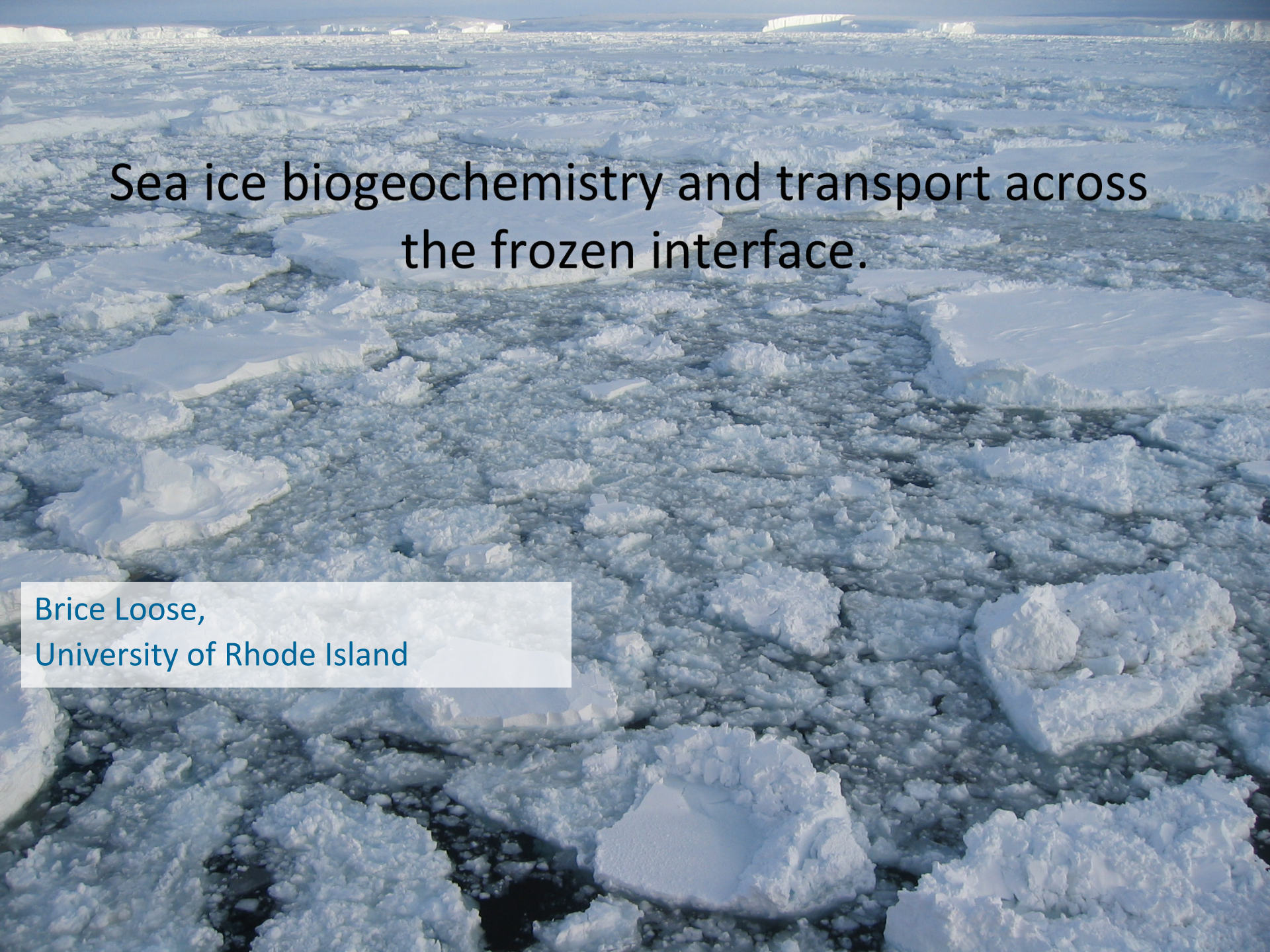


Sea ice biogeochemistry and transport across the frozen interface.

Brice Loose,
University of Rhode Island

Acknowledgements

1. ITP Program: John Toole, Rick Krishfield, Andrey Proshutinsky, Mary-Louise Timmermans, Sylvia Cole and the rest of the team..

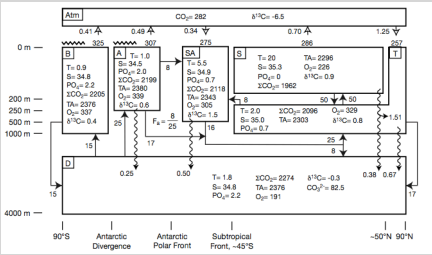
2. GAPS Collaborators: Peter Schlosser, Don Perovich, Wade McGillis and Chris Zappa.

3. IDEAr Collaborators: Jim Ledwell, David Ho, Peter Schlosser

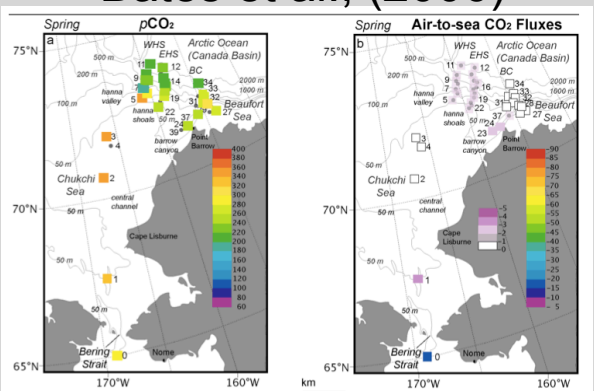
4. Other collaborators: Bill Jenkins, Andrey Proshutinsky, Brad Moran, Bill Smethie

Carbon and biogeochemistry of the sea ice zone

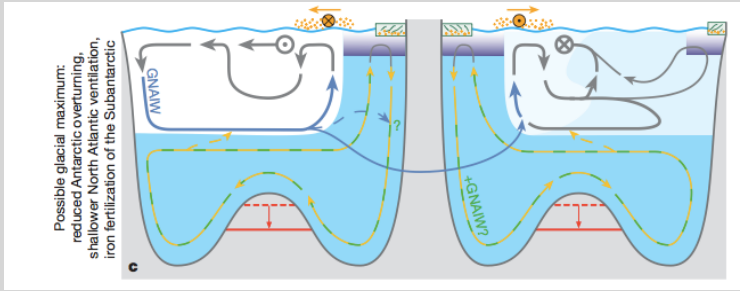
Stephens and Keeling (2002)



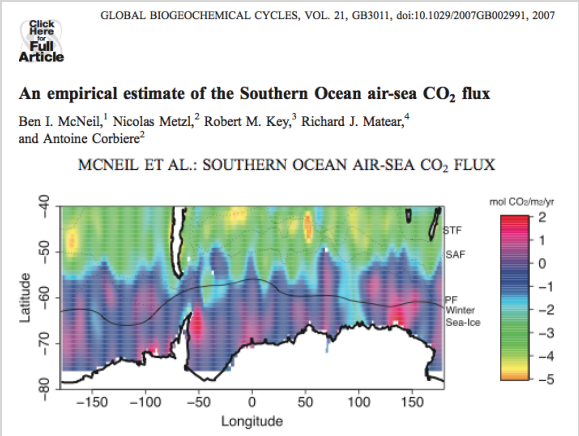
Bates et al., (2006)



Sigman et al., (2010)



McNeil et al., (2007)



GLOBAL BIOGEOCHEMICAL CYCLES, VOL. 21, GB3011, doi:10.1029/2007GB002991, 2007

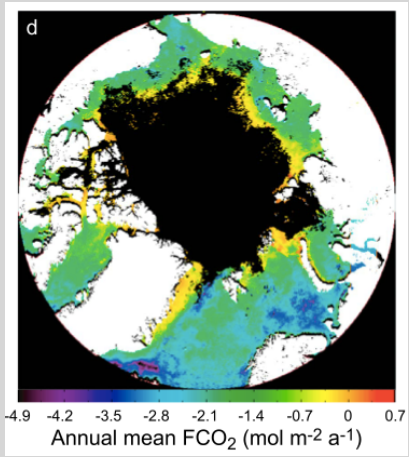
Click Here for Full Article

An empirical estimate of the Southern Ocean air-sea CO_2 flux

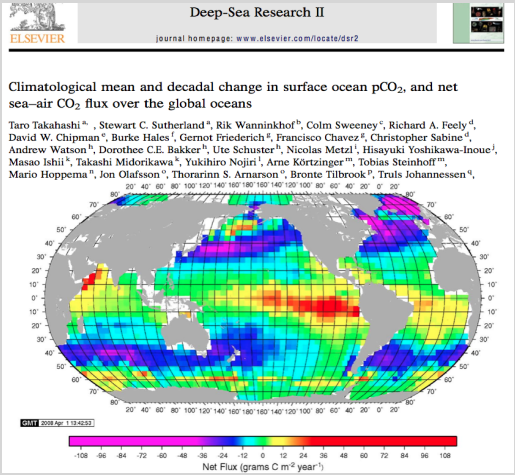
Ben I. McNeil,[1] Nicolas Metzl,[2] Robert M. Key,[3] Richard J. Matear,[4] and Antoine Corbiere[2]

MCNEIL ET AL.: SOUTHERN OCEAN AIR-SEA CO_2 FLUX

Arrigo et al., (2010)



Takahashi et al., (2009)



ELSEVIER

Deep-Sea Research II

journal homepage: www.elsevier.com/locate/dsr2

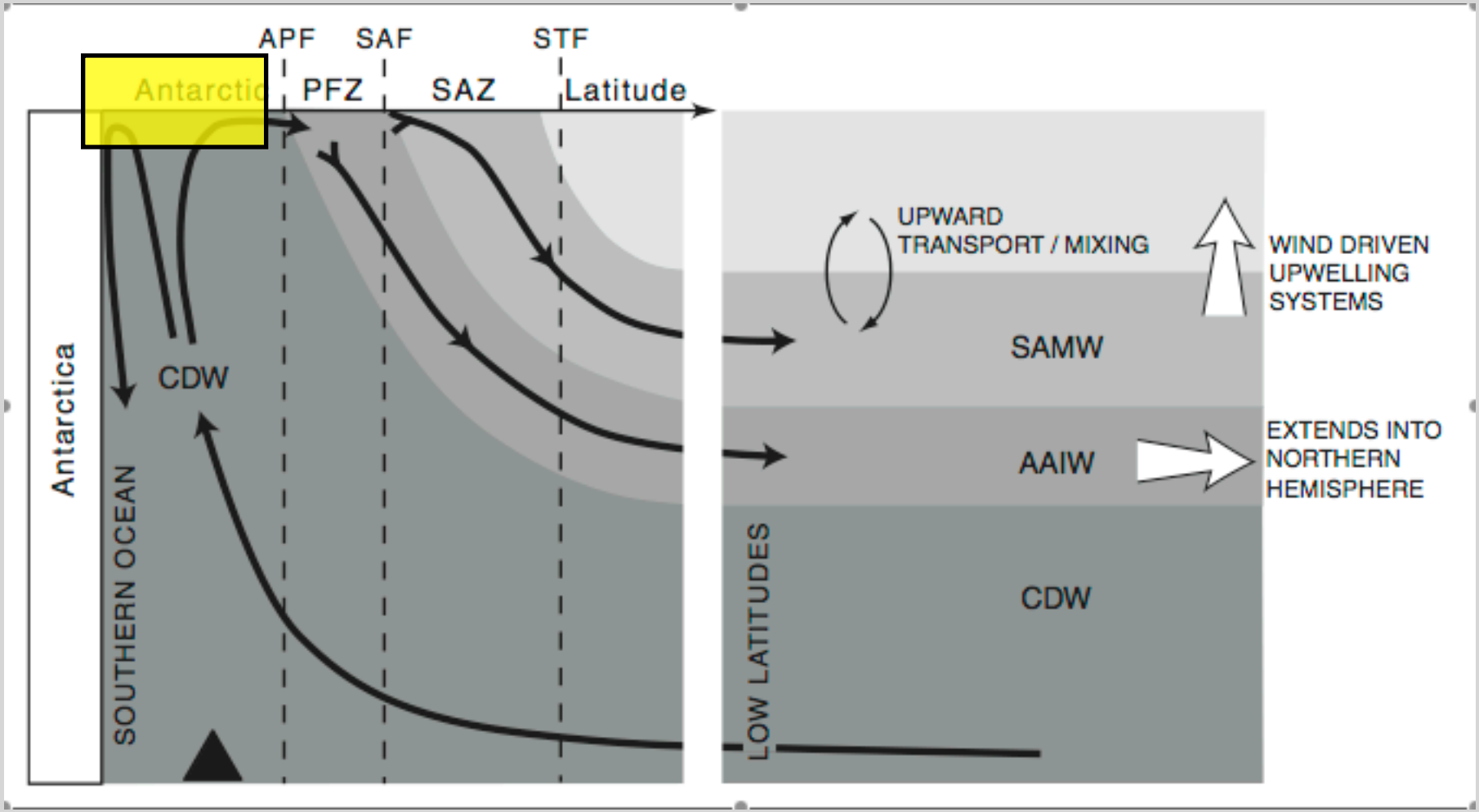
Climatological mean and decadal change in surface ocean pCO_2, and net sea–air CO_2 flux over the global oceans

