Air-Sea Gas Exchange at Ice Surfaces

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gas transfer controls through ice pack

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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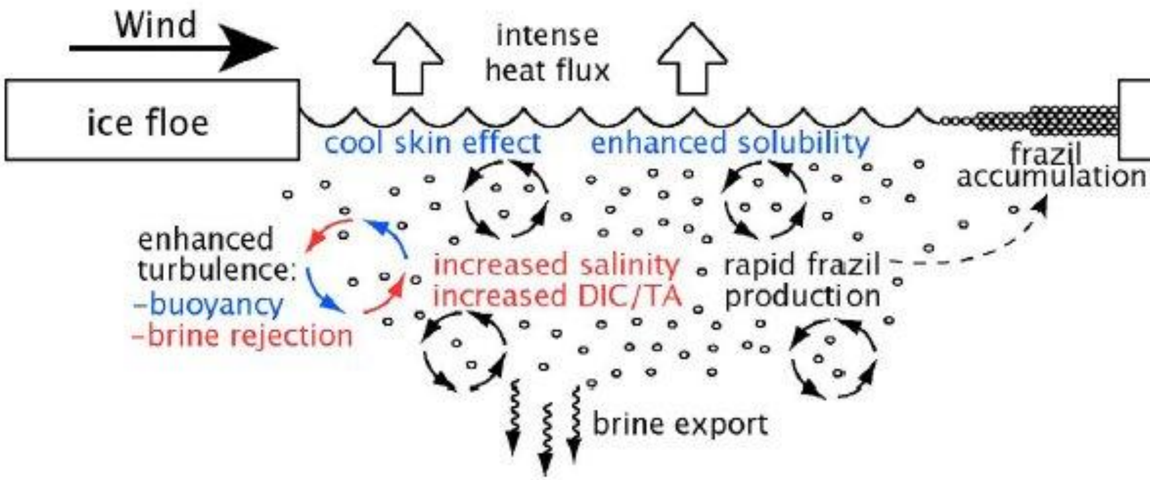
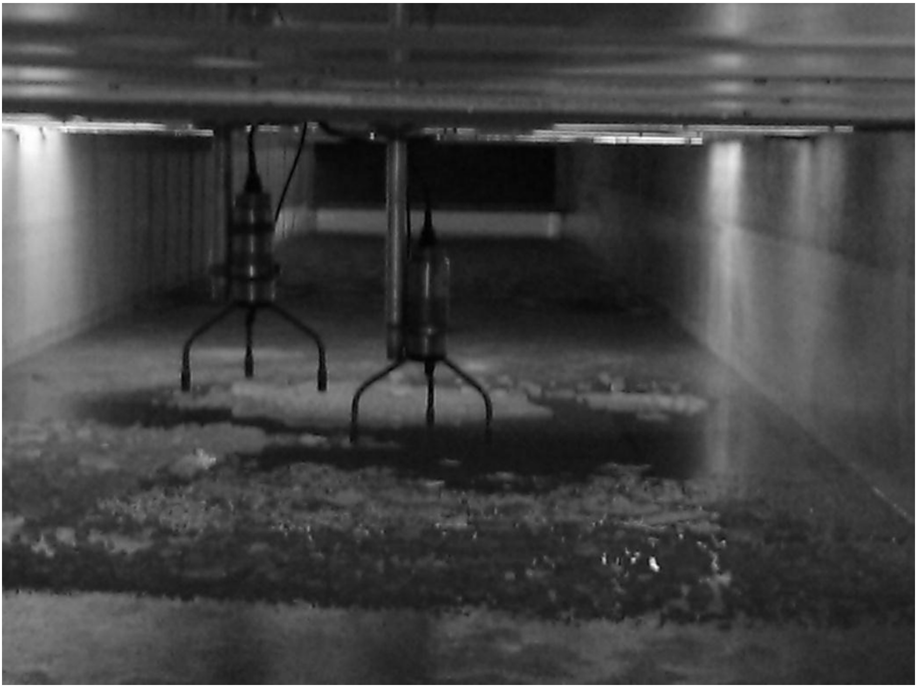
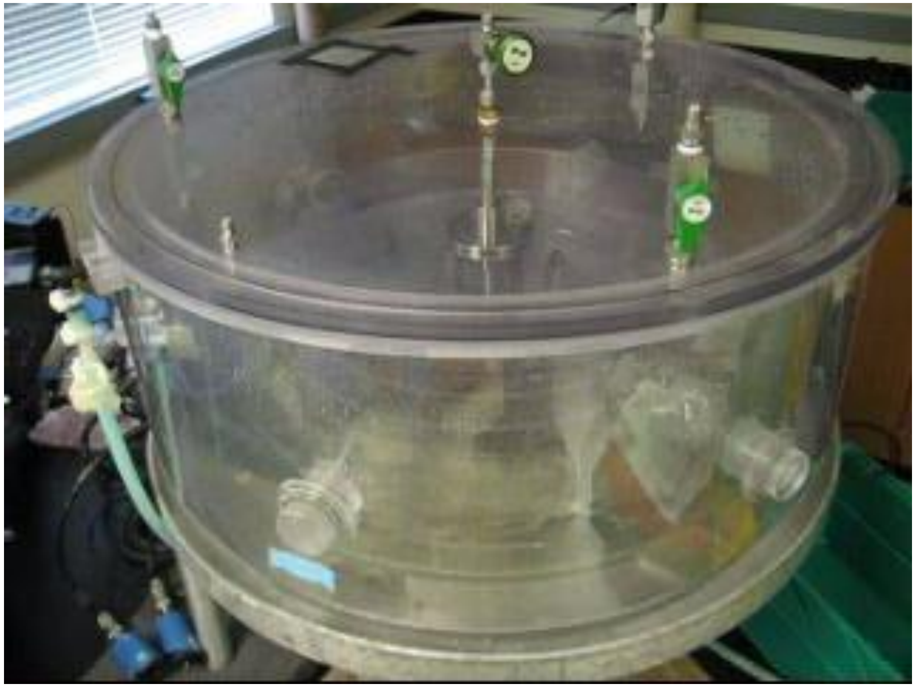


The processes highlighted in blue/red are those which likely have a direct effect on air-sea gas exchange.



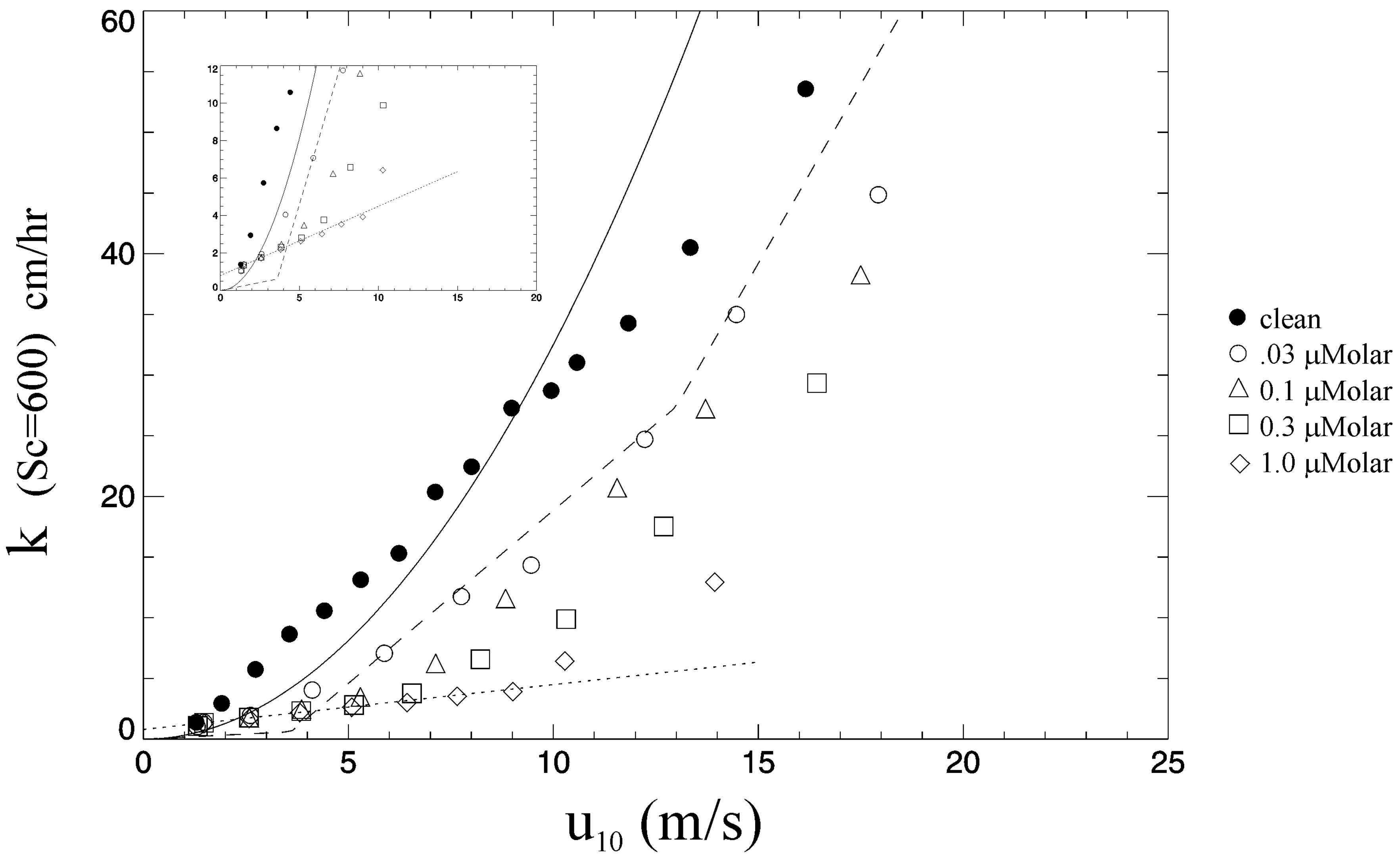
$$F = V\frac{dC}{dt}$$

$$F = K\frac{dC}{dz}$$

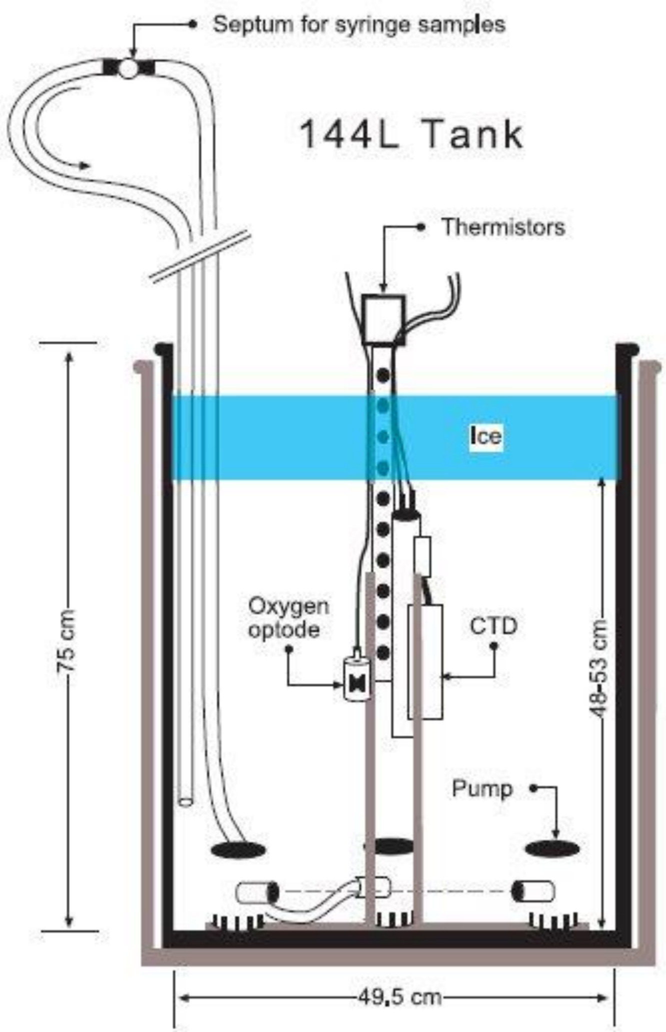


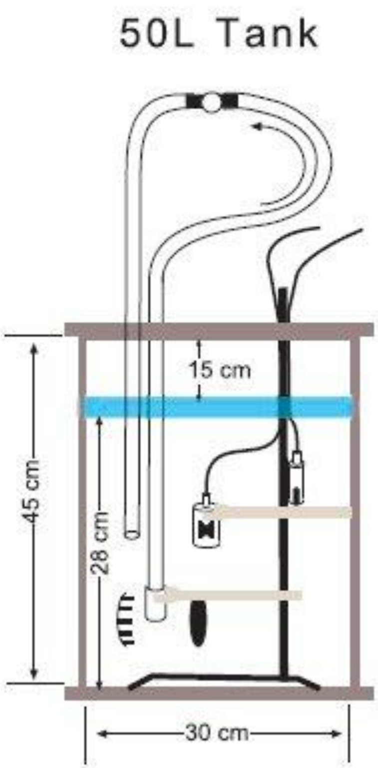
role of surface films on k

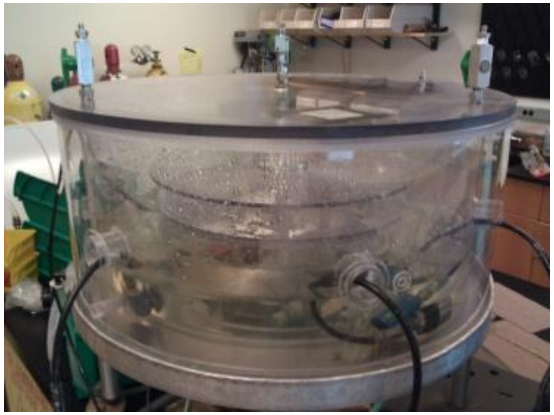
$$FLUX_{air\text{-}water} = k\,[\Delta C]_{air\text{-}water}$$



