Air-sea gas transfer in the sea ice zone

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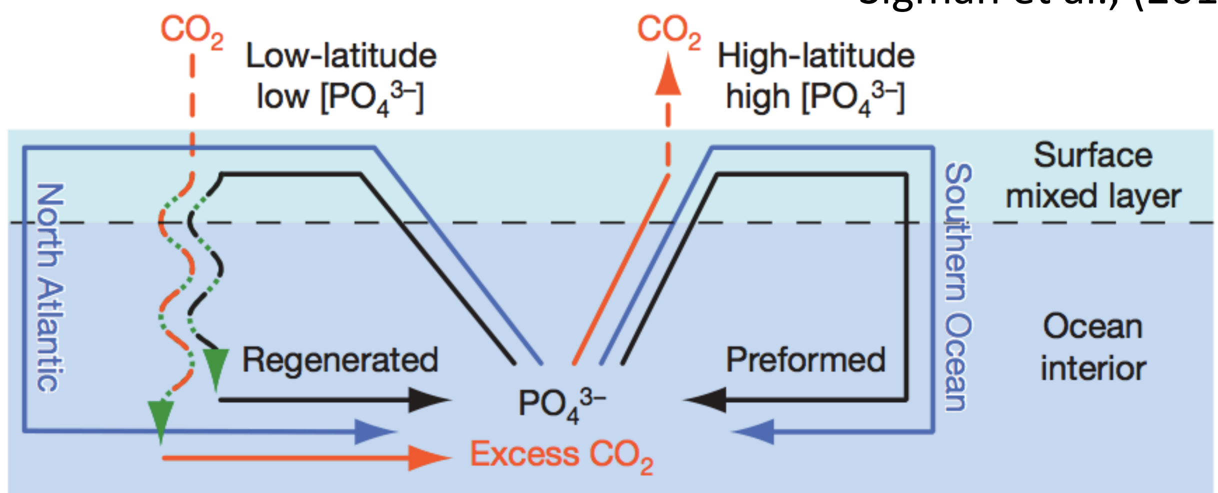
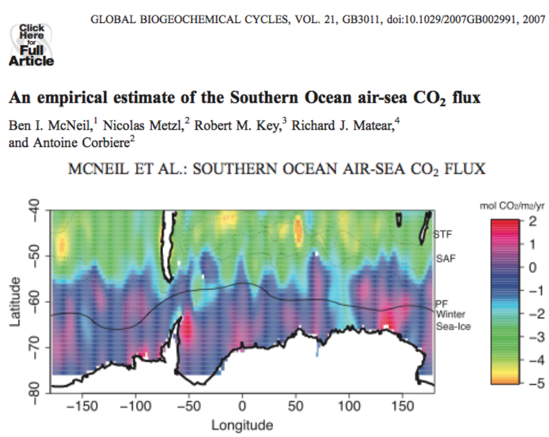
We’re looking for the drains and backups of ocean carbon plumbing

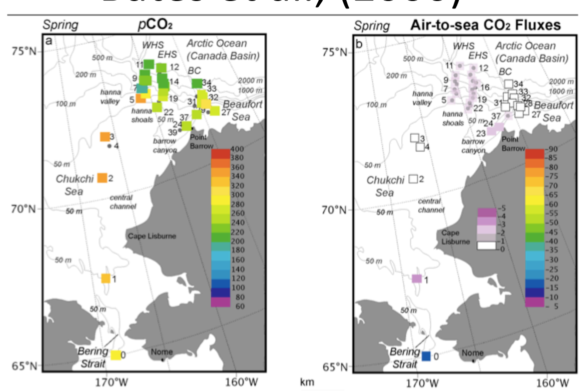
Sigman et al., (2010)



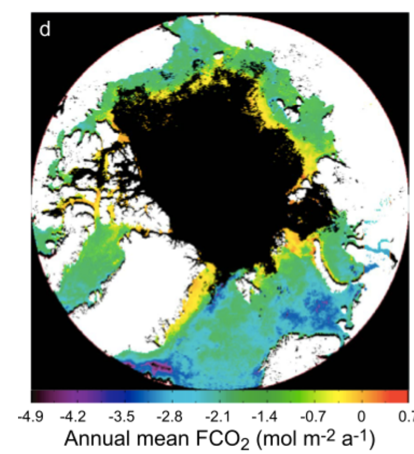
McNeil et al., (2007)



Bates et al., (2006)



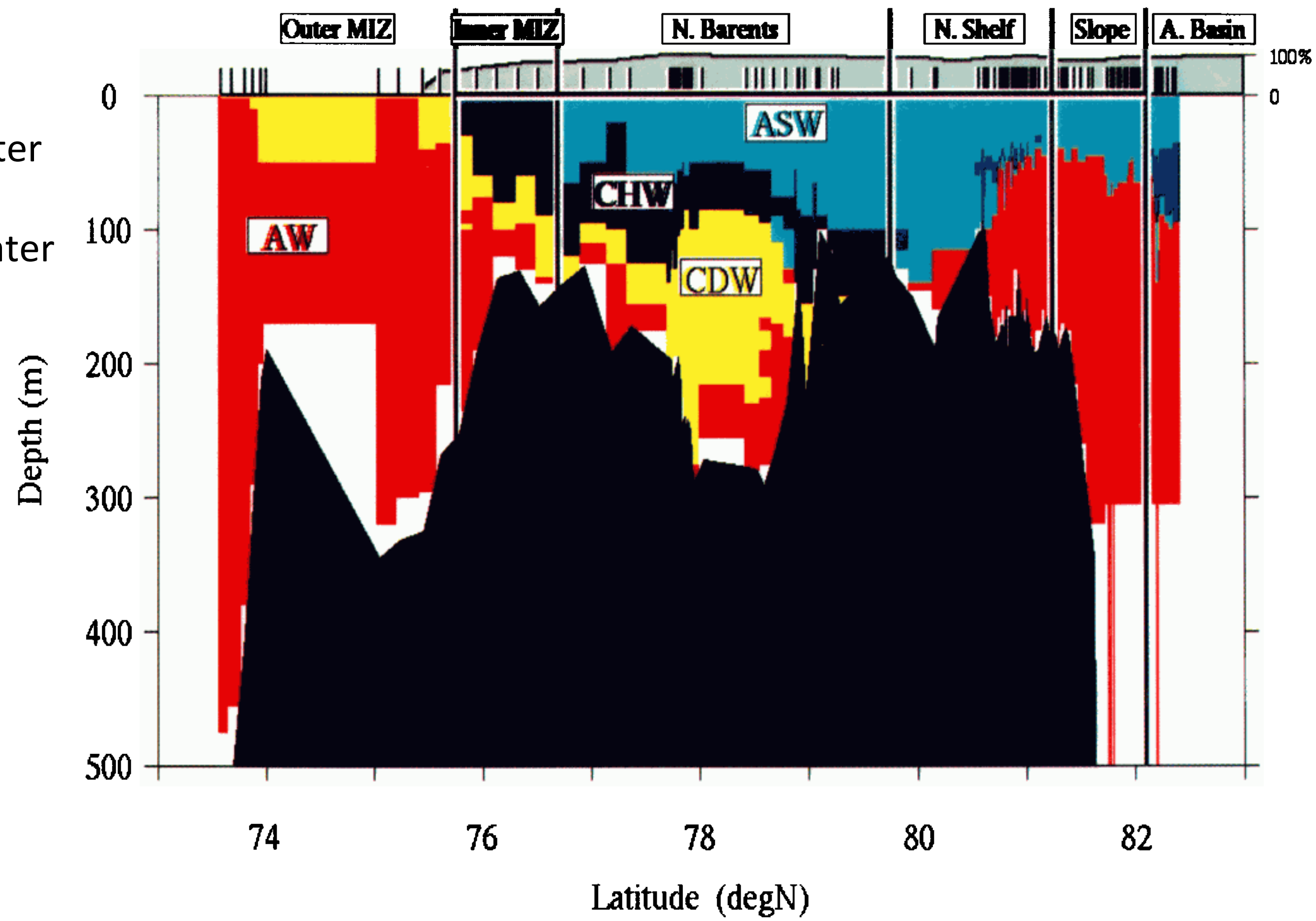
Arrigo et al., (2010)



Subduction and Shelf-Basin Interactions in the Arctic Ocean

Steele et al., (1995)

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



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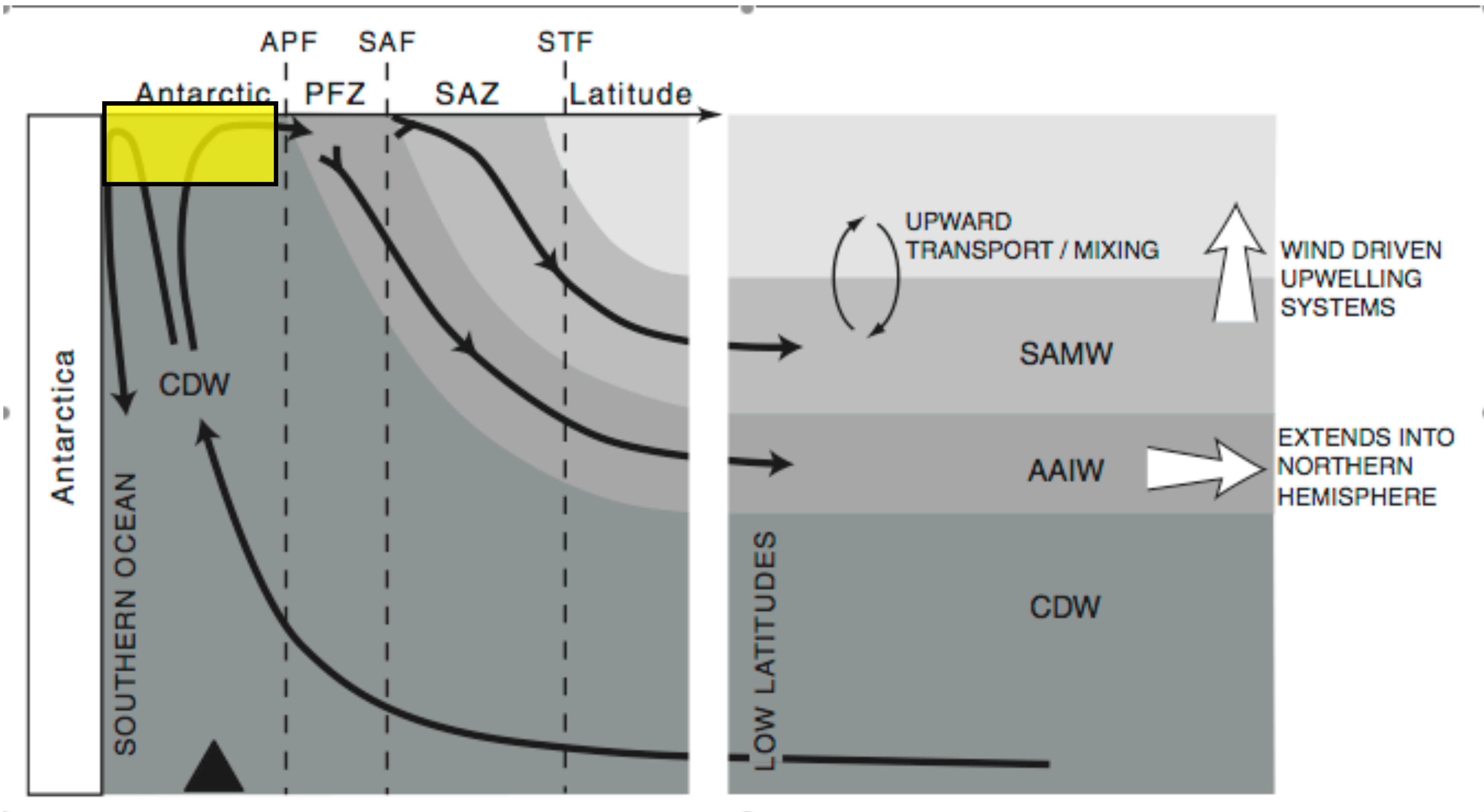
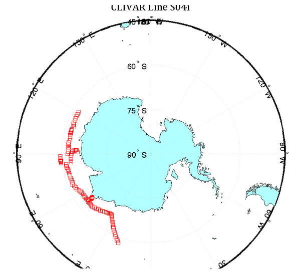
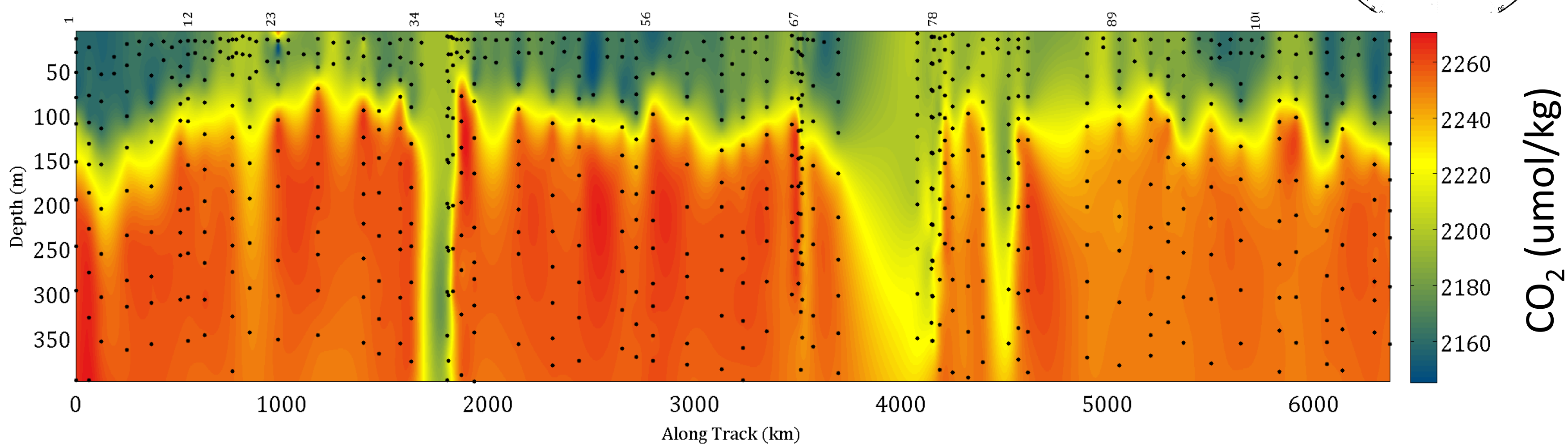
Polynyas, deep convection and CO_2 ventilation