Taro Takahashi[a,*], Stewart C. Sutherland[a], Rik Wanninkhof[b], Colm Sweeney[c], Richard A. Feely[d], David W. Chipman[e], Burke Hales[f], Gernot Friederich[g], Francisco Chavez[g], Christopher Sabine[d], Andrew Watson[h], Dorothee C.E. Bakker[h], Ute Schuster[h], Nicolas Metzl[i], Hisayuki Yoshikawa-Inoue[j], Masao Ishii[k], Takashi Midorikawa[k], Yukihiro Nojiri[l], Arne Körtzinger[m], Tobias Steinhoff[m], Mario Hoppema[n], Jon Olafsson[o], Thorarinn S. Arnarson[o], Bronte Tilbrook[p], Truls Johannessen[q],

Net Flux (grams C m⁻² year⁻¹)

Ventilation and subduction in the sea ice zone (Antarctic)

Anderson et. al., 2009

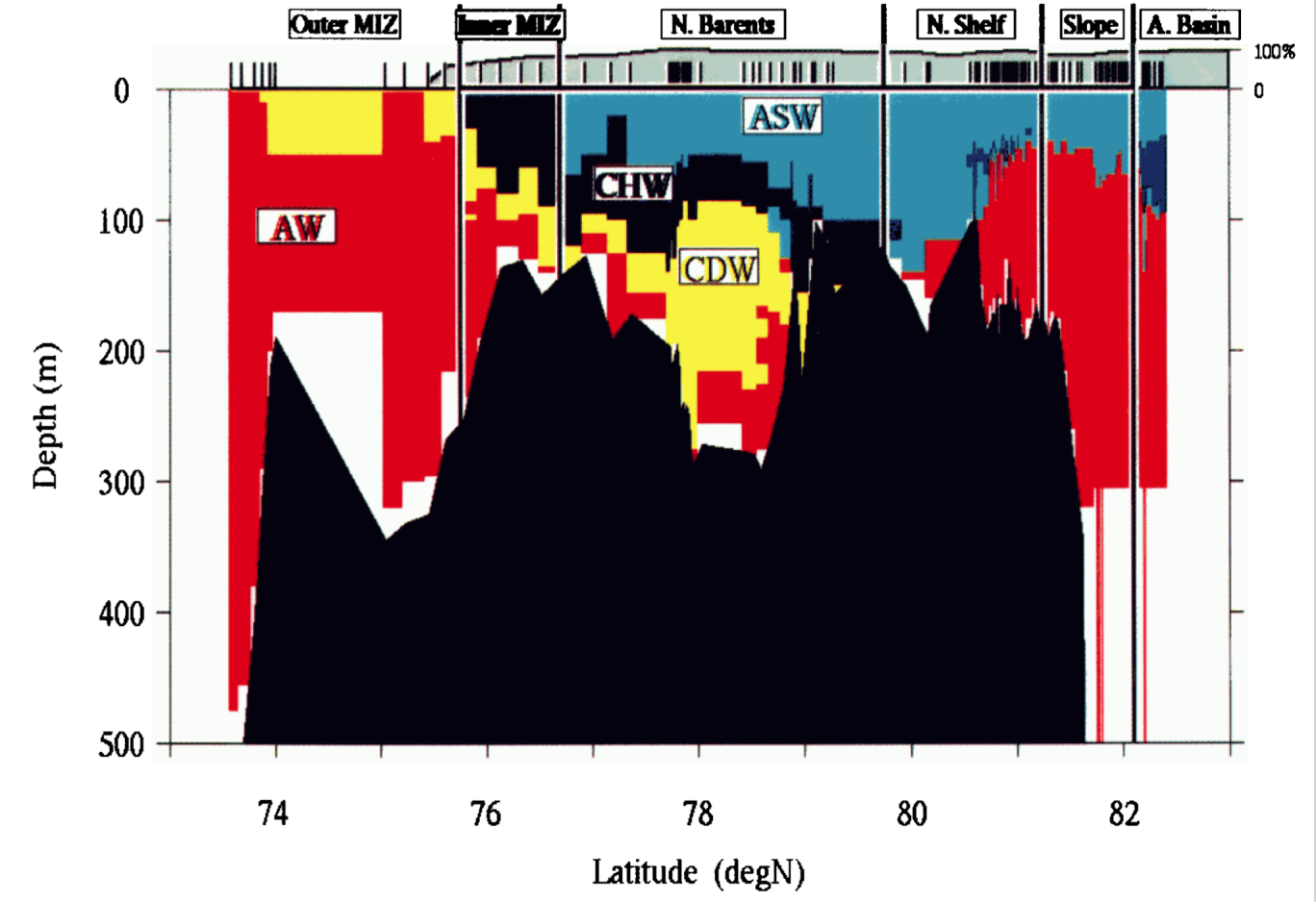


Sea ice regions form deep water, therefore sea ice may help “set properties” of deep ocean water masses.

Ventilation and subduction in the sea ice zone (Arctic)

AW = Atlantic water
ASW = Arctic surface water
CDW = Cold deep water
CHW = Cold halocline water

Steele et al., (1995)



Outline

Clara Deal

Steve Ackley

Biogeochemical processes

Ice algae

MIZ Blooms

$CaCO_3$ Precip.

Jacqueline Stefels

Biogeochemical *hypotheses*

CO_2

DMS

Sea ice-ML Exchange

DIC pump

Physical factors that determine the scaling

Air --- Ice transport (Diffusion)

Air --- sea exchange (in leads)

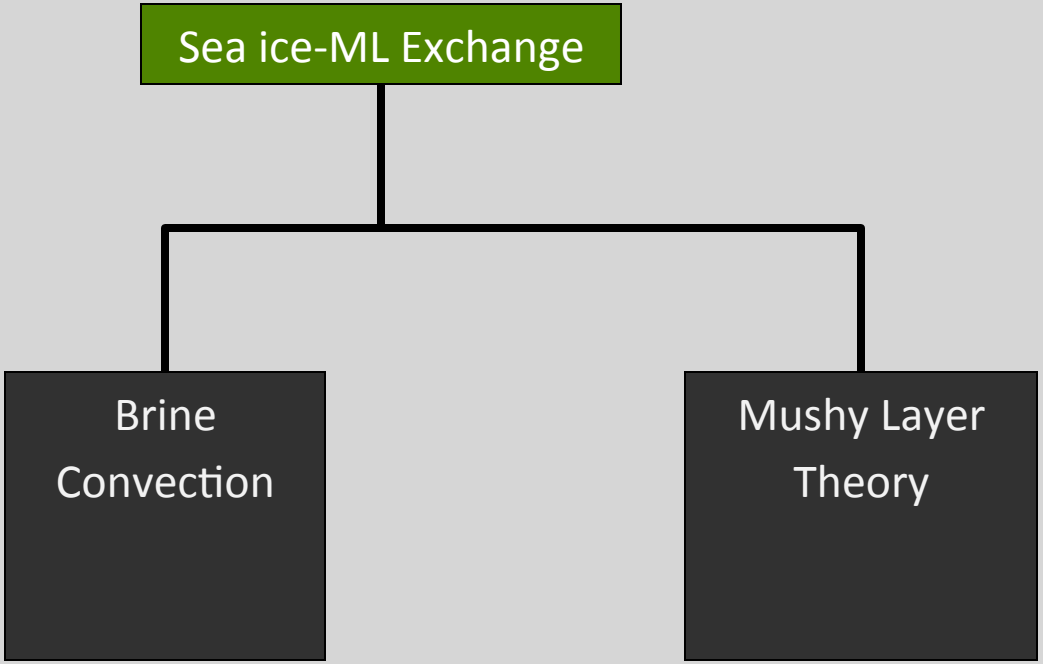
Brine convection (Polynyas)

Upwelling deep water

Mushy Layer Theory

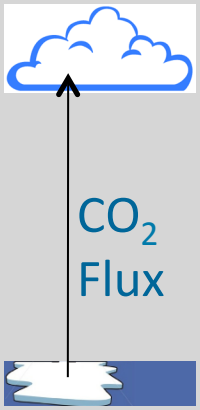
- Both biogeochemical flux and reservoir size are determined by the physical processes that drive transport.
- Will try to emphasize how modeling can advance insight and integrate processes.

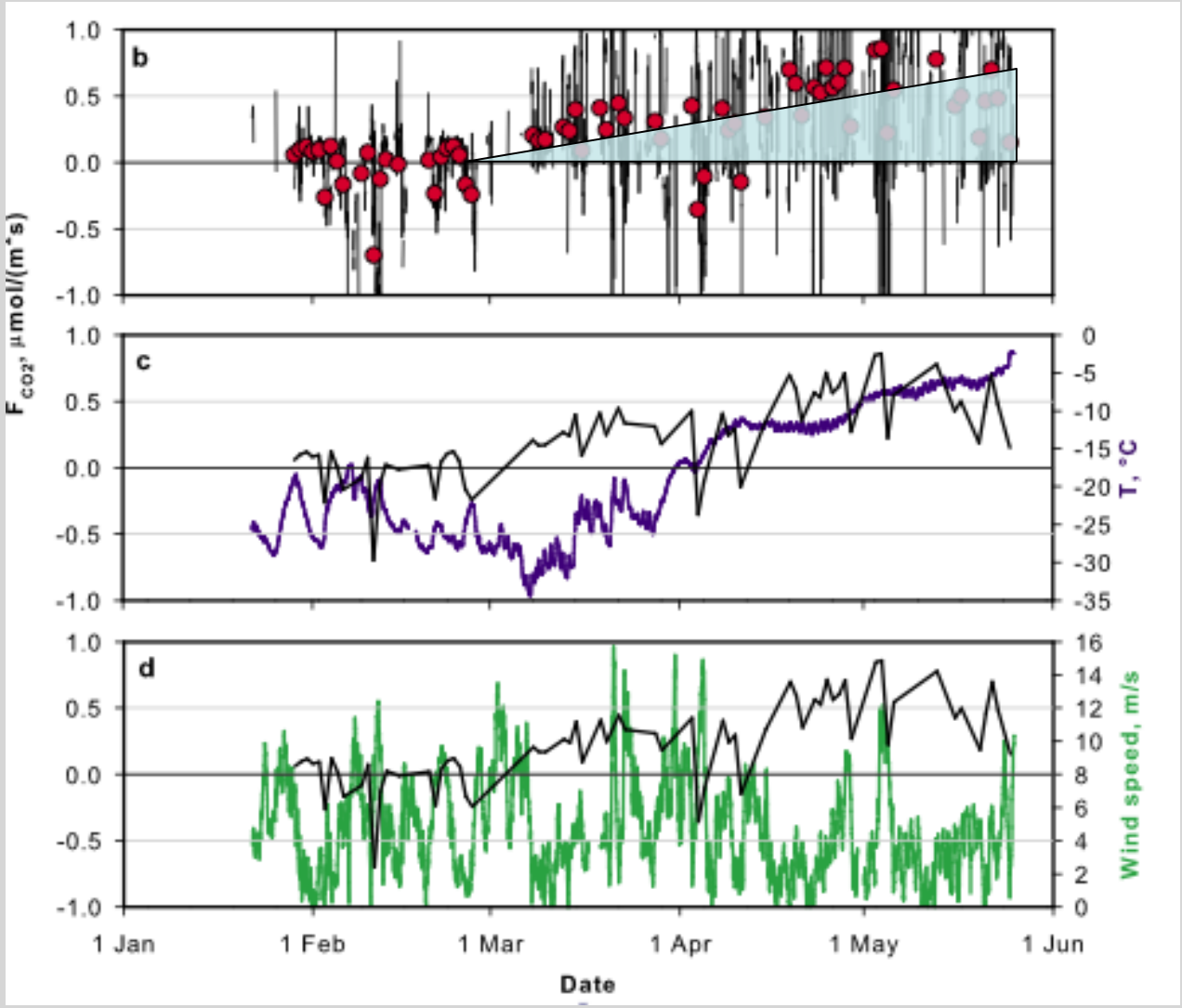
Sea ice-ML Exchange

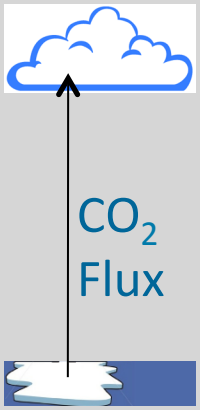


Total CO_2 flux over winter ice

Miller et al., (2011)