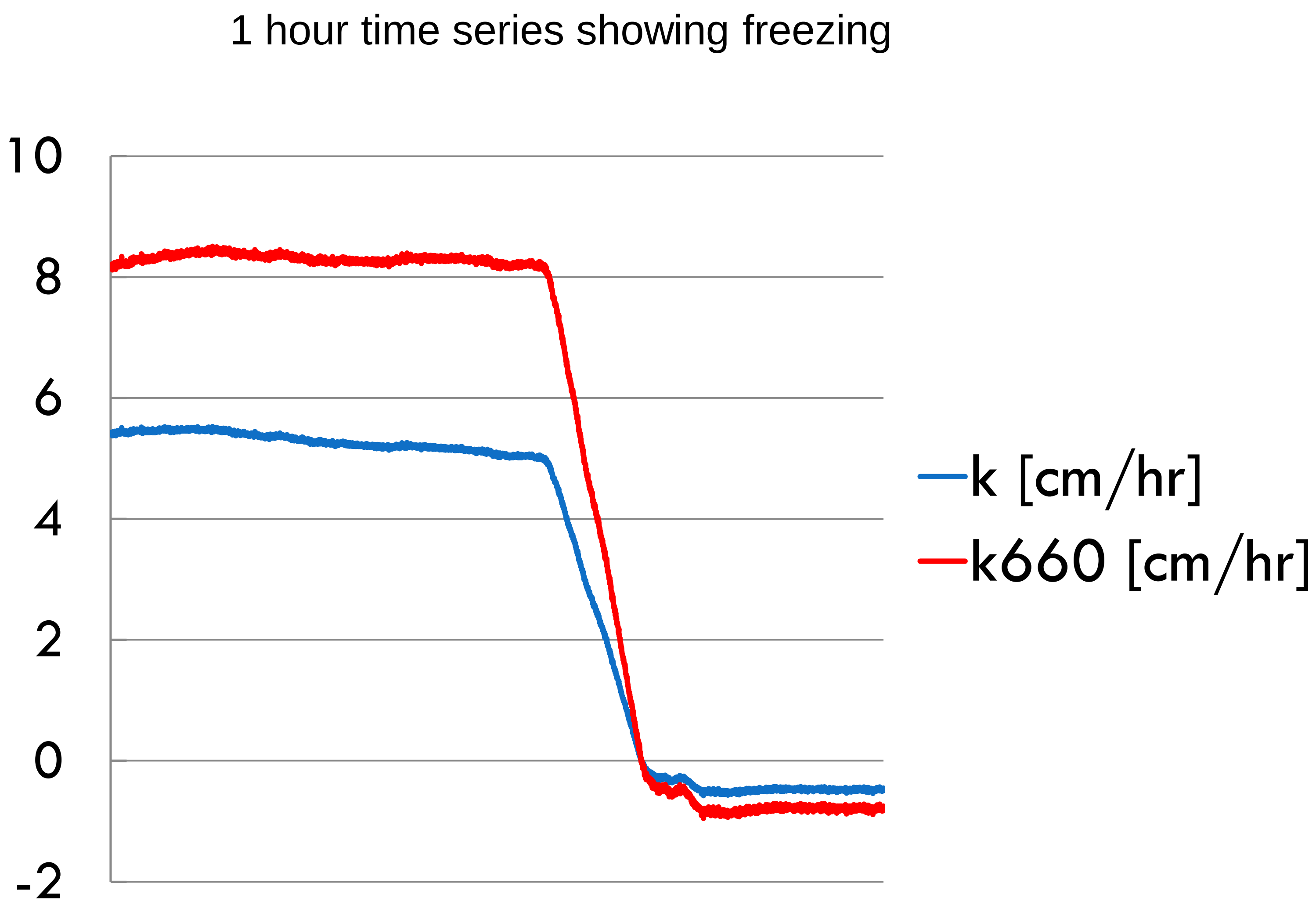
gas exchange and freezing ice



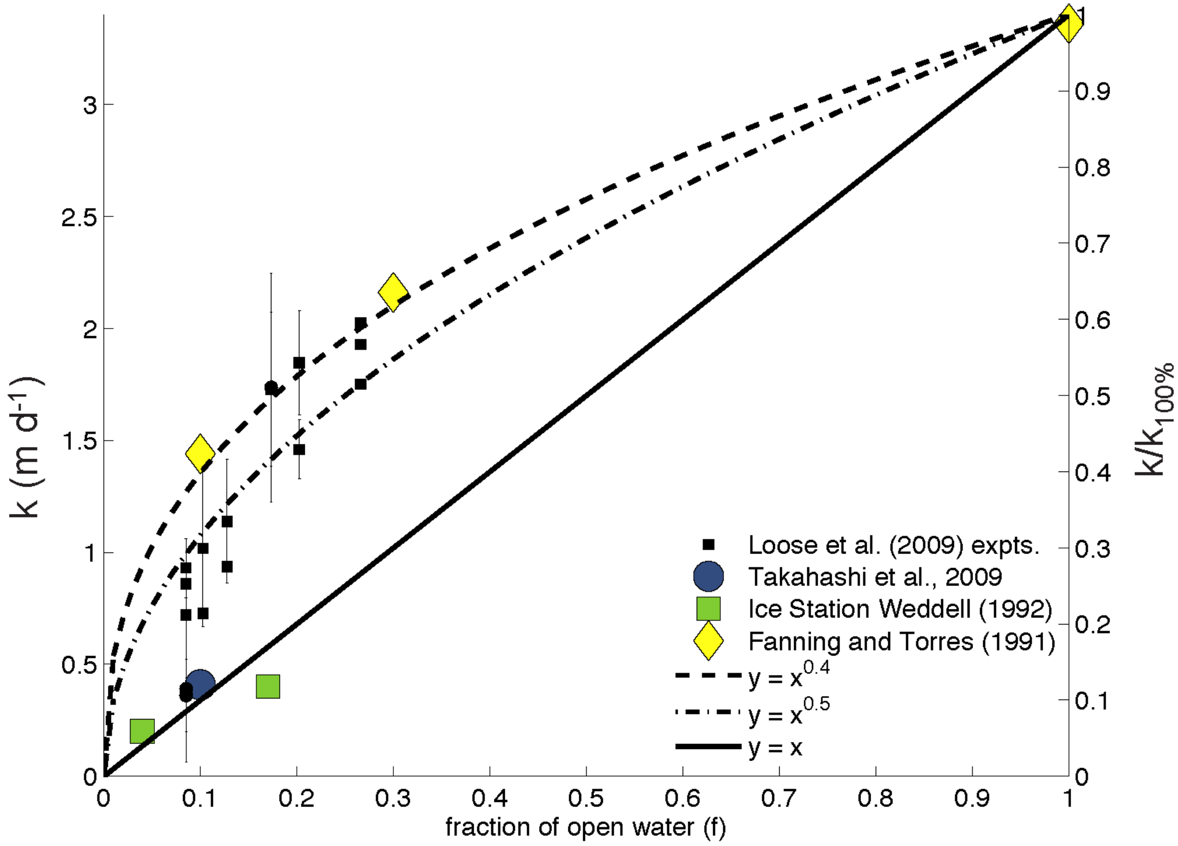




freezing and k (Schmidt No.)



freezing and ice growth



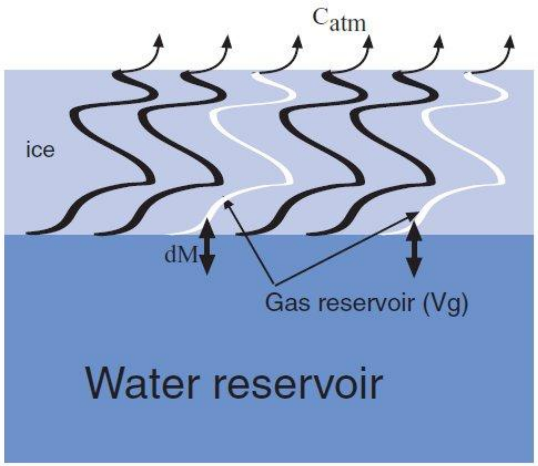
f = 0 is no water

normalized k versus *f*

solid line equals 1:1

hatched line power law

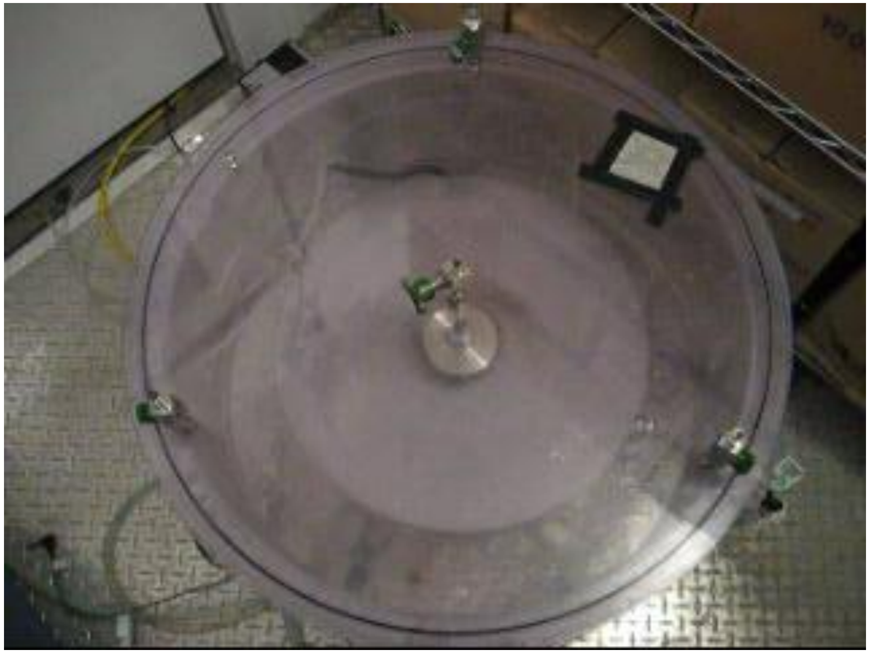
k increases with increased mixing



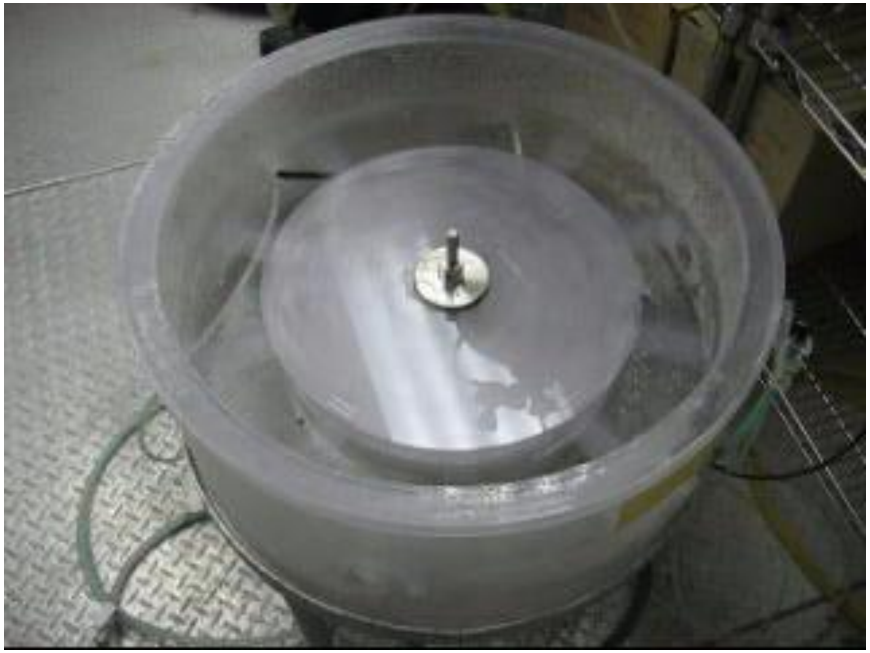
Effects of freezing, growth, and ice cover on gas transport processes in laboratory seawater experiments

