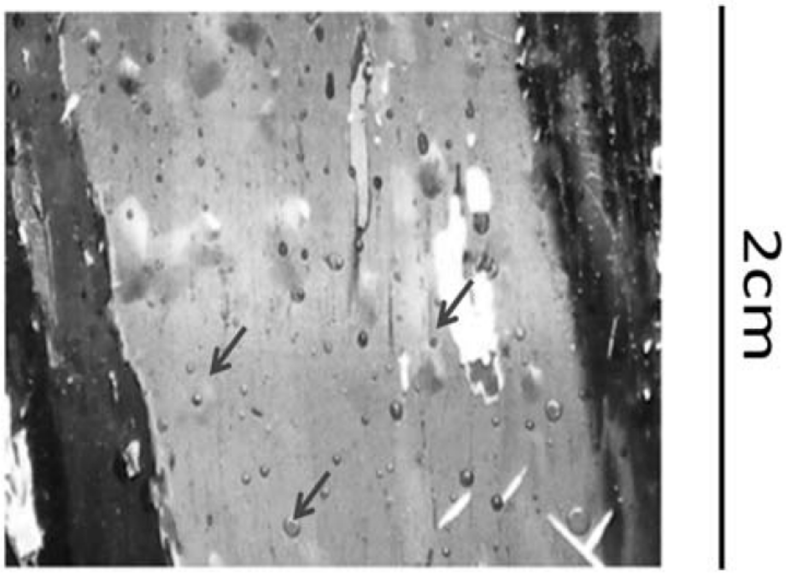
McMurdo sound winter 2012

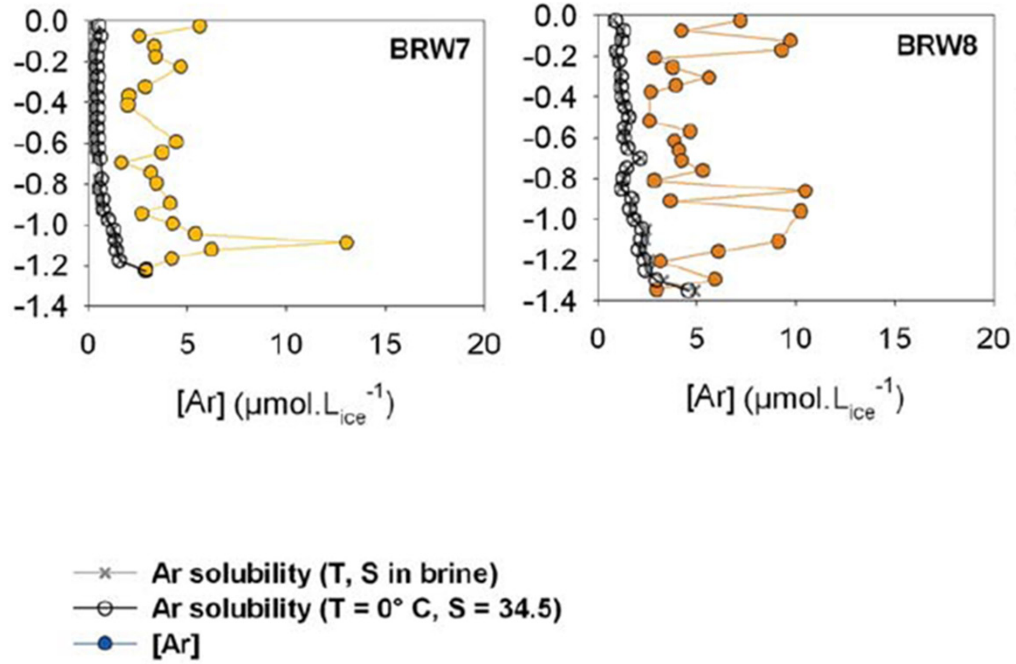
Université de Liège



CO_2 release in June: 84 mgC m^{-2}

Bubbles ?