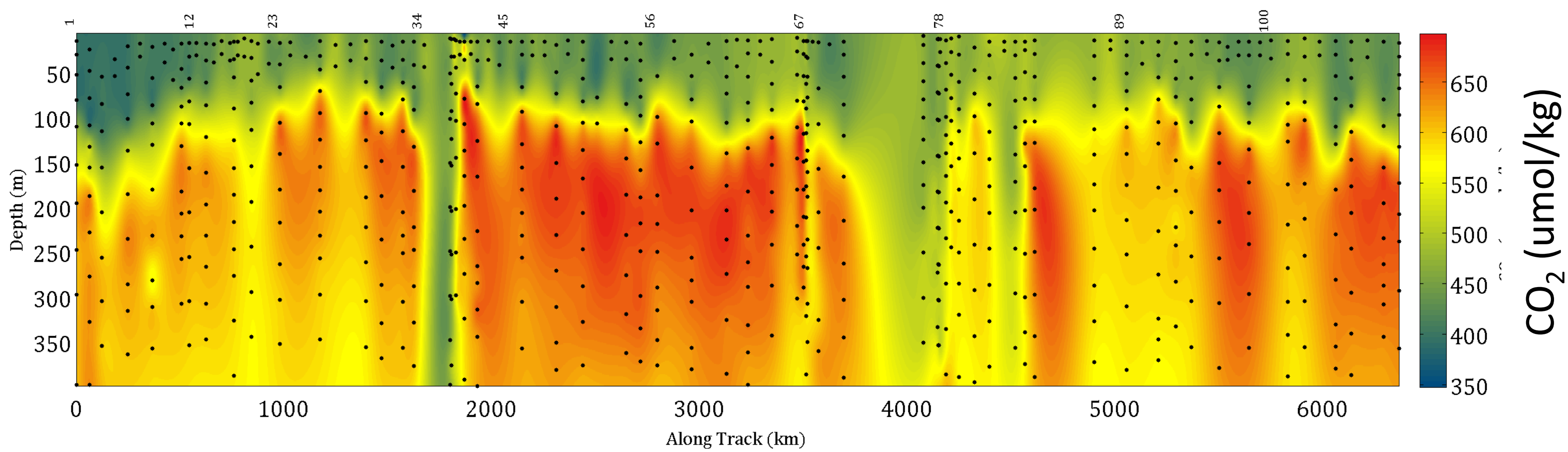
Anderson et. al., 2009



Natural CO_2 ventilation in the S.O.







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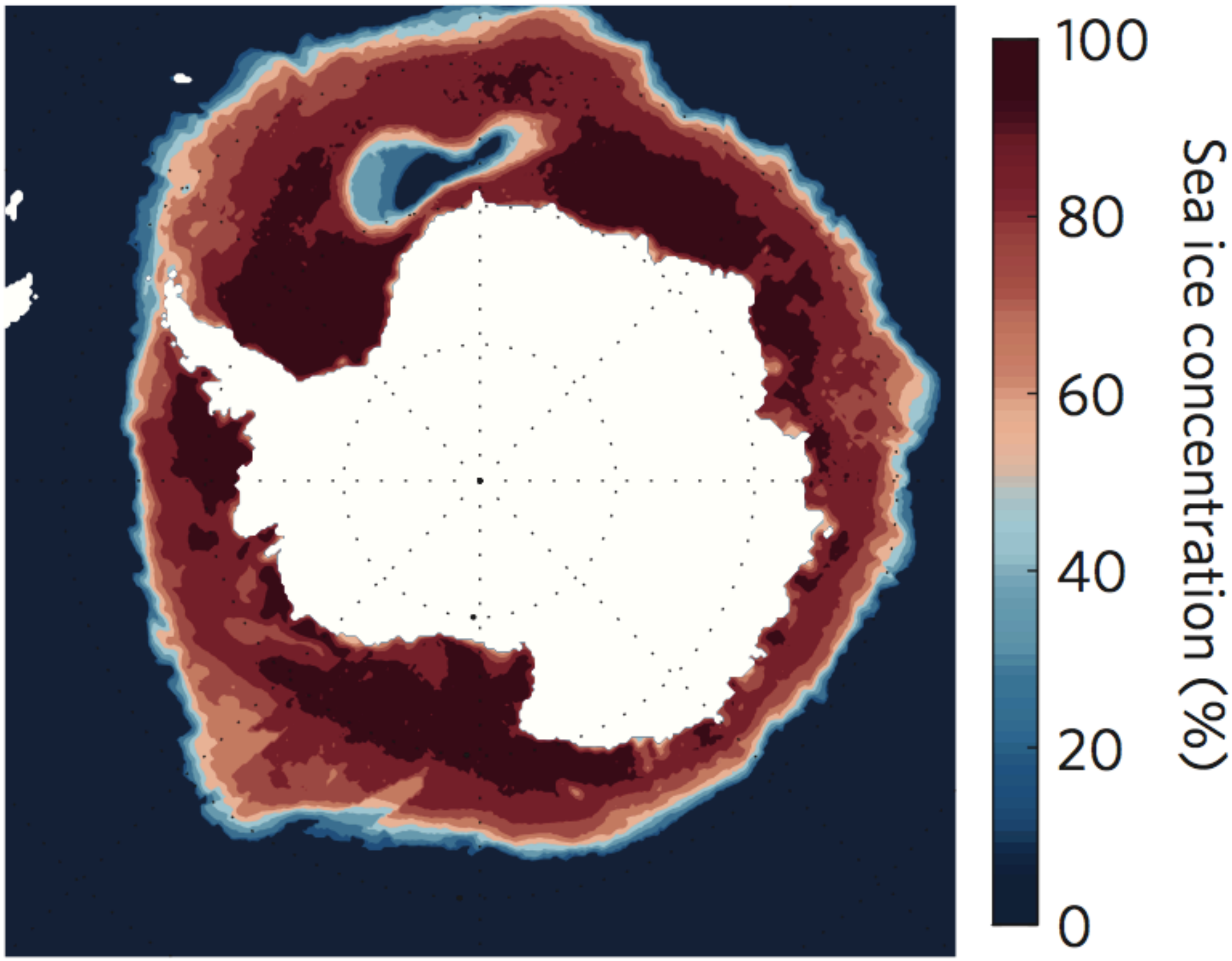
Polynyas, deep convection and CO_2 ventilation



de Lavergne et al., (2014)

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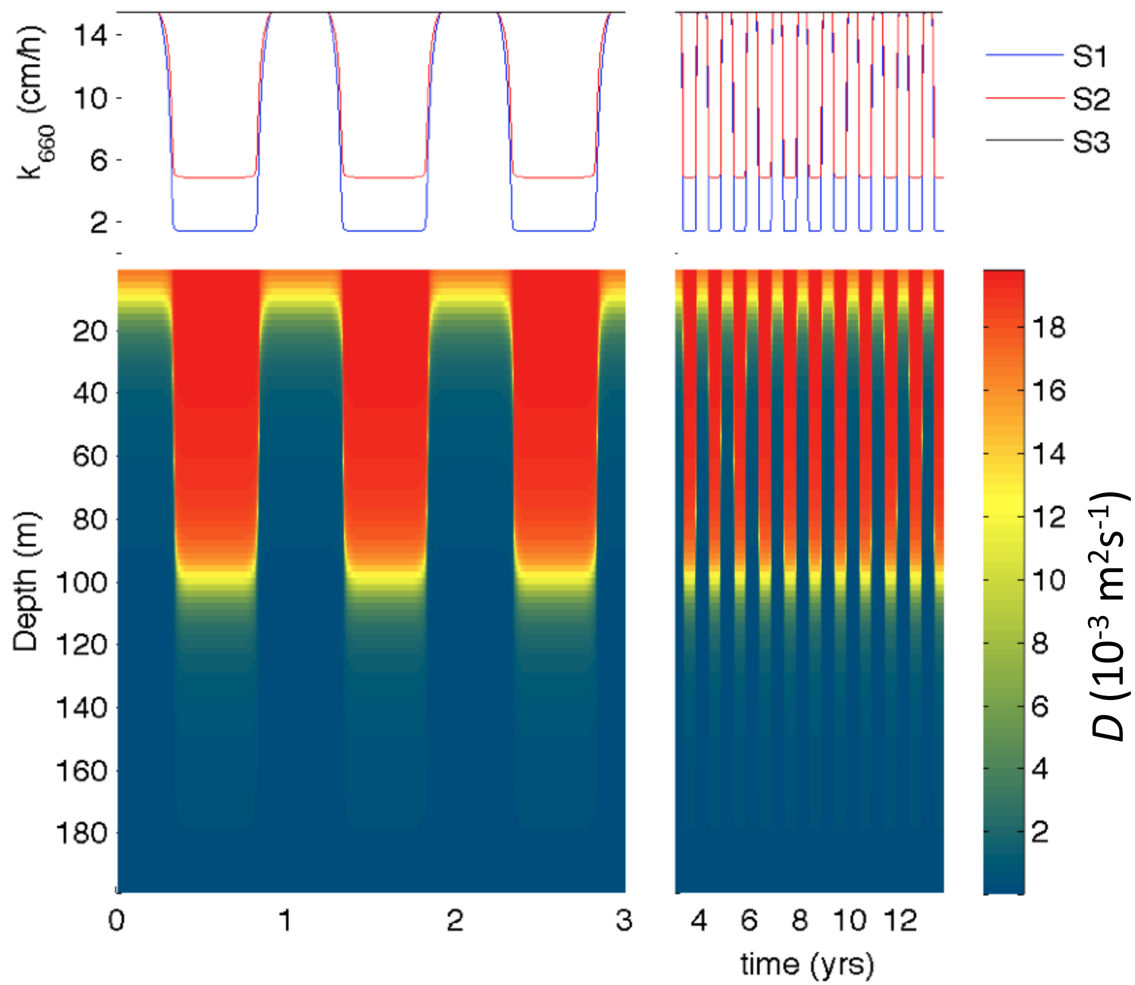
Seasonal forcing in a DIC transport model

Loose and Schlosser (2011)