Total CO_2 flux over winter ice

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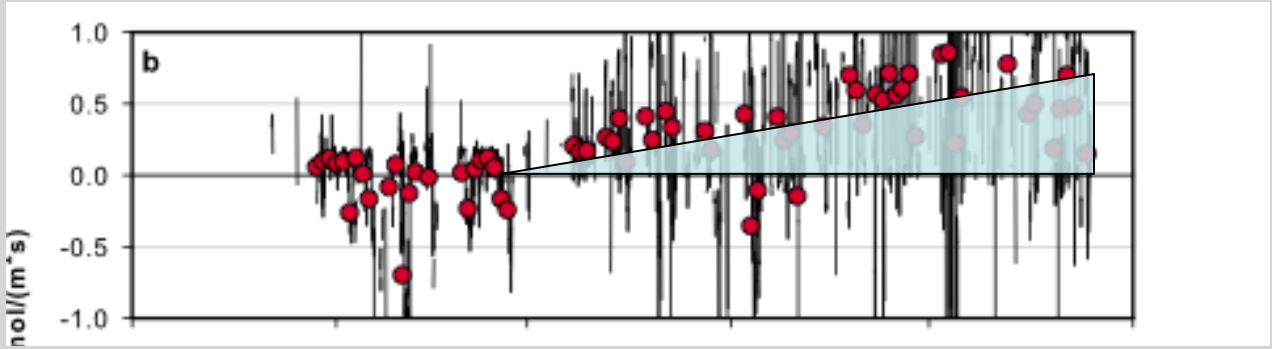


Total Flux = ½ x 0.75 (μmols m^{-2} s^{-1}) x 79 (days) x CF

= 2.6 mols m^{-2}

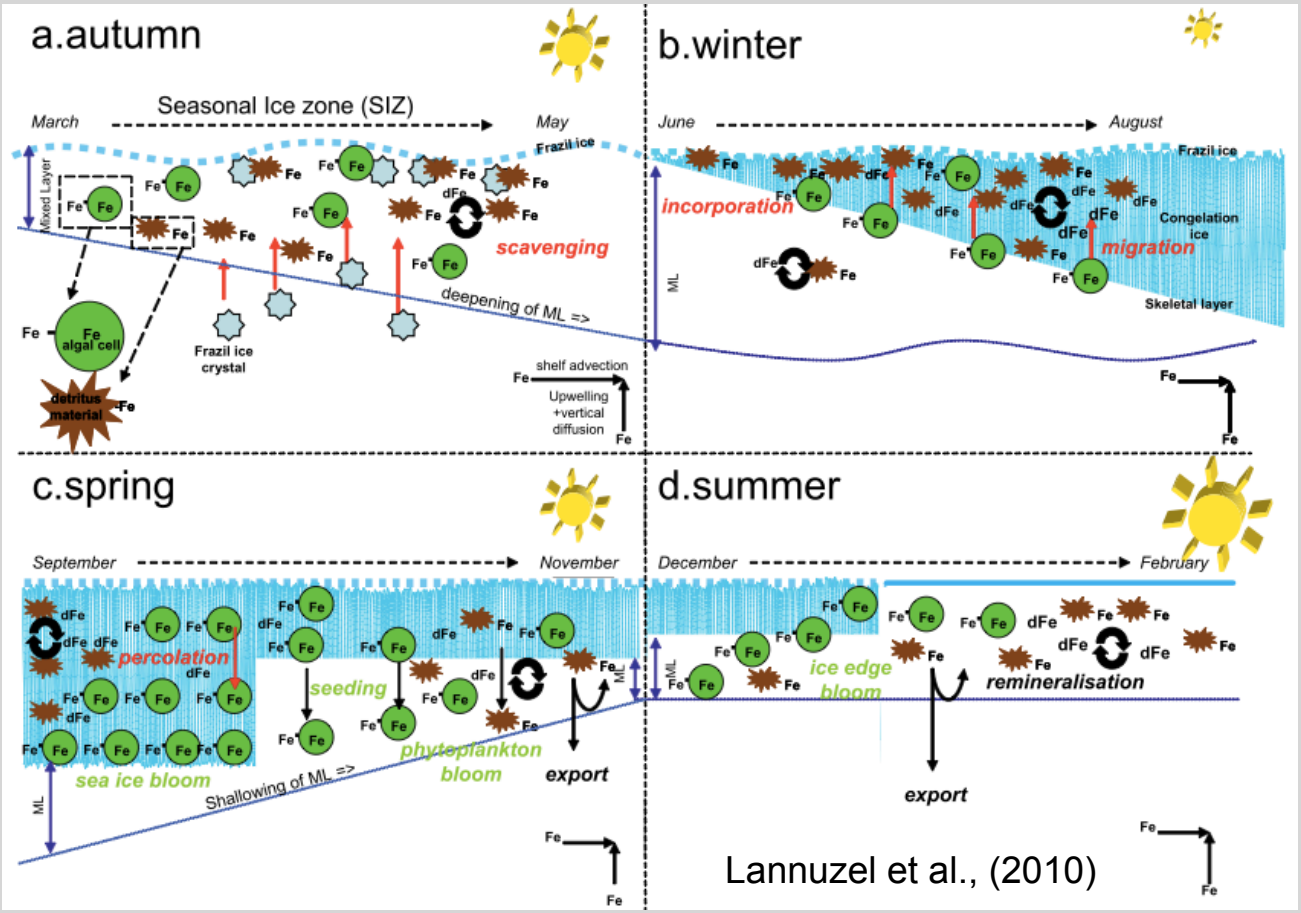
DIC in ice = (DIC in S.W.) x (ice/water partition) x zice (m) x rho

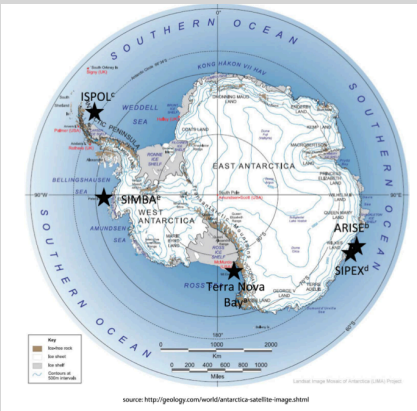
= 2130 (μmol kg^{-1}) x 0.5 x 2 (m ice) x 917 kg m^{-3}

= 1.95 mol m^{-2}

The ice lost more DIC than it started with ?!

Buildup of bioavailable iron in sea ice





Lannuzel et al., (2007, 2008, 2010)

Total Fe in sea ice was 8-15 times greater than in underlying seawater

Nutrient re-supply to the ice

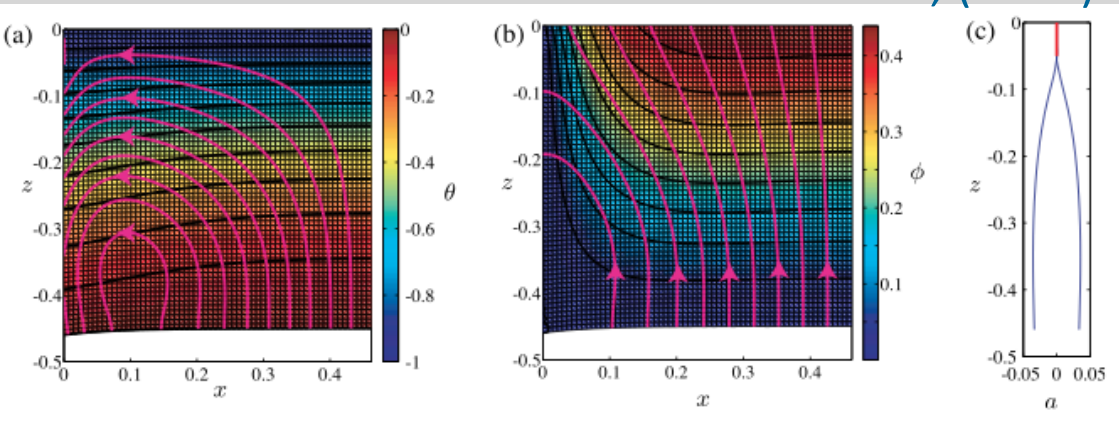
Steve Ackley is going to revisit this..

- There is an accumulation of biogeochemical evidence that sea ice is not a closed system.
- Seawater entrainment is *continuous* or *event-driven* and occurs in multiple seasons?

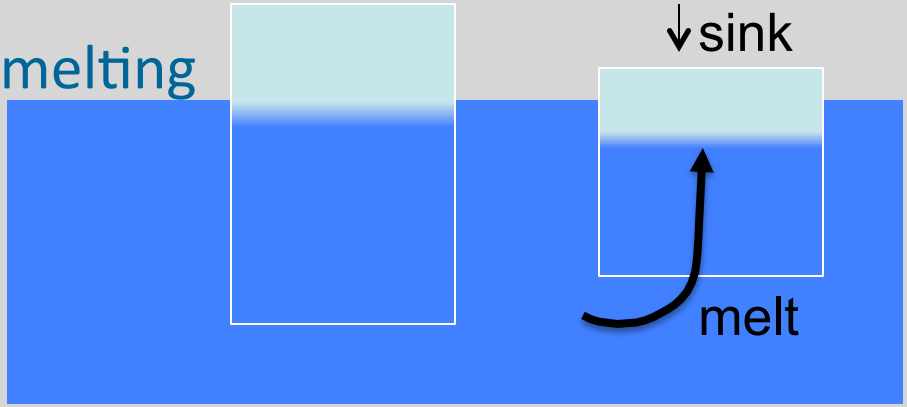
Mechanisms for seawater cycyling in sea ice

Wells et al., (2011)

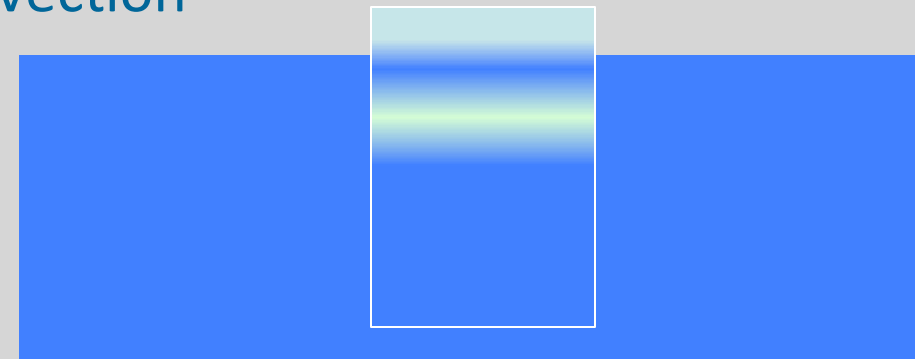
1. Mushy layer siphon:
   (winter)



2. Hydrostatic inflow from bottom melting
   (spring/summer)

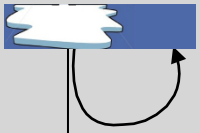


3. Gap layer refreezing and new convection
   (fall)



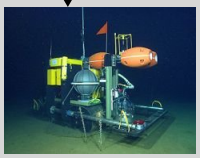
4. What else?

DIC Pump Hypothesis



Alk.
flux ?

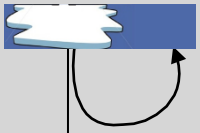
DIC
pump



DIC pump

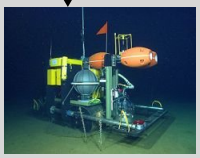
Brine
Convection
(polynyas)

DIC Pump Hypothesis



Alk.
flux ?