B. Loose,[1] W. R. McGillis,[1] P. Schlosser,[1] D. Perovich,[2] and T. Takahashi[1]

wind wave tank in a freezer

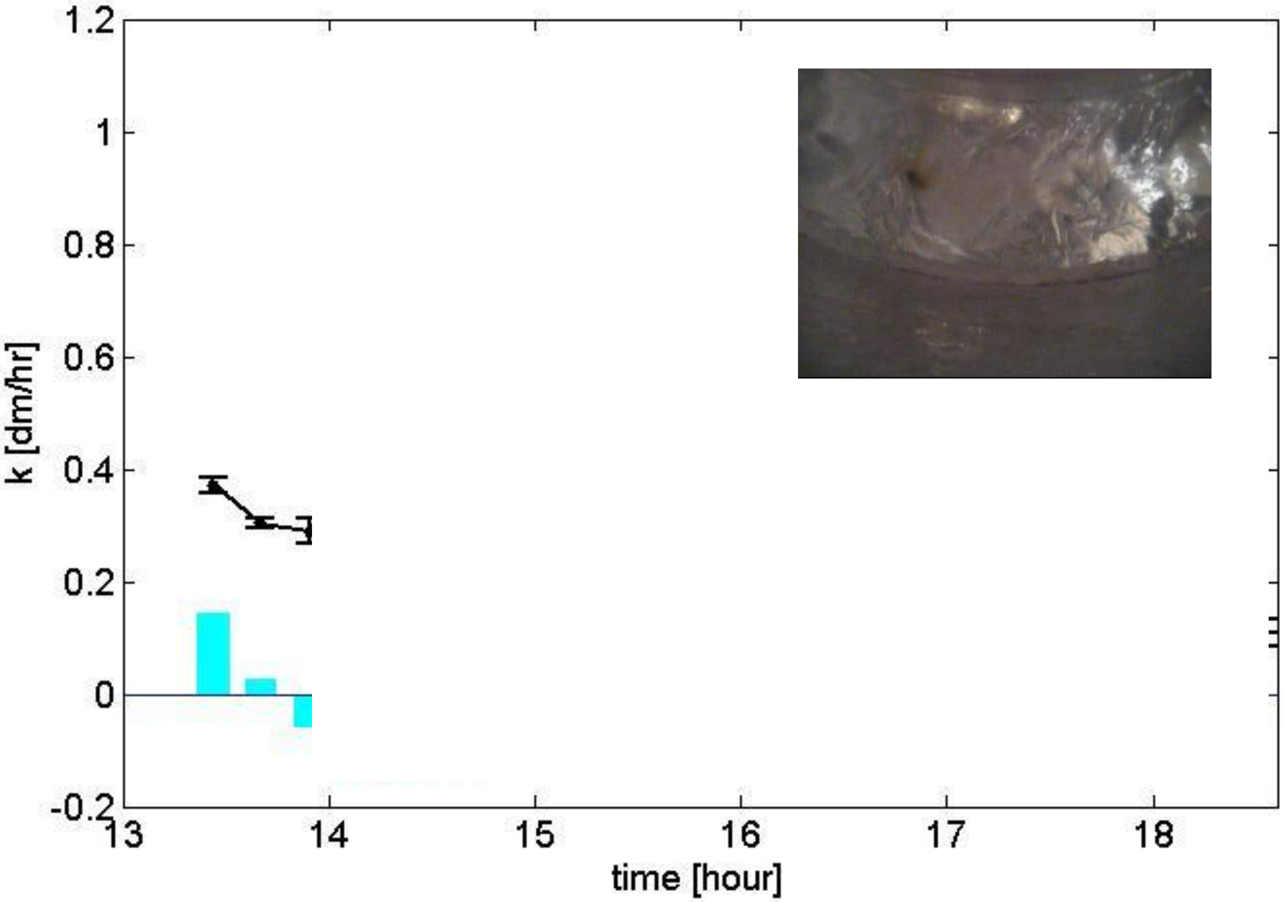


100% open water

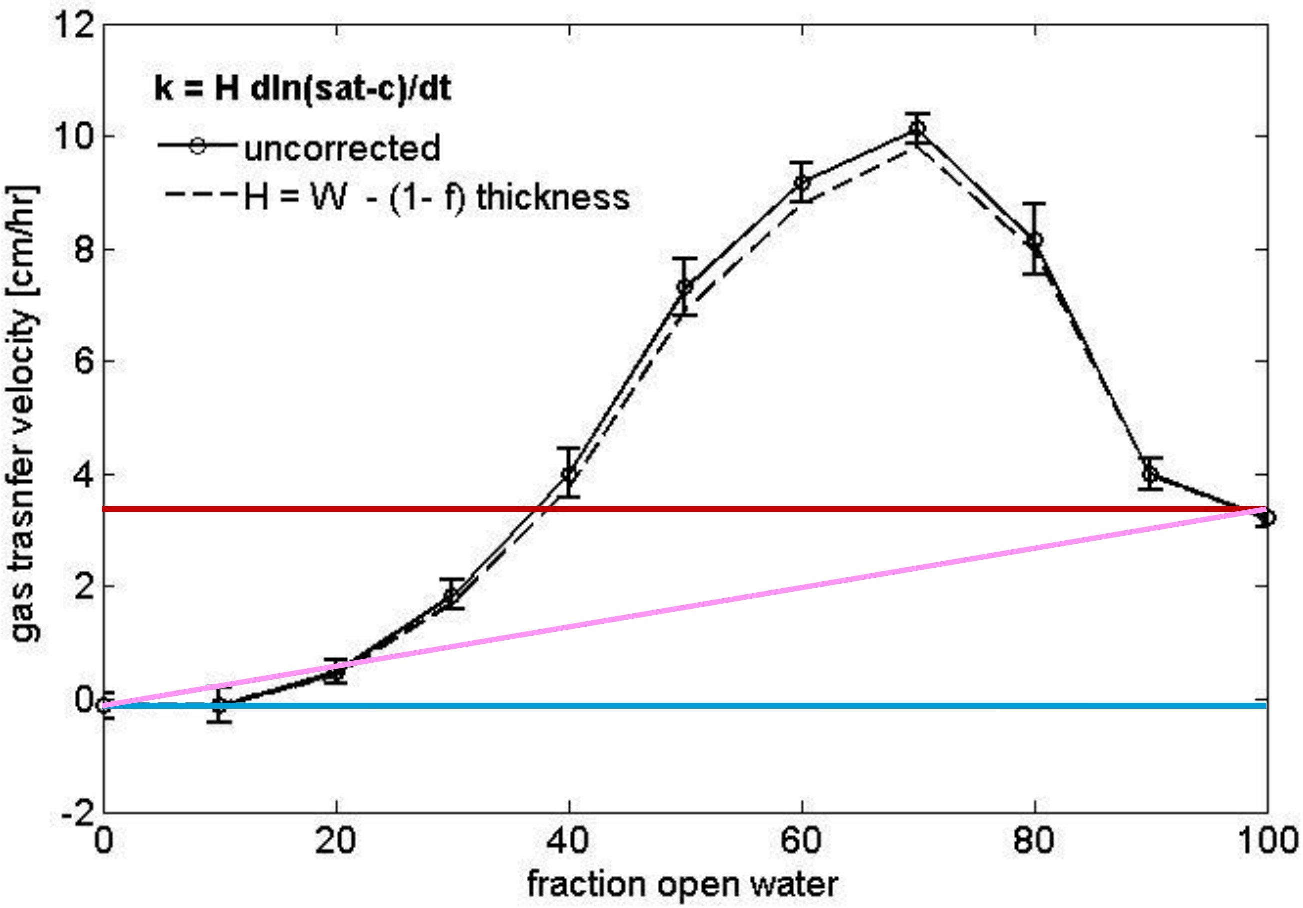


0% open water

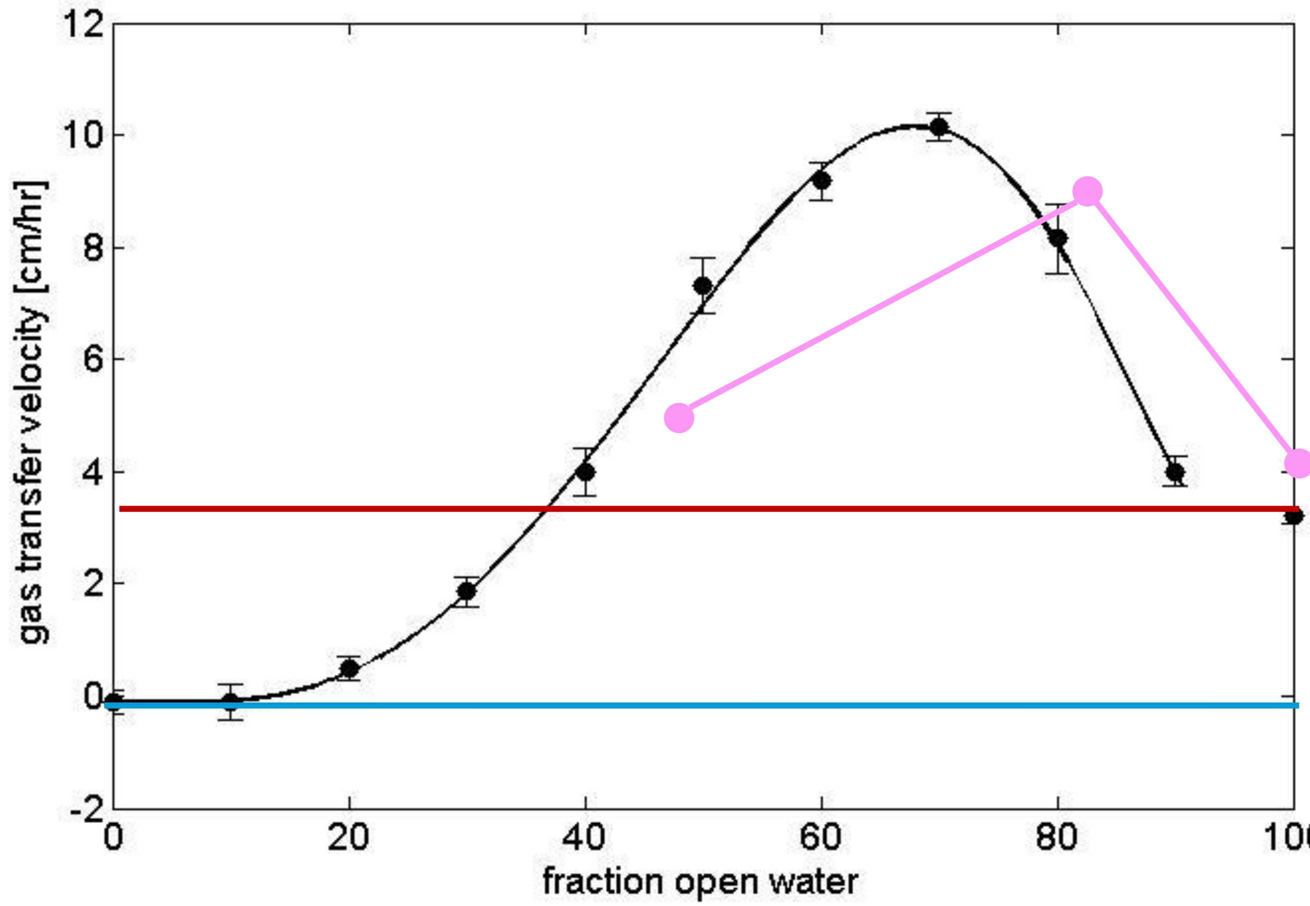
k and ice growth

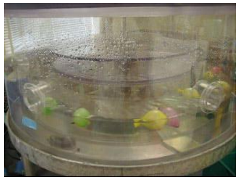


gas transfer velocity and open water

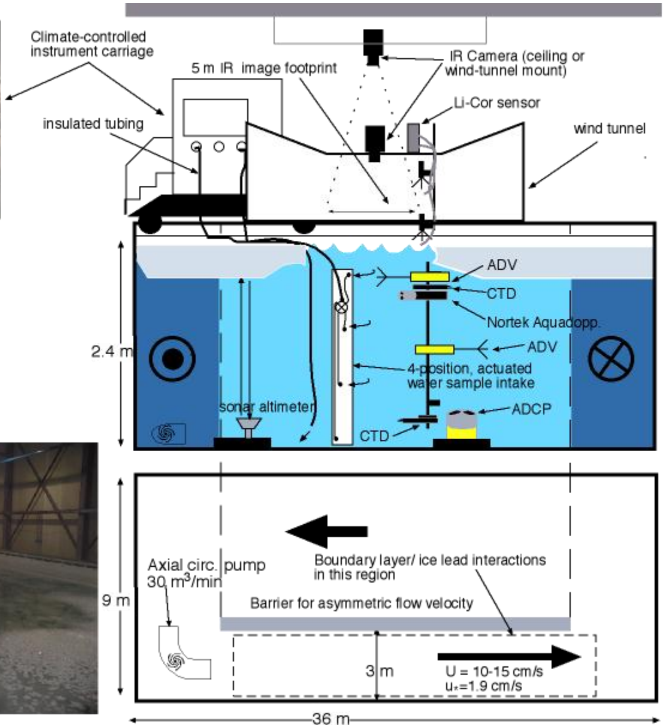


simulating ice chunks





laboratory scale: CRREL, NH

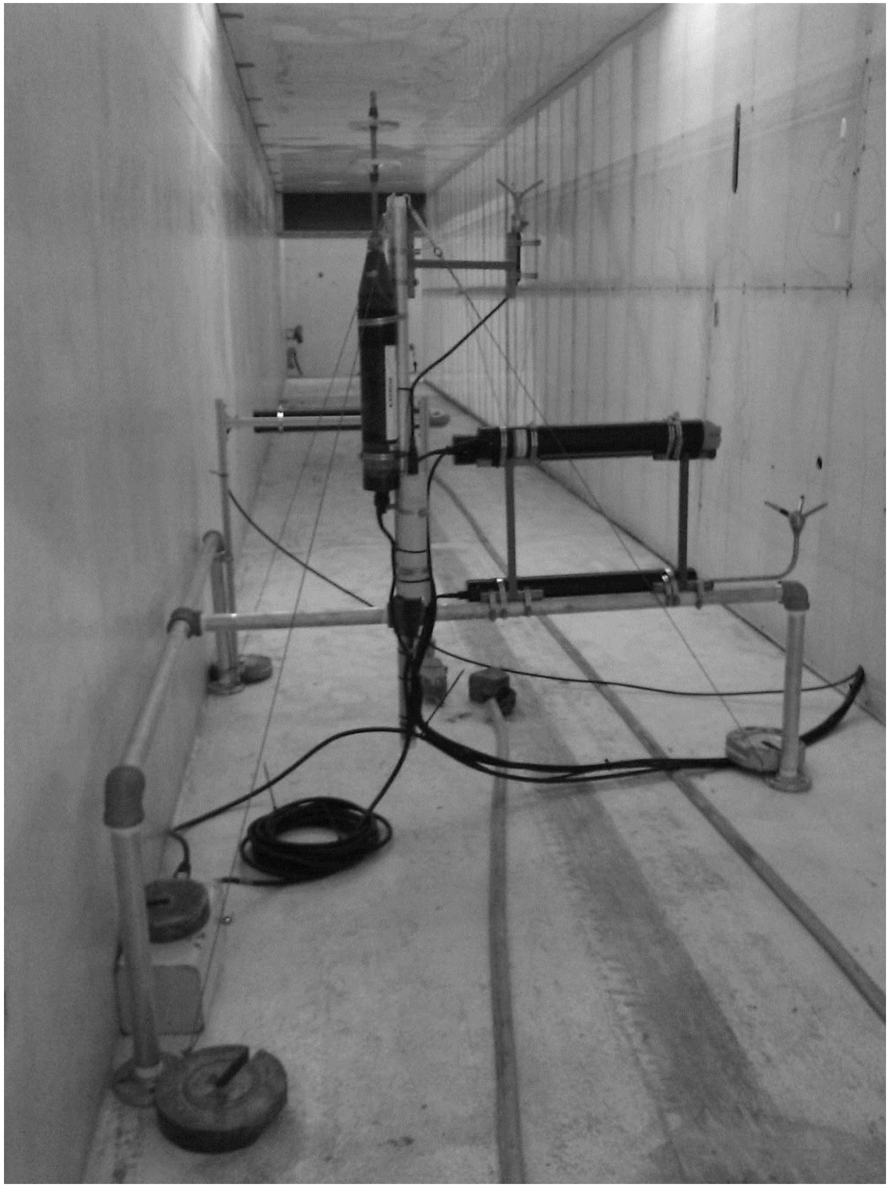


- 3-Tracer estimate of k (He, O_2, SF_6) for gas transfer and ice-water segregation.
