Eddy Covariance as a Means of Improving Gas Exchange Parameterizations

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