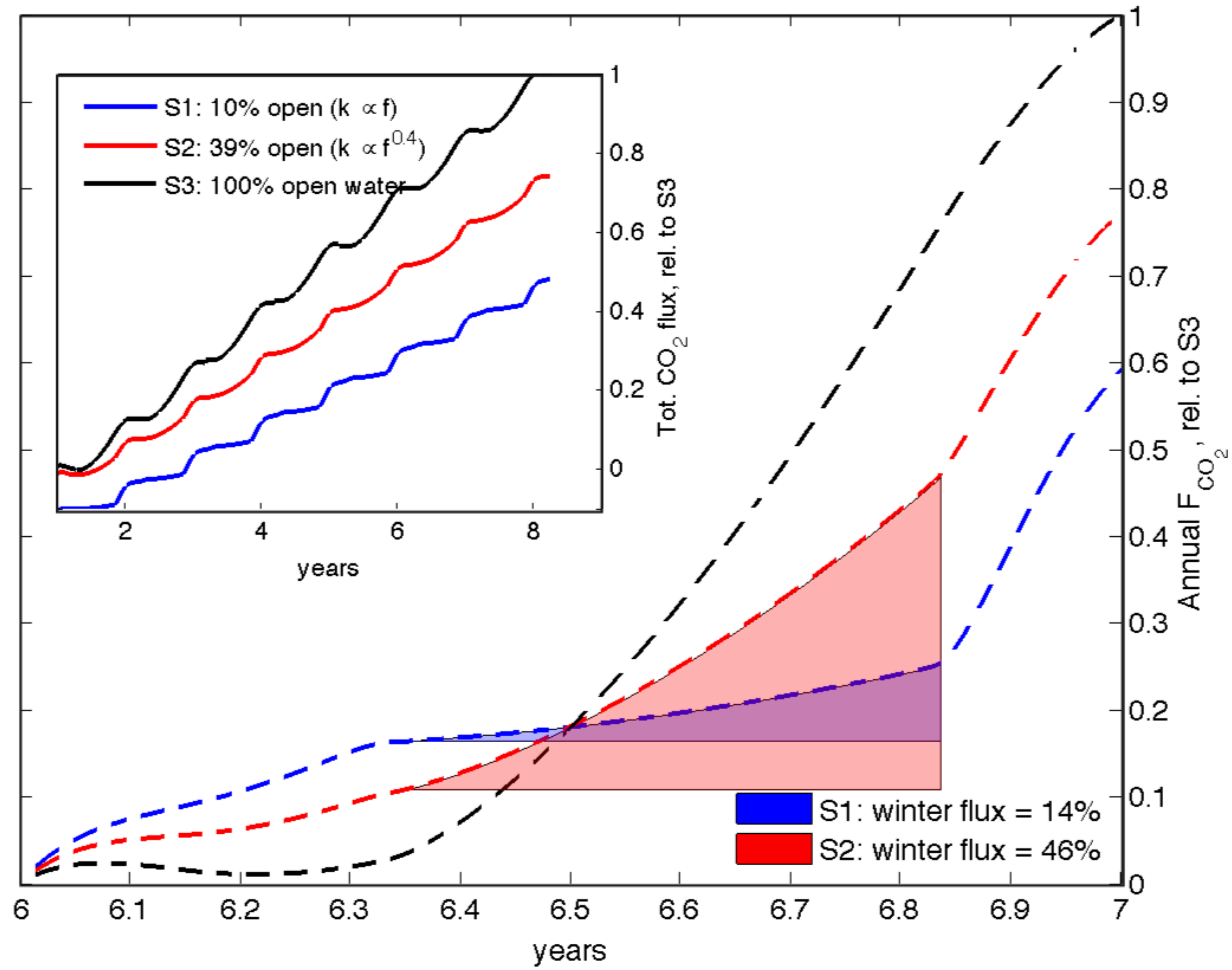


C = Dissolved inorganic carbon

Primary Production = based upon data from sea ice zone

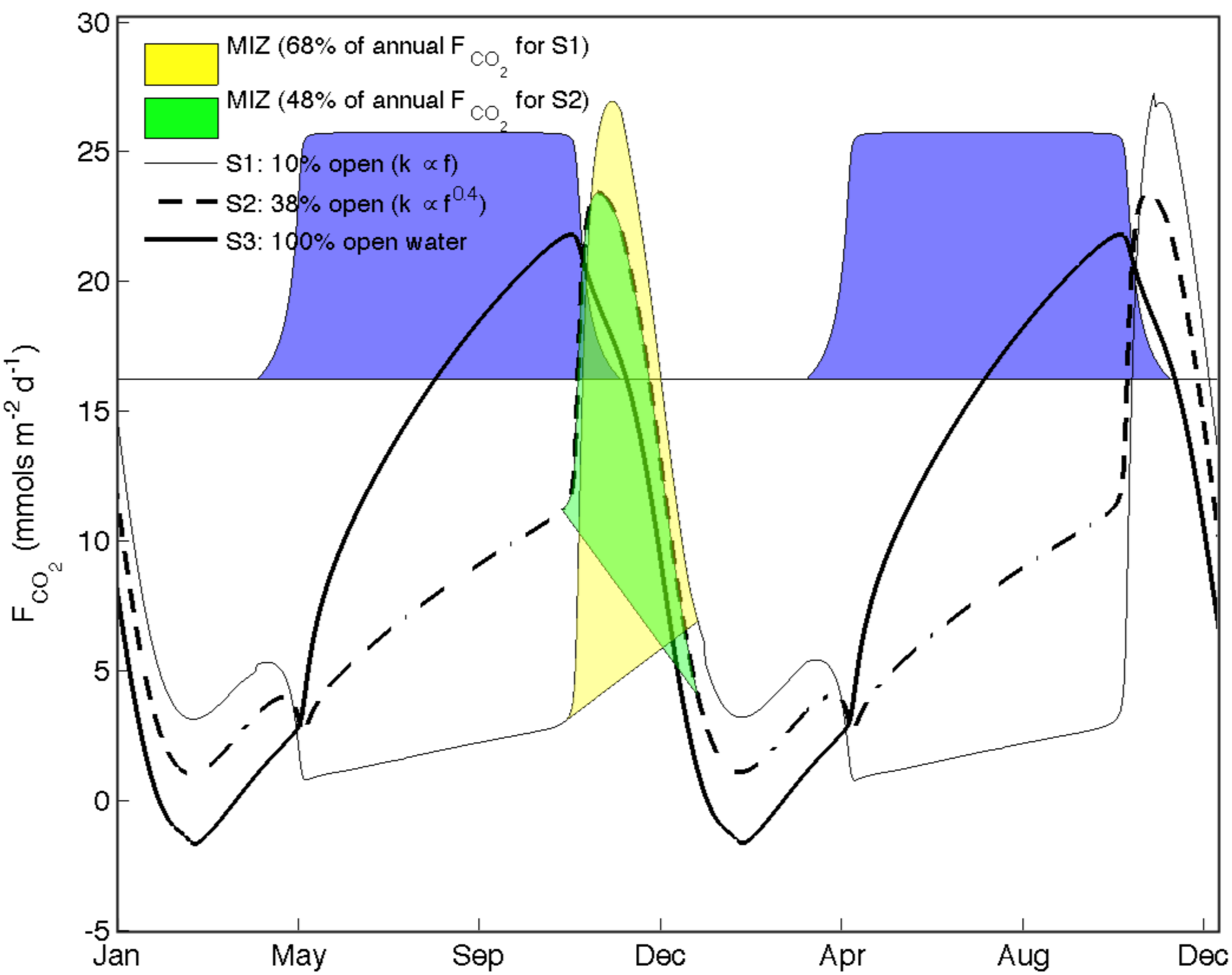
Annual FCO_2 through ice zone

Loose and Schlosser (2011)



Springtime fluxes

Loose and Schlosser (2011)



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Timing of ice breakup and spring bloom

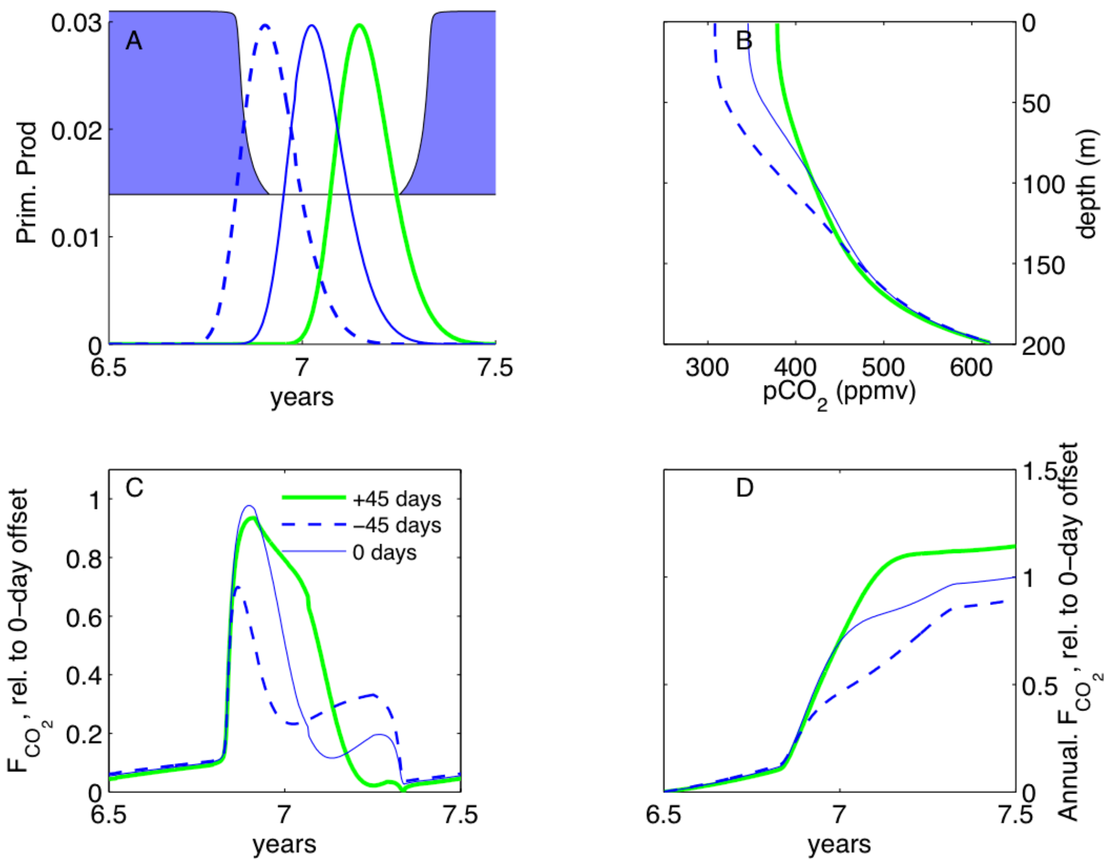
-45 days: peak F_{CO2} is reduced by 27%

Net annual F_{CO2}:

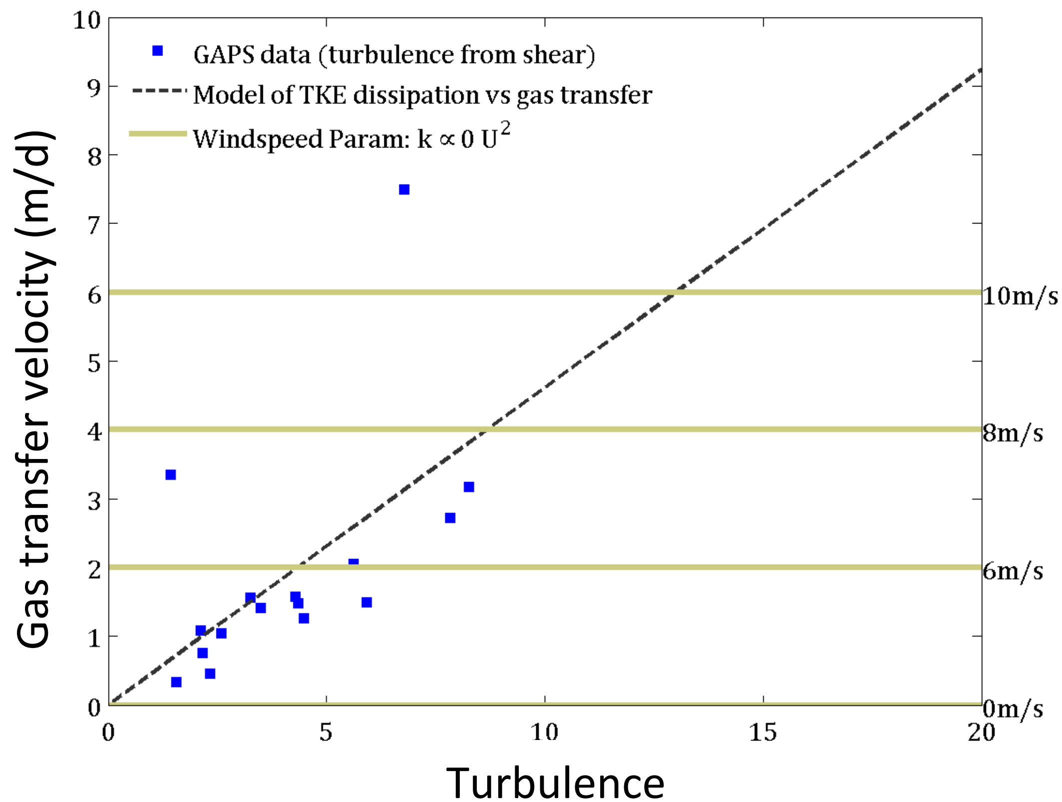
-45 day shift: 89%

0 day shift: 100%

+45 day shift: 114%



Here's the punchline..



There are other first-order processes (in addition to wind) driving gas exchange in the ice zone

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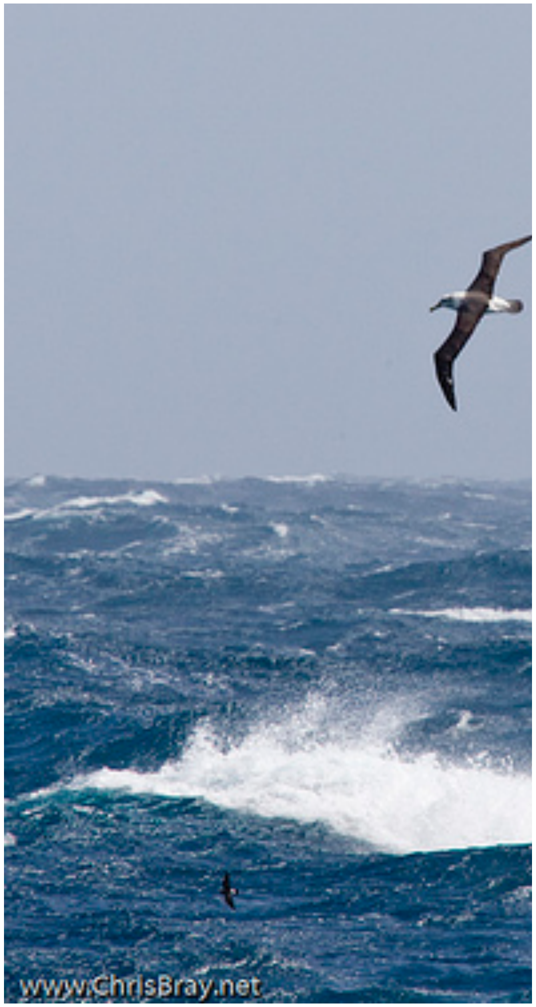
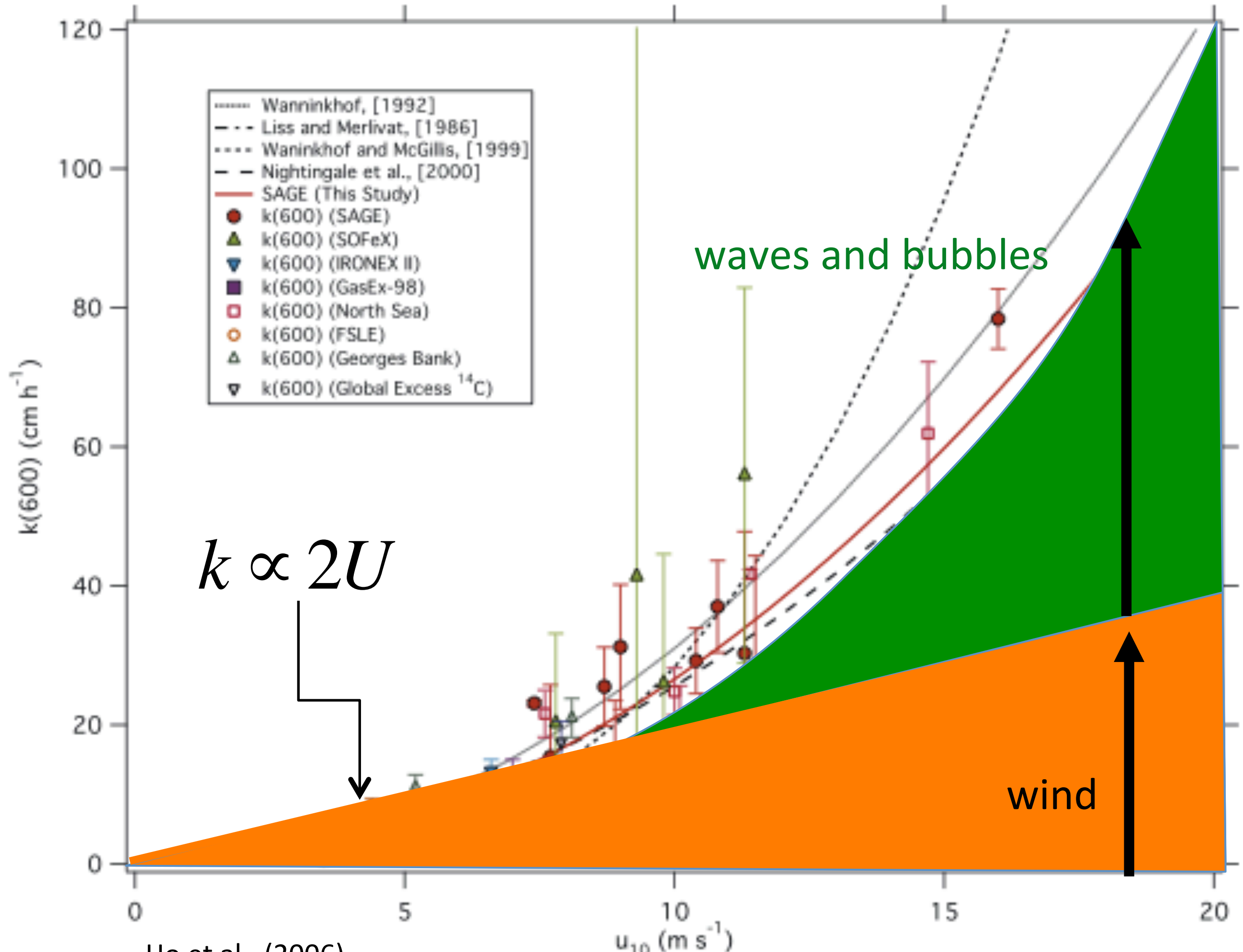
Contents