- Boundary layer CO_2 fluxes in the air boundary layer, CFT IR imaging
- Determination turbulent dissipation (ε) in presence of wind, surface waves, brine drainage, and heat-driven convection
- Surface area descriptions and gas transfer with an IR camera

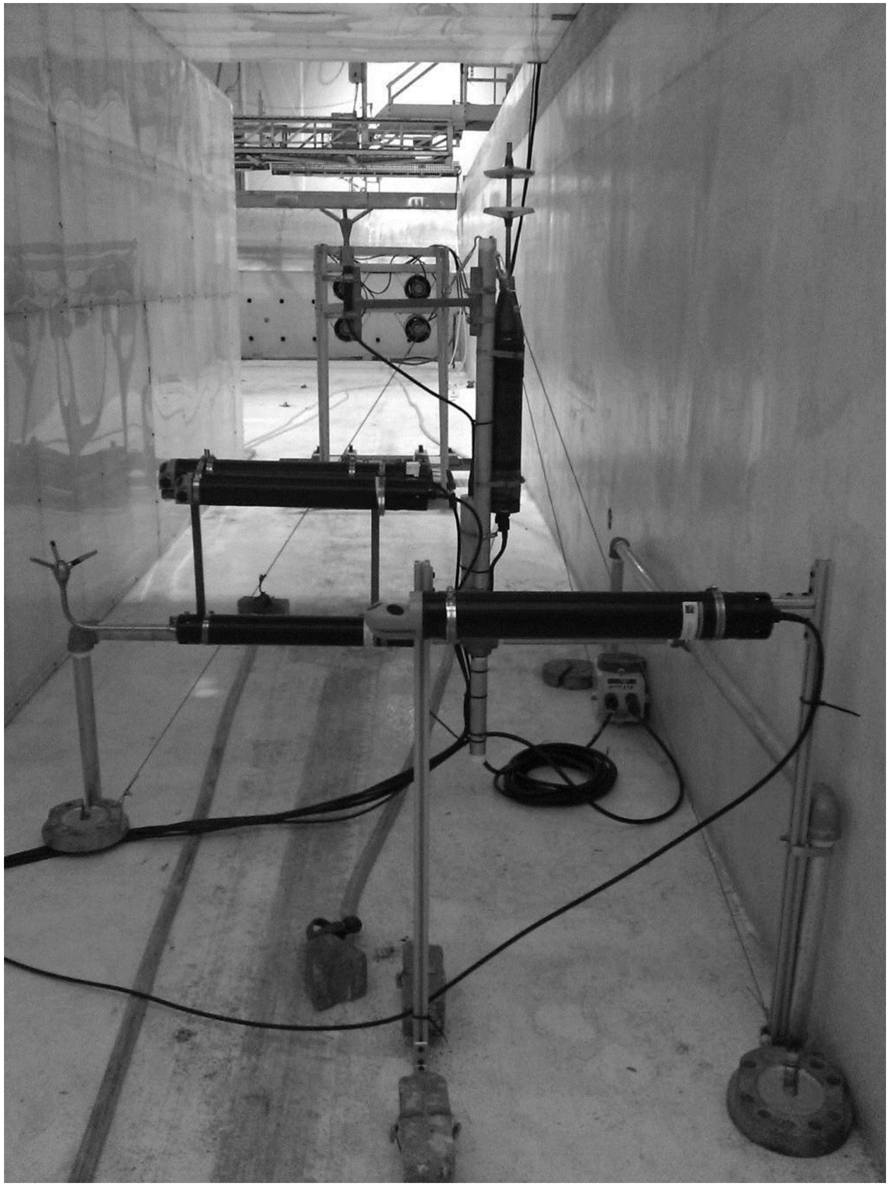
$$\varepsilon = u_*^{\,2}\frac{\partial \overline{u}}{\partial z} + \overline{b'w'}$$

wind tunnel complete

wind tunnel with no ocean

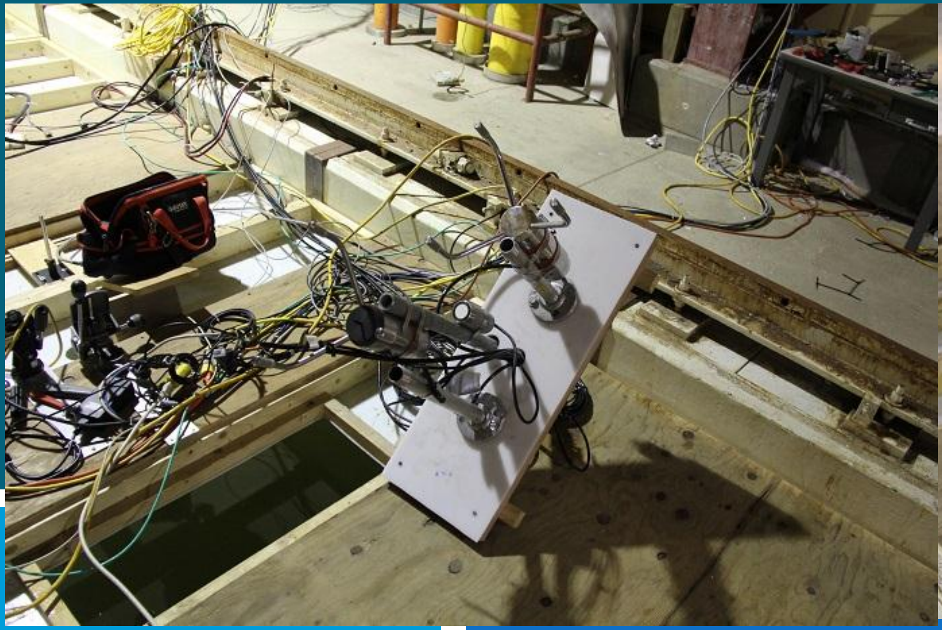


upstream

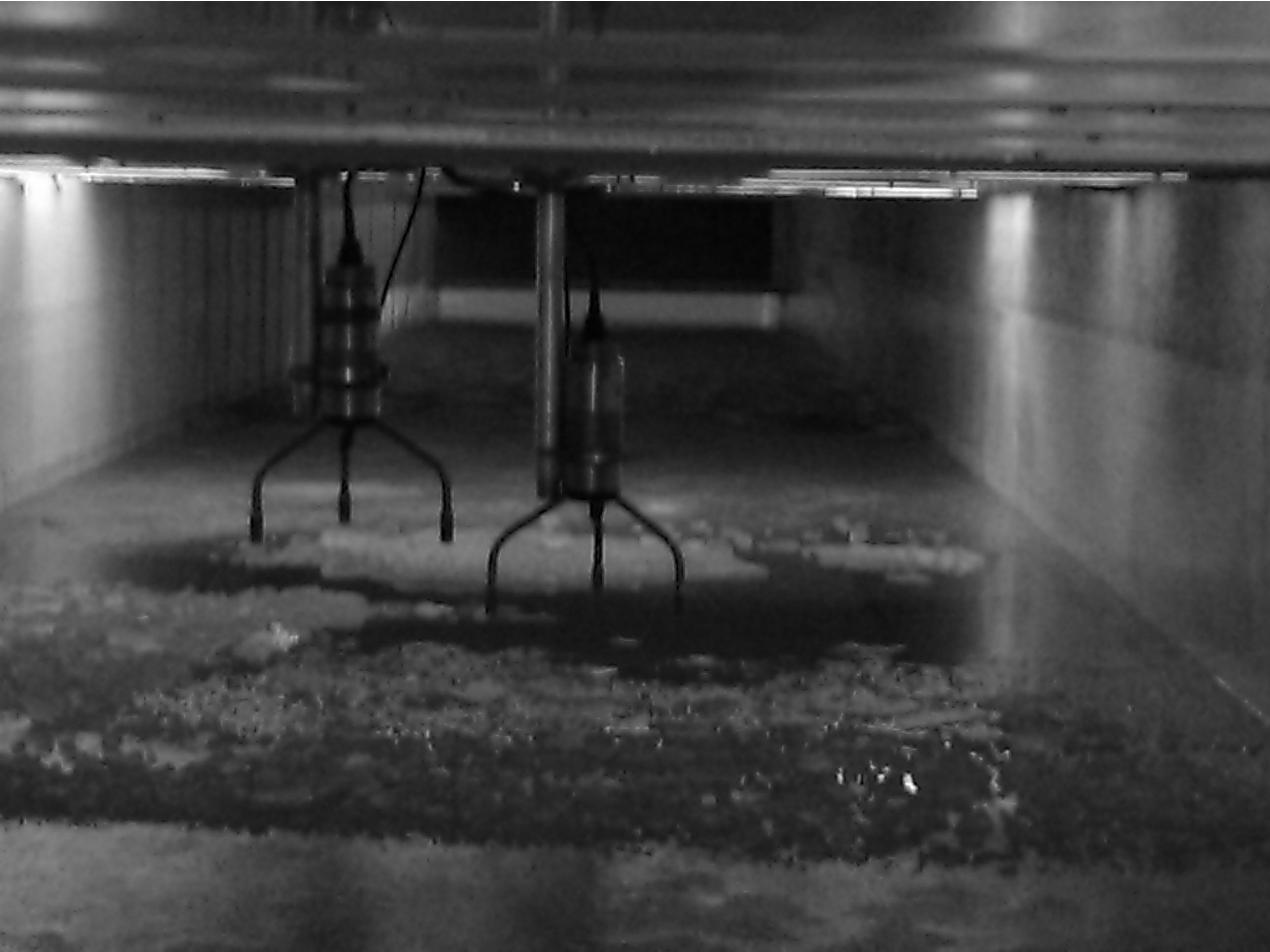


downstream

2 sonic anemometers
2 RH/T
2 Picarro/Licors
(CO_2/H_2O)