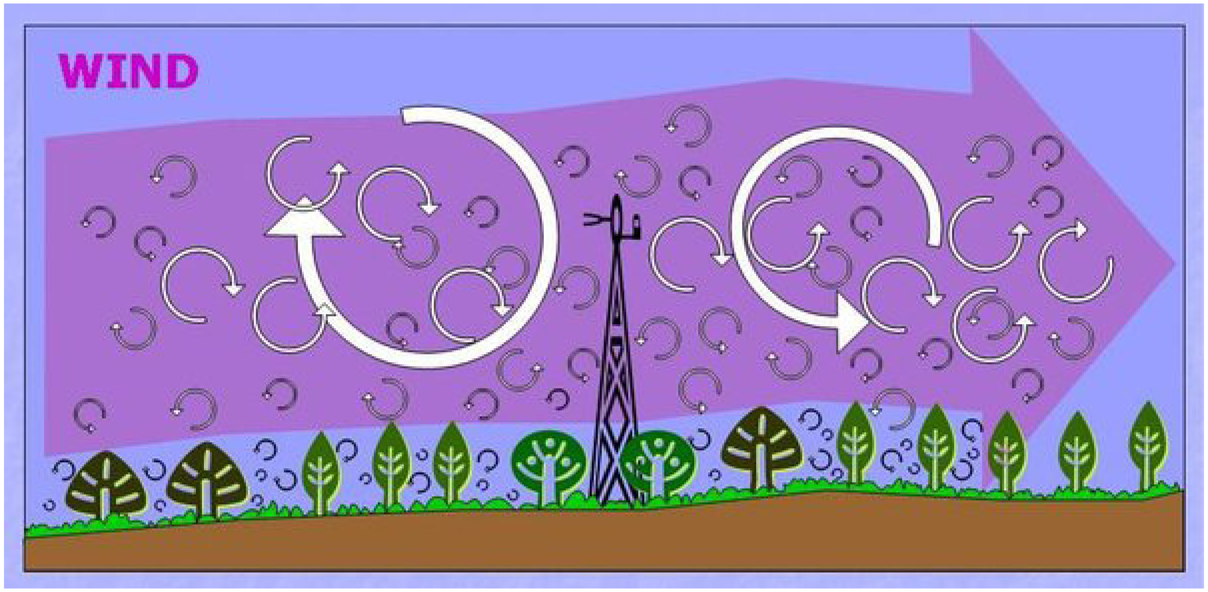


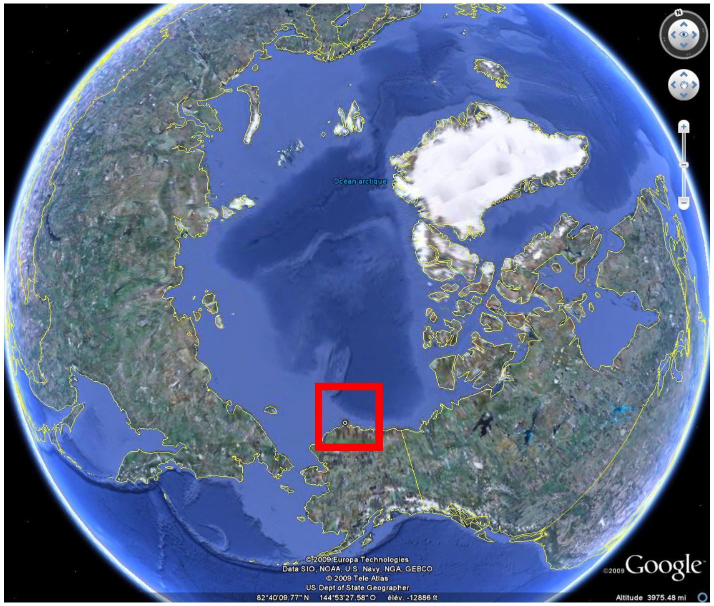
Zhou et al. 2013

Why fall and winter release of CO_2 ?

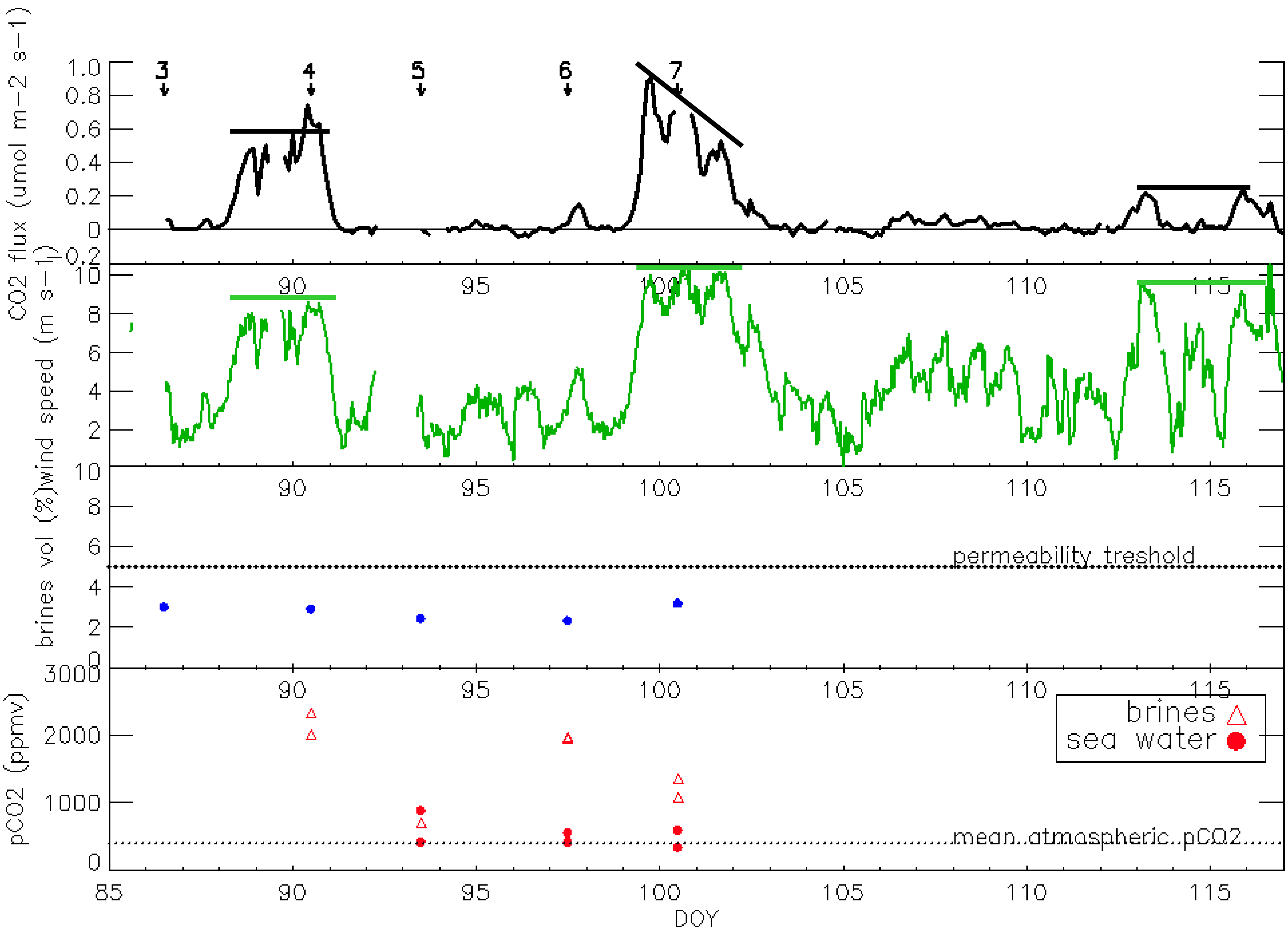
- Sea ice can be permeable at the top even in winter thanks to higher bulk salinity
- Sea ice rejects impurities both at the bottom of the ice but also at the top (case of frost flowers)
- At that time sea ice is strongly oversaturated in CO_2 due to brines concentration
- Bubbles are forming. CO_2 is transferred upwards with bubbles.