1. Differences between gas exchanges in the open ocean and the sea ice zone.
   - Turbulence and gas transfer from **shear in the Ice-Ocean Boundary Layer**.
   - Turbulence and gas transfer from **buoyant convection in the Ice-Ocean Boundary Layer**.
2. Results from GAPS laboratory experiment.

Gas exchange over open water





Ho et al., (2006)

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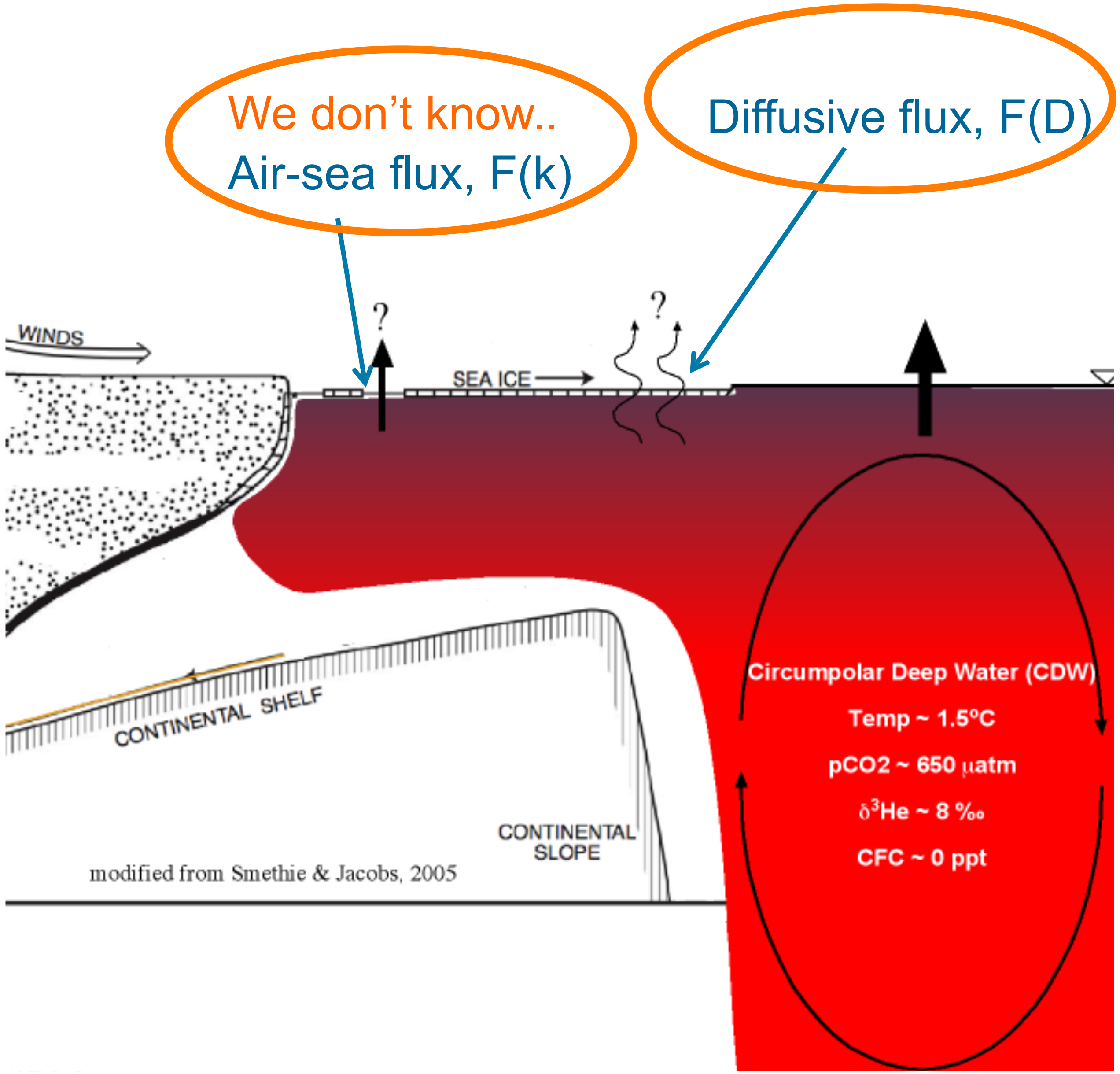
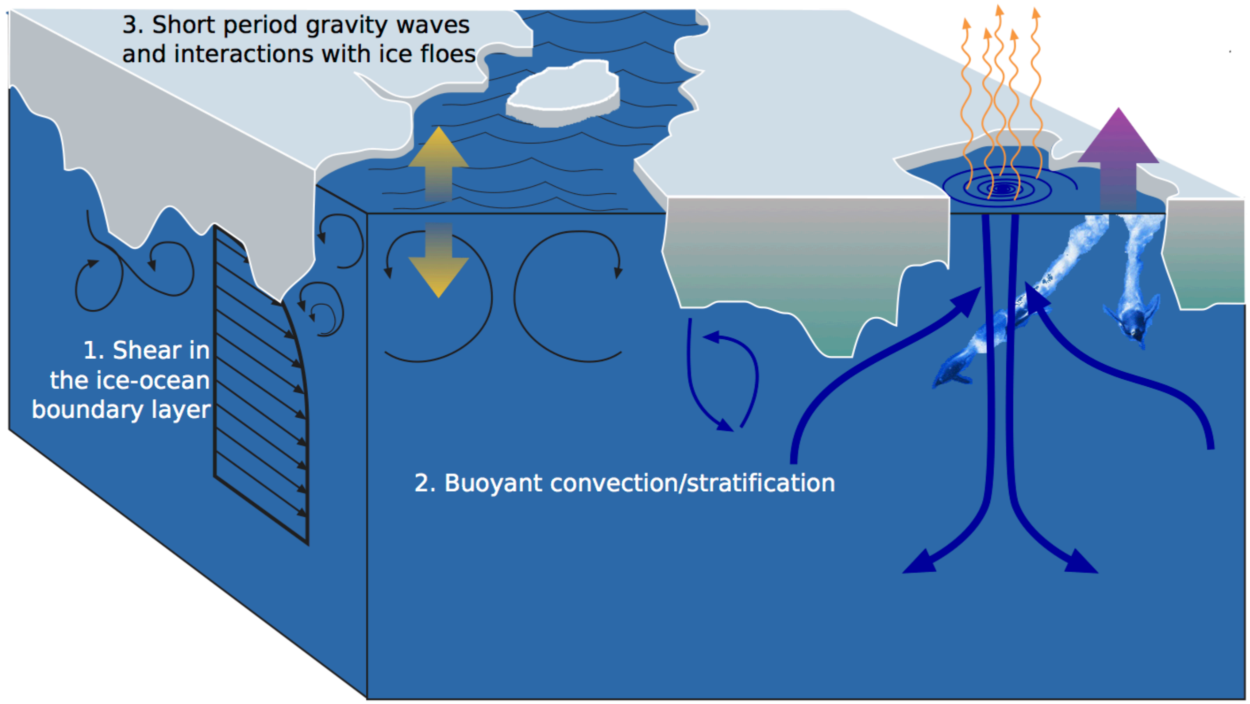
Gas transport pathways in the ice pack

k = gas transfer velocity (L/t)

D = gas diffusivity (L^2/t)



How to model k in the ice pack?



- Shear in the ice-ocean boundary layer (IOBL) (McPhee, 1992; McPhee, 2008).
- Buoyant convection/stratification (Martinson, 1990; 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);

How to model k in the ice pack?

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

0

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

f is the fraction of open water

How to model k in the ice pack?

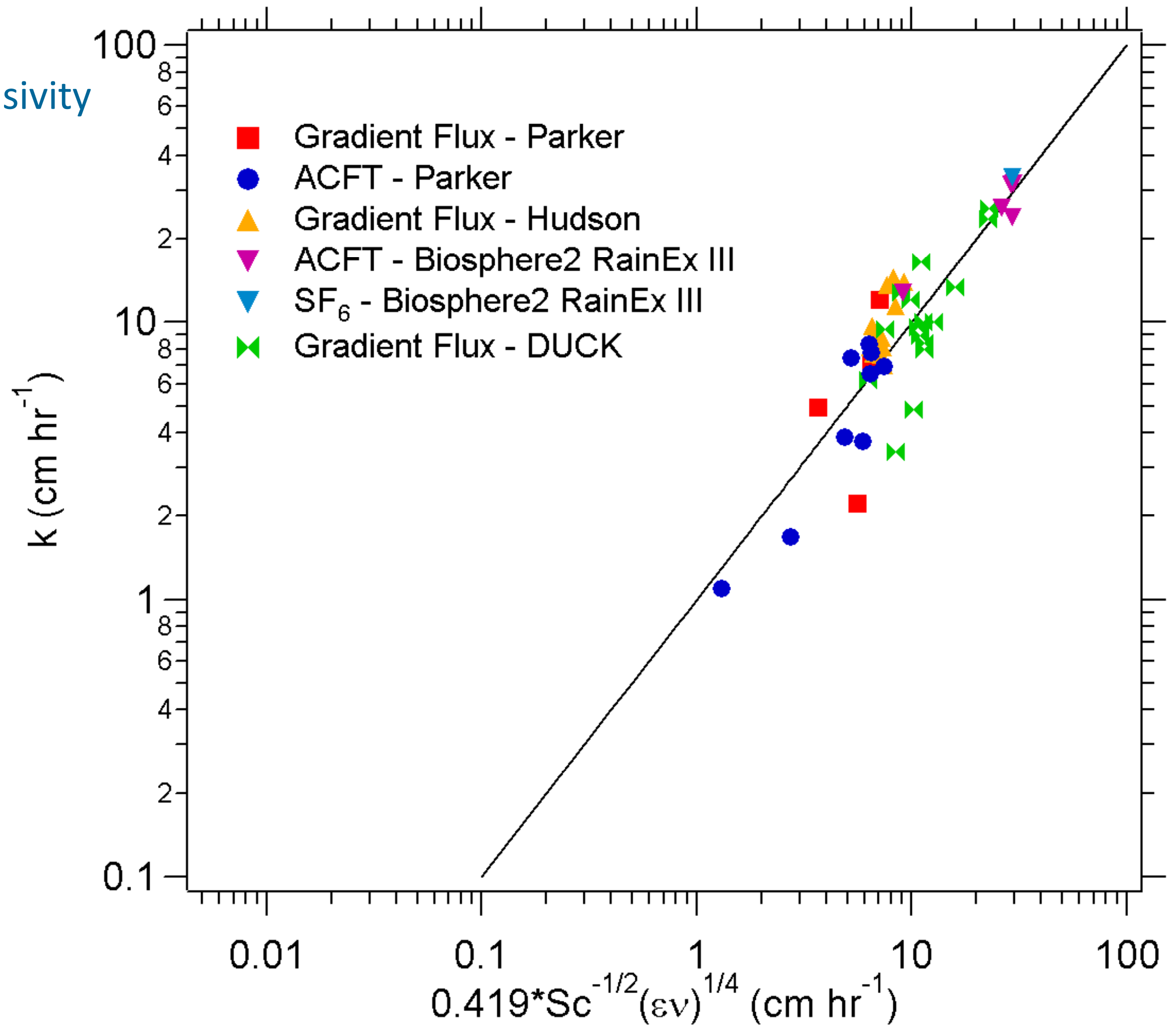
Viscosity

Molecular diffusivity

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

Turbulence dissipation

Lamont and Scott (1974)



Zappa et al., (2007)

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How to model k in the ice pack?