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

$$\frac{\partial c}{\partial t} + \vec{\nabla}_h c \cdot \vec{U}_h = -\frac{\partial\left(-D_c \partial c / \partial z + \langle w'c' \rangle\right)}{\partial z} + \overline{Q}_c \qquad \frac{\partial c}{\partial z} = -\frac{\langle w'c' \rangle}{u_* \kappa z} \Phi_c\left(\frac{z}{L}\right)$$

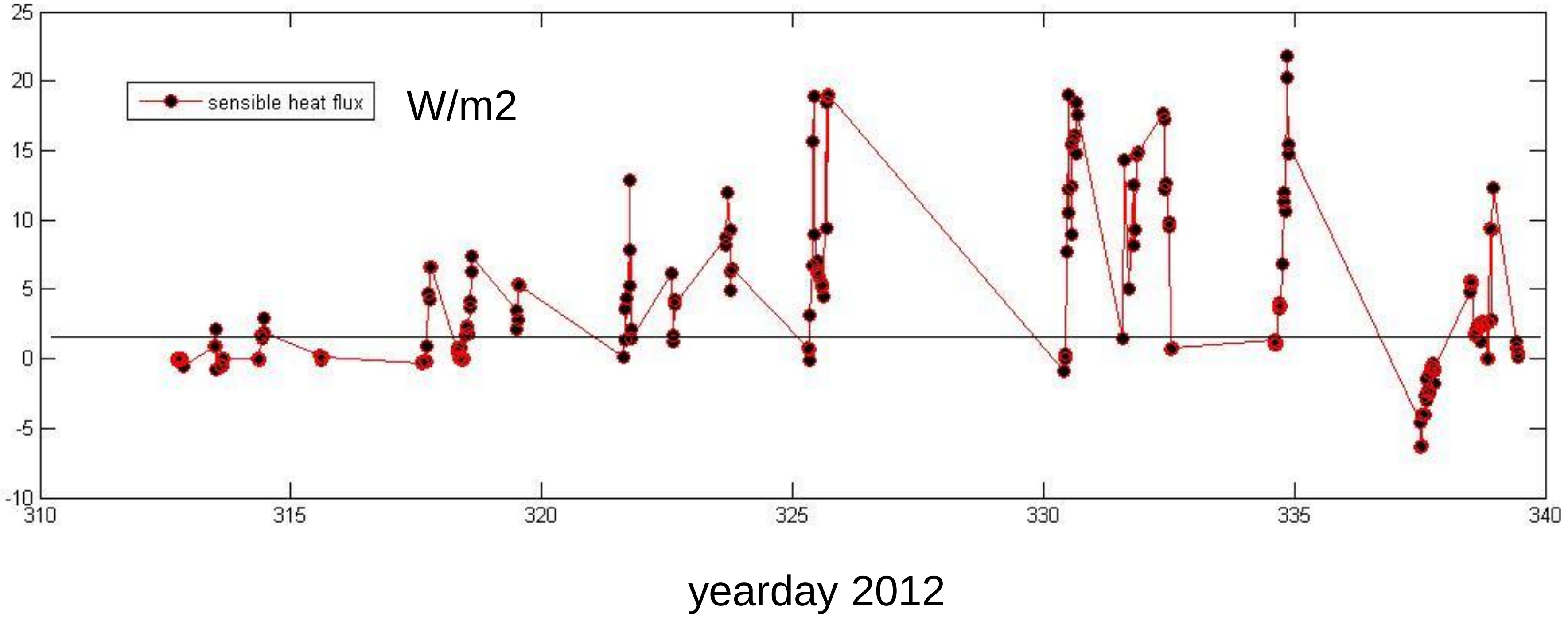
momentum $\quad \tau = -\rho \overline{wu} = \rho u_*^2 = \rho C_D (U_a - U_s)^2 \qquad \frac{\kappa z}{u_*}\frac{\partial U}{\partial z} = \varphi_M(\varsigma)$

sensible $\quad H = \rho c_p \overline{w\theta} = -\rho c_p u_* \theta_* = \rho c_p U C_H (T_s - T_a) \qquad \frac{\kappa z}{\theta_*}\frac{\partial T}{\partial z} = \varphi_H(\varsigma)$

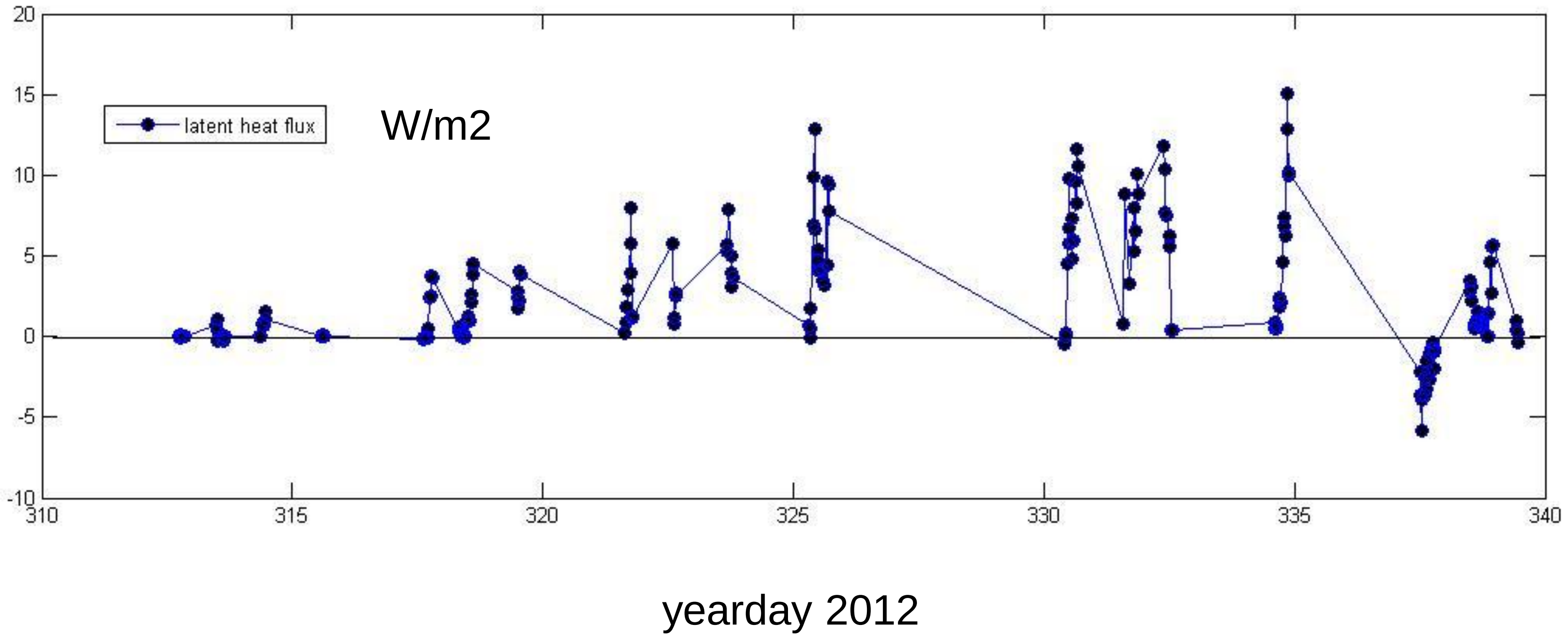
latent $\quad E = \rho L_E \overline{wq} = -\rho L_E u_* q_* = \rho L_E U C_E (Q_s - Q_a) \qquad \frac{\kappa z}{q_*}\frac{\partial Q}{\partial z} = \varphi_Q(\varsigma)$

gas $\quad F = \overline{wc} = -u_* c_* = U C_G (C_w - C_a) = k\,\Delta C \qquad \frac{\kappa z}{c_*}\frac{\partial C}{\partial z} = \varphi_G(\varsigma)$

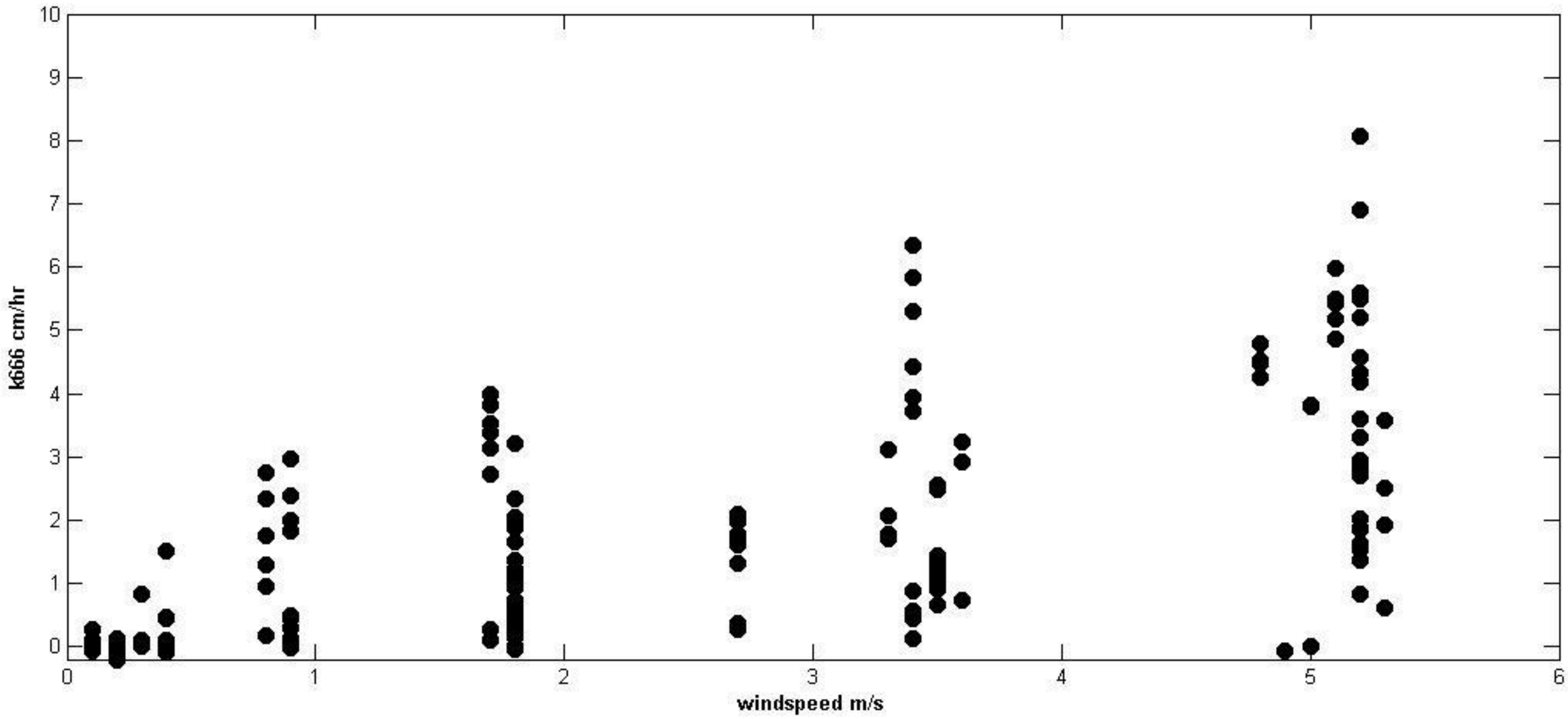
direct covariance ↑ $\qquad$ ↑ K-theory profiles $\qquad$ ↑ bulk methods