- Eddy-covariance



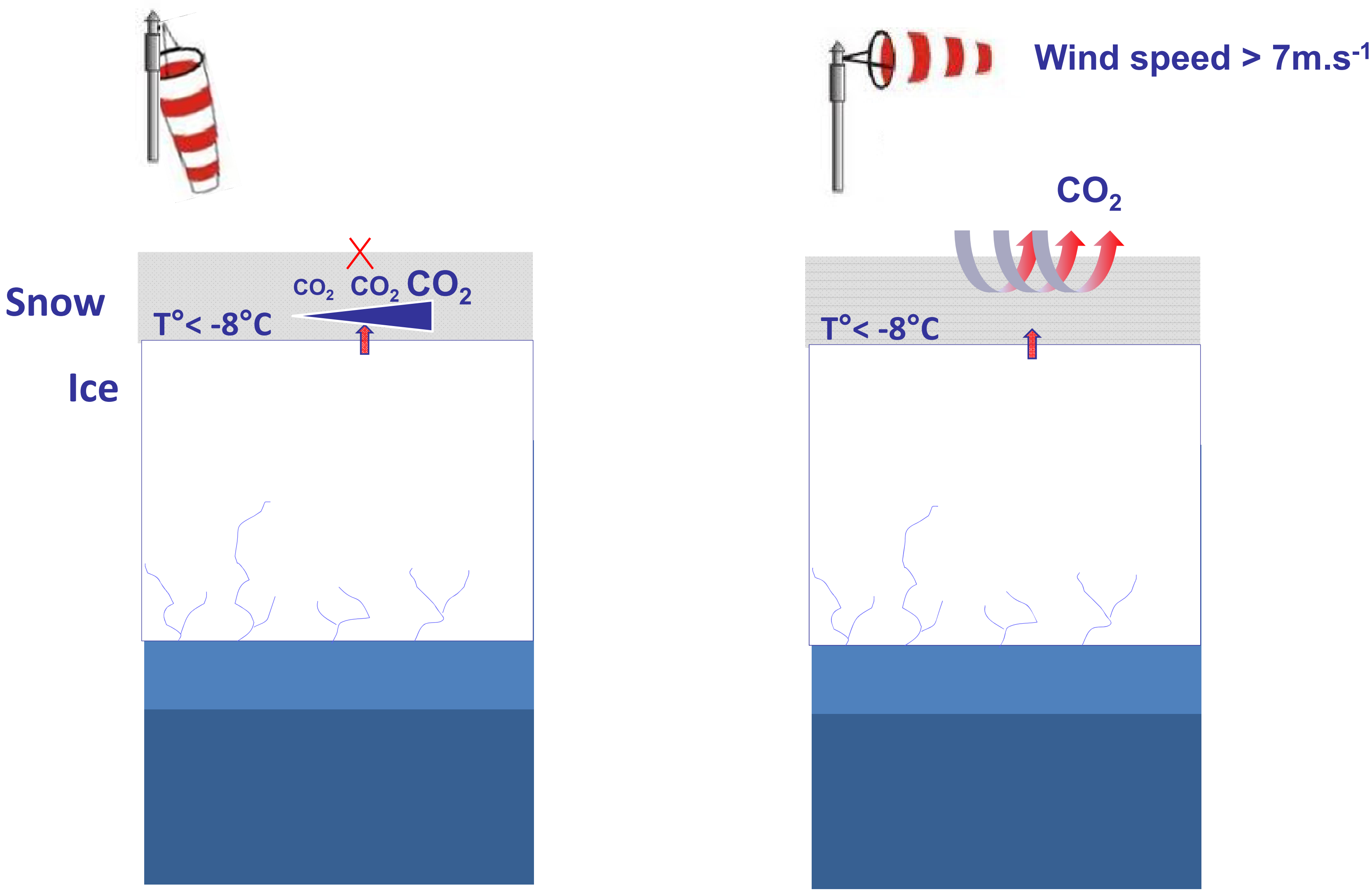

Océan arctique
© 2009 Europa Technologies
Data SIO, NOAA, U.S. Navy, NGA, GEBCO
© 2009 Tele Atlas
US Dept of State Geographer
Google