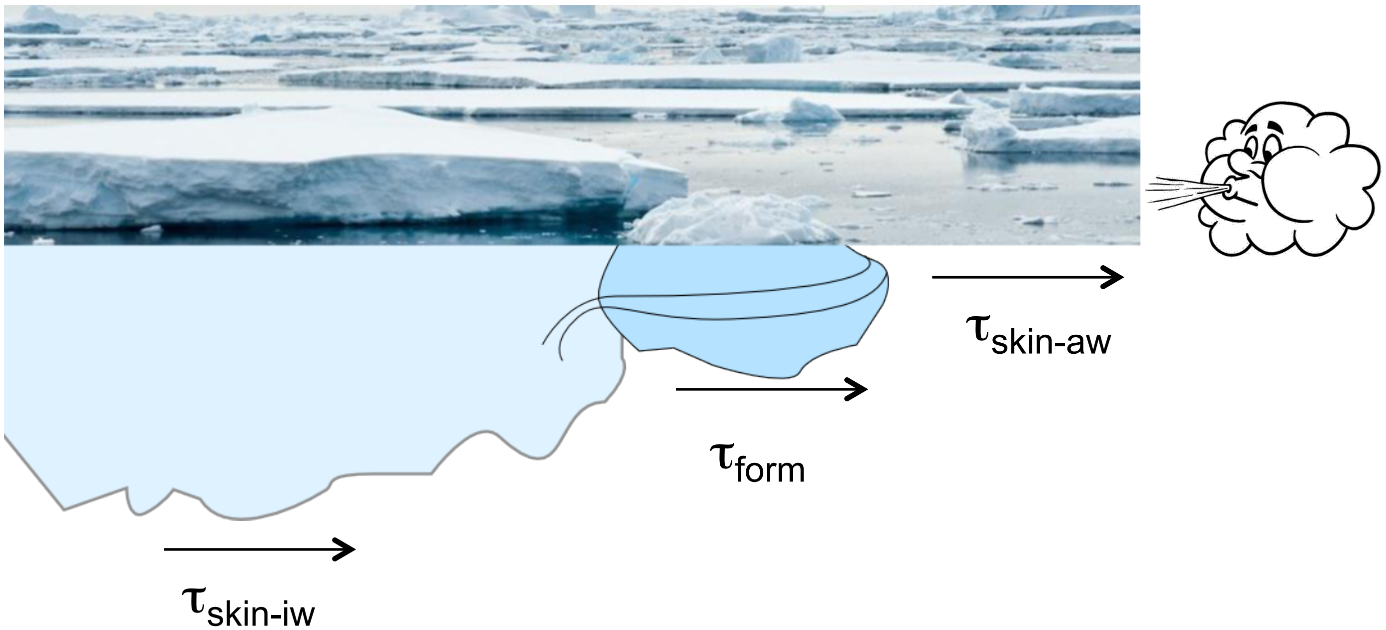
$$\varepsilon = {u_*}^2 \frac{\partial \bar{u}}{\partial z} + \overline{b' w'}$$

Buoyant convection/ stratification

Ice/water current shear

Wind-driven shear

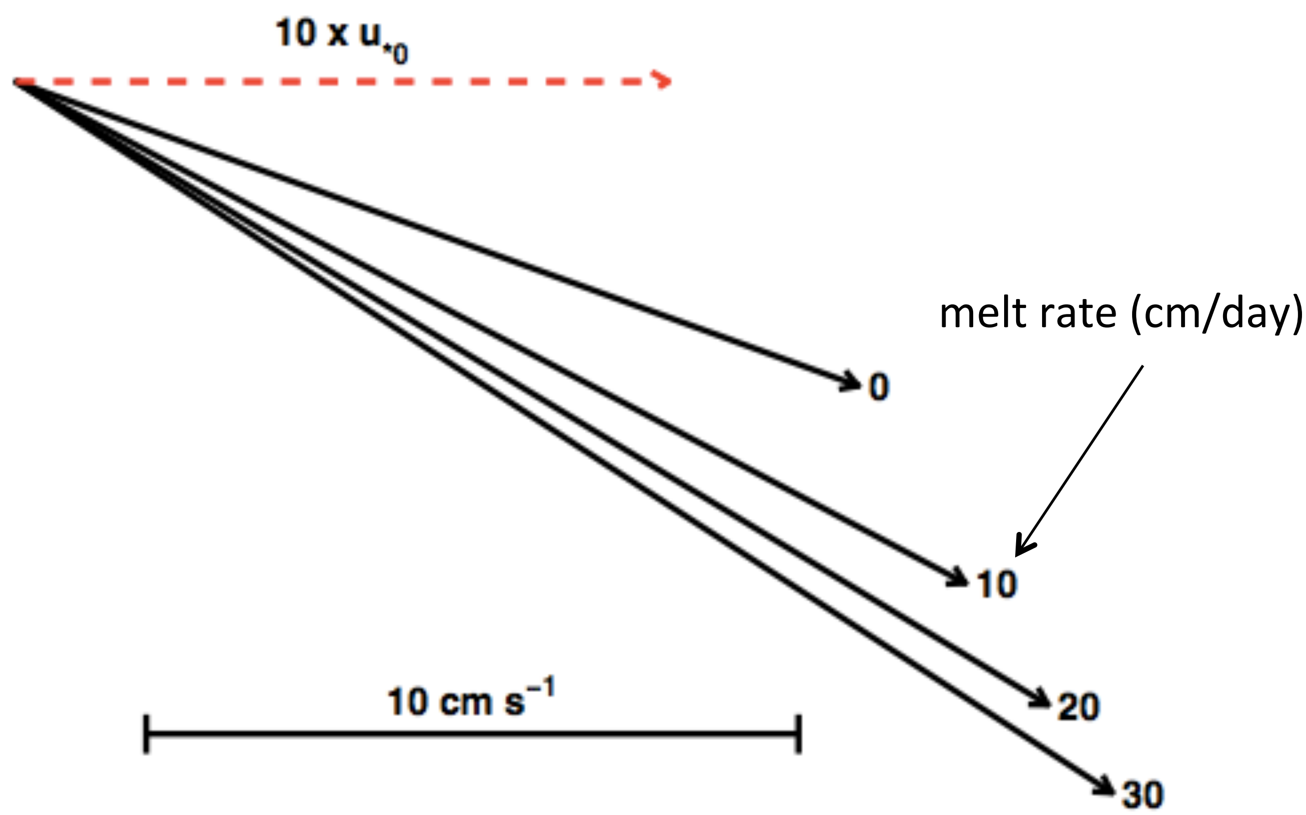
Ice drag on the Ice-ocean boundary layer



$$\tau = (1-\mathrm{f})\left(\tau_{skin-iw} + \tau_{form}\right) + (\mathrm{f})(\tau_{skin-aw})(1-W)$$

Steele et al., (1995)

Ice melt increases ice-water relative velocity

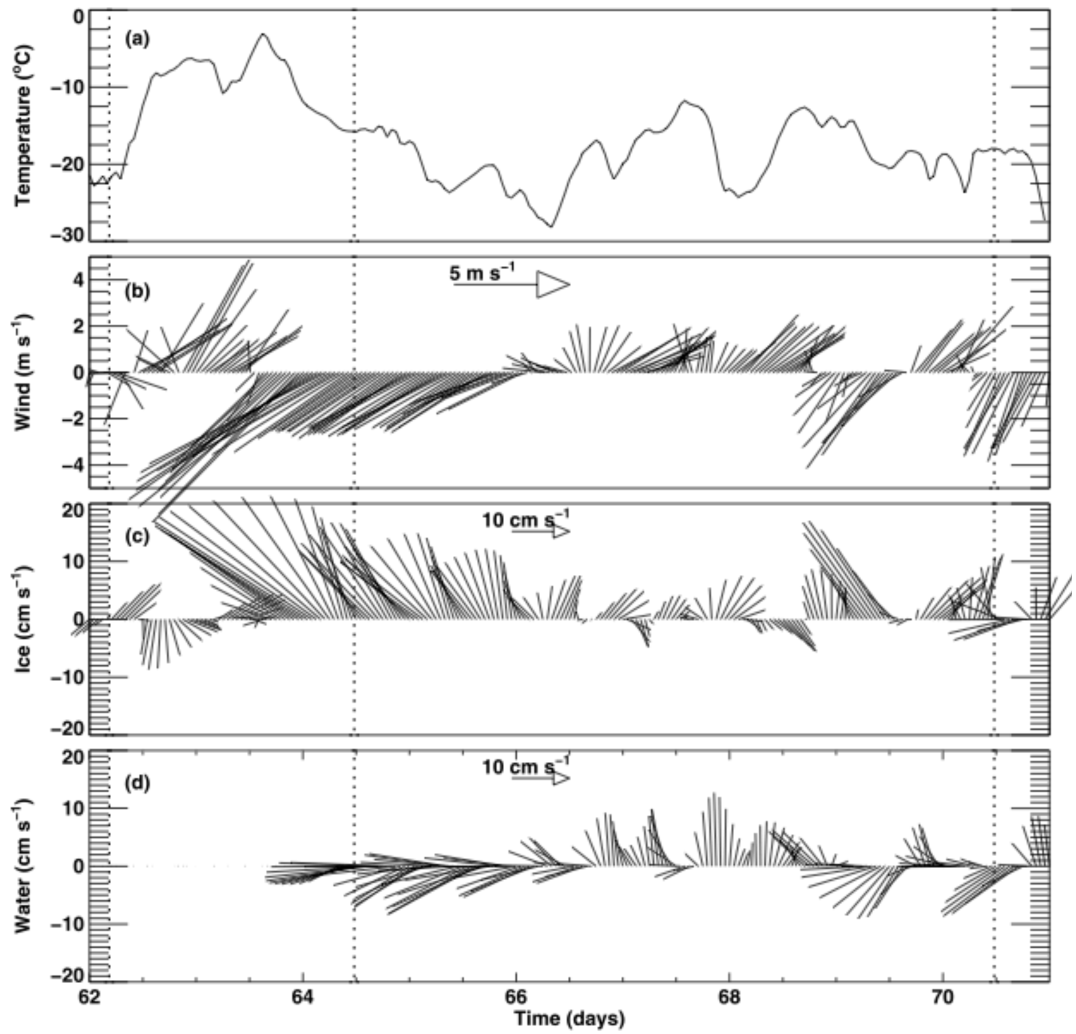


McPhee (2010)

Water-ice relative velocities ($U_{ice} - U_{water}$)

Geiger and Drinkwater, JGR (2005)

- Wind, ocean tides, inertial oscillations and other motions affect sea ice divergence.
- Sea ice divergence affects air sea fluxes, new ice production and thermohaline structure of upper ocean.



Buoyant convection

- J_{bo} = Surface buoyancy flux (W/kg).
- (f) and (1-f) weight the open water and ice covered flux terms, respectively.

Heat flux

Precipitation

$$J_{b0} = -\frac{g\alpha}{\rho c_p}(J_q^{SH} + J_q^{LH})(\mathrm{f}) + J_b^{ice}(1-\mathrm{f}) + g\beta(E-P)S_0(\mathrm{f})$$

