Air-Sea Gas Exchange at Ice Surfaces

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Wintertime CO$_2$ fluxes in an Arctic polynya using eddy covariance: Evidence for enhanced air-sea gas transfer during ice formation

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The processes highlighted in blue/red are those which likely have a direct effect on air-sea gas exchange.
\[ F = K \frac{dC}{dz} \]

\[ F = V \frac{dC}{dt} \]
role of surface films on $k$

$$\text{FLUX}_{\text{air-water}} = k [\Delta C]_{\text{air-water}}$$
gas exchange and freezing ice
freezing and k (Schmidt No.)

1 hour time series showing freezing

-2
-2

k [cm/hr]
k660 [cm/hr]
freezing and ice growth

\( f = 0 \) is no water

normalized \( k \) versus \( f \)

solid line equals 1:1

hatched line power law

\( k \) increases with increased mixing

Effects of freezing, growth, and ice cover on gas transport processes in laboratory seawater experiments

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wind wave tank in a freezer

100% open water

0% open water
k and ice growth
gas transfer velocity and open water

\[ k = H \frac{d \ln(\text{sat-c})}{dt} \]

- **uncorrected**
- **\( H = W - (1 - f) \) thickness**

![Graph showing gas transfer velocity vs. fraction open water](Image)
simulating ice chunks
3-Tracer estimate of $k$ ($\text{He, O}_2, \text{SF}_6$) for gas transfer and ice-water segregation.

Boundary layer $\text{CO}_2$ fluxes in the air boundary layer, CFT IR imaging

Determination turbulent dissipation ($\varepsilon$) in presence of wind, surface waves, brine drainage, and heat-driven convection

Surface area descriptions and gas transfer with an IR camera

$$\varepsilon = u_*^2 \frac{\partial u}{\partial z} + b'w'$$
wind tunnel complete
wind tunnel with no ocean
2 sonic anemometers
2 RH/T
2 Picarro/Licors
(CO$_2$/H$_2$O)
CO$_2$, N2O, SF6, He, Ar
Micrometeorological Approach

- Direct covariance and measured gradients in temp, water vapor, CO$_2$, and windspeed. Boundary layer gradients are measured at one fixed-elevation reference and one profiling, the gradients are then calculated by difference.

Surface Boundary Layer Exchange

\[ \frac{\partial c}{\partial t} + \nabla_h c \cdot \vec{U}_h = - \frac{\partial}{\partial z} \left( - D_c \frac{\partial c}{\partial z} + \langle w'c' \rangle \right) + Q_c \]

\[ \frac{\partial c}{\partial z} = - \frac{\langle w'c' \rangle}{u_* \kappa_z} \Phi_c \left( \frac{z}{L} \right) \]

**momentum**

\[ \tau = - \rho \overline{wu} = \rho u_*^2 = \rho C_D (U_a - U_s)^2 \]

\[ \frac{k_z}{u_*} \frac{\partial U}{\partial z} = \varphi_M(\zeta) \]

**sensible**

\[ H = \rho c_p \overline{w\theta} = - \rho c_p u_* \theta_* = \rho c_p UC_H (T_s - T_a) \]

\[ \frac{k_z}{\theta_*} \frac{\partial T}{\partial z} = \varphi_H(\zeta) \]

**latent**

\[ E = \rho L_E \overline{wq} = - \rho L_E u_* q_* = \rho L_E UC_E (Q_s - Q_a) \]

\[ \frac{k_z}{q_*} \frac{\partial Q}{\partial z} = \varphi_Q(\zeta) \]

**gas**

\[ F = \overline{wc} = - u_* c_* = UC_G (C_w - C_a) = k \Delta C \]

\[ \frac{k_z}{c_*} \frac{\partial C}{\partial z} = \varphi_G(\zeta) \]

Direct covariance | K-theory profiles | bulk methods
yearday 2012

W/m²
Gas Exchange in ICE lead (GAPS)

Wind [m/s]

Gas Transfer Velocity [cm/hr]

- Pump 60
- Pump 40
- Pump 20
- Pump 5

Legend:
- 5p
- 20p
- 40p
- 60p
- Poly. (60p)
- Poly. (40p)
- Poly. (20p)
- Poly. (5p)
- wind, waves, and turbulence
- bubbles and spray
- chemical enhancement (including carbonic anhydrase)
- surfactants
- buoyancy and atmospheric stability
- rain and dilution
- evaporation, condensation, magnetic fields
“I didn’t see this one coming”
summary

- nucleation experiment - high solubility and low diffusivity
  - no incipient enhancement, low brine channel diffusion
- Ice cover not sufficient; freezing and ice floe
  - enhanced k and high mixing
    - relating k to ice cover
  - holistic to prognostic modeling
- continue to explore role of scale, seawater, temperature on k-ice
surface ice
fresh water crystals
seawater crystals
Using the annular wind wave tank we used for 1990’s surfactant studies
gas transfer and ice
LATENT HEAT FLUX