EC tower
Barrow, AK
© 2009 Tele Atlas
Google

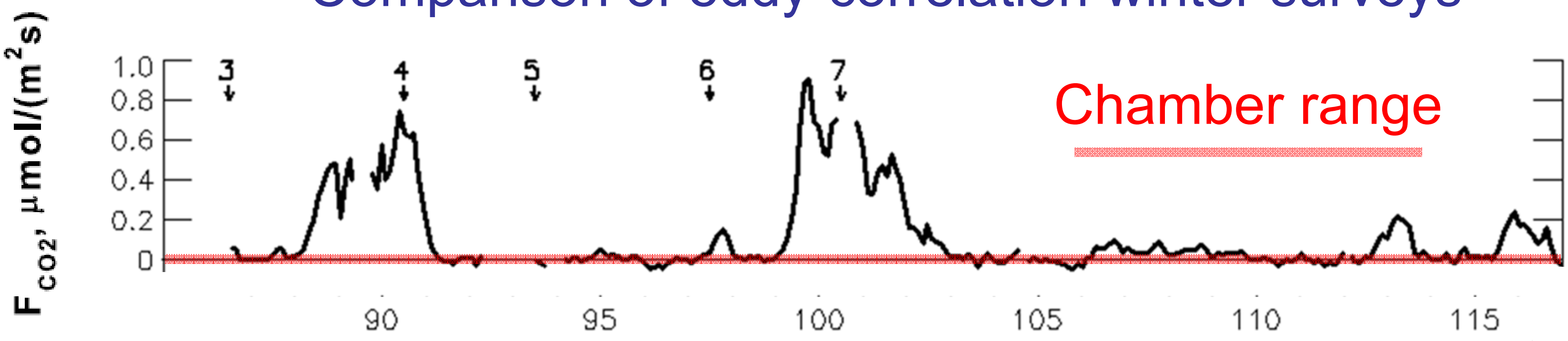


CO2 flux (umol m−2 s−1)
wind speed (m s−1)
brines vol (%)
pCO2 (ppmv)
3
4
5
6
7
permeability treshold
mean atmospheric pCO2
brines
sea water
DOY