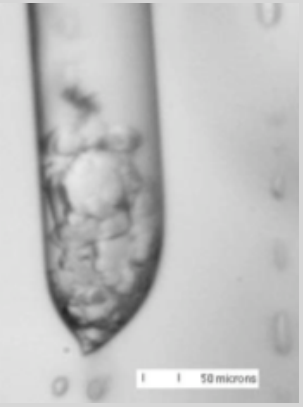
DIC
pump



Mirabilite crystals

$Na_2SO_4 \cdot 10H_2O$

(Arctic sea ice)

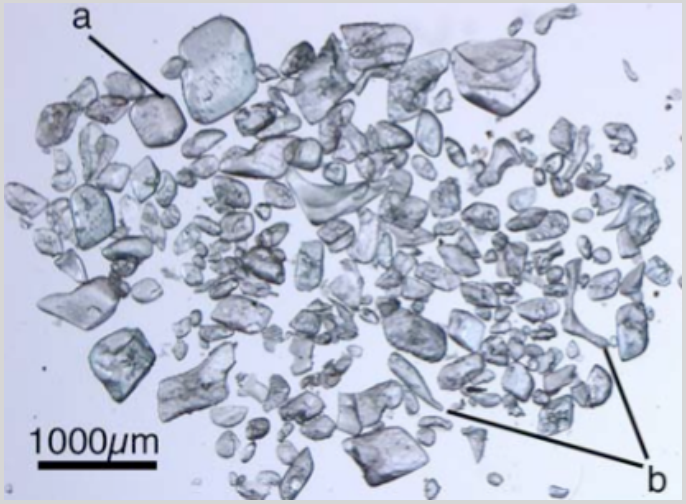


(Light et. al, 2003)

Ikaite crystals

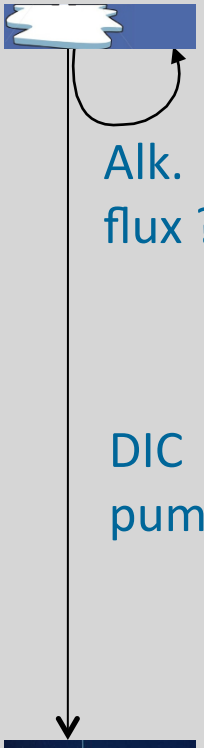
$CaCO_3 \cdot 6H_2O$

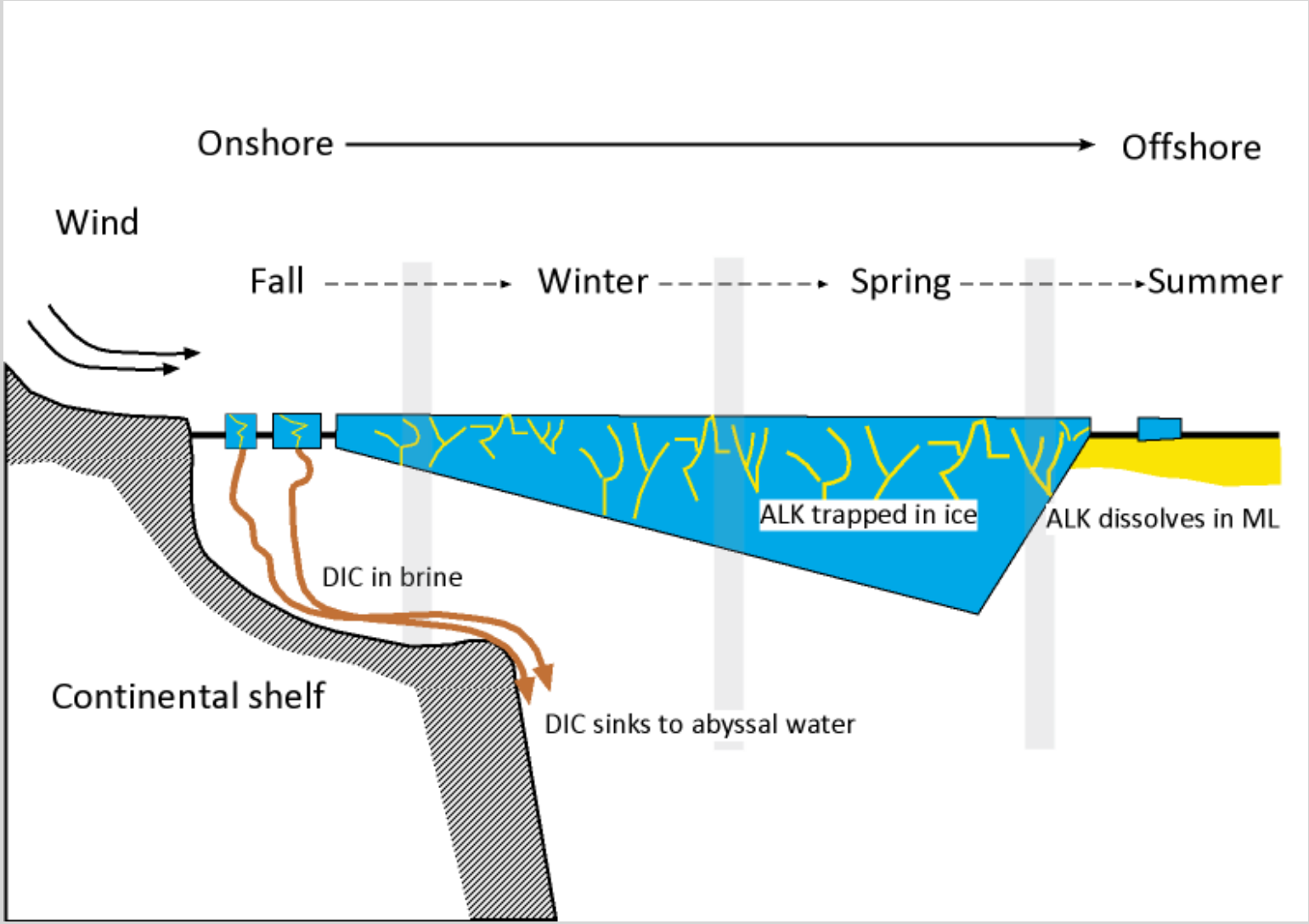
(Weddell Sea ice)



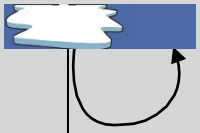
(Dieckmann et. al, 2008)

Conditions for the DIC pump to occur



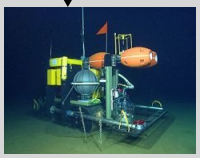


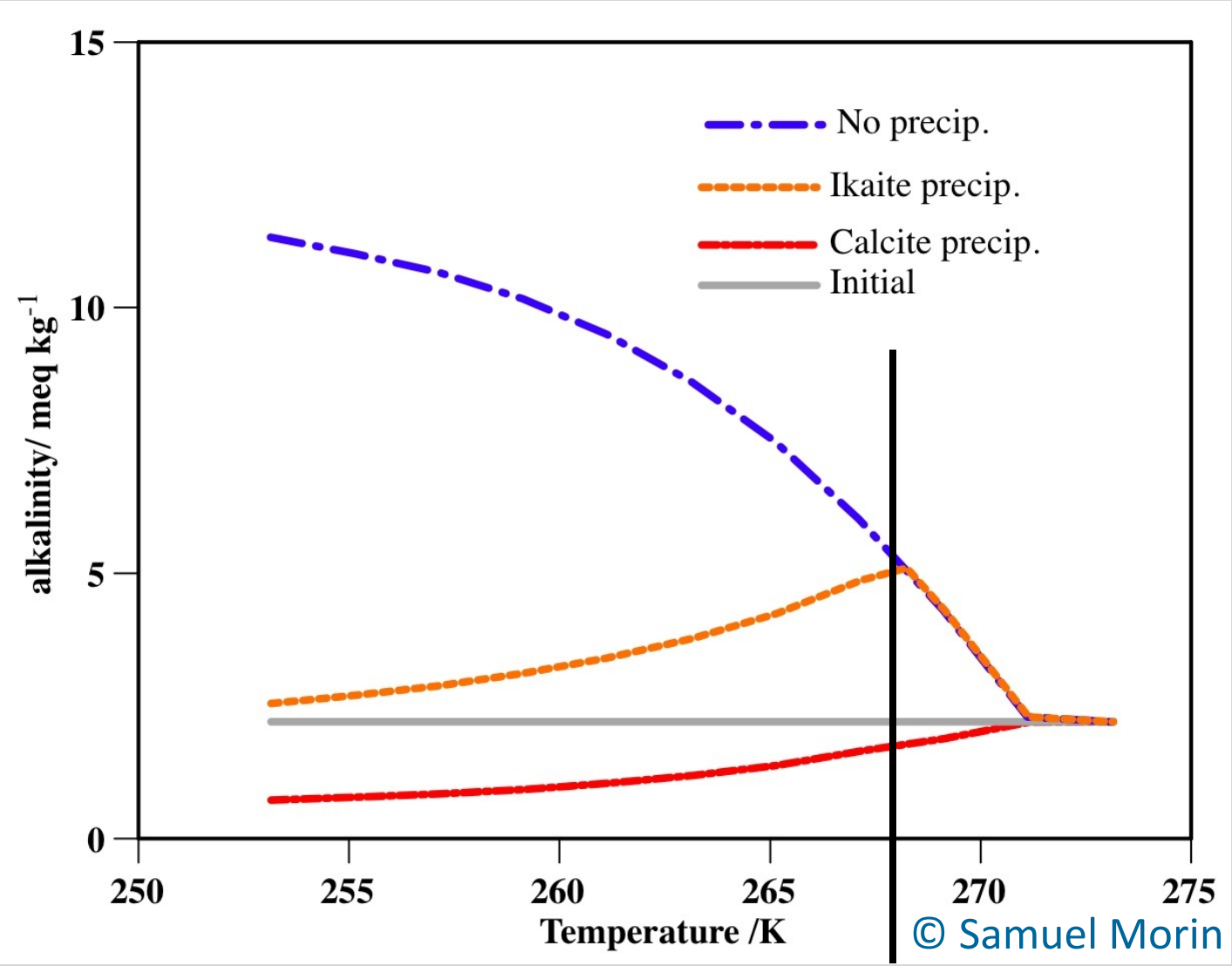
Conditions for DIC pump to occur



Alk.
flux ?

DIC
pump





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Frezchem (Marion et al., 2001) and PHREEQC (USGS)

How can we test for the DIC pump?

We lack a good geochemical proxy for sea ice brine.

Tracers: ^{14}C spike, or inert tracer (SF_5CF_3).

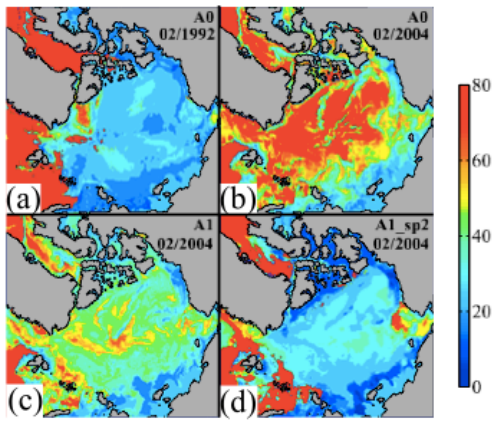
Models could put an upper bound on this process (best case scenario)

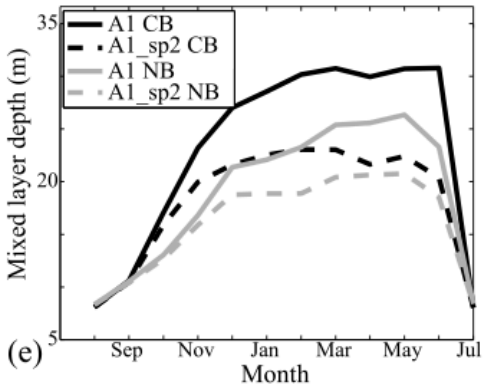
Suggestion of Nguyen et al., (2009),..

Convective parameterization +

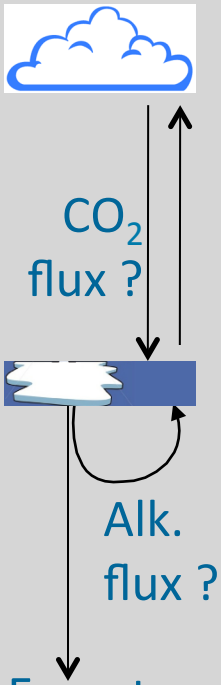
Sea ice model +

Brine chemistry model





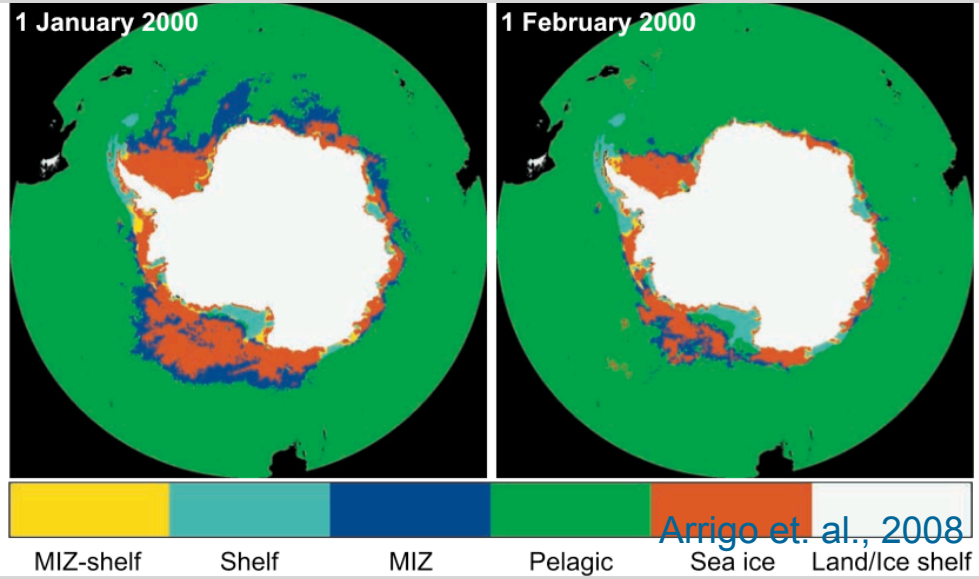
What's really going on in the MIZ?