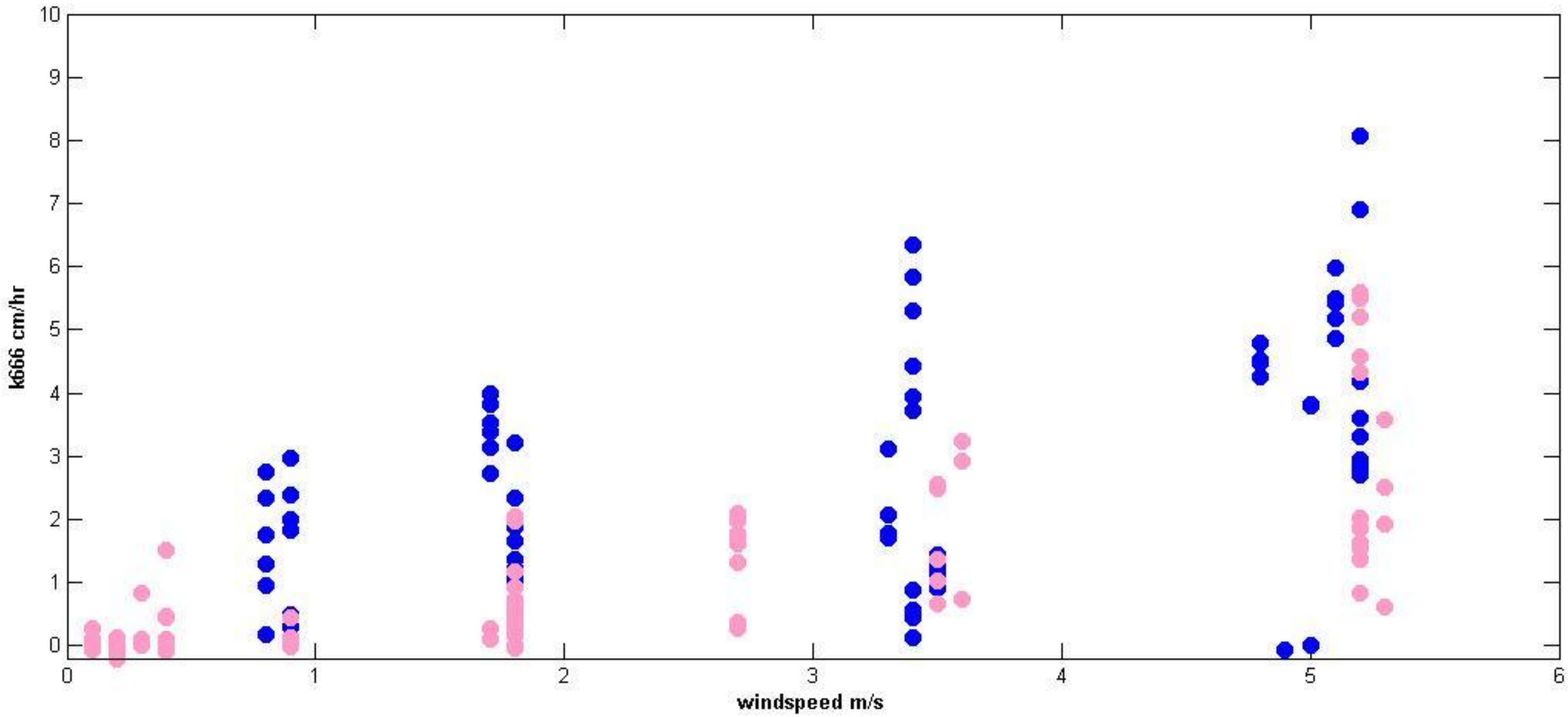


sensible heat flux
W/m2
yearday 2012



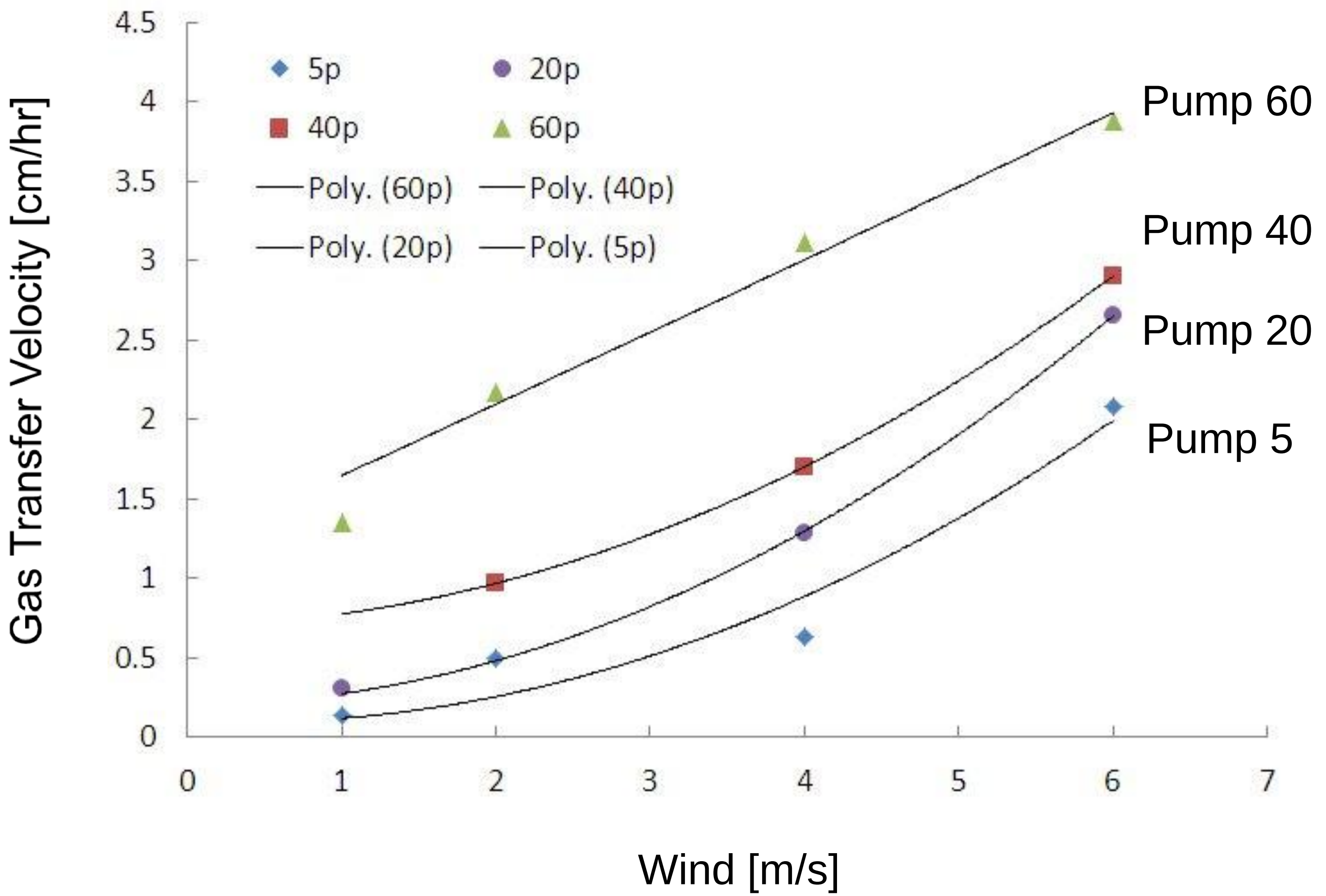
20
15
10
5
0
-5
-10
latent heat flux
W/m2
310
315
320
325
330
335
340
yearday 2012