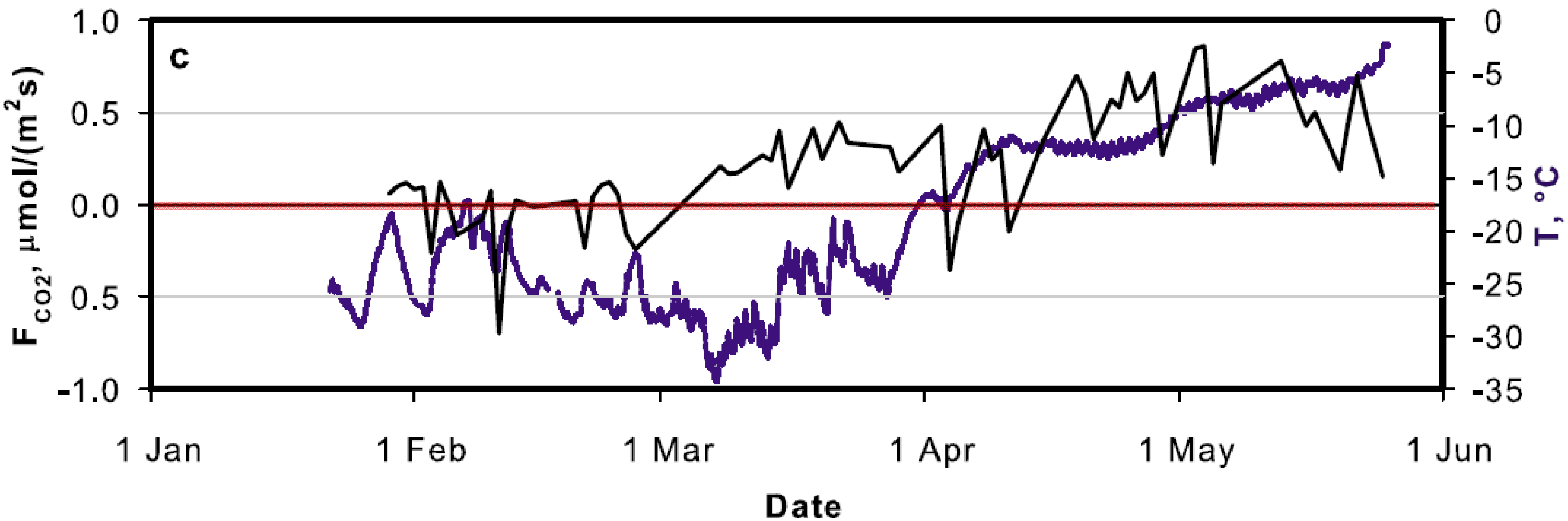
Snow acts as a CO_2 transient reservoir



Comparison of eddy-correlation winter surveys



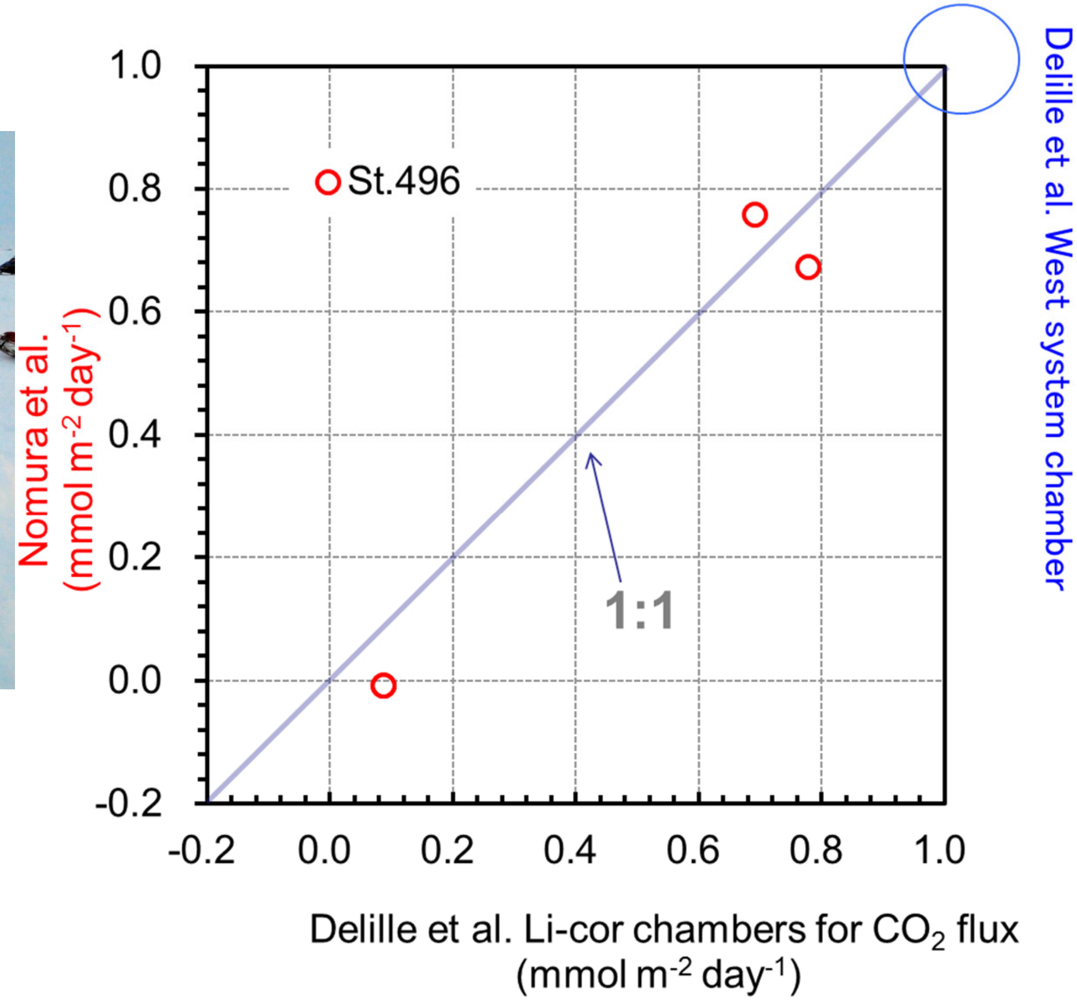
Barrow 2009

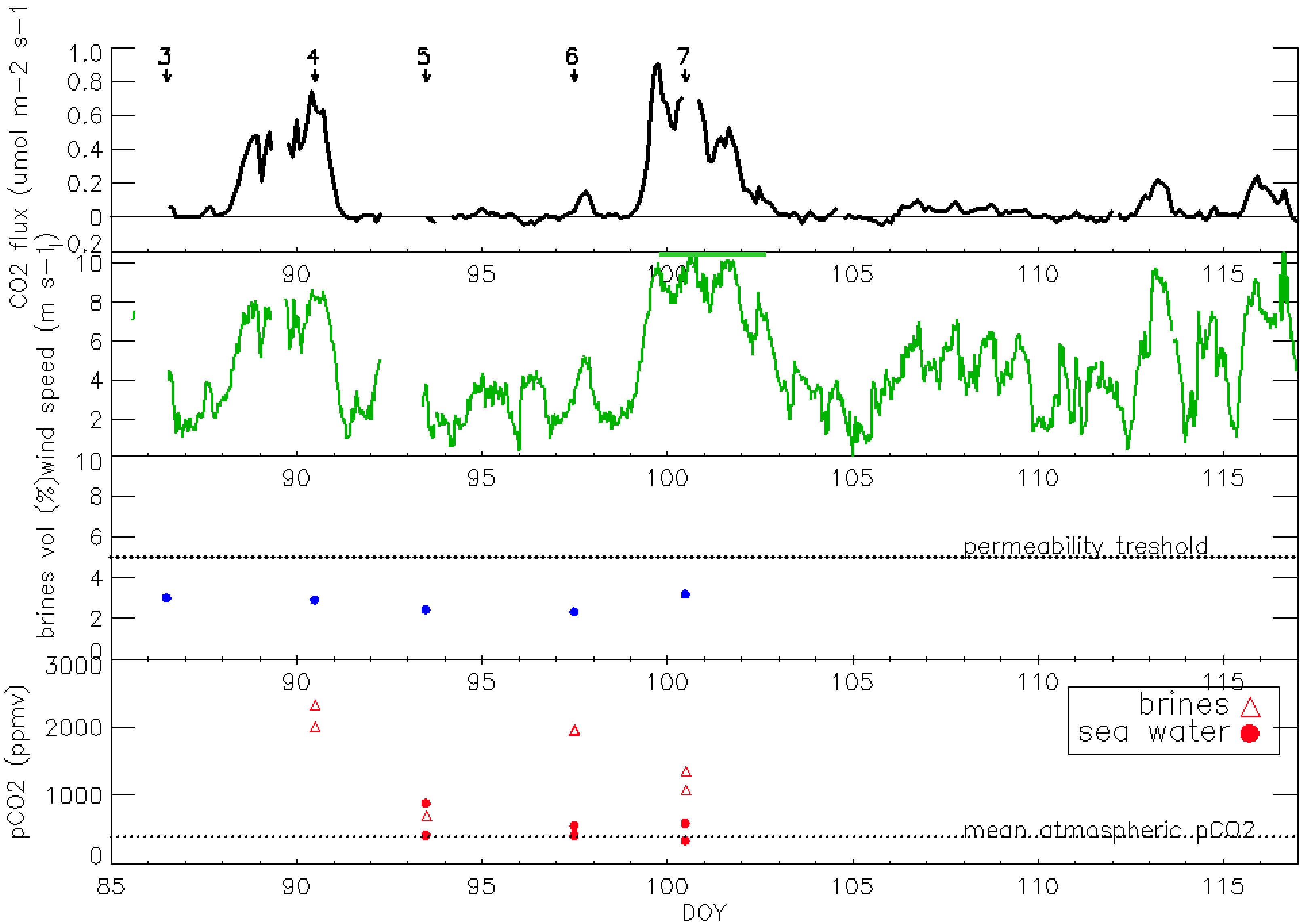


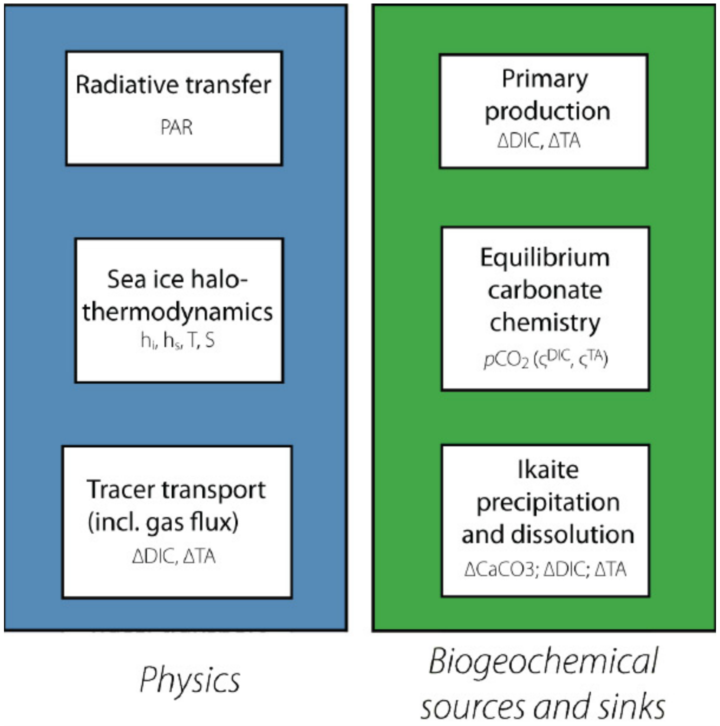