- Region of ocean surface exposed in past 30 days

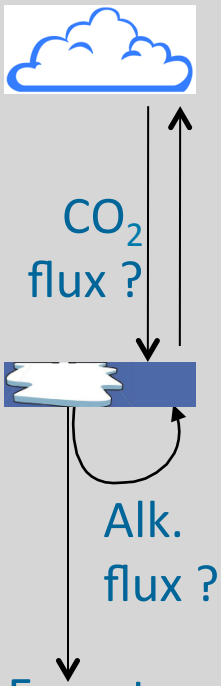
© National Geographic

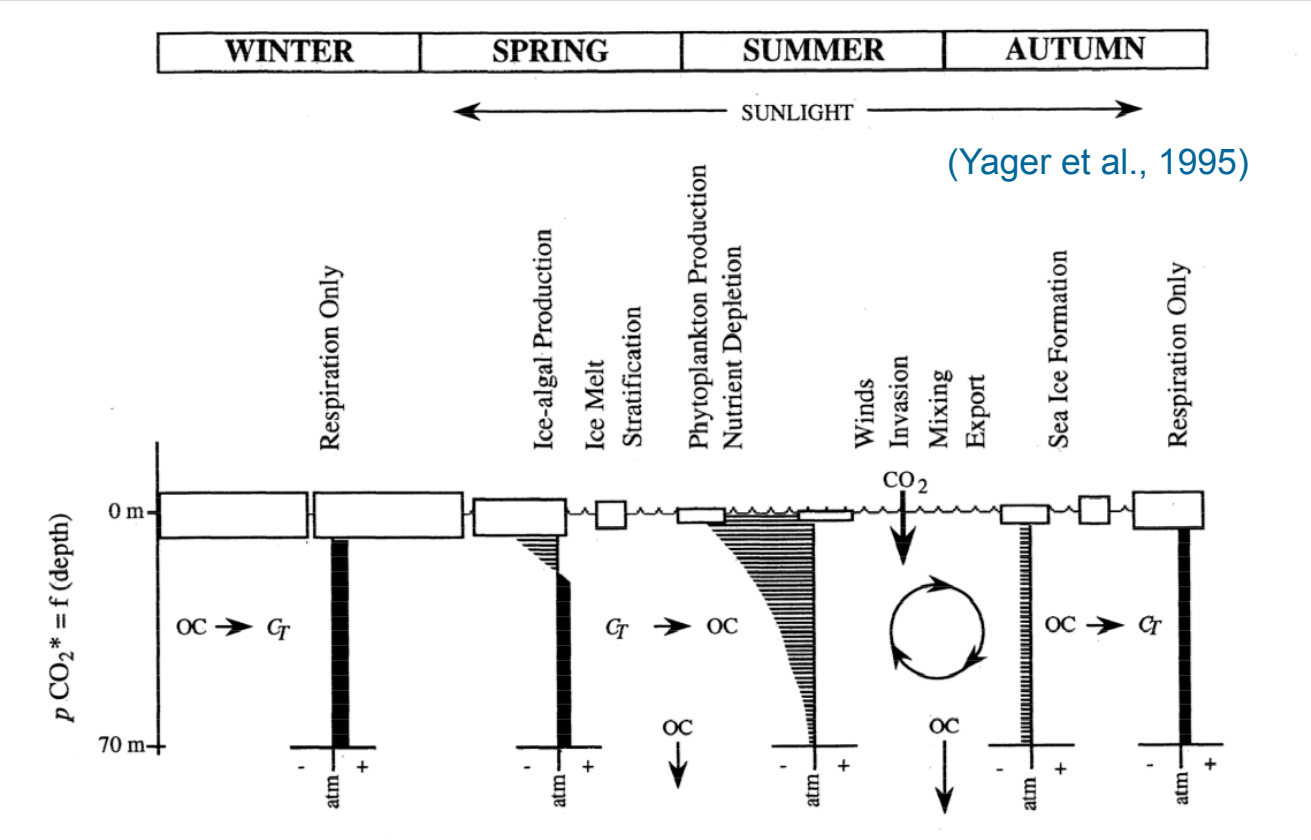
- MIZ Accounts for ~ 9% of annual primary production.



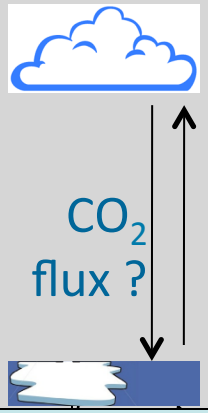
Arrigo et. al., 2008

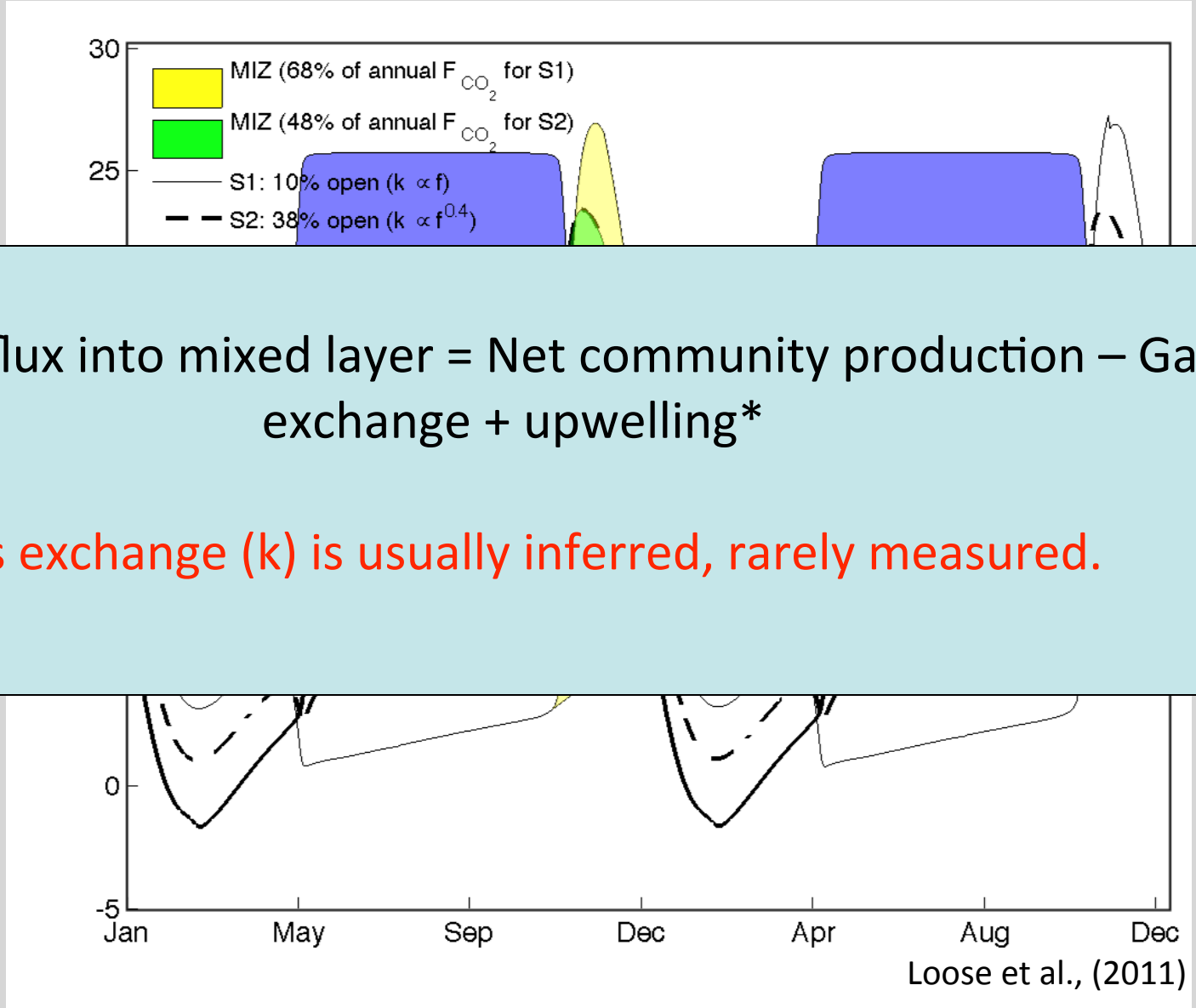
CO_2 rectification hypothesis





Springtime fluxes (S.O.)





Loose et al., (2011)

- Net CO_2 flux into mixed layer = Net community production – Gas exchange + upwelling*
- Gas exchange (k) is usually inferred, rarely measured.

