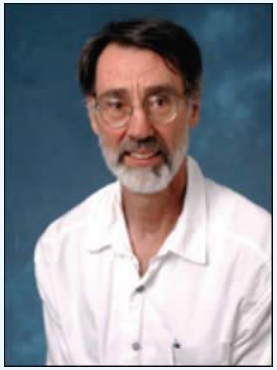
Measurement and Parameterization of Sea-Air Trace Gas Transfer using Micrometeorological Techniques

A Decade of Progress



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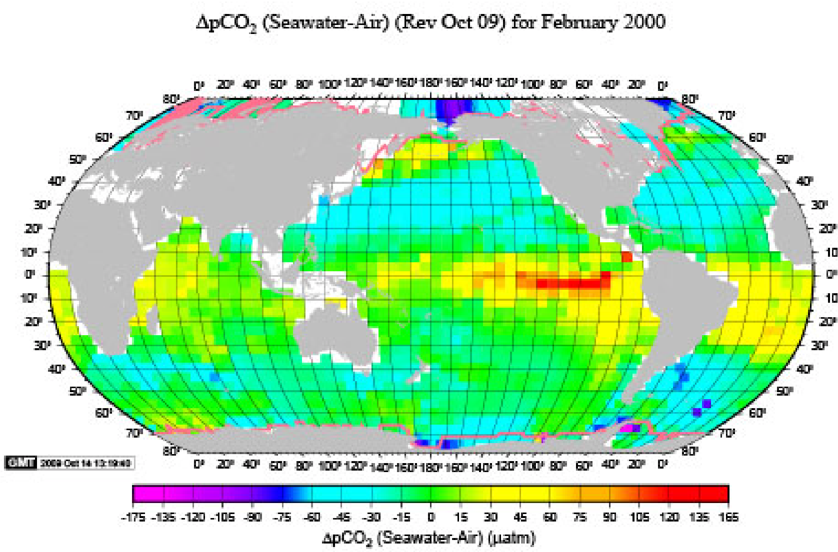
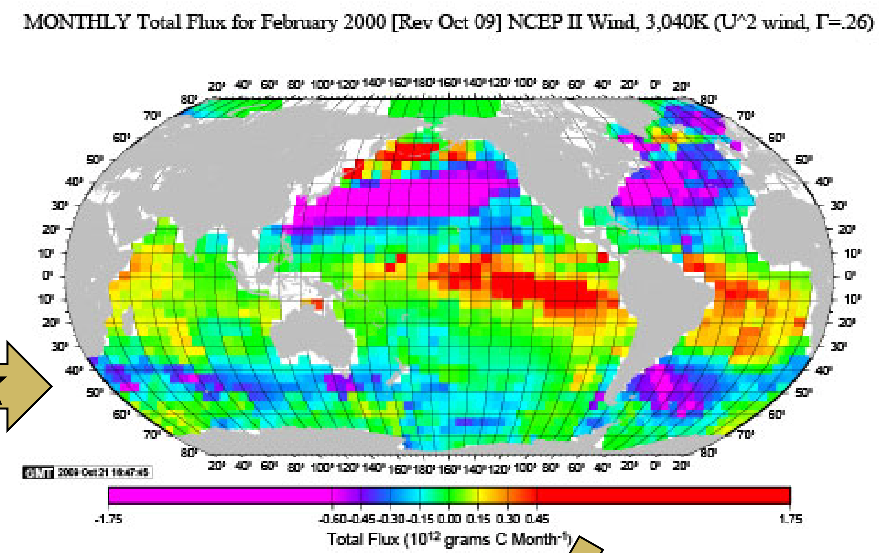
Outline

- The need for air-sea gas transfer velocity (example for global CO_2)
- Wind speed parameterizations of *k*
- Direct observations of the flux (GasEx and more)
- COARE micro-meteorological *k* parameterization
- Addition of other gas flux observations into COARE
- Investigations of solubility and bubble effects
- Operational application of the COARE gas transfer parameterization

The need for *k*



k

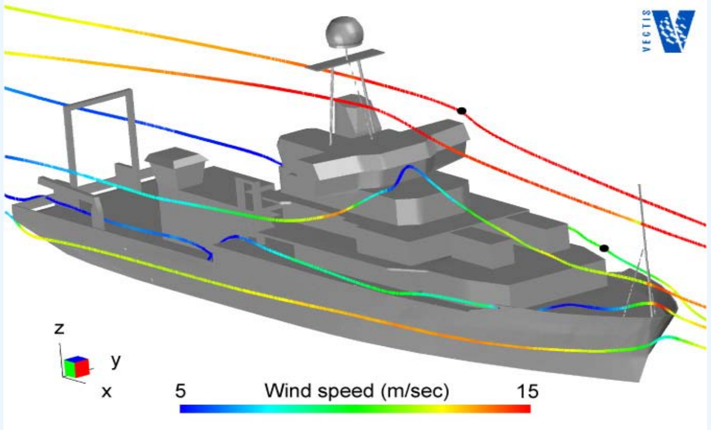


$$\Delta pCO_2 \ * \ k \ = \ \text{Flux}$$

Takahashi, et al. (2009), *DSR II*, **56**, pp 554-577

$k = \sim 0.26\ U^2$ Wanninkhof (1992)

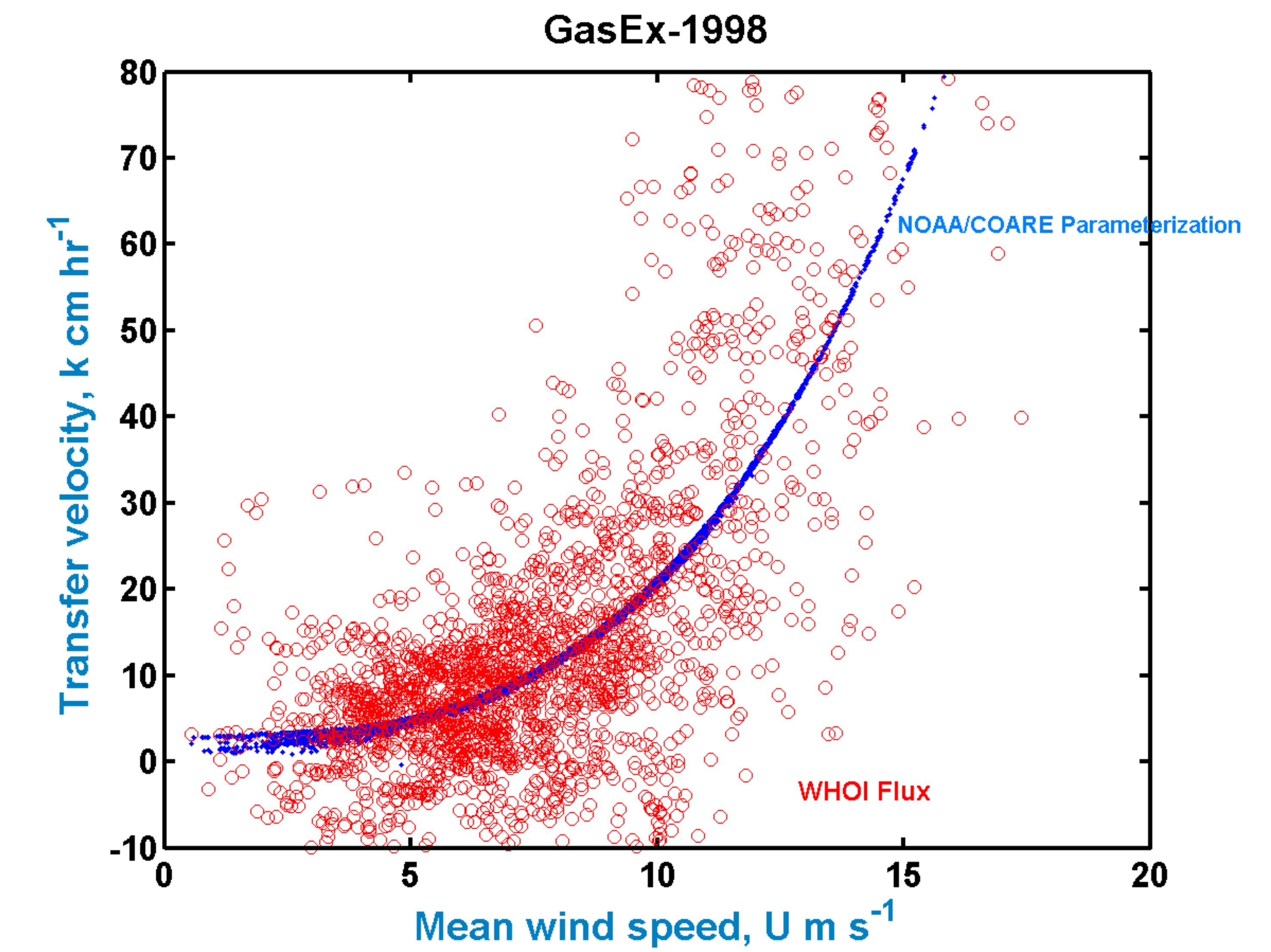
Motion-Corrected Eddy-Covariance Turbulence Observations (momentum, sensible heat, and latent heat fluxes since 1990)