Beaufort sea Miller et al. 2011

100% ice cover !!!

Intercomparison of chambers measurements

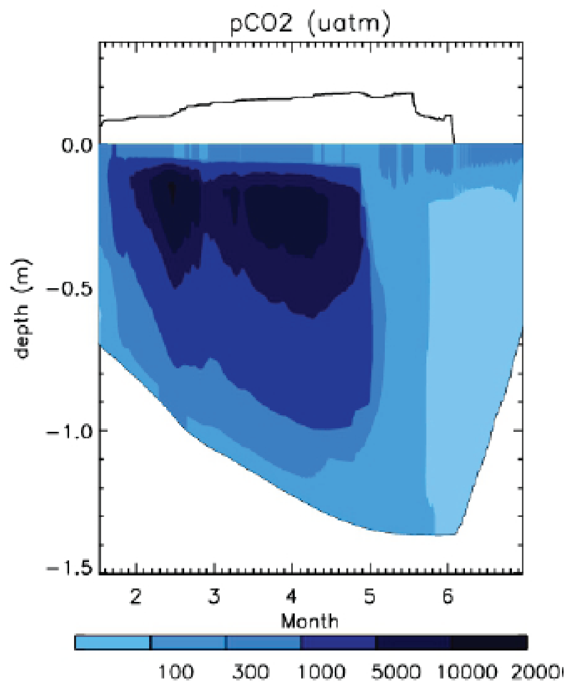



CO2 flux (umol m−2 s−1)
wind speed (m s−1)
brines vol (%)
pCO2 (ppmv)
3
4
5
6
7
permeability treshold
mean atmospheric pCO2
brines
sea water
DOY