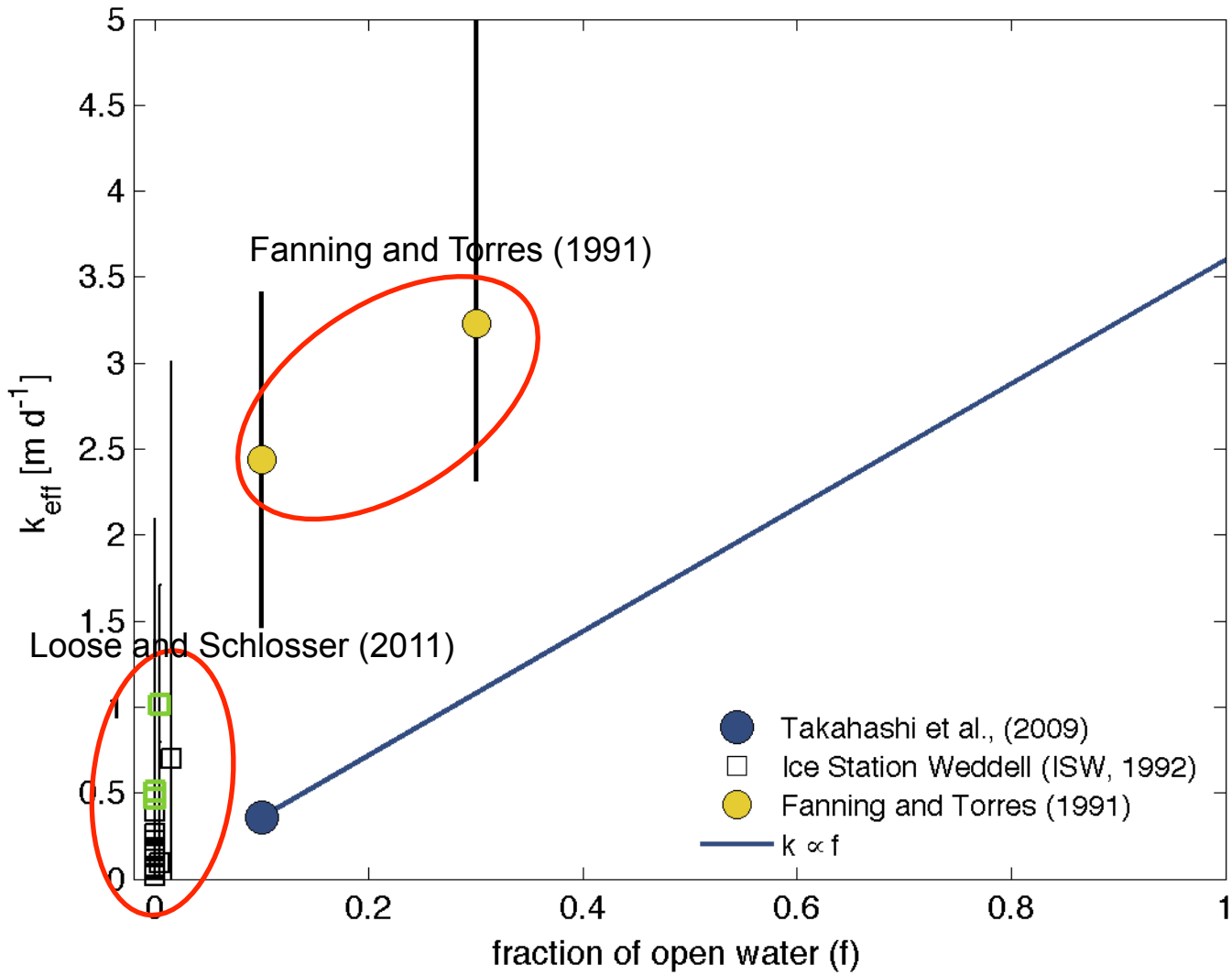
A parameter model for k in the ice pack

$$F = k_{eff}\Delta C \qquad k_{eff} = \cancelto{0}{(1-f)k_{ice}} + (f)k$$

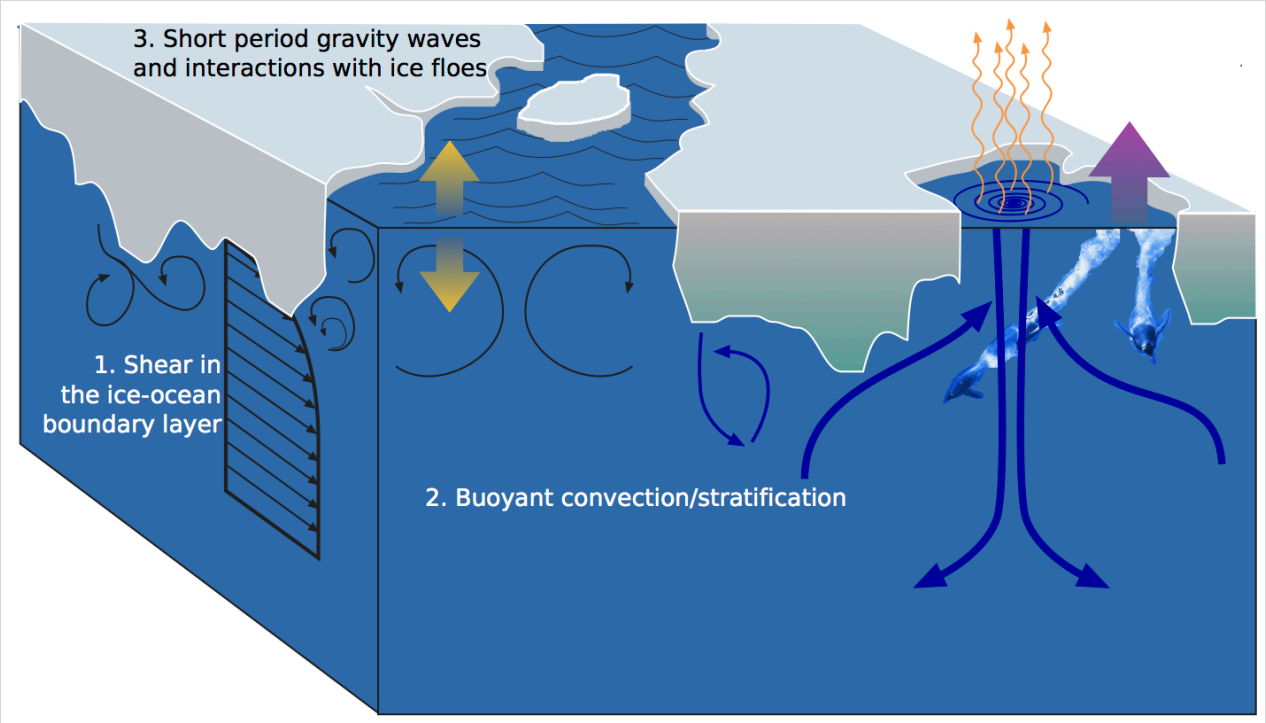
$$k_{eff} = (f)k$$

f is the fraction of open water

Do we have estimates of k in sea ice cover and do we believe them?



Air-sea gas exchange depends on aqueous turbulence



✔ • Shear in the ice-ocean boundary layer (IOBL) (McPhee, 1992; McPhee, 2008, Andreas, 1986).

✔ • Buoyant convection/stratification (Lombardo and Gregg, 1989; Morison et al., 1992)

? • Surface roughening by short-period wind waves (Frew et al., 2004) and their interactions with ice floes (Squire et al., 1995)

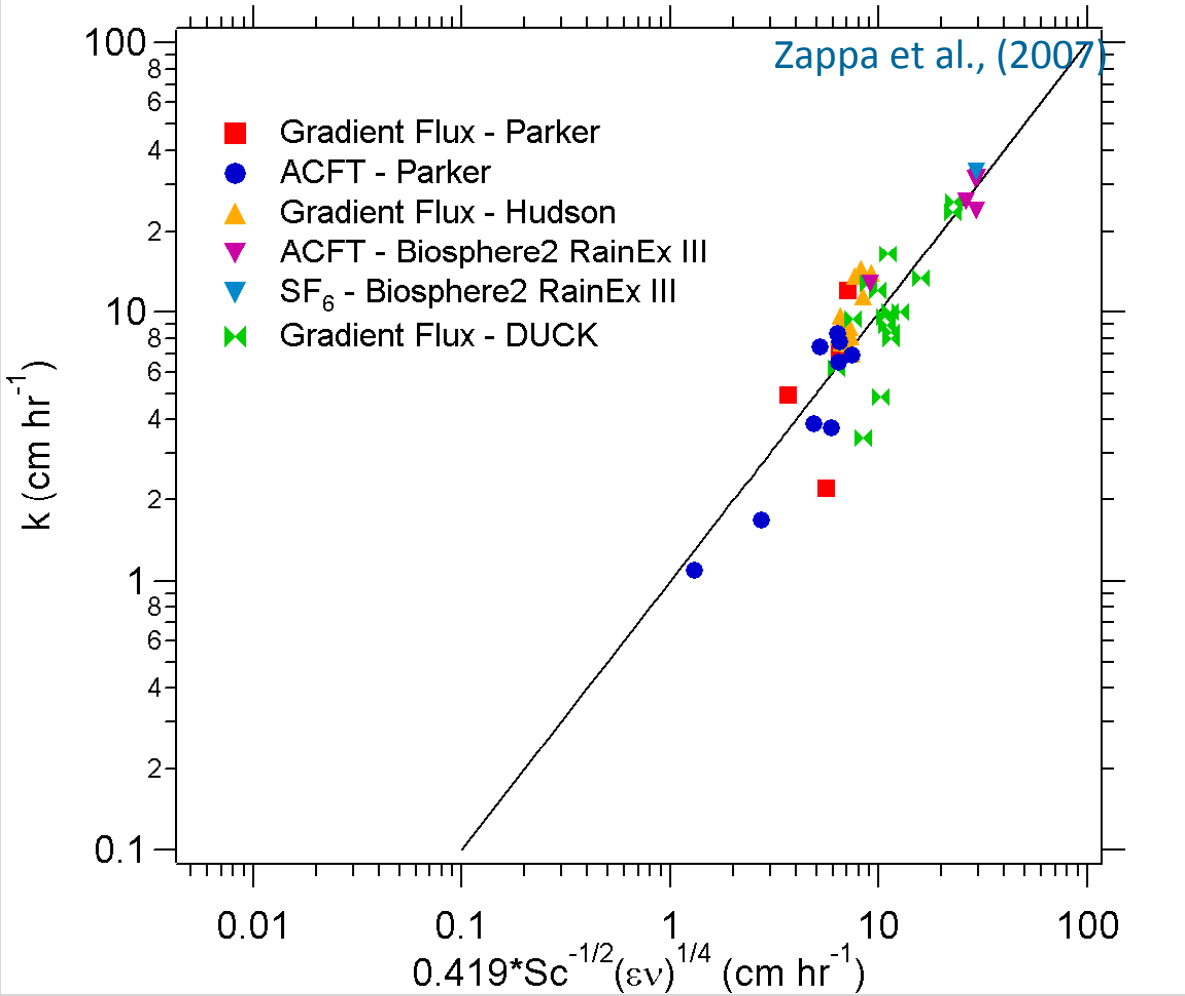
Turbulence in the ice-water boundary layer

Viscosity

Molecular diffusivity

$$k \propto (\varepsilon \upsilon)^{1/4} Sc^{-n}$$

Turbulence dissipation



A parameter model for k in the ice pack

$$\varepsilon = u_*^{\,2} \frac{\partial \bar{u}}{\partial z} + \overline{b' w'}$$

Buoyant convection/ stratification

Ice/water current shear

Wind-driven shear

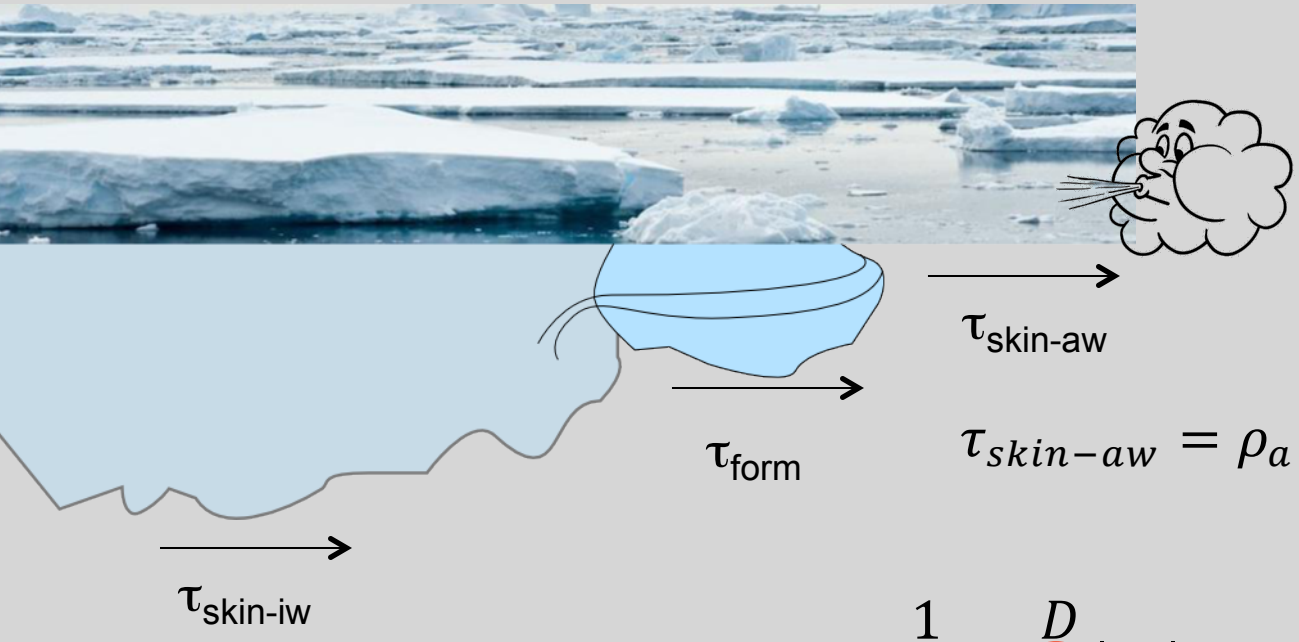
$$\varepsilon = f\left(V, U, T_{air}, T_w, N(z)\right)$$

Ice velocity

10-m wind speed

Buoyancy Frequency

Ice drag on the Ice-ocean boundary layer



$$\tau_{skin-aw} = \rho_a C_d U|U|$$

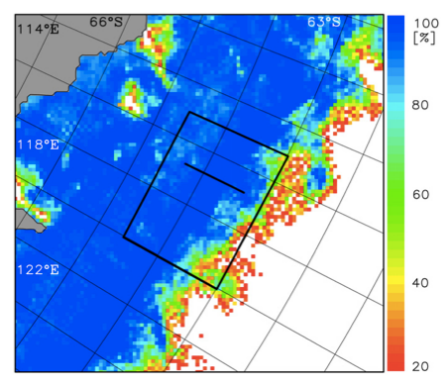
$$\tau_{form} = \frac{1}{2}\rho_w \frac{D}{L}|V_0|V_0$$

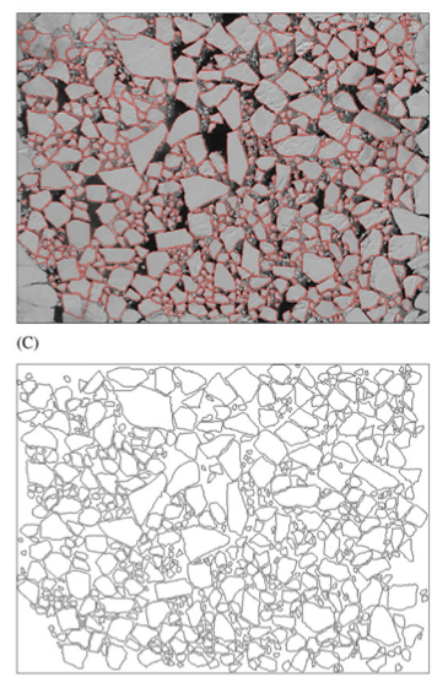
$$u_{*0} = \frac{U(z)}{\kappa}\left(\ln\frac{z}{z_0} - \Psi(\zeta)\right)$$