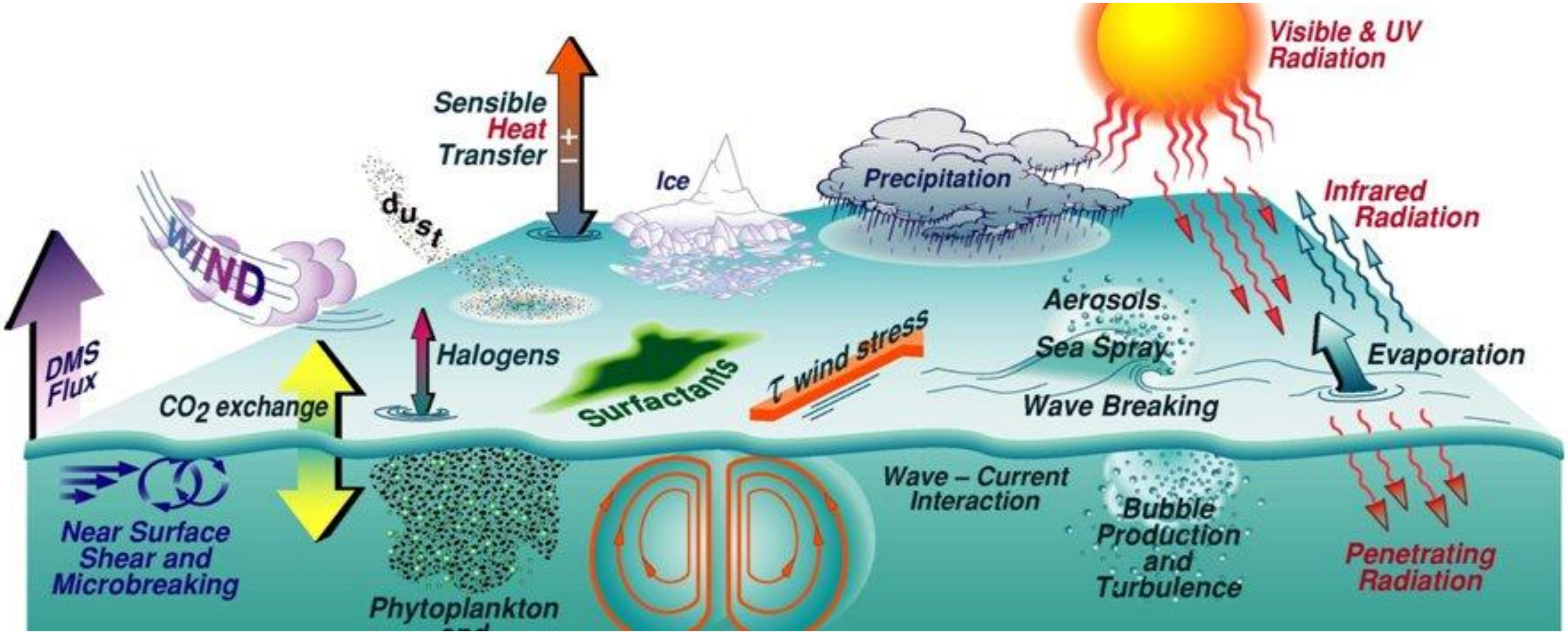

k666 cm/hr
windspeed m/s
0
1
2
3
4
5
6
7
8
9
10



10
9
8
7
6
5
4
3
2
1
0
k666 cm/hr
0
1
2
3
4
5
6
windspeed m/s

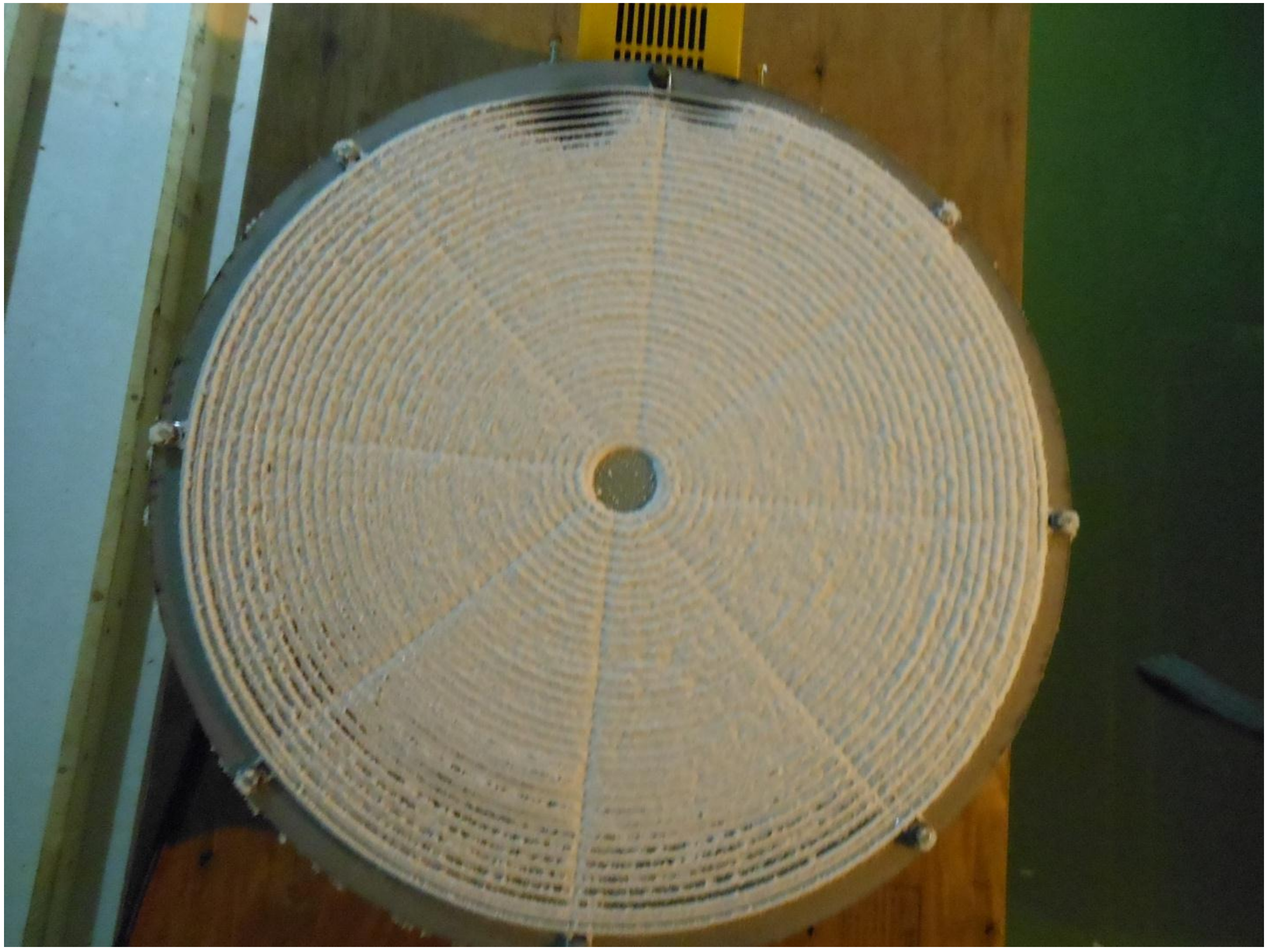
Gas Exchange in ICE lead (GAPS)





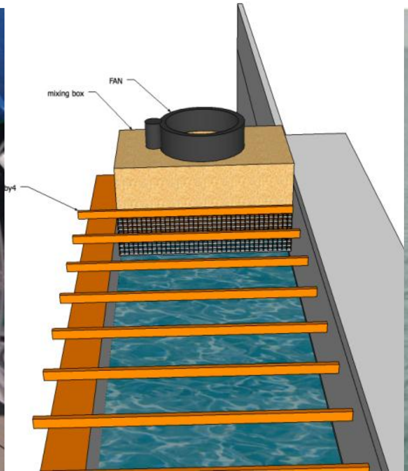
- wind, waves, and turbulence
- bubbles and spray
- chemical enhancement (including carbonic anhydrase)
- surfactants
- buoyancy and atmospheric stability
- rain and dilution
- evaporation, condensation, magnetic fields

“I didn’t see this one coming”



summary

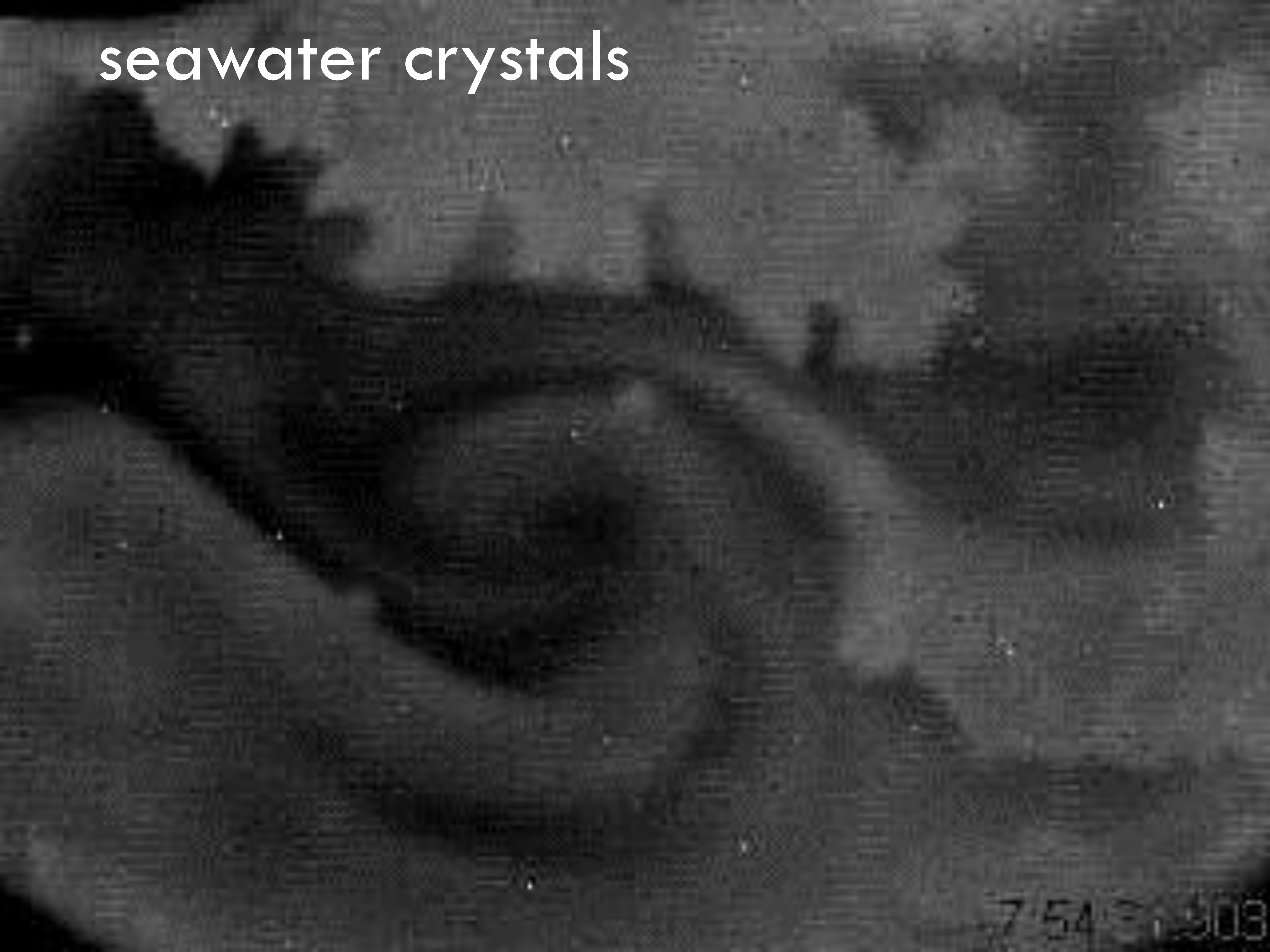
- nucleation experiment - high solubility and low diffusivity
  - no incipient enhancement, low brine channel diffusion
- Ice cover not sufficient; freezing and ice floe
  - enhanced k and high mixing
    - relating k to ice cover
  - holistic to prognostic modeling
- continue to explore role of scale, seawater, temperature on k-ice