Physical flux: $\langle w'x' \rangle = C_x U(X_r - X_s) = C_x U \Delta X$

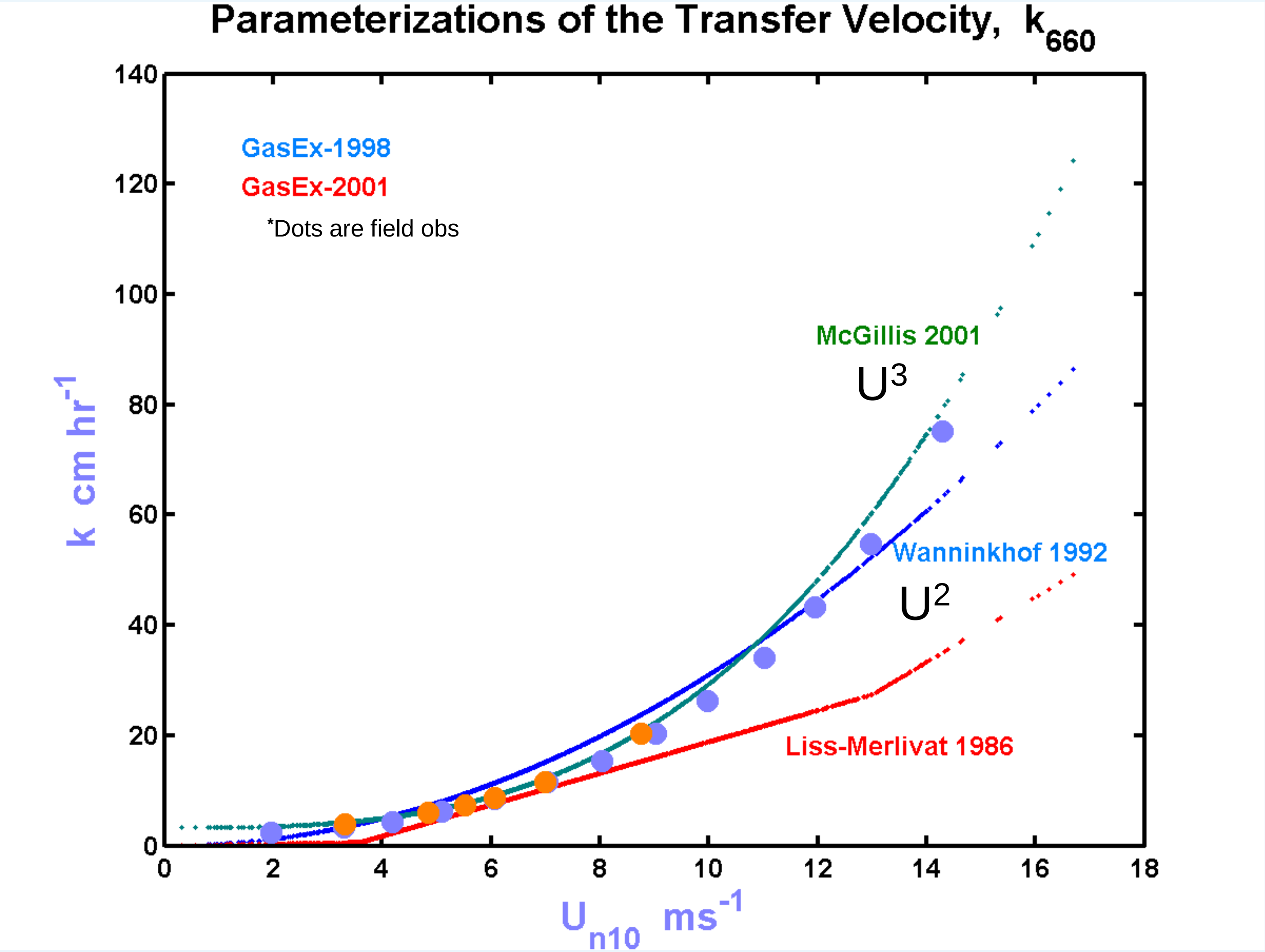
Gas flux: $\langle w'x' \rangle = k_x \alpha_x \Delta X$ ***α is solubility***

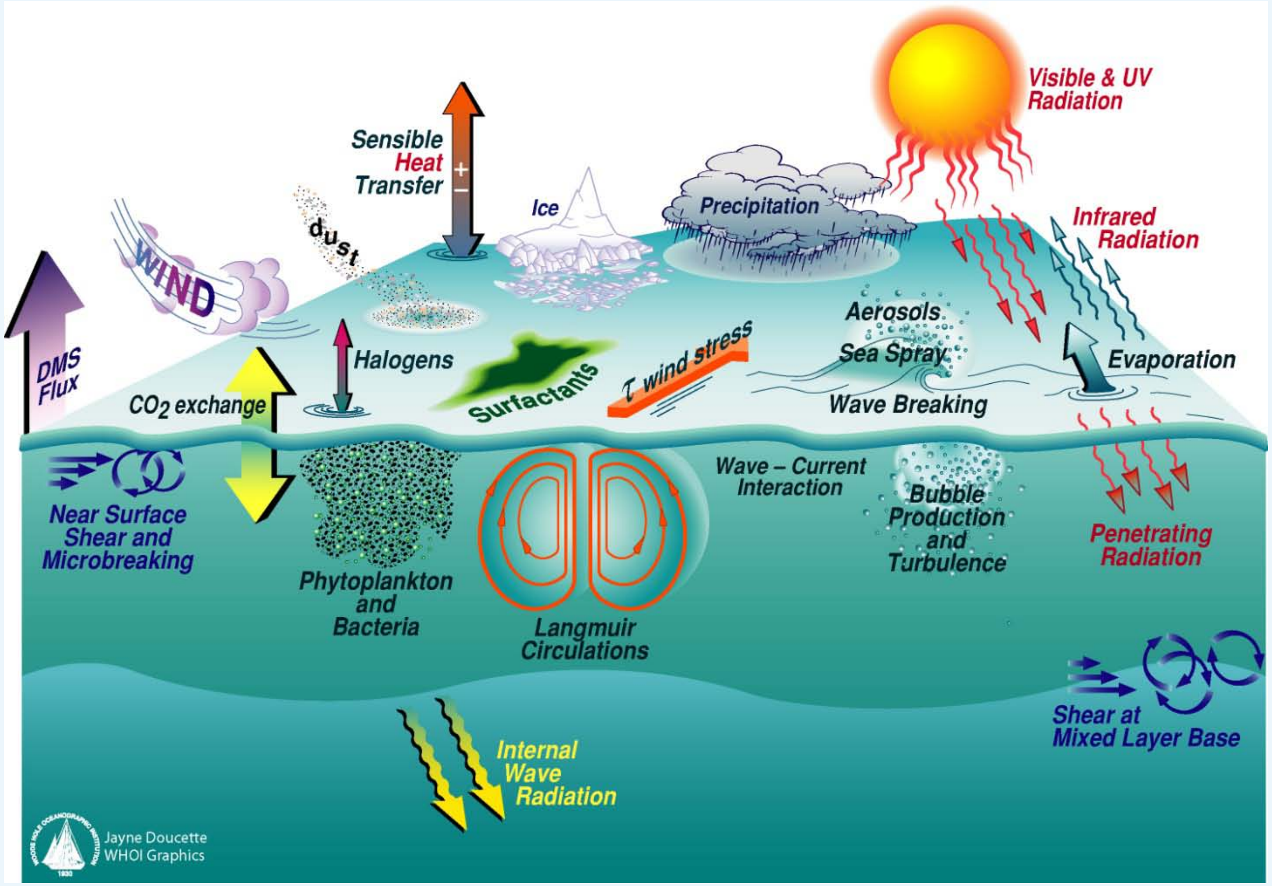
GasEx-98 cruise in the North Atlantic (~June 1998)



$F = k\ \Delta pCO_2$

Quadratic, Cubic, relationships with U





k varies only with U ?