flux to ice

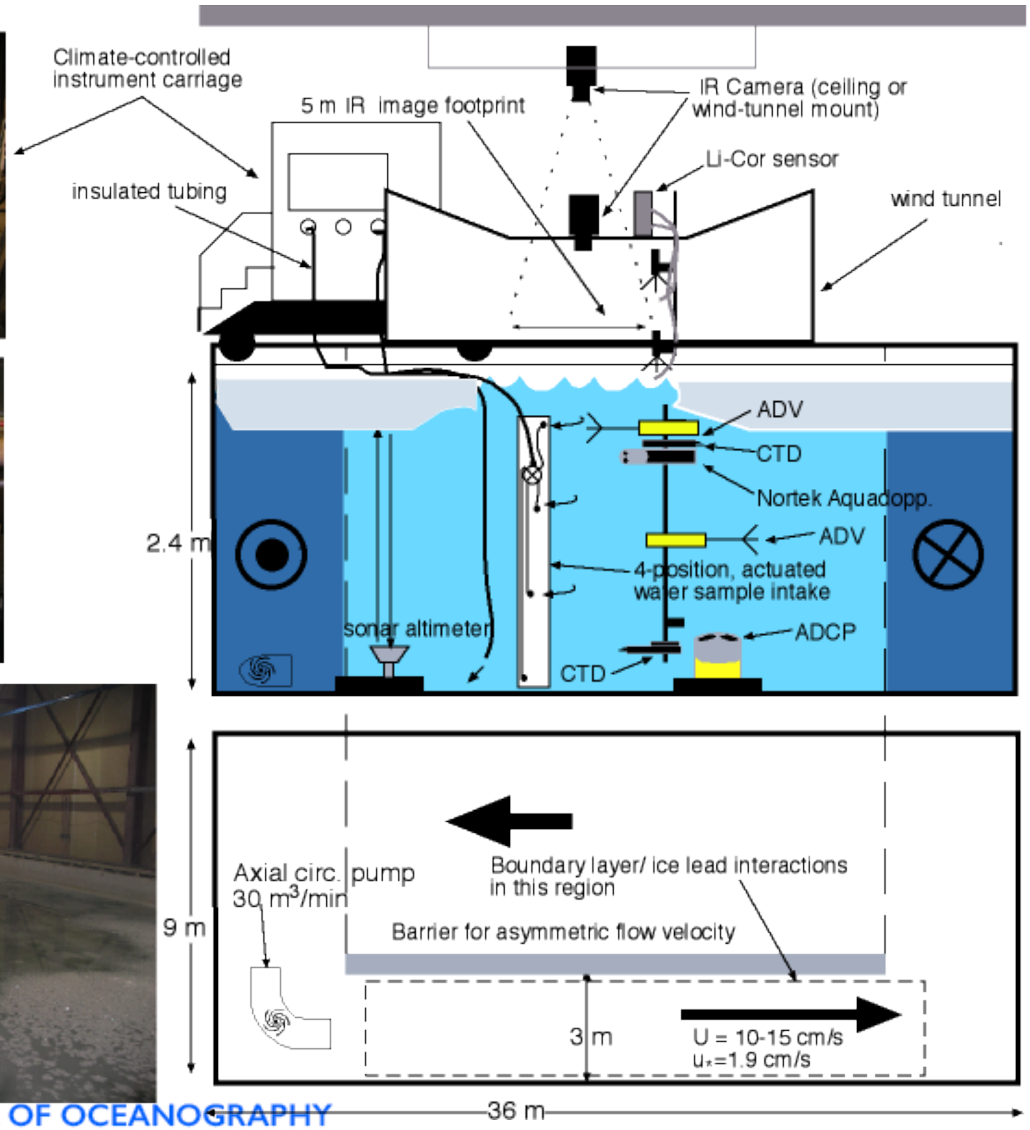
Evaporation

GAPS Experiment at USACE CRREL

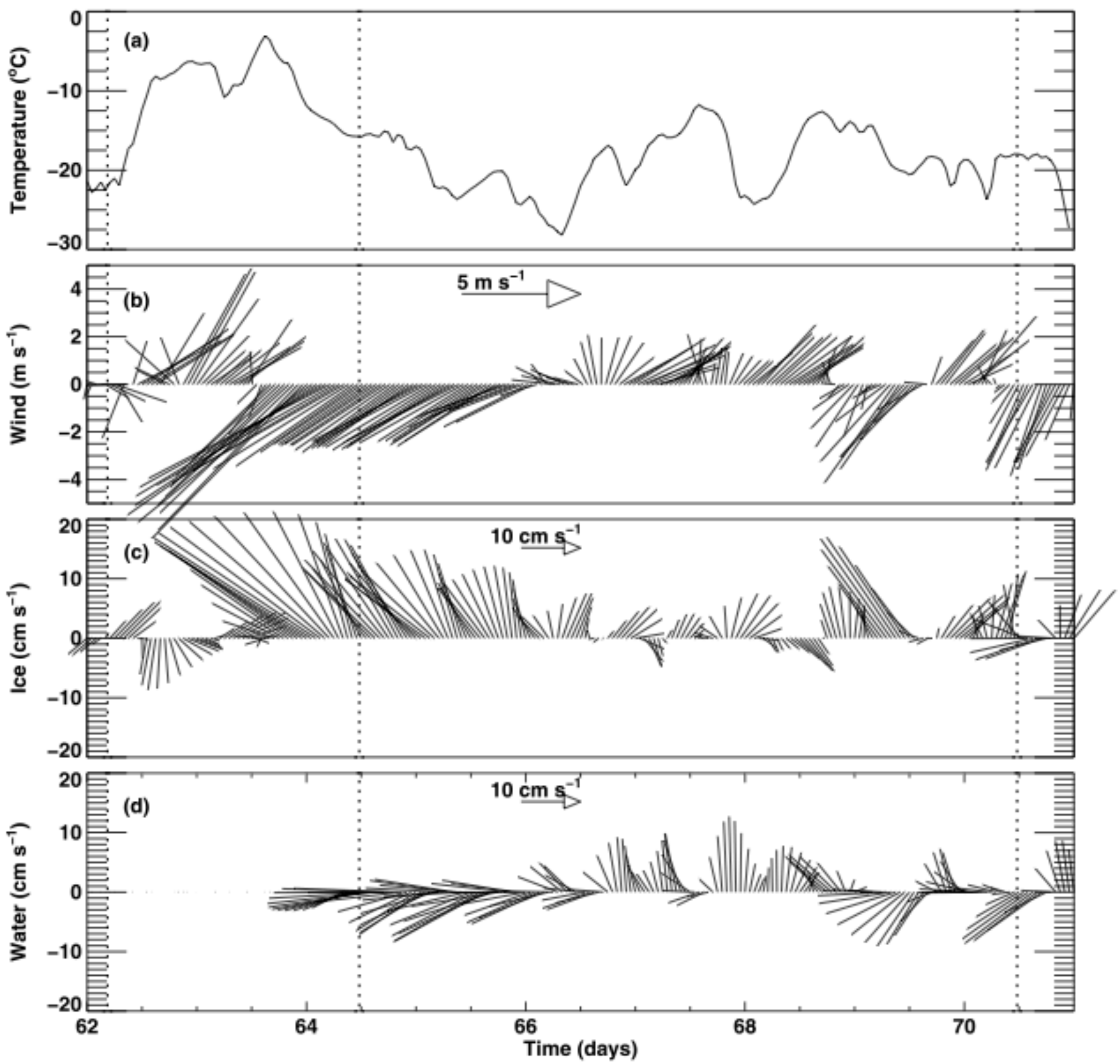
GAPS: (Gas Transfer through Polar Sea ice).

https://www.youtube.com/watch?v=yrXycJLWGpU

GAPS: (Gas Transfer through Polar Sea ice).



Water-ice relative velocities ($U_{ice} – U_{water}$)



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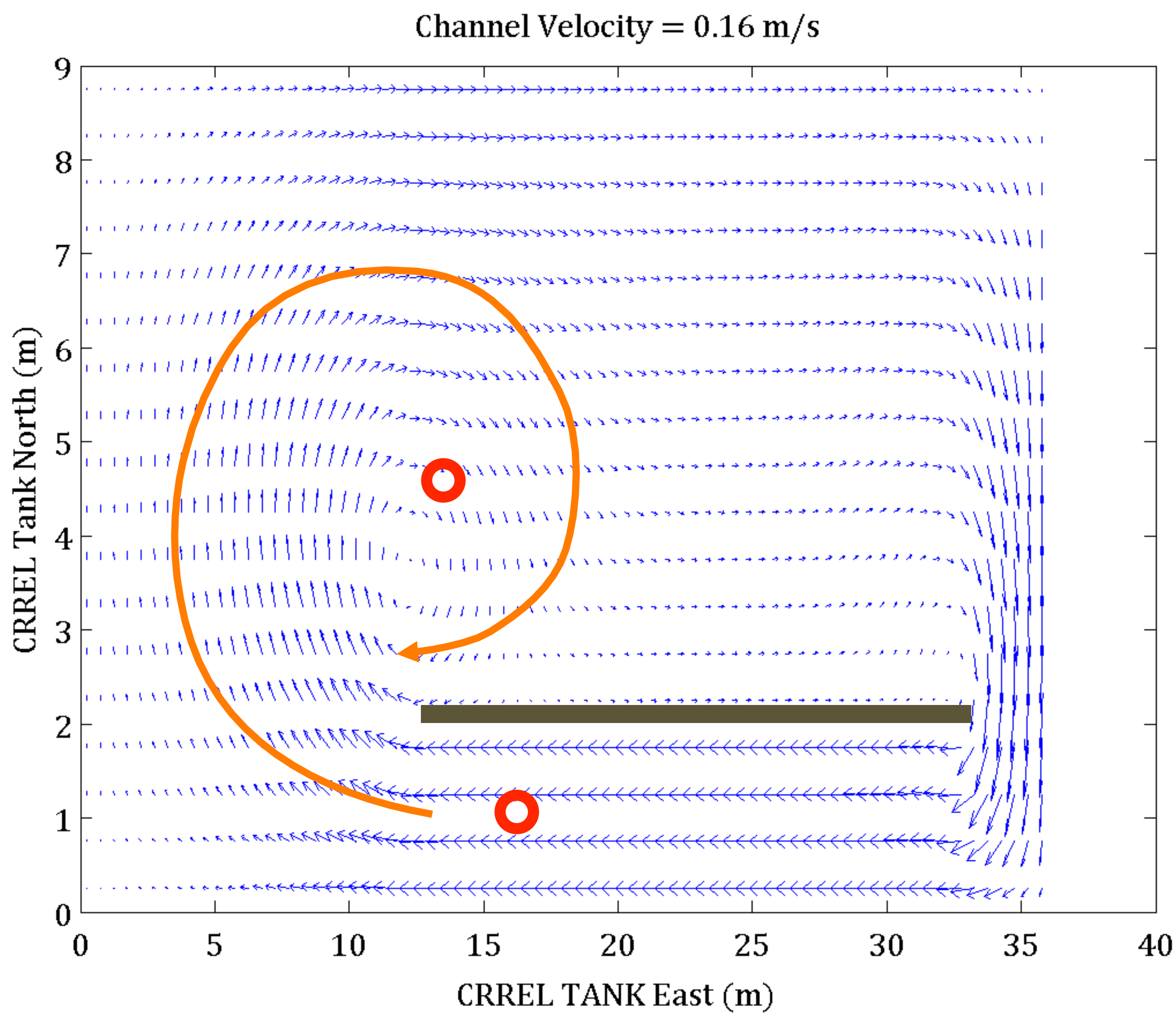
Steady state velocity field in experiment tank