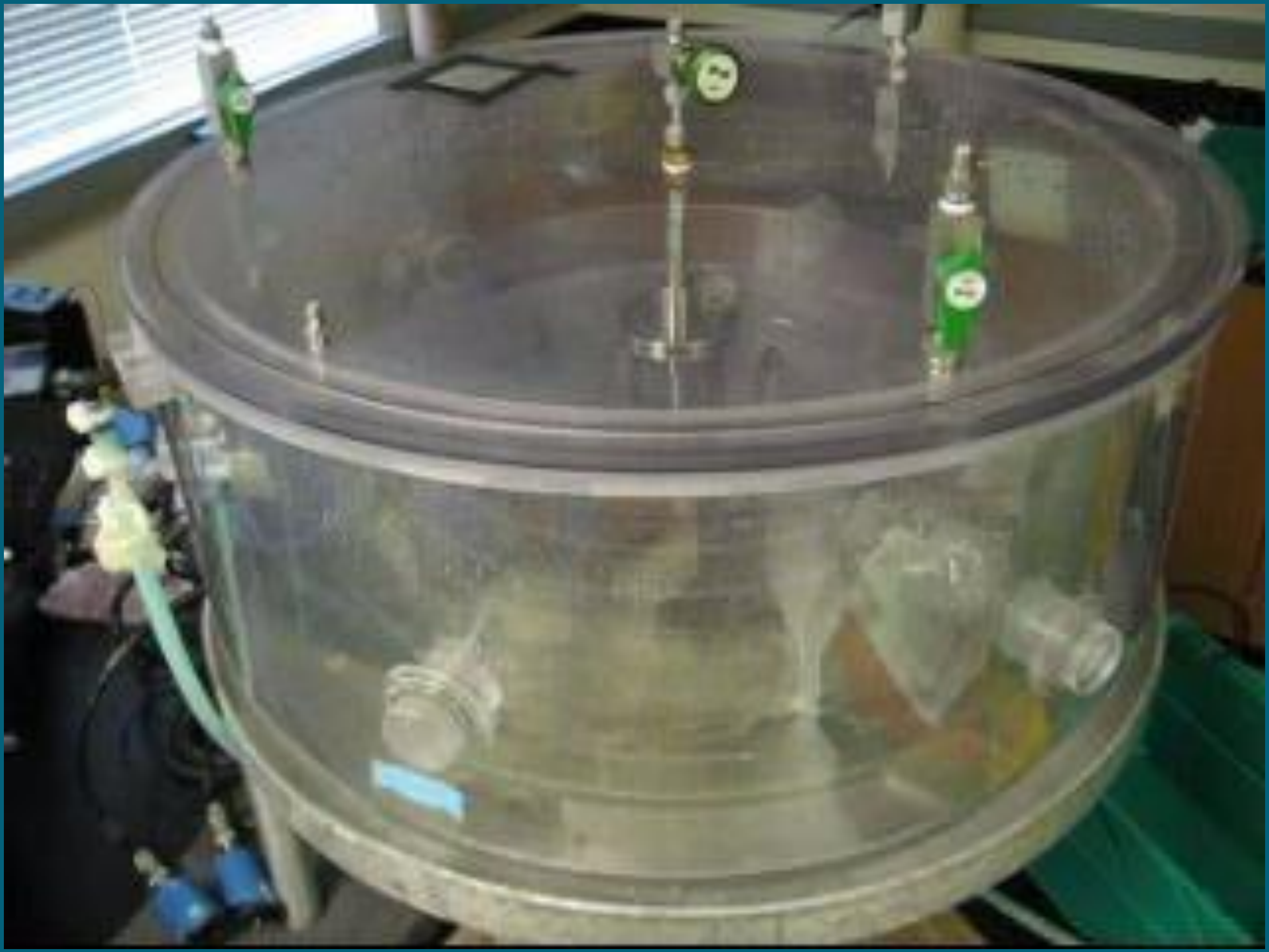


surface ice

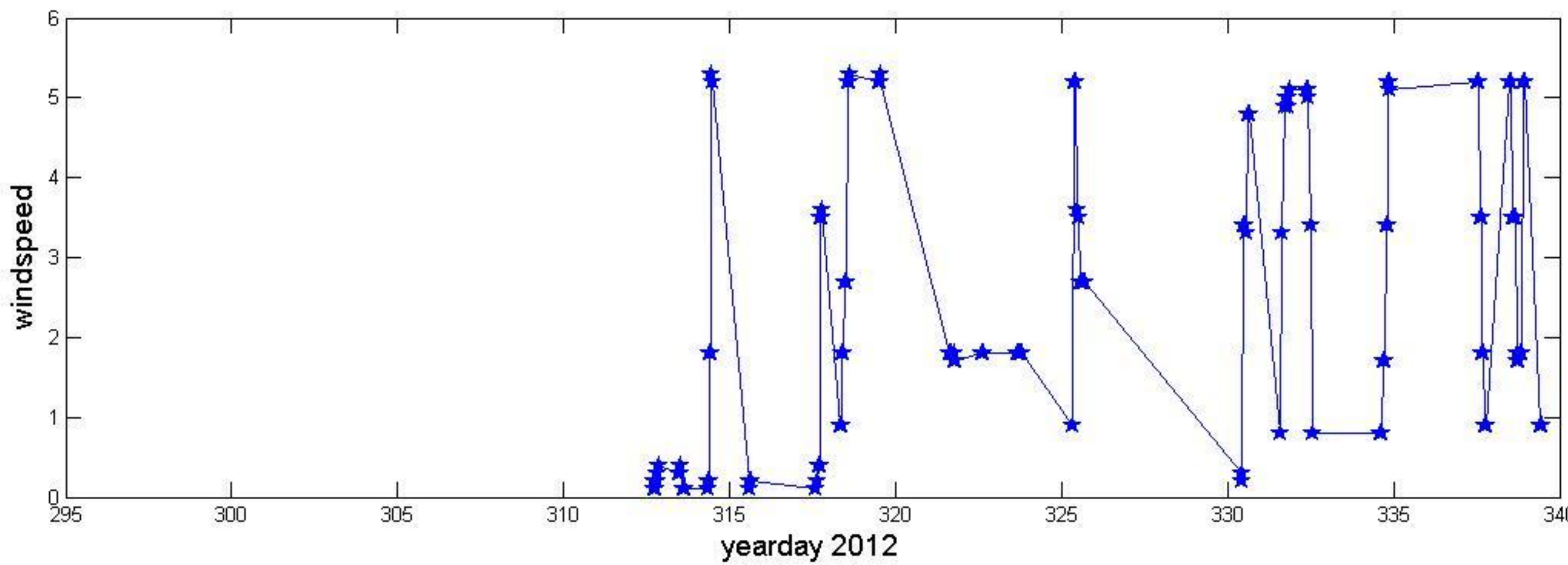
fresh water crystals

seawater crystals

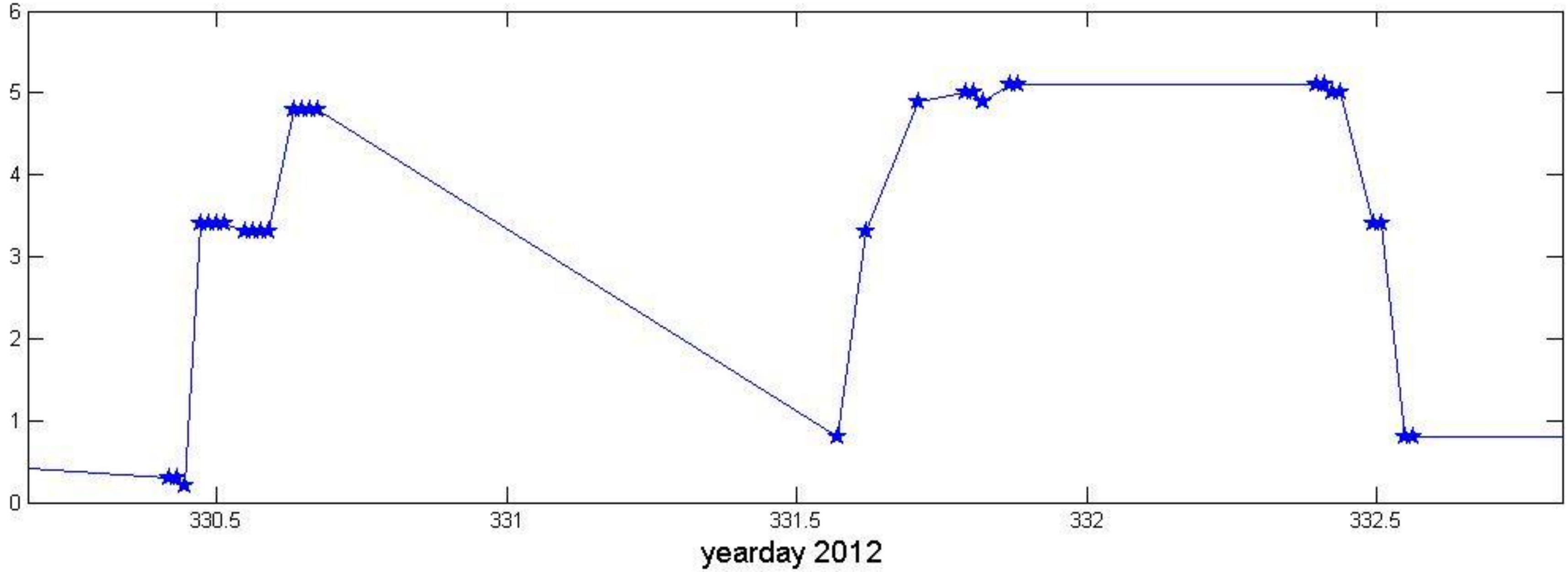




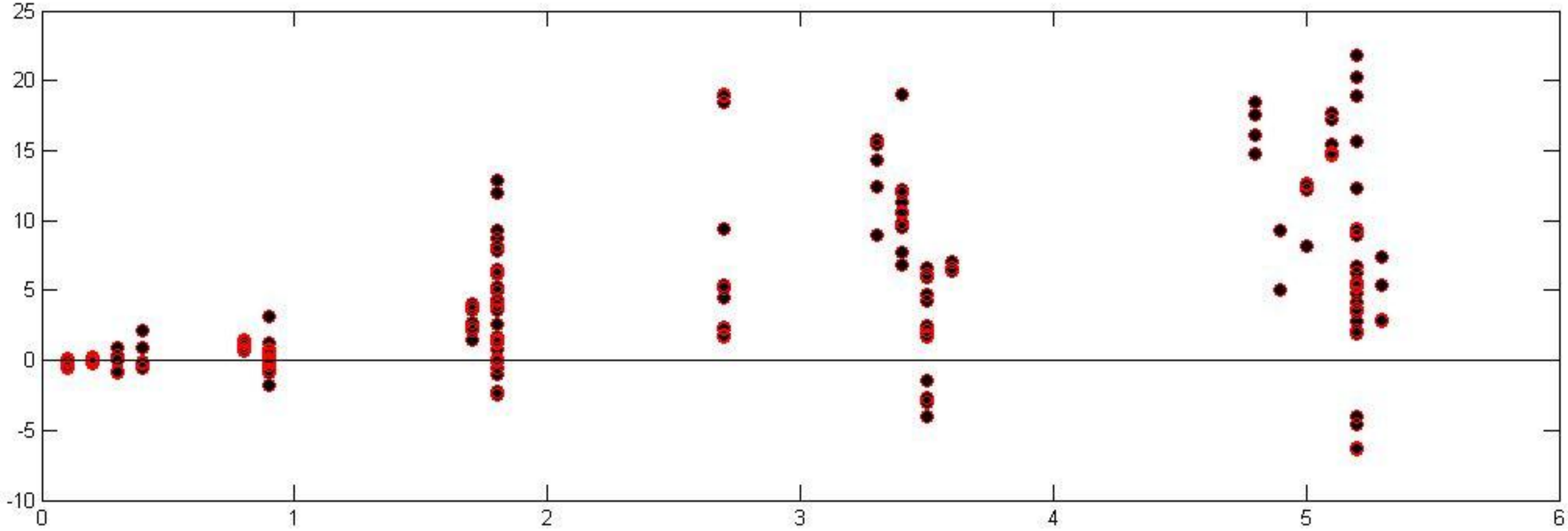
Using the annular wind wave tank we used for 1990’s surfactant studies



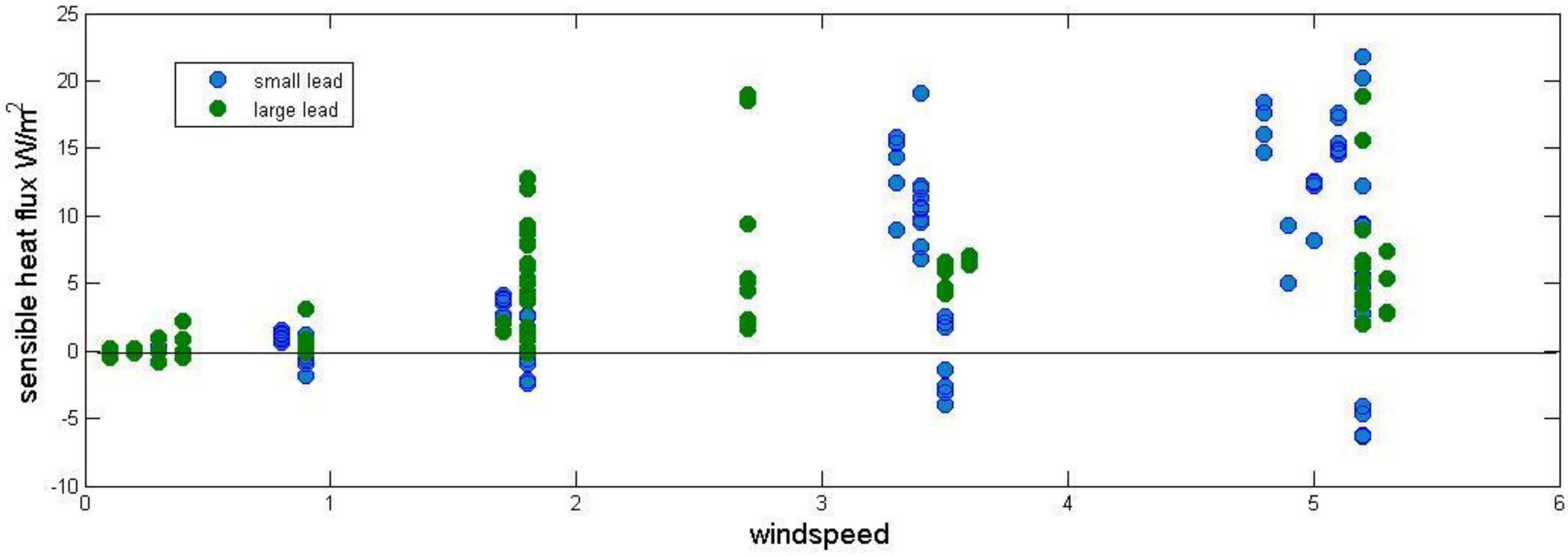
windspeed
yearday 2012
0
1
2
3
4
5
6
295
300
305
310
315
320
325
330
335
340



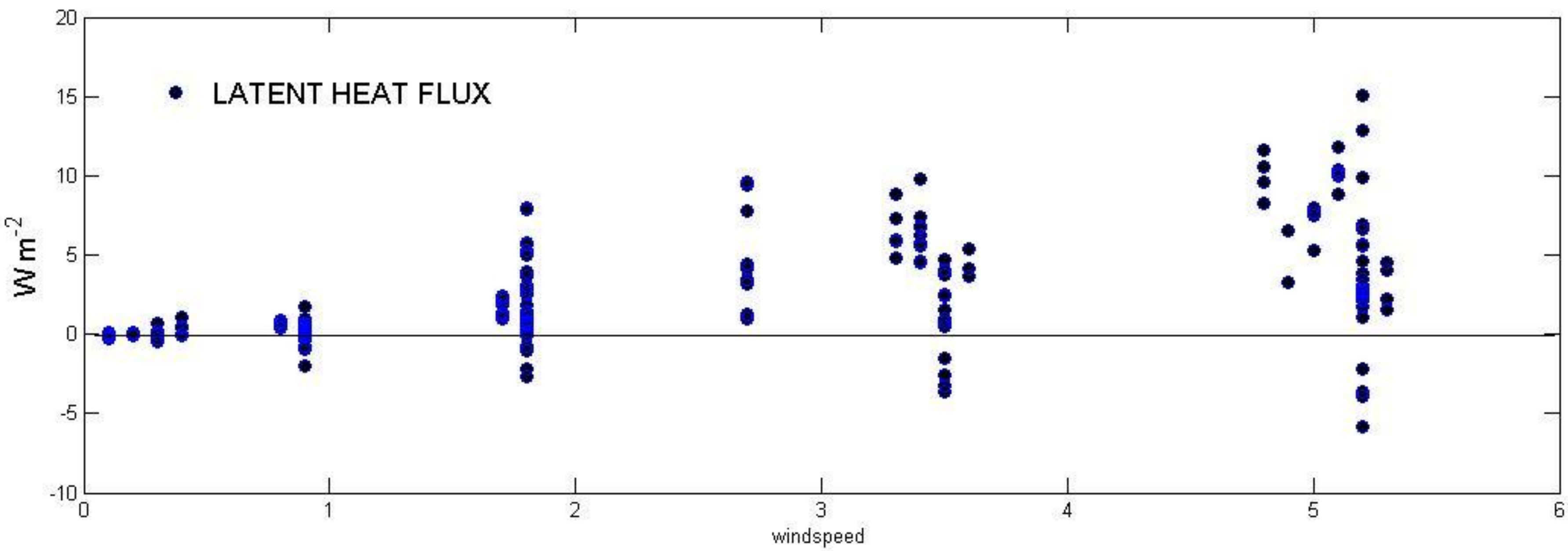
6
5
4
3
2
1
0
330.5
331
331.5
332
332.5
yearday 2012



25
20
15
10
5
0
-5
-10
0
1
2
3
4
5
6



small lead
large lead
sensible heat flux W/m2
windspeed
25
20
15
10
5
0
-5
-10
0
1
2
3
4
5
6



LATENT HEAT FLUX
W m-2
windspeed
20
15
10
5
0
-5
-10
0
1
2
3
4
5
6