Development of a micro-meteorological parameterization for gas transfer velocity, *k*

*** Based on COARE bulk flux algorithm**

X_w = concentration in the water
X_a = concentration in air

$$F_x = \overline{w'x'} = \alpha_x k_x (X_{wr} / \alpha_x - X_{ar})$$

$$\alpha_x = X_{ws} / X_{as}$$

Express *k* in terms of water-side and air-side RESISTANCES, *R*

***R* will express transfer processes**

$$k_x = [R_{xw} + \alpha_x R_{xa}]^{-1}$$

Gases reactive in water

- **Chemical enhancement factor β**
- **For large β, *k* becomes a deposition velocity**

$$\alpha = \beta \alpha_x$$

$$F_x \rightarrow -\frac{X_{ar}}{R_{xa}} = -V_{dx} X_{ar}$$

Expressions for resistances

Bubbles enhance transfer on ocean side

$$k_x = [(R_{wx}^{-1} + k_b)^{-1} + \alpha_x R_{ax}]^{-1}$$

Air-side resistance

$$u_{*a} R_{ax} = [h_a S_{ca}^{1/2} + C_d^{-1/2} - 5 + \ln(S_{ca}/(2\kappa))]$$

Water-side resistance

$$u_{*a} R_{wx} = \sqrt{\rho_w / \rho_a}[h_w S_{cw}^{1/2} + \ln(z_{wr} / \delta_{uw})]$$

***A* is adjustable constant**

$$h_w = \frac{13.3}{A\phi}$$

Soloviev & Schlussel '94

***Φ* is a buoyancy function**

Bubble velocity (Woolf)

$$k_b = \frac{V_o}{B} W_b \alpha_x^{-1} [1 + (e\alpha_x S_{cw}^{-1/2})^{-1/n}]^{-n}$$

