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)


Arrigo et al., (2010)
Subduction and Shelf-Basin Interactions in the Arctic Ocean

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

Steele et al., (1995)
Polynyas, deep convection and CO$_2$ ventilation

Anderson et. al., 2009
Natural CO$_2$ ventilation in the S.O.
Polynyas, deep convection and CO$_2$ ventilation

de Lavergne et al., (2014)
Seasonal forcing in a DIC transport model

Loose and Schlosser (2011)

$C = \text{Dissolved inorganic carbon}$

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)
Timing of ice breakup and spring bloom

-45 days: peak $F_{CO_2}$ is reduced by 27%

Net annual $F_{CO_2}$:
-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.
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

$\kappa \propto 2U$

waves and bubbles

wind

Ho et al., (2006)
Gas transport pathways in the ice pack

\[ k = \text{gas transfer velocity (L/t)} \]

\[ D = \text{gas diffusivity (L}^2/\text{t)} \]

We don’t know...

Air-sea flux, \( F(k) \)

Diffusive flux, \( F(D) \)

Circumpolar Deep Water (CDW)

- Temp \( \sim 1.5^\circ\text{C} \)
- pCO2 \( \sim 650 \mu\text{atm} \)
- \( ^3\text{He} \sim 8 \% \)
- CFC \( \sim 0 \text{ ppt} \)

modified from Smethie & Jacobs, 2005
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?

\[ F = k_{\text{eff}} \Delta C \]

\[ k_{\text{eff}} = (1-f)k_{\text{ice}} + (f)k \]

\[ k_{\text{eff}} = (f)k \]

$f$ is the fraction of open water
How to model $k$ in the ice pack?

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

Viscosity  Molecular diffusivity  Turbulence dissipation

Lamont and Scott (1974)

Zappa et al., (2007)
How to model $k$ in the ice pack?

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

- Ice/water current
- Wind-driven shear
- Buoyant convection/stratification
Ice drag on the Ice-ocean boundary layer

\[
\tau = (1 - f)(\tau_{\text{skin-iw}} + \tau_{\text{form}}) + (f)(\tau_{\text{skin-aw}})(1 - W)
\]

Steele et al., (1995)
Ice melt increases ice-water relative velocity

McPhee (2010)
Water-ice relative velocities \((U_{\text{ice}} - U_{\text{water}})\)

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

- $J_{bo} = \text{Surface buoyancy flux (W/kg)}$.

- $(f)$ and $(1-f)$ weight the open water and ice covered flux terms, respectively.

\[
J_{b0} = -\frac{g\alpha}{\rho c_p} (J^{SH}_q + J^{LH}_q)(f) - J^{ice}_b (1 - f) + g\beta (E - P)S_0 (f)
\]
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 \((U_{\text{ice}} - U_{\text{water}})\)
Steady state velocity field in experiment tank

Channel Velocity = 0.16 m/s
Comparison of velocity: model vs. measure
Shear-driven turbulence leads to $k$
No relationship between $k$ and ice cover

![Graph showing relationship between gas transfer velocity and fraction of open water](image)

- Wind + Currents
- Currents only

Gas transfer velocity, $k$ (m/d)

Fraction of open water ($f$)
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

Model of convection

Convection caused 37-56% increase in k

Currents only

Currents + convection

21% ice cover

0% ice cover
All processes in the turbulence model

Reproduced from Zappa et al., (2007)
Returning to gas exchange over open water

Using \( k \approx C U^2 \), it's likely to overestimate \( k \) by as much as ???.

Using \( k \approx C U^2 \), it's likely to underestimate \( k \) by as much as 40%.
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.

Acknowledgements

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