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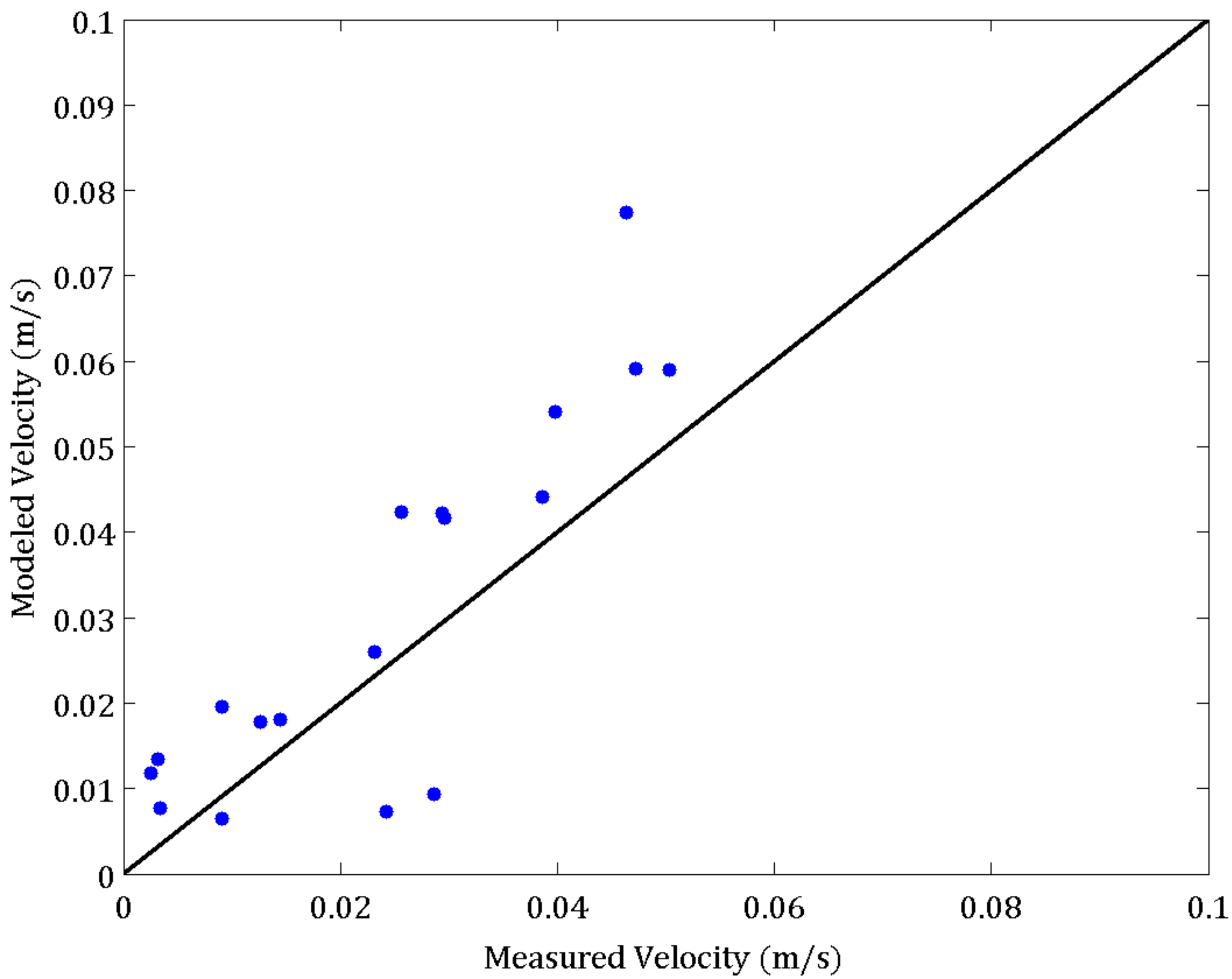
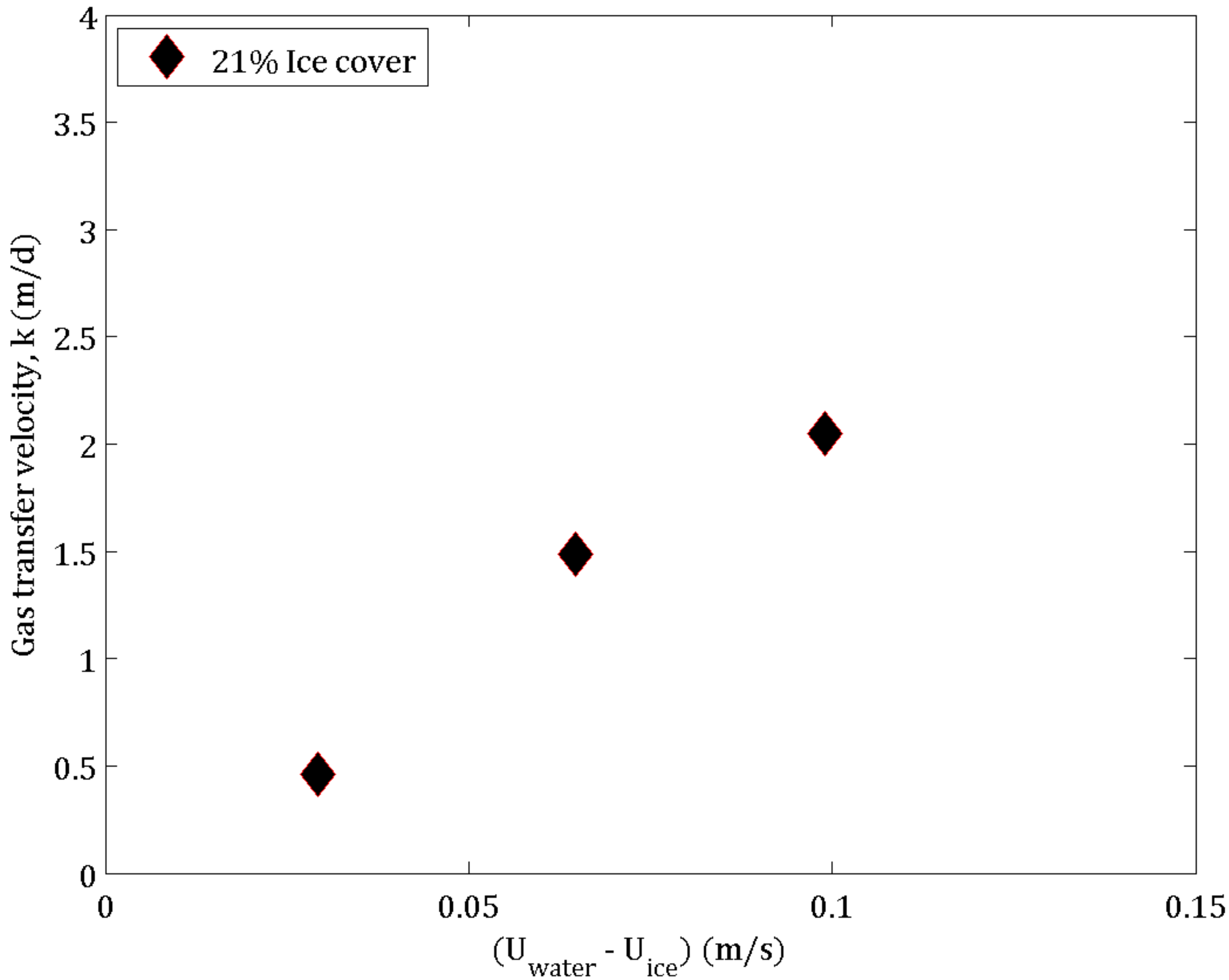
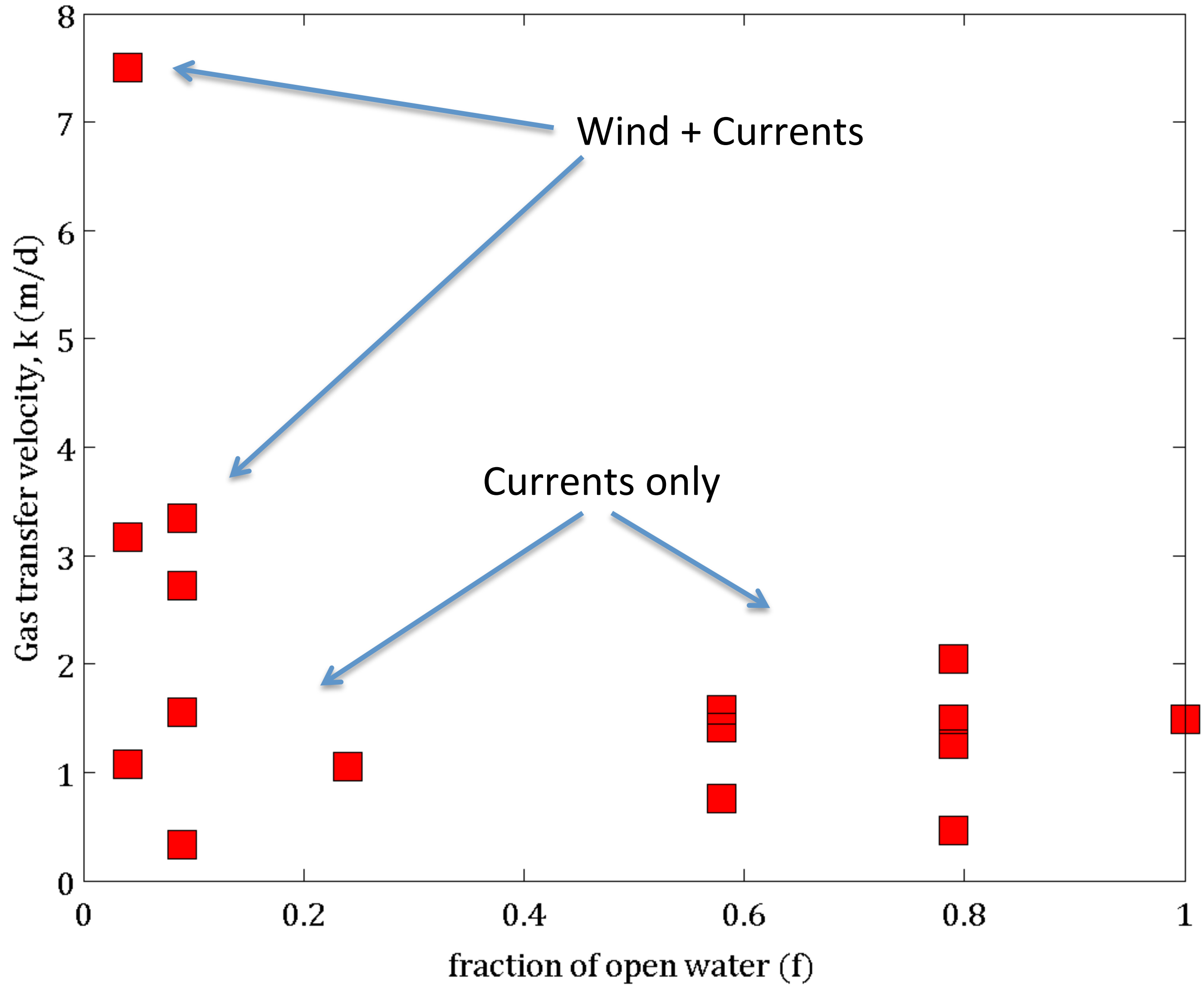
Comparison of velocity: model vs. measure



Shear-driven turbulence leads to k



No relationship between k and ice cover



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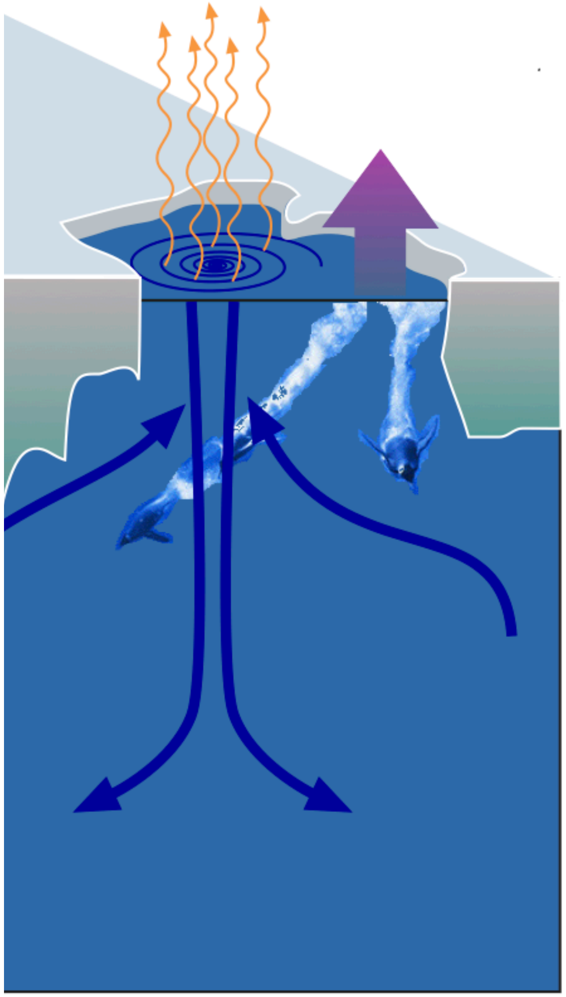
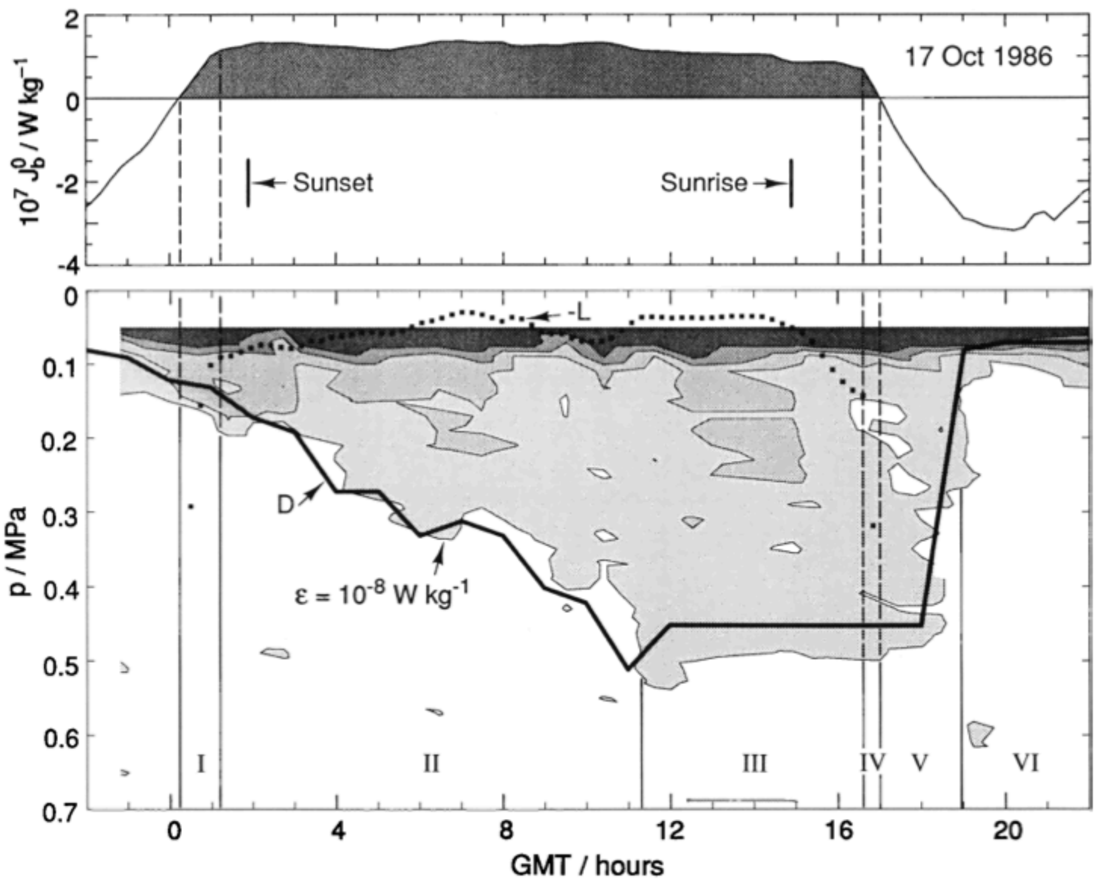
Buoyant convection



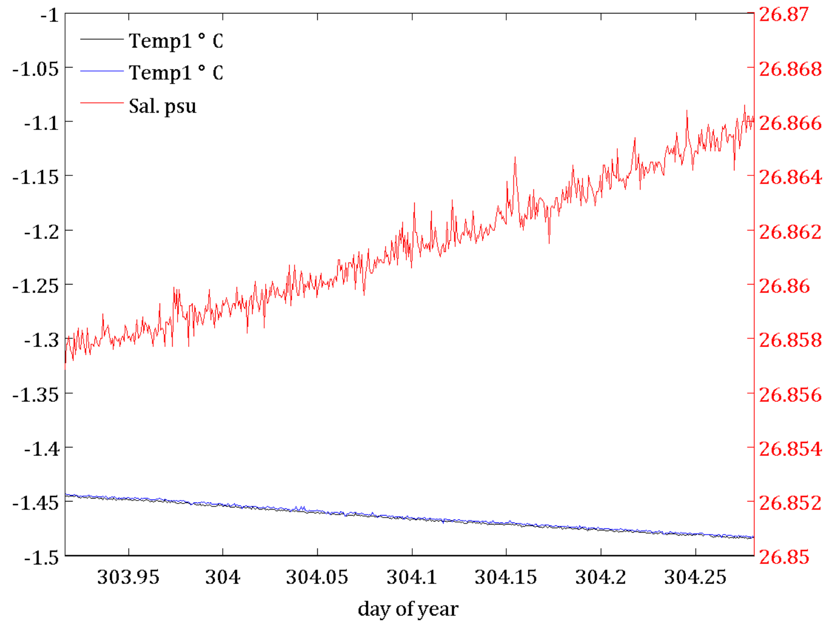
Convective turbulence model



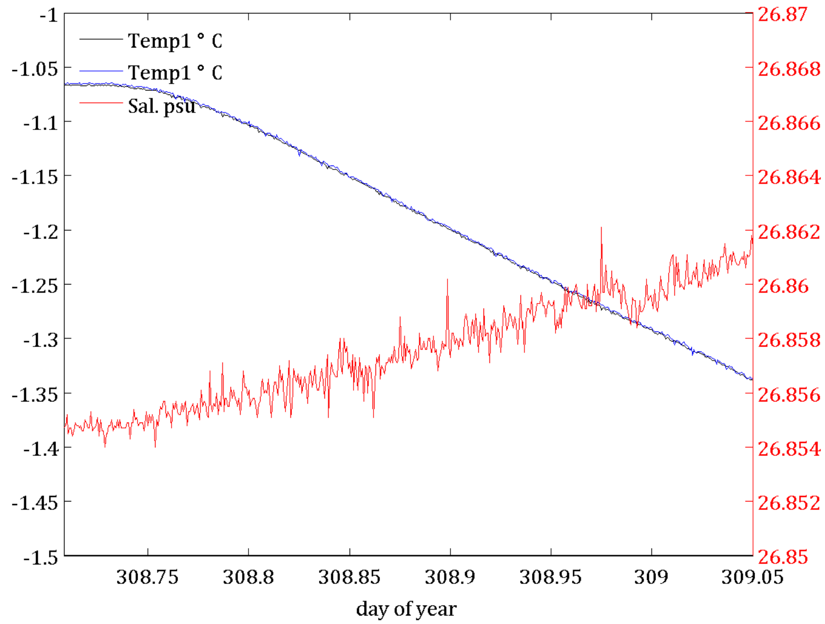
$$\varepsilon = (0.58 \cdot \text{Buoyancy} + 1.76 \cdot \text{Shear})$$