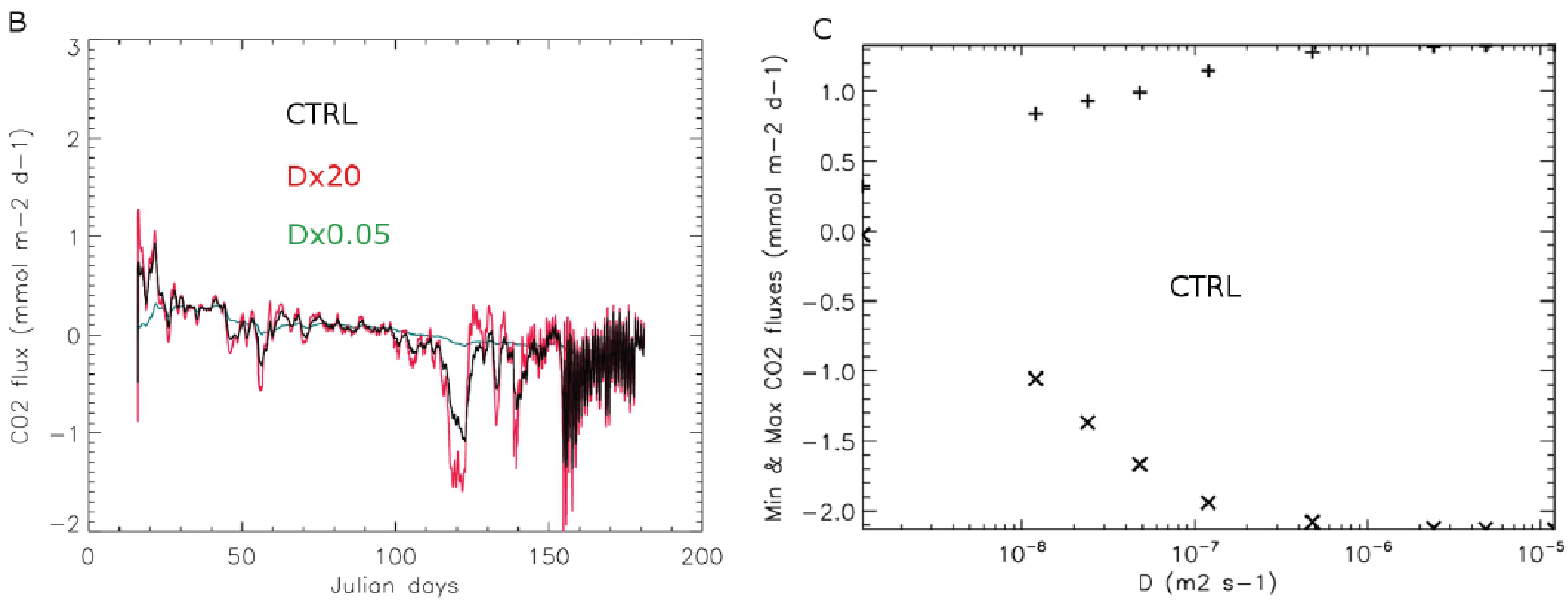


Moreau et al. in pep

Moreau et al. 2014 1D model for Argon
+ CO_2
+ ikaite precipitation according to
Papadimirtriou et al. 2013 & 2014
+ primary production

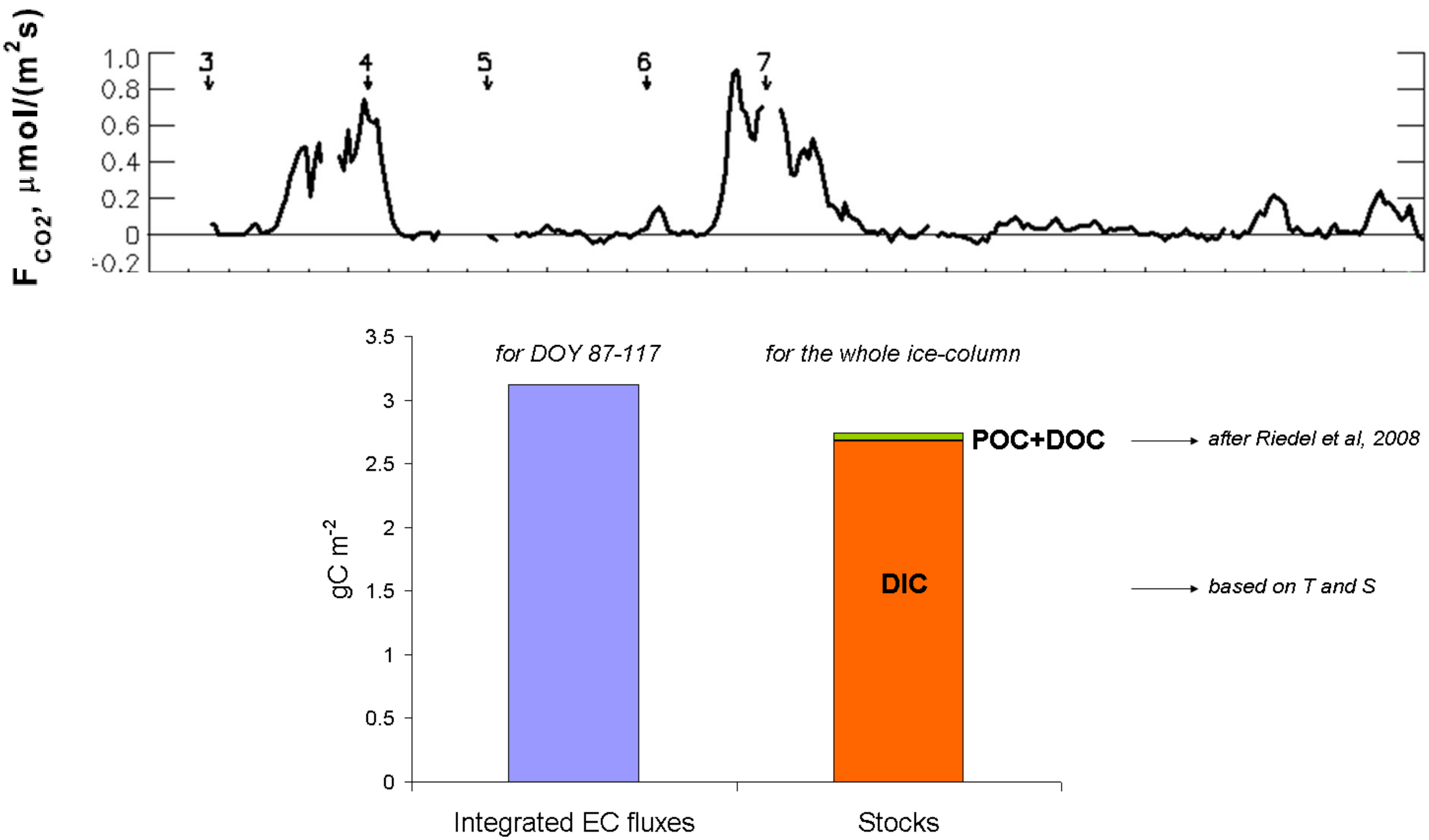


D diffusion coefficient at the air-ice interface



Moreau et al. in pep

Sensitivity tests: if we increase the diffusion at the ice-air interface we are unable to reproduce the observations