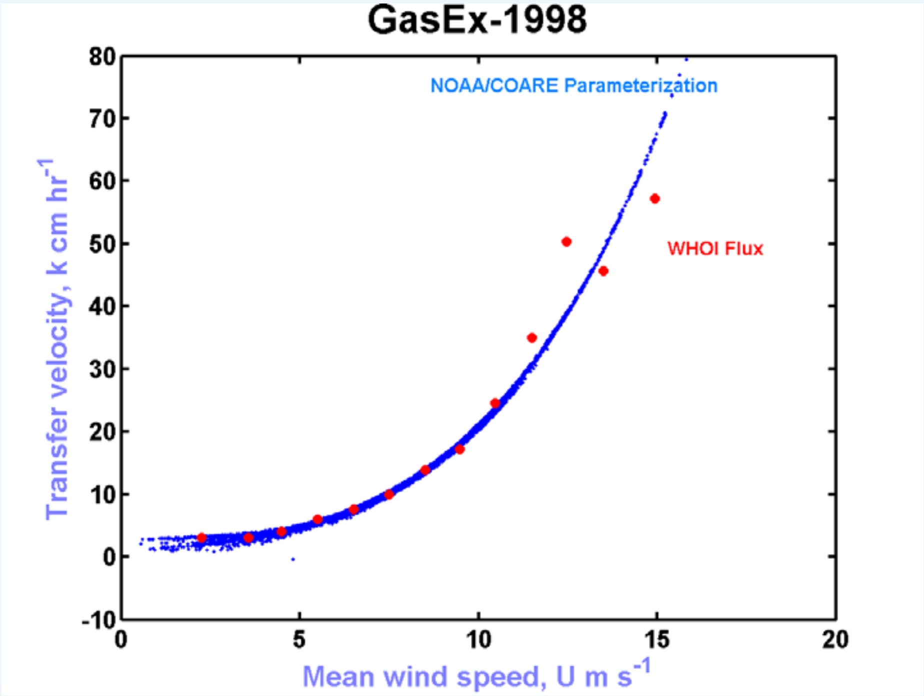
***B* is adjustable constant**

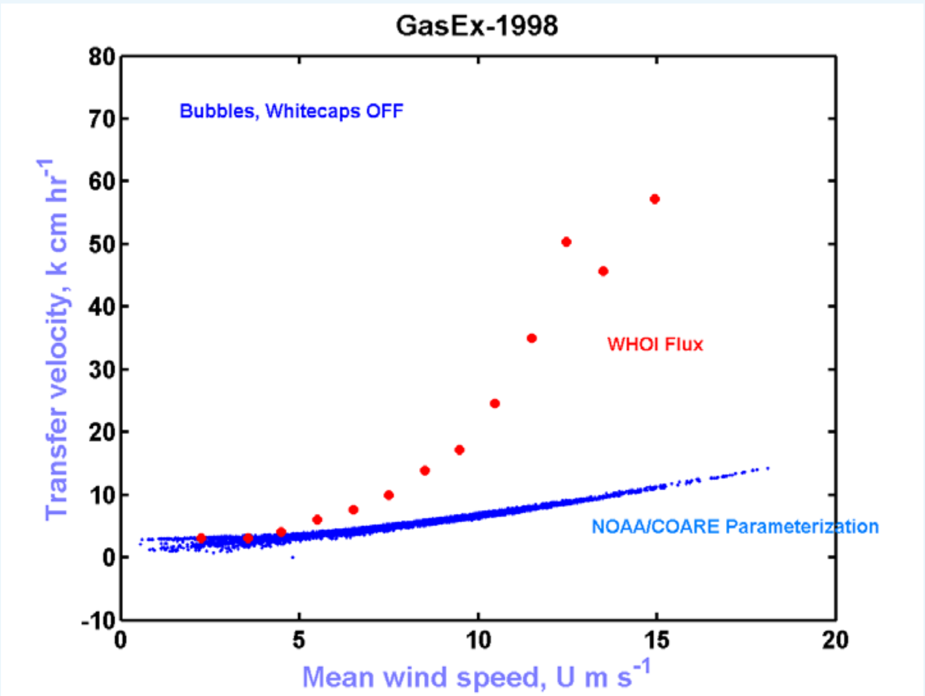
***W_b* is whitecap fraction**

$$W_b = 3.8 * 10^{-6} U^{3.4}$$

Applied COARE gas parameterization

***A* and *B* adjustments**

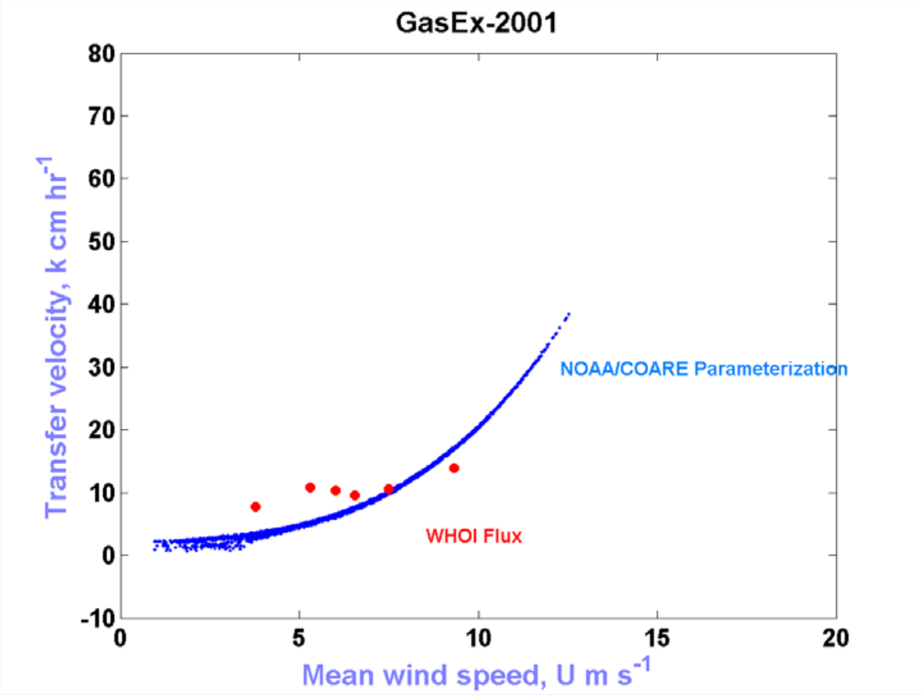


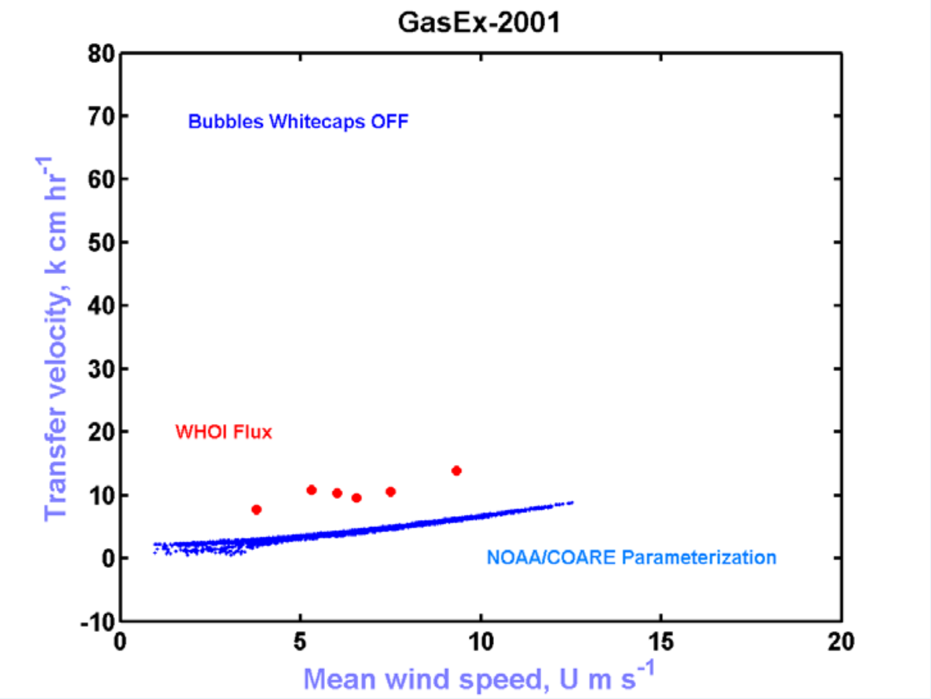


With bubbles (k_b)

Without bubbles (~~k_b~~)

GasEx-01 cruise in the Equatorial Pacific (~Feb 2001)

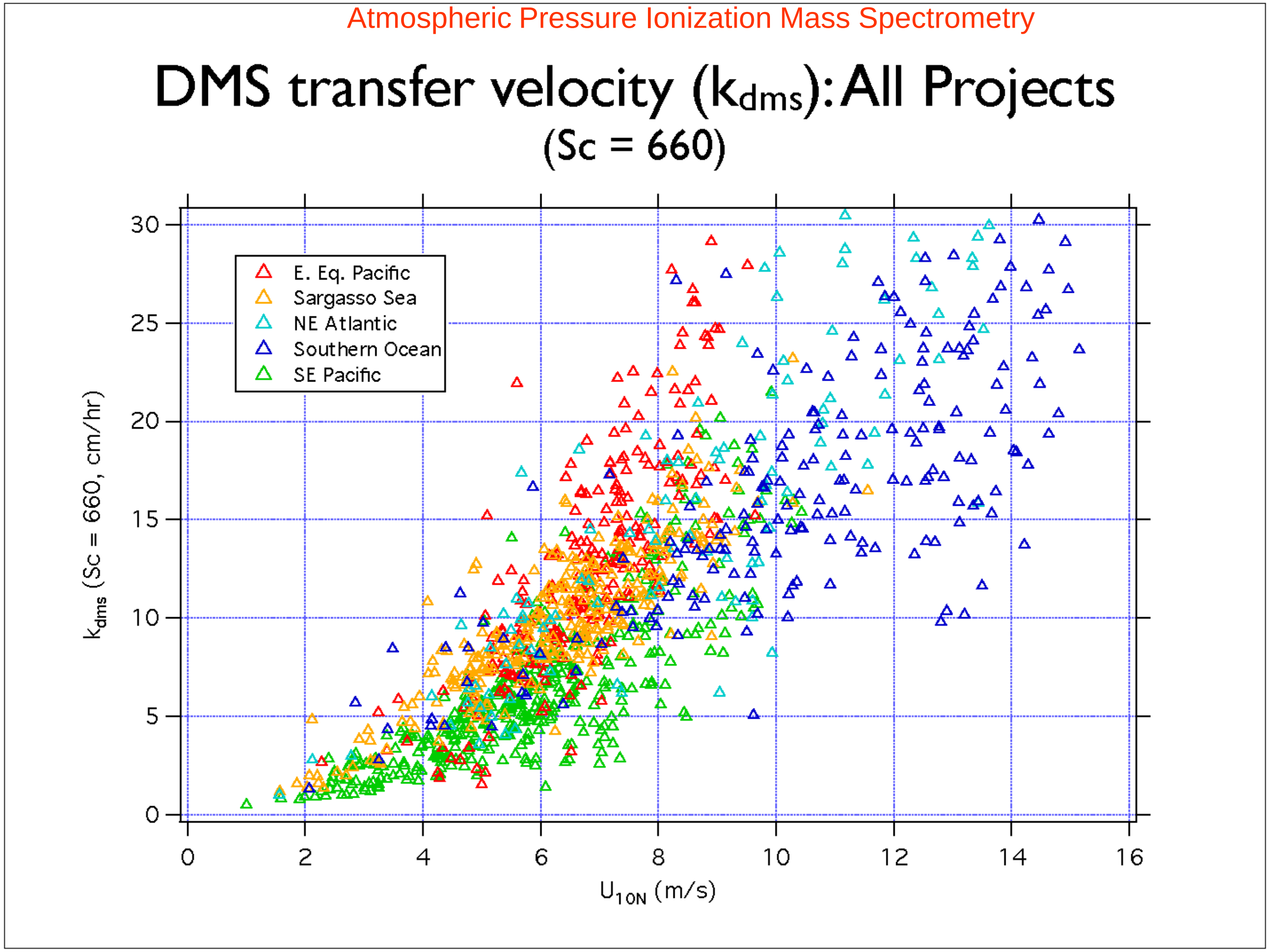




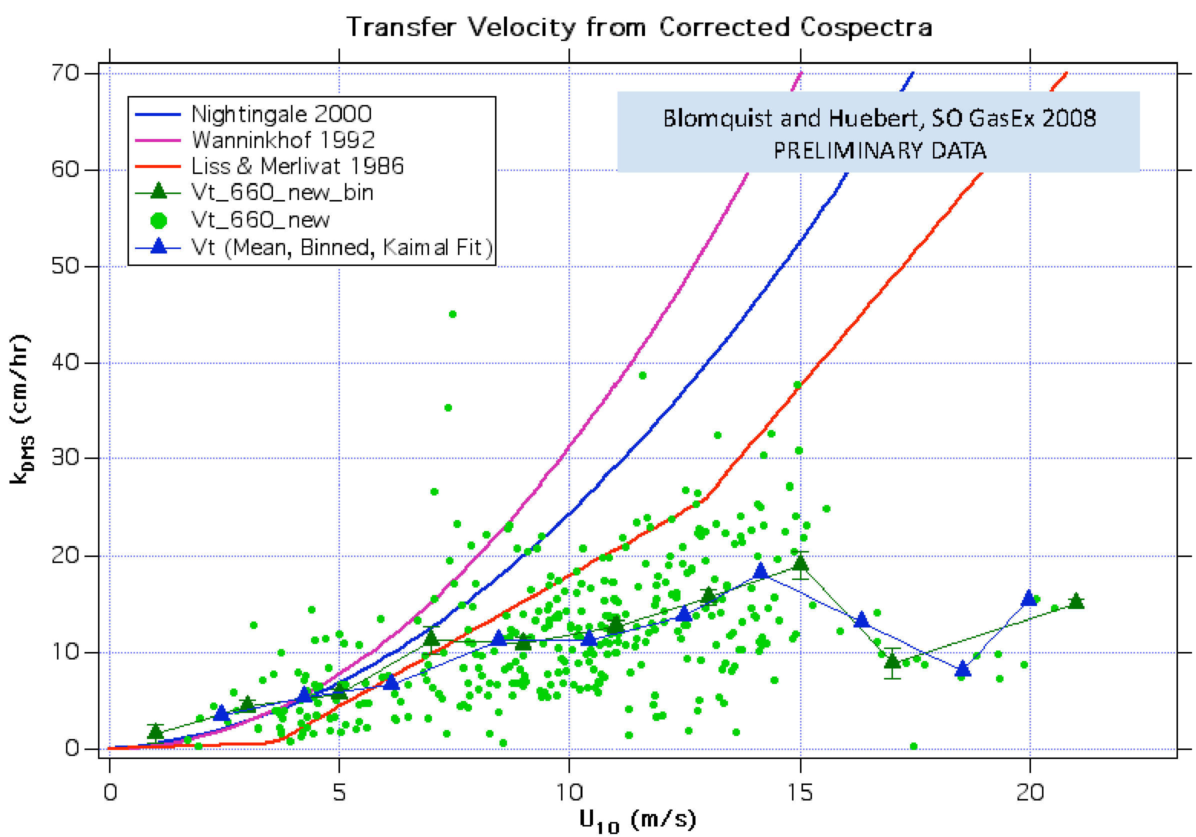
***To match, A*⇩x3 *B*⇧x2**

Adding more gases – DMS (CLAW)

Huebert and Blomquist - UHawaii



Increase data set, develop range of solubilities, elucidate the physics, etc



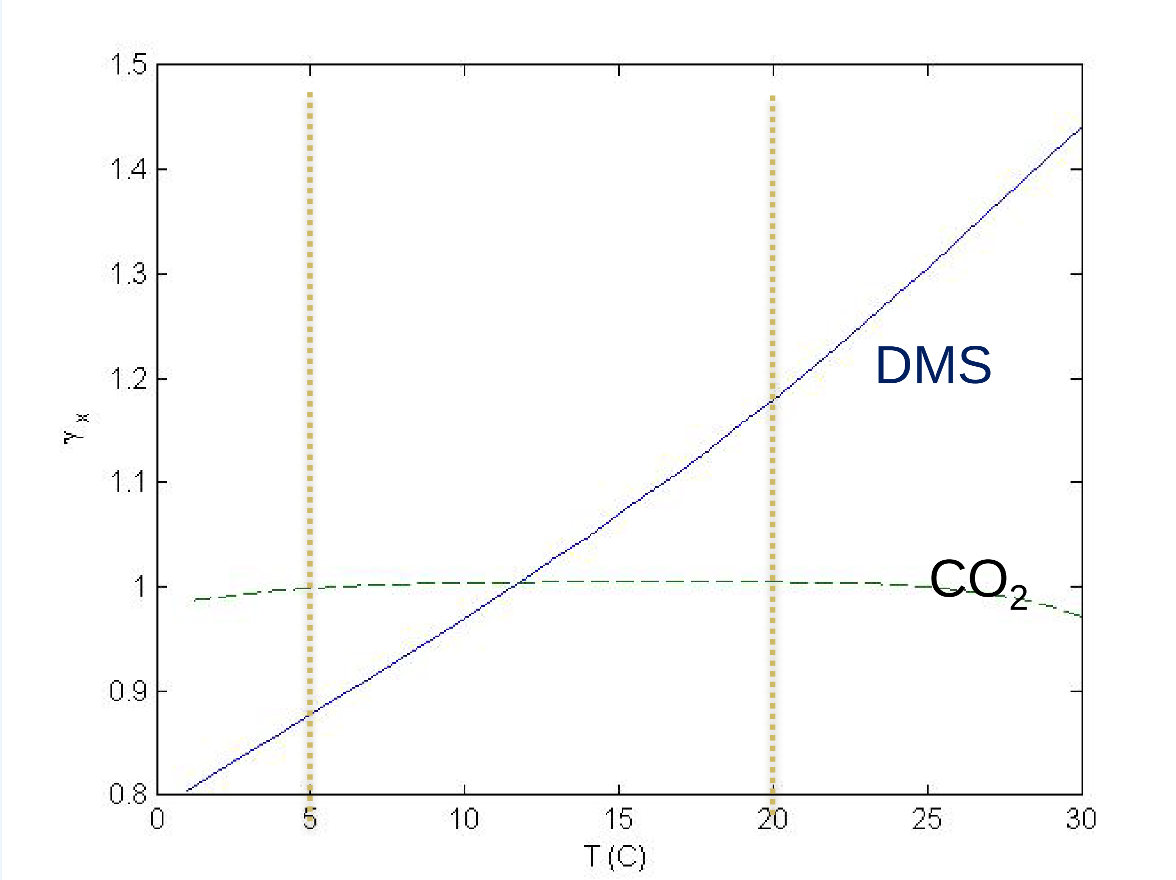
Highlights the need to include solubility in *k* parameterization

Temperature effects of bubble-solubility normalization

$$\left[\frac{S_{cw}}{660}\right]^{1/2}\frac{k_b}{u_*} \cong \frac{BV_o f_{wh}}{u_*}\frac{\gamma g_b}{\alpha(20)}$$

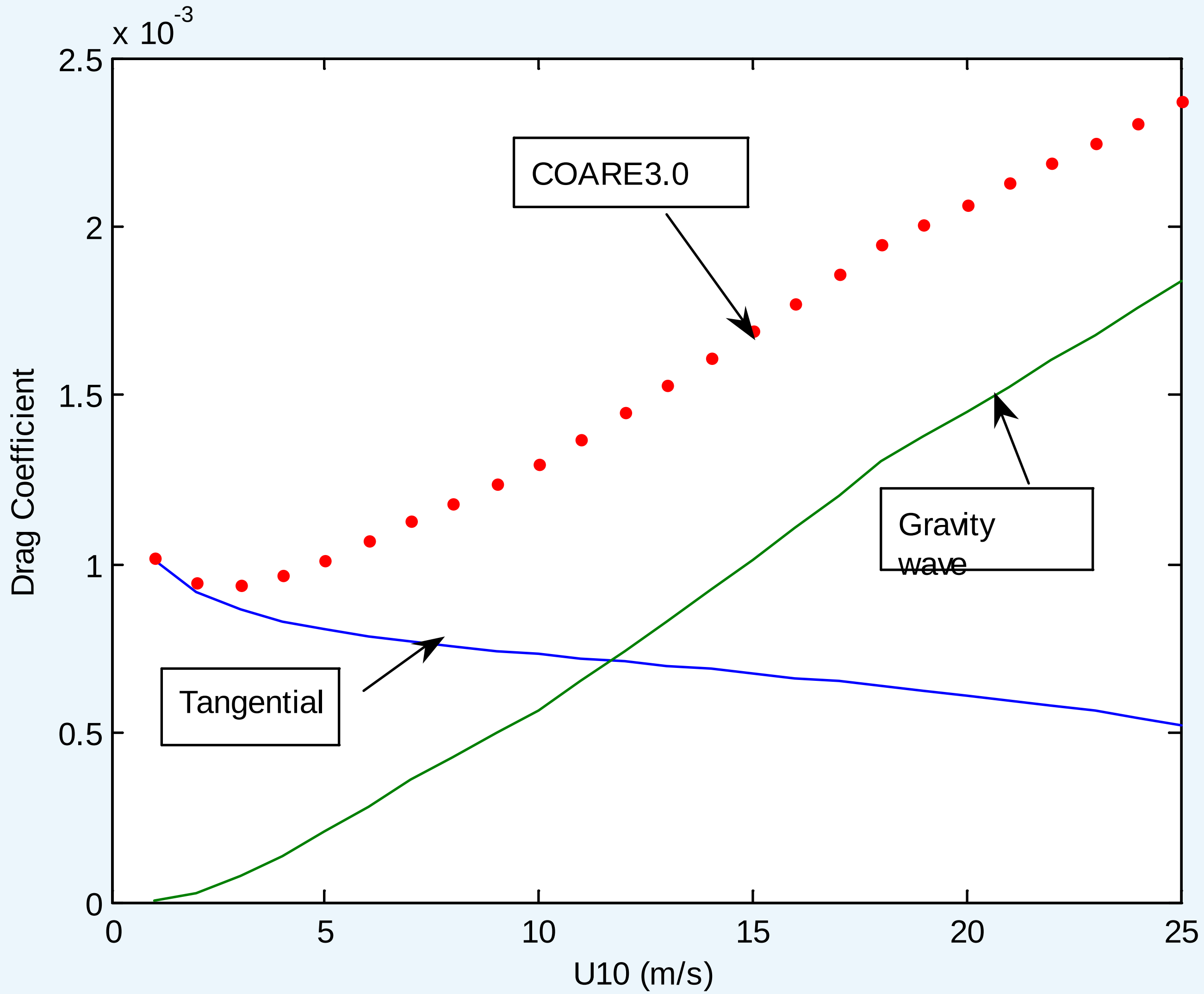
$$\gamma = \left[\frac{S_{cw}}{660}\right]^{1/2}\frac{\alpha(20)}{\alpha(T)}$$

$$g_b = [1+(e\frac{\alpha(20)}{\sqrt{660}}\gamma^{-1})^{-1/n}]^{-n}$$

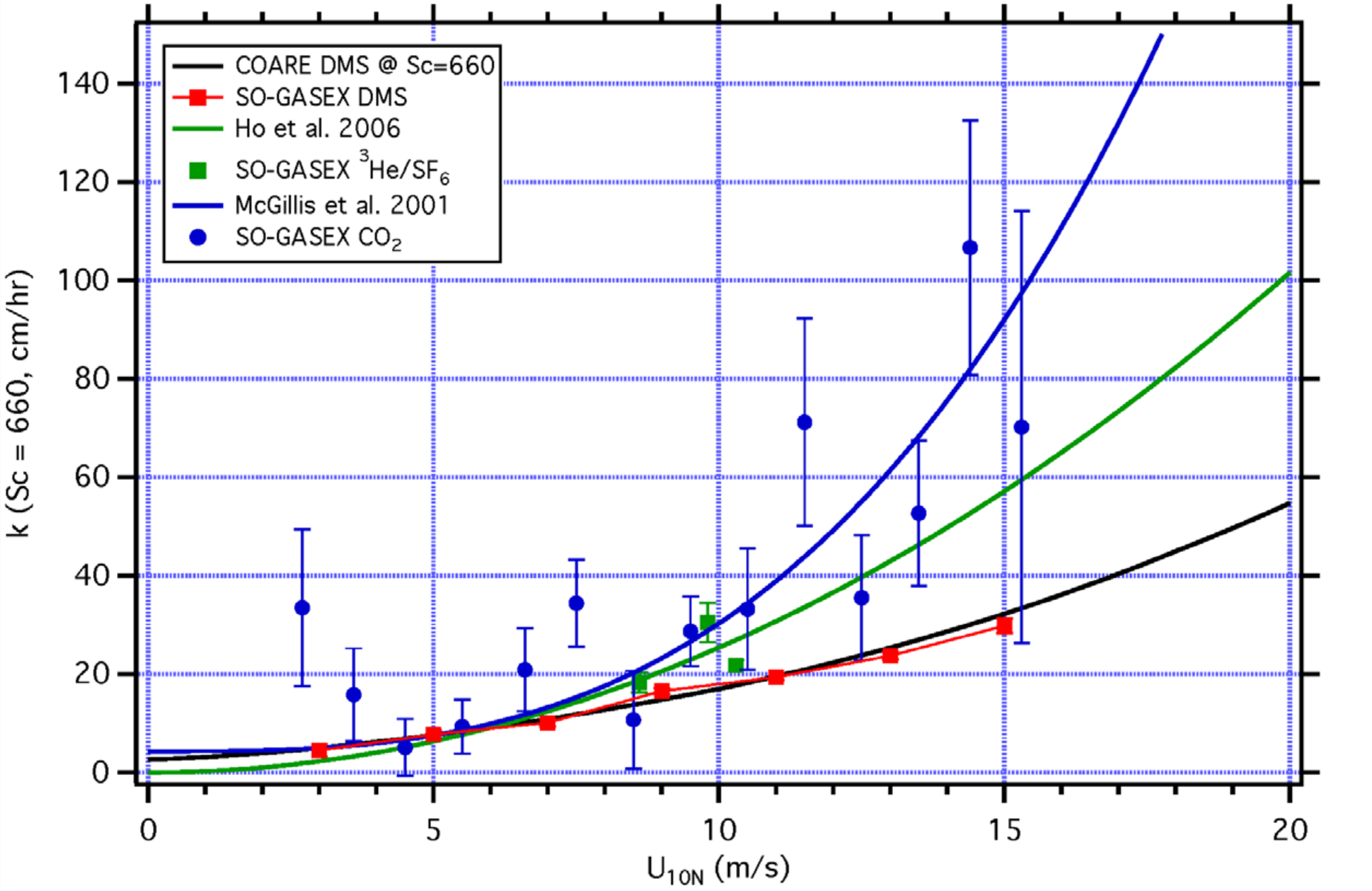


How to discern bubble vs. interfacial transfer for field observations of the flux?

Partitioning of wind stress into tangential and form drag components

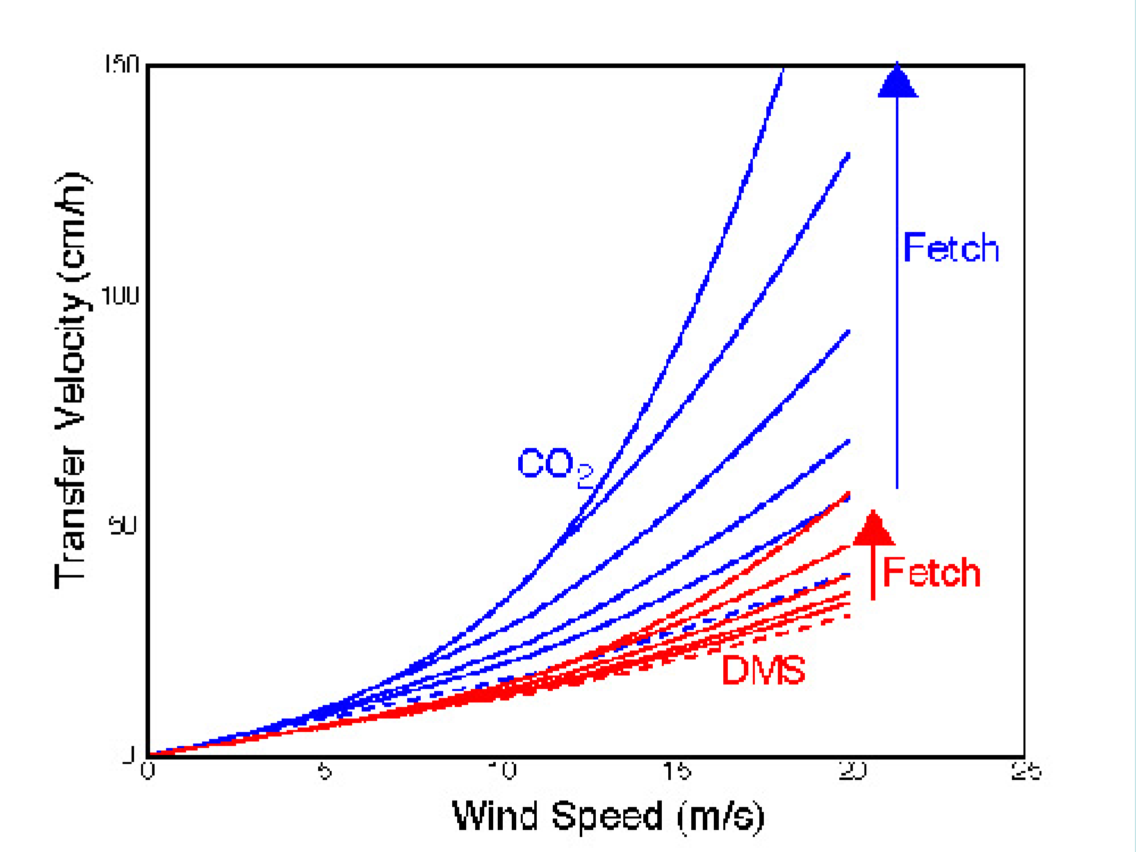


GasEx-08 cruise in the Southern Ocean (~March 2008)

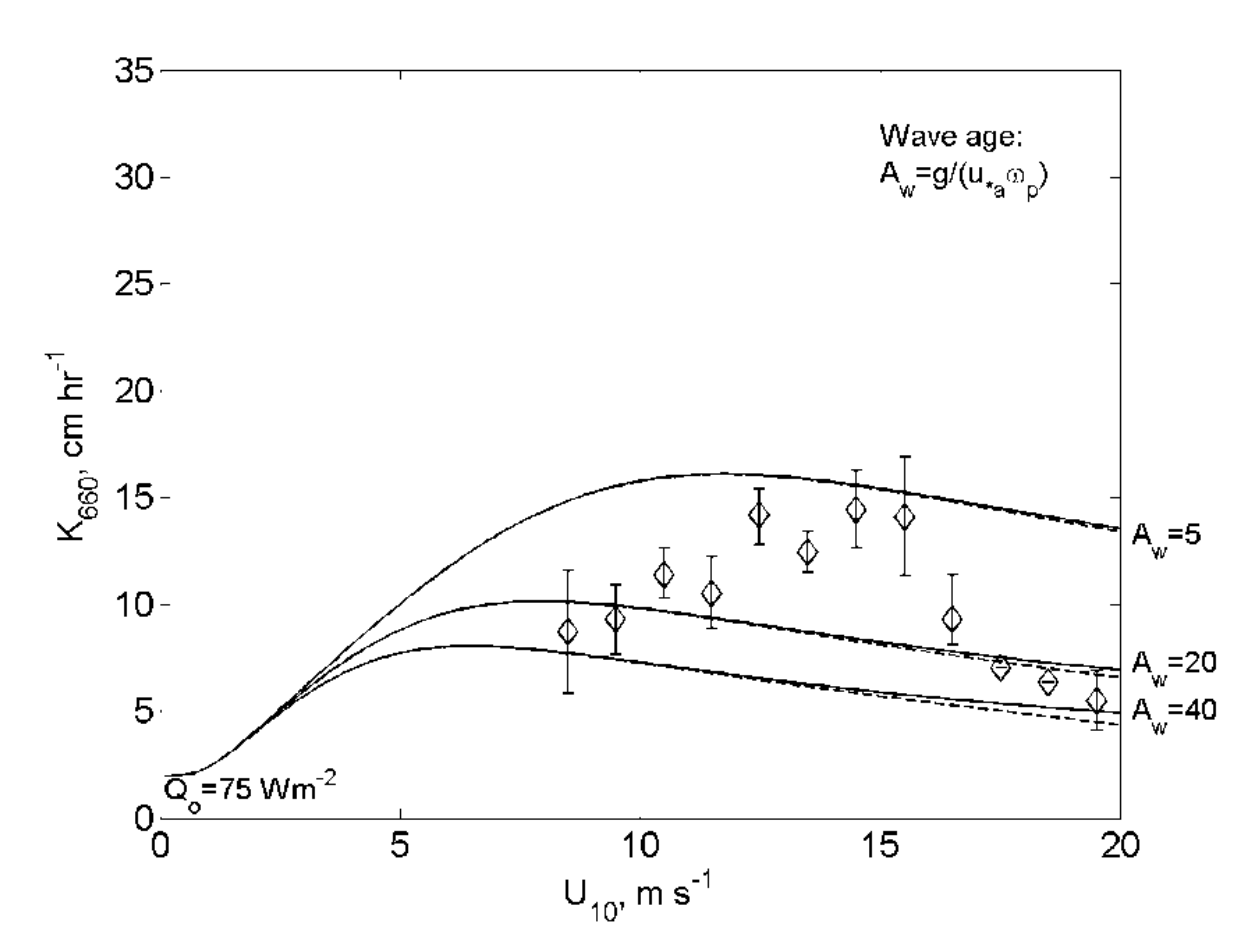


NOAA/COARE revised

Woolf, D.K. 2006. Recent developments in parameterization of air-sea gas exchange. Flux News, 2,. In Press.



Wave state effects

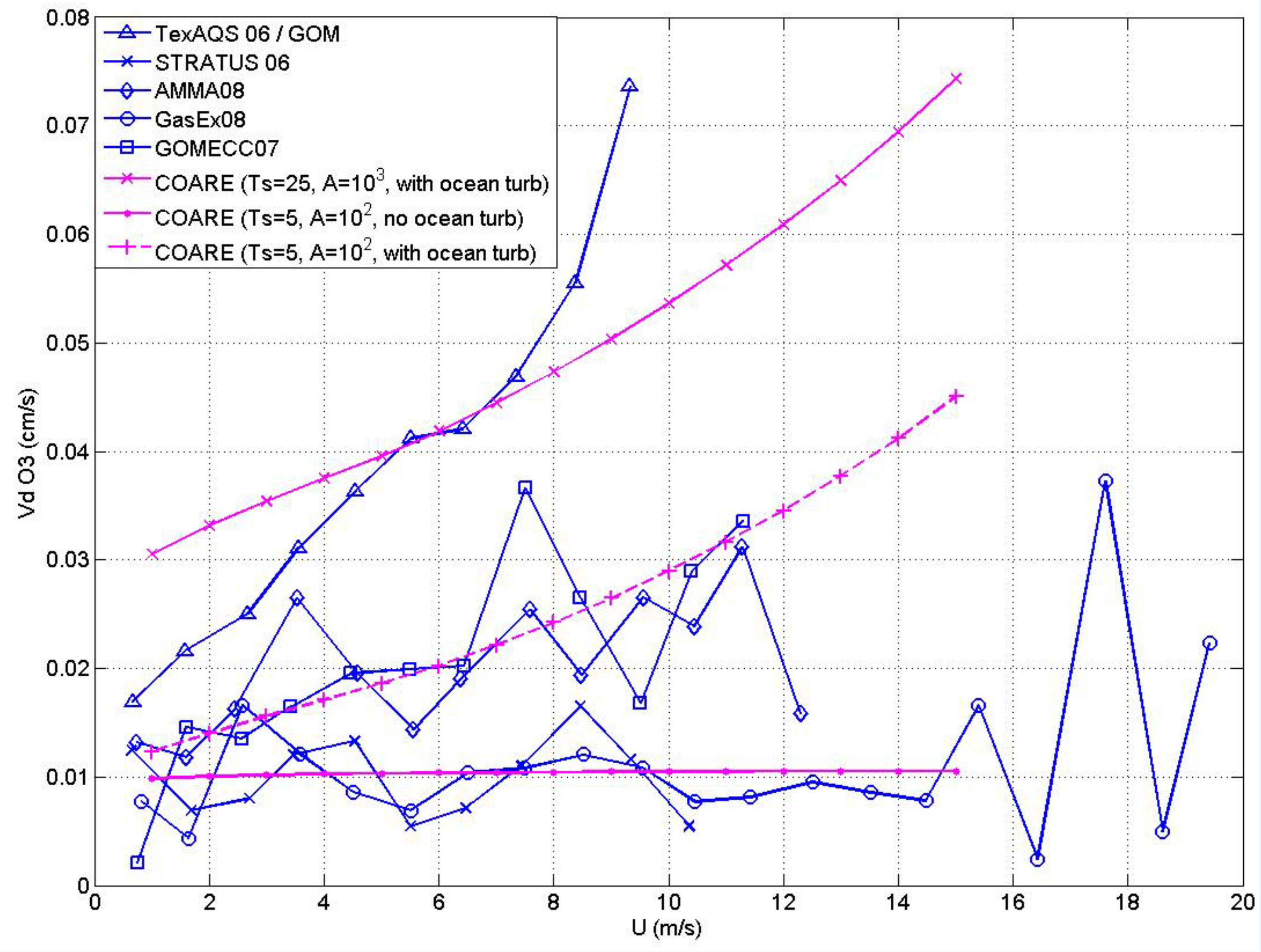


For a given wind speed, *k* drops for older waves (partitioning/breaking)

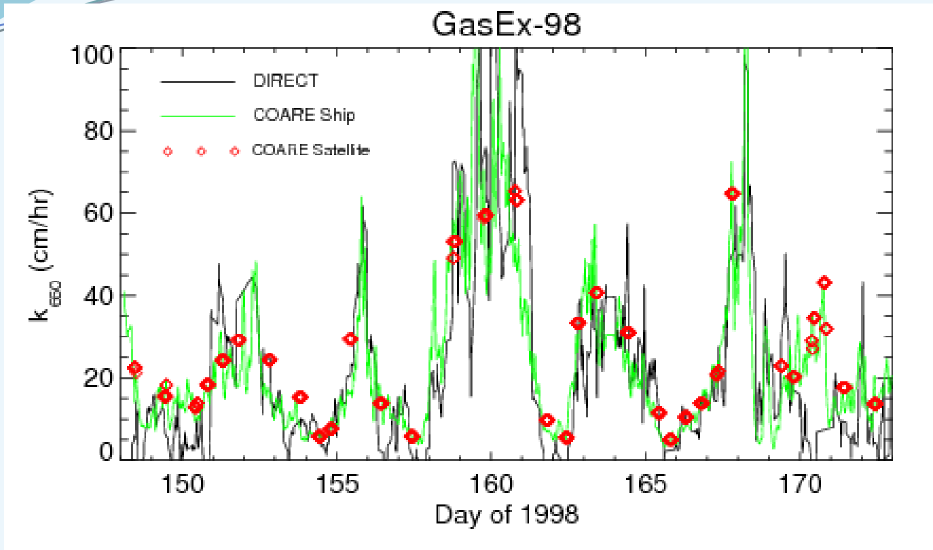
Adding more gases – O_3 (MBL and sfc chemistry)

Helmig – INSTAAR, University of Colorado

O_3-NO-chemiluminescence

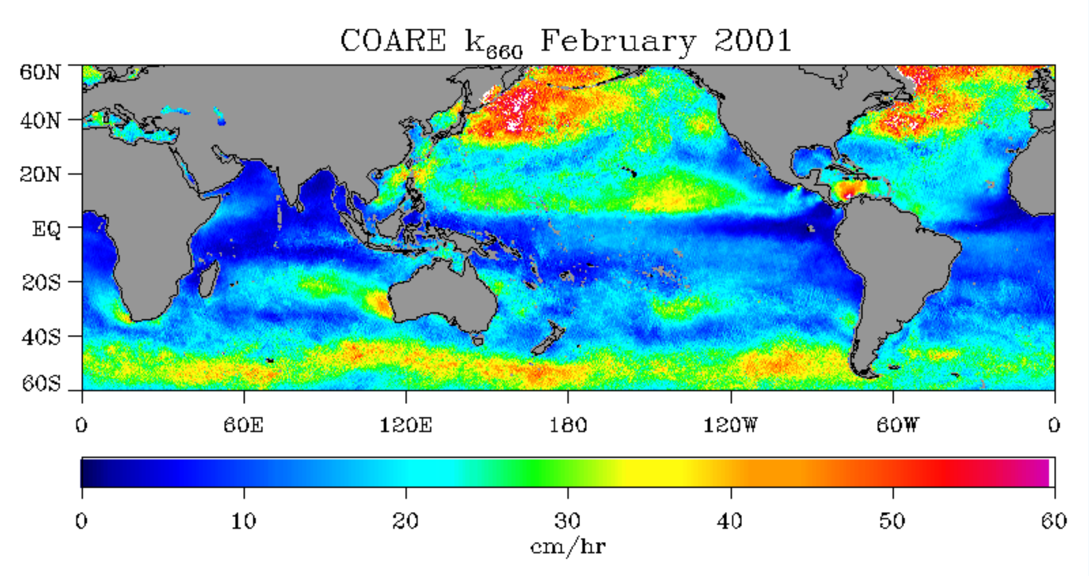


Satellite-derived CO_2 Transfer Velocities using COARE

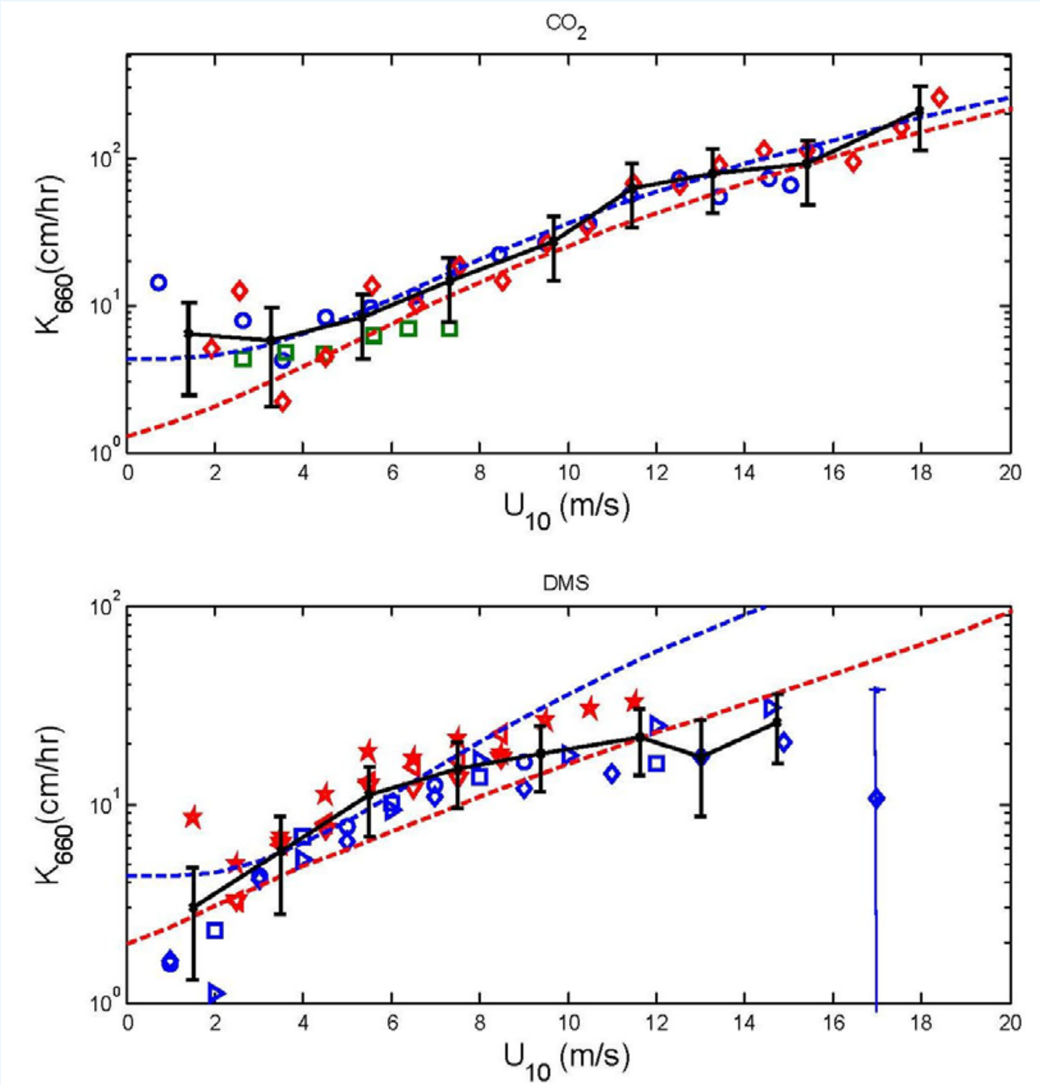


COARE-modeled transfer velocities using satellite observations (*A*=1.31, *B*=2.57)

Monthly-mean *k* for CO_2 COARE with satellite inputs of U_{10}, T_{air}, T_{sea}, Q_{air}



Contrast to Stress/Heat Coefficients: Large Uncertainties Remain for **Gas Transfer**



Gas Transfer Sensitivity to:
*Solubility
*Wave breaking
*Bubbles
*Tangential vs Pressure (wave) stress
*Surfactants
*Temperature
*Complex chemistry
*Biology

Summary

- Progress on observational capabilities for air-sea gas flux observations
  - Instrumentation
  - Suite of gases

- Progress on development of comprehensive gas transfer algorithm
  - Gas transfer velocity determined at forcing scales
  - Development needed for bubbles/whitecap range

- Significant gaps exist in understanding gas exchange at high winds
  - Bubbles
  - Wave state

- Understanding of surface and boundary layer biogeochemistry is needed
  - Ozone deposition