Buoyancy losses and convection

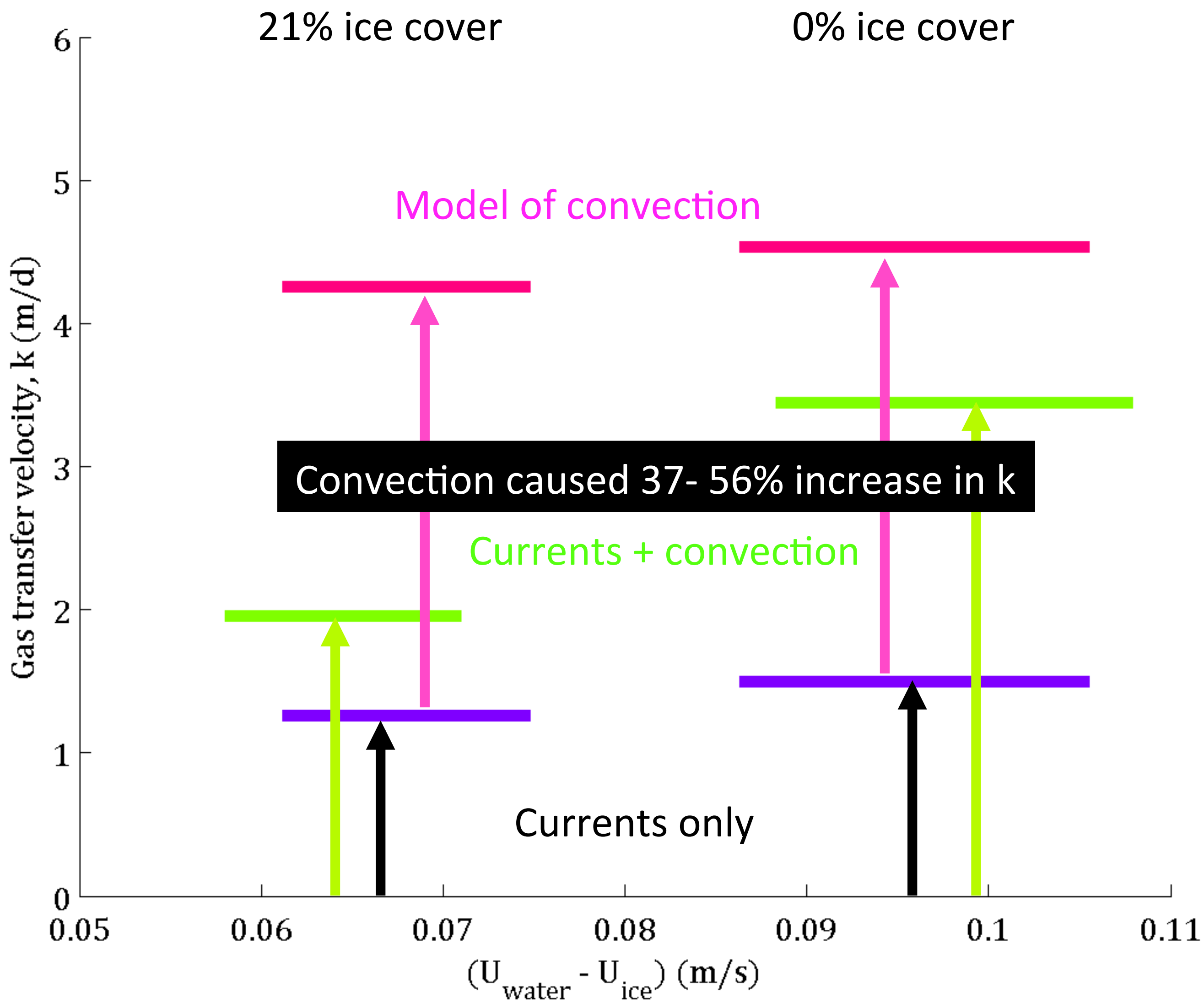
Ice cover = 21 %



Ice cover = 0 %

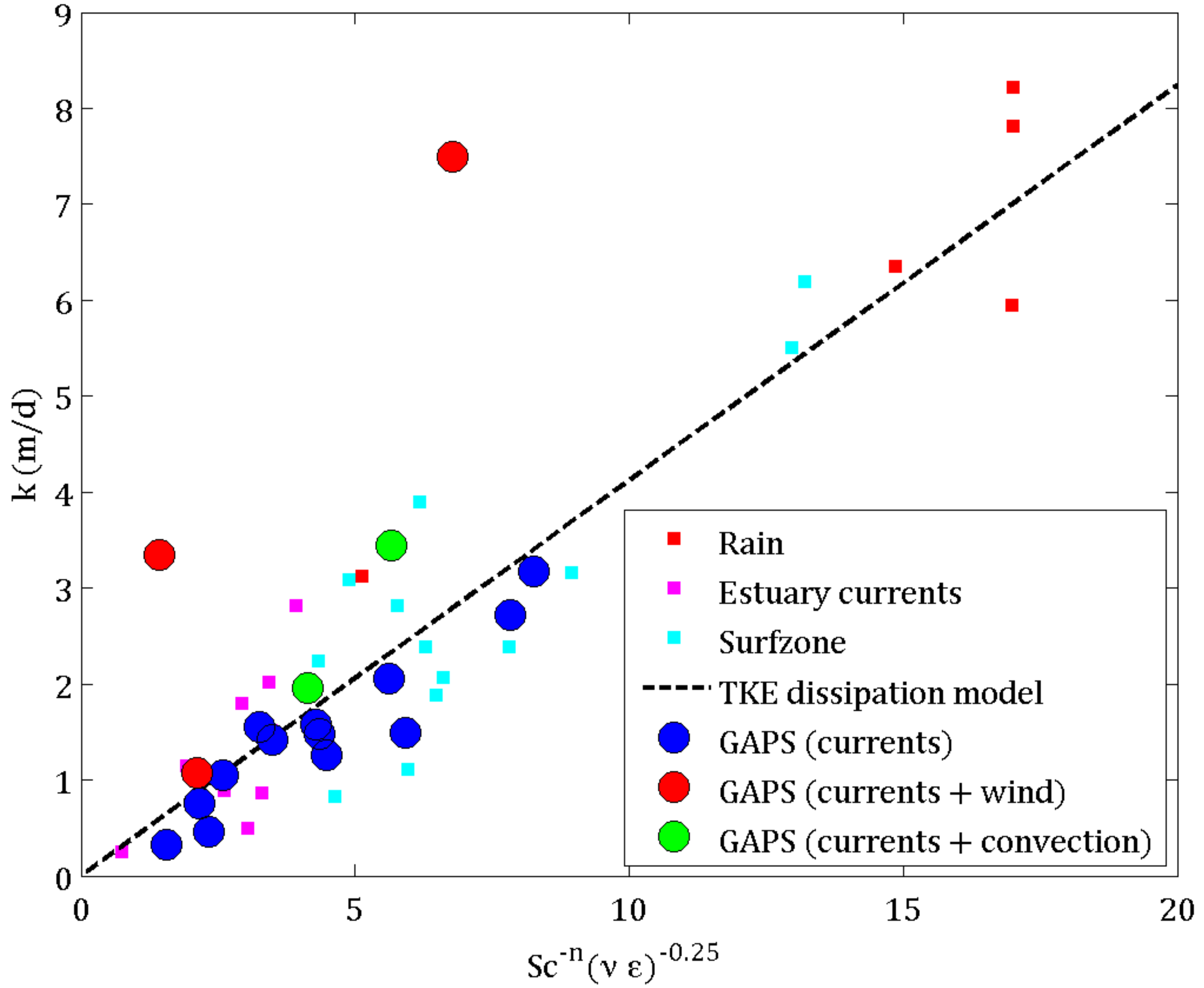


Buoyancy losses and convection

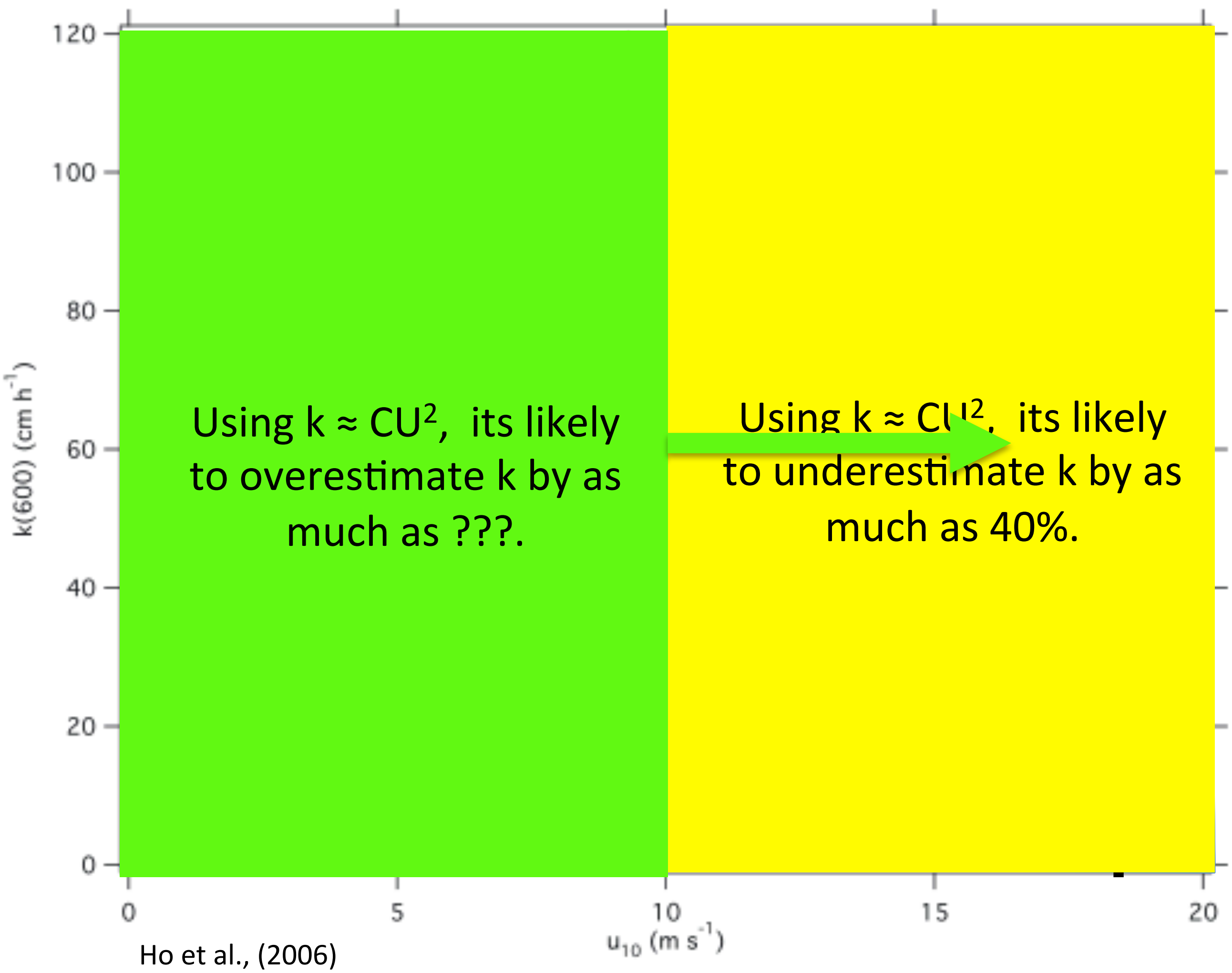


All processes in the turbulence model

Reproduced from Zappa et al., (2007)



Returning to gas exchange over open water



Ho et al., (2006)

Summary

1. Convection and Boundary-layer shear lead to gas exchange rates that are similar magnitude k as wind does (below 10 m/s).

2. The turbulence from (1) is additive with wind in its effect on k.

3. We need a way to measure the wind wave spectrum in SIZ and correlate to gas exchange.

4. We need more direct measurements of gas transfer velocity in the sea ice zone that correlate the magnitude with the processes.

5. Matlab code available at: http://looselab.gso.uri.edu/?p=183

Acknowledgements

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

2. GAPS Collaborators: Peter Schlosser, Don Perovich, Wade McGillis Chris Zappa, Leonard Zabilansky, Scott Brown, Diana Hsueh, and Tom Morrell.