F CO2, µmol/(m2s)
1.0
0.8
0.6
0.4
0.2
0
-0.2
3
4
5
6
7
3.5
3
2.5
2
1.5
1
0.5
0
gC m-2
for DOY 87-117
for the whole ice-column
POC+DOC
after Riedel et al, 2008
DIC
based on T and S
Integrated EC fluxes
Stocks

If we consider that there is no methodological biais in eddy-correlation air-ice CO_2 fluxes measurement, the only suggestion to explain the large air-ice CO2 fluxes is direct connection between the atmosphere and the underlying layer through fractures at meso-scale. They exist, but they are poorly documented

However…

this is not supported by lab experiments at small scale from Loose et al. 2011 using deliberate tracers or at large scale using $^{222}Rn/^{226}Ra$ ratios (Rutger Van der Loef et al. 2014)

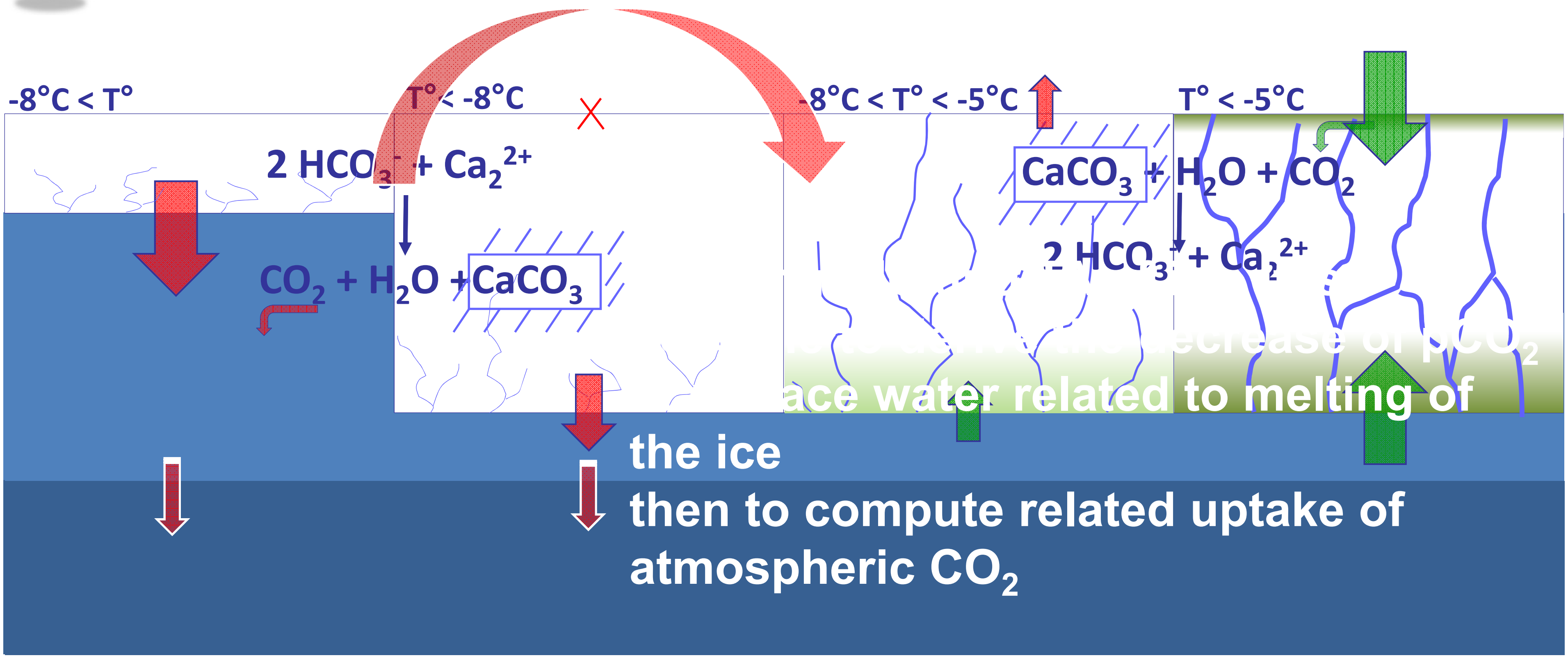
Take home messages

- Sea-ice exchanges CO_2 directly with the atmosphere. These exchanges are driven by sea ice particular processes
- In spring and summer sea ice acts as a transient source of CO_2 for the atmosphere, then shift to a sink. Uptake of atmospheric CO_2 by ice cover in spring and summer is significant compared to the fluxes over open waters of polar oceans
- However, this sink is counterbalanced by CO_2 release in fall and summer, not evaluated yet
- Micrometeorological measurements show fluxes one or two order of magnitude higher compared to chamber measurements. These fluxes are difficult to explain, unless there are some direct connections between underlying layer and the atmosphere through sea ice fractures at mesoscale

AWECS - Winter Weddell Sea 2013

Université de Liège

What happens when ice melts ?



Net CO_2 fluxes	**without ikaite formation**	**-0.033 PgC yr^{-1}**
	including ikaite formation	**-0.083 PgC yr^{-1}**
To be compared to fluxes of polar open oceans		**-0.199 PgC yr^{-1}**

Sea ice accounts for 17 to 42 % of CO_2 uptake of the polar oceans

Rysgaard et al. 2012