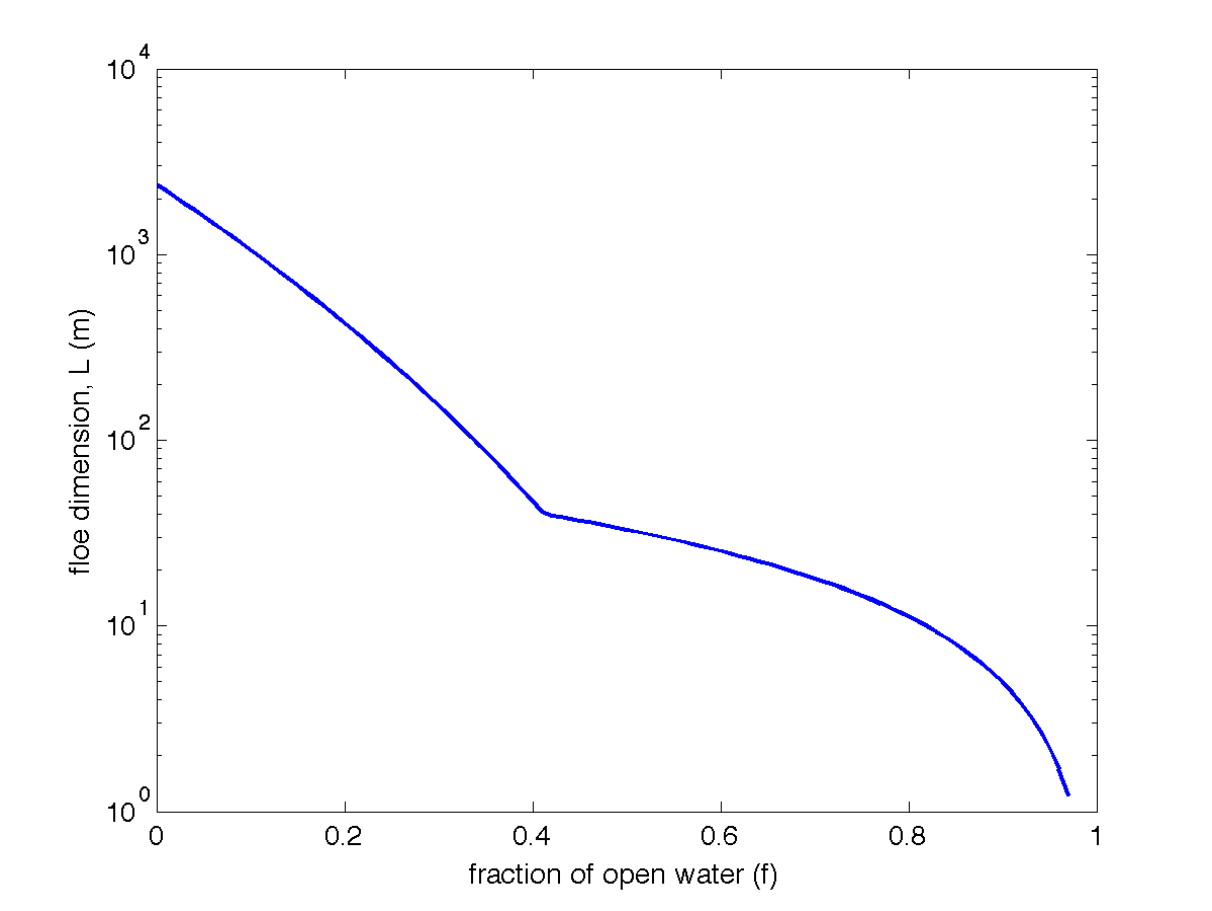
$$\tau_{skin-iw} = u_{*0}^2\rho$$

Steele et al., (1989)

Floe size distribution



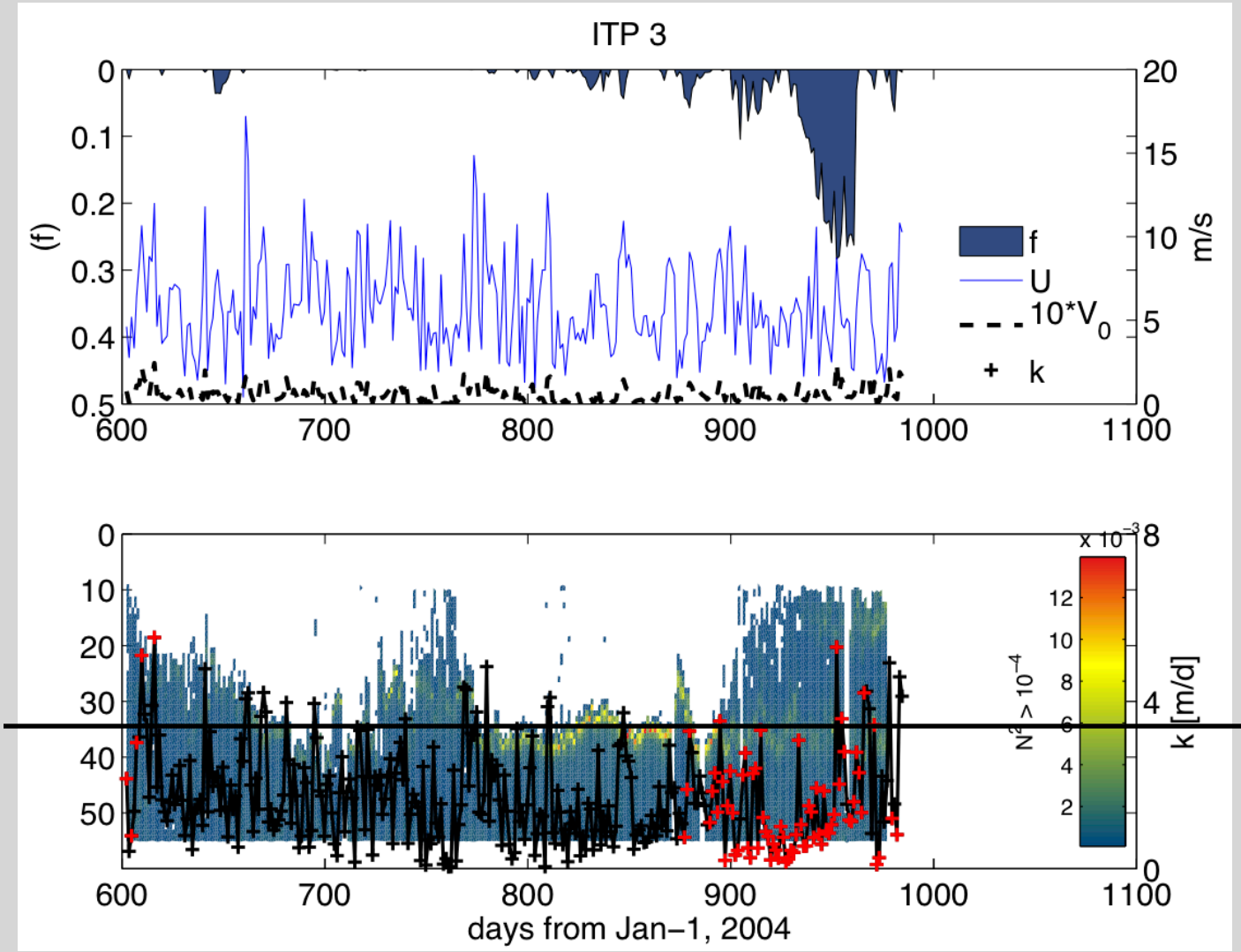


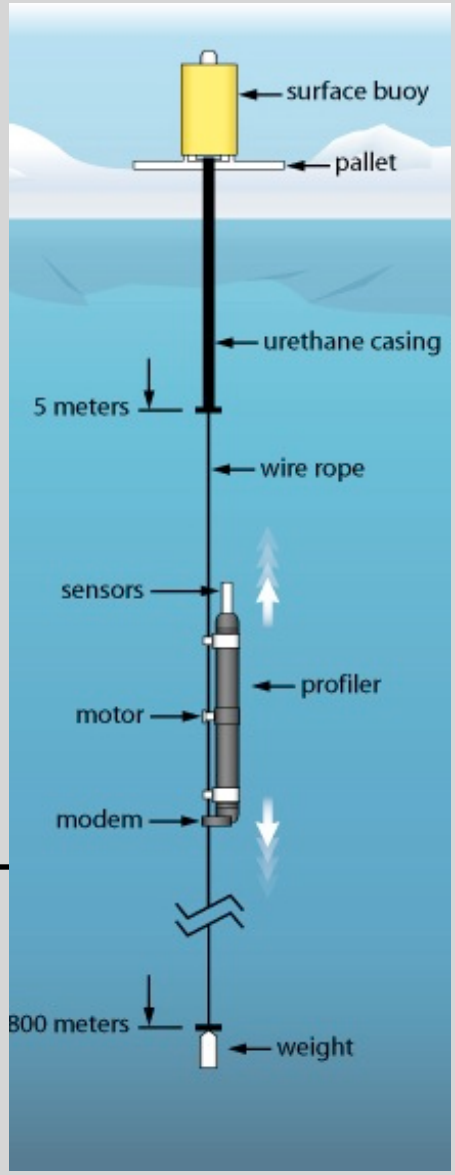


$$N = aL^{-b}$$

Toyota et al., (2006)

Ice-ocean boundary layer shear, ITP 3

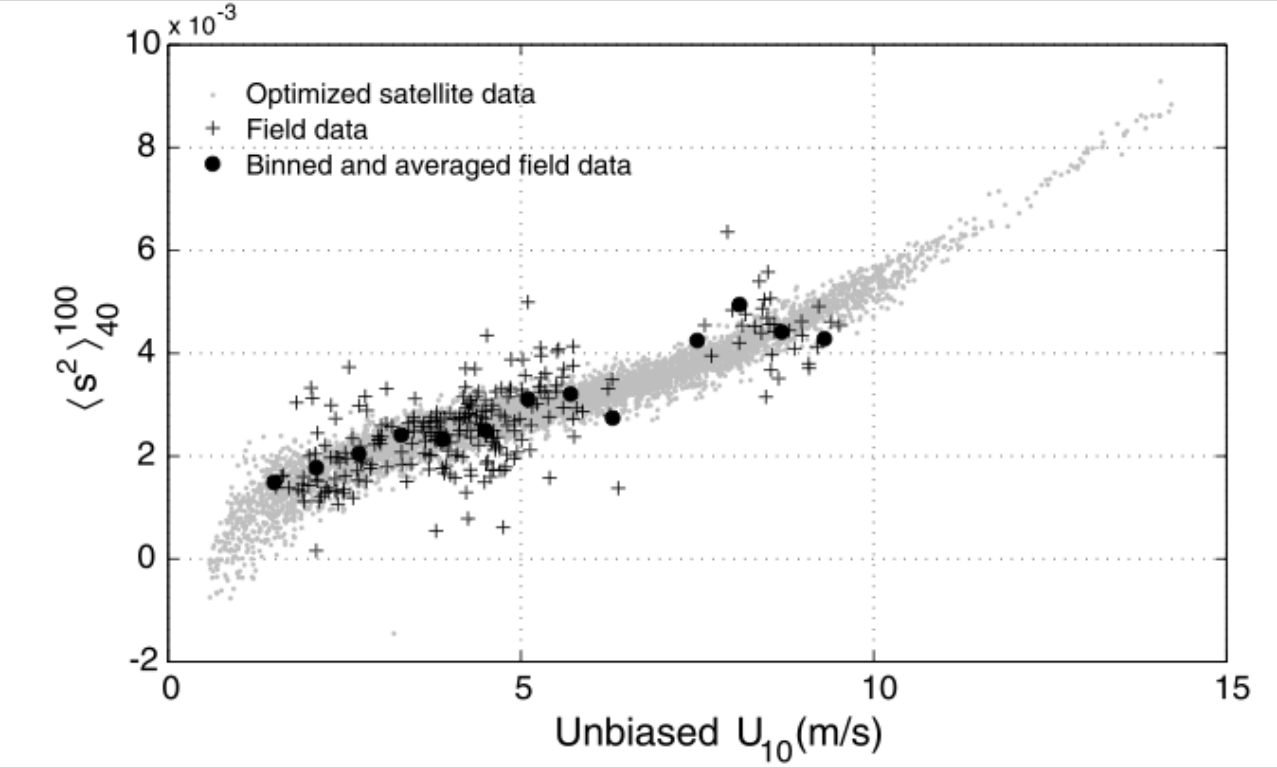




SOURCE: http:// www.whoi.edu/itp

Wave-driven turbulence

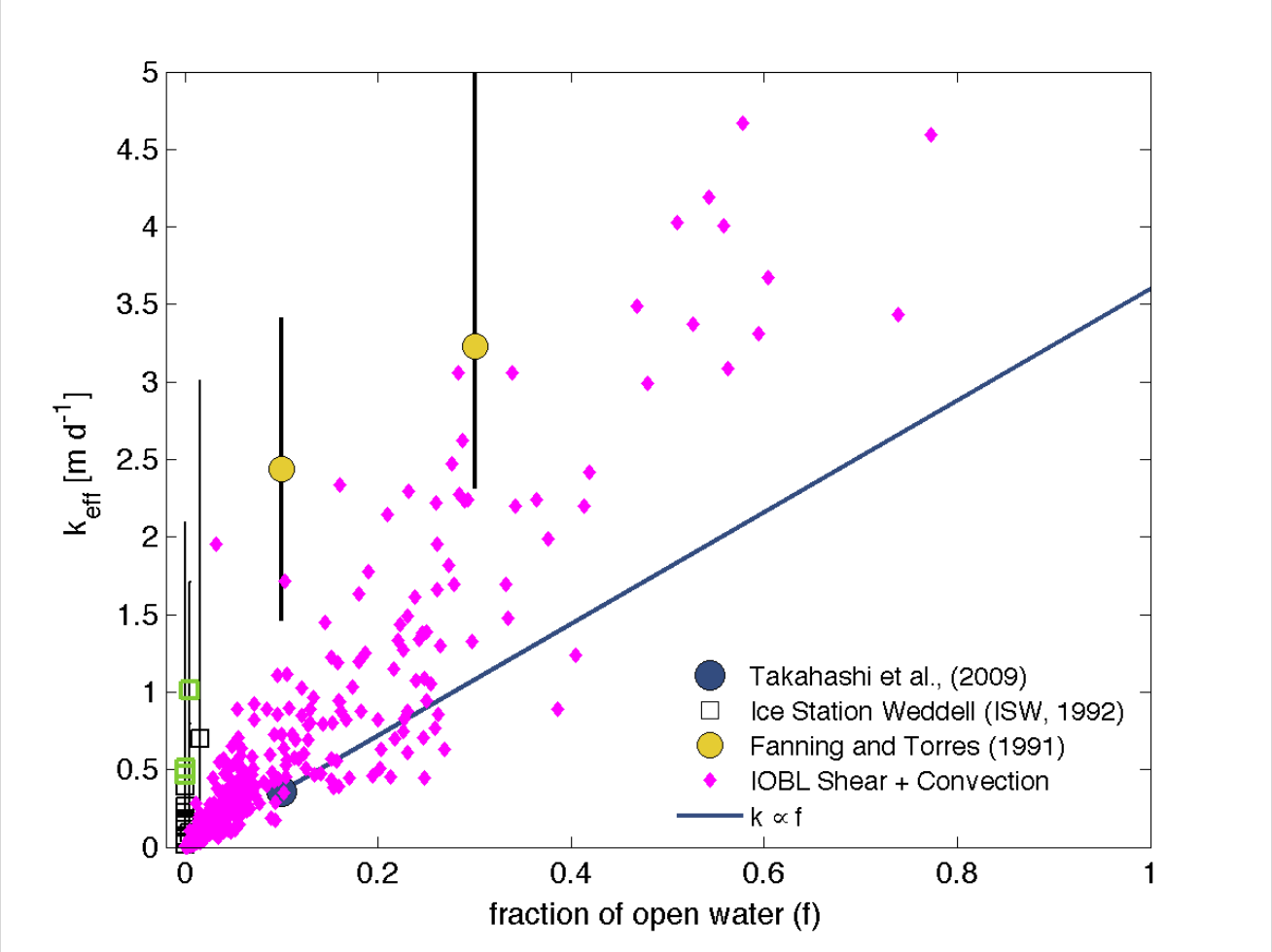
$<s^2>$ of 40 – 100 rad m^{-1} waves correlate well with gas exchange (and they account for surfactant effects…. for Scott).

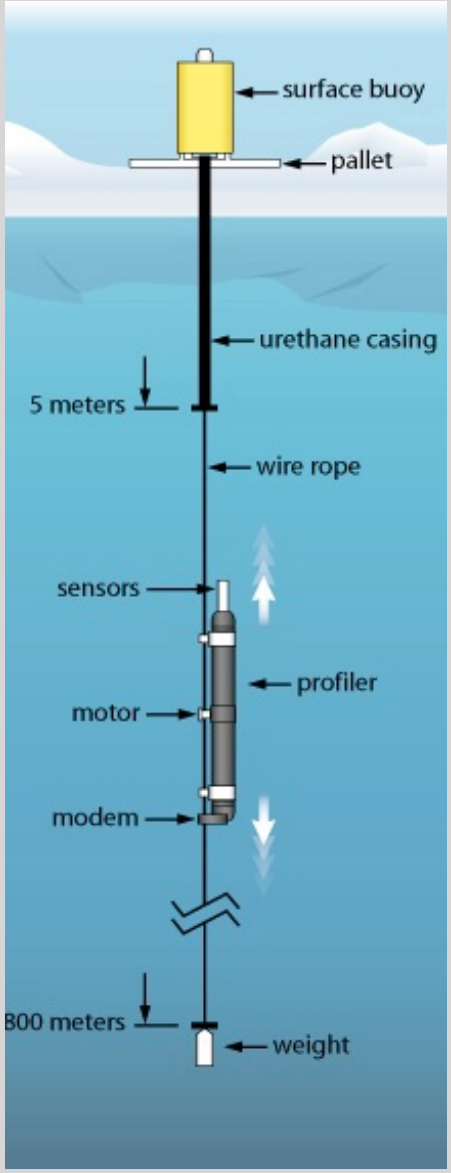


Frew et al., (2007)

Eff. gas transfer velocity (k_{eff}) from 4 ITP drifts

$$k_{eff} = (f)k$$





SOURCE: http:// www.whoi.edu/itp

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Ocean Science Discussions

This discussion paper is/has been under review for the journal Ocean Science (OS).
Please refer to the corresponding final paper in OS if available.

A parameter model of gas exchange for the seasonal sea ice zone

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Discussion points

1. Is there a consensus on sea ice-mixed layer exchange processes for models?

	Time range	Depth range
Mushy layer siphon	Winter?	??
Hydrostatic flooding	Spring/summer?	
Gap layer freezing	Fall?	
What else?		

2. We have the models necessary to set upper bounds on the DIC pump hypothesis: Solute chemistry model + sea ice model + Mixed-layer parameterization. *Can we try it?*

3. (how) Does CICE/CESM estimate the ocean carbon cycle and air-sea gas exchange? Is there

Old Model: Timing of ice breakup and spring bloom

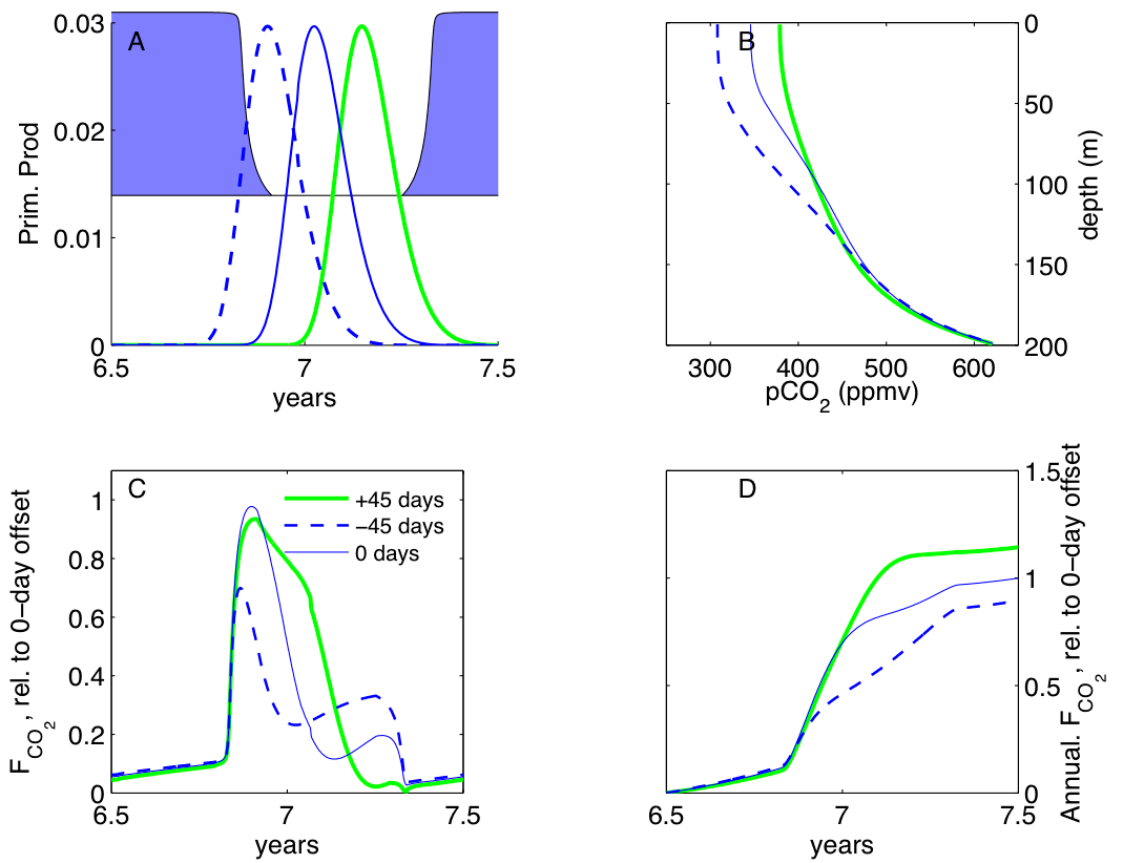
- 45 days: peak F_{CO2} is reduced by 27%

Net annual F_{CO2}:

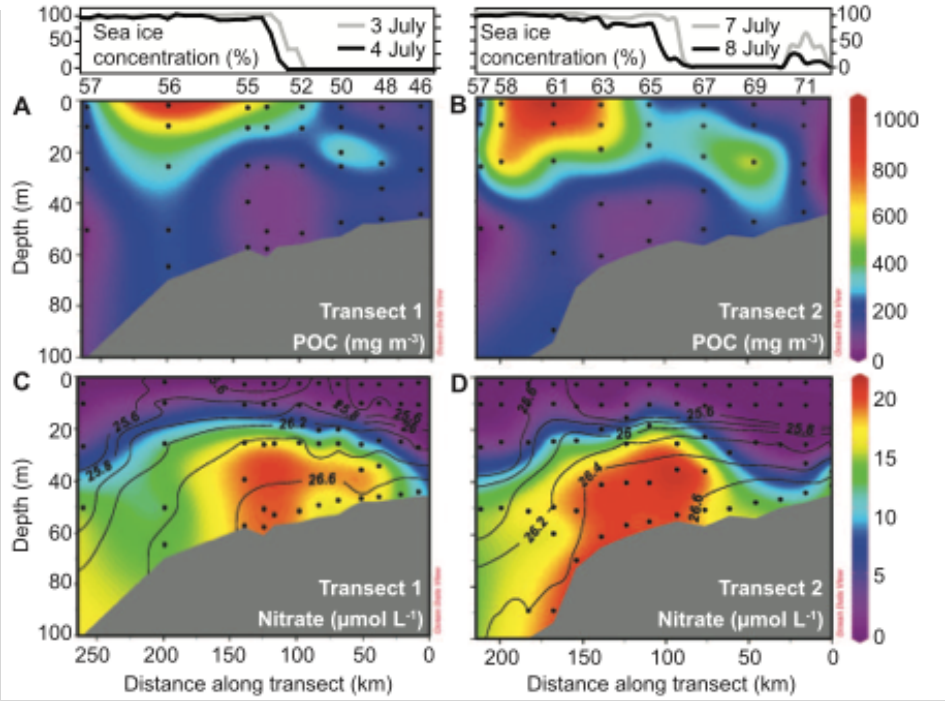
-45 day shift: 89%

0 day shift: 100%

+45 day shift: 114%



Under ice blooms

Massive Phytoplankton Blooms Under Arctic Sea Ice

Kevin R. Arrigo,*† Donald K. Perovich, Robert S. Pickart, Zachary W. Brown, Gert L. van Dijken, Kate E. Lowry, Matthew M. Mills, Molly A. Palmer, William M. Balch, Frank Bahr, Nicholas R. Bates, Claudia Benitez-Nelson, Bruce Bowler, Emily Brownlee, Jens K. Ehn, Karen E. Frey, Rebecca Garley, Samuel R. Laney, Laura Lubelczyk, Jeremy Mathis, Atsushi Matsuoka, B. Greg Mitchell, G. W. K. Moore, Eva Ortega-Retuerta, Sharmila Pal, Chris M. Polashenski, Rick A. Reynolds, Brian Schieber, Heidi M. Sosik, Michael Stephens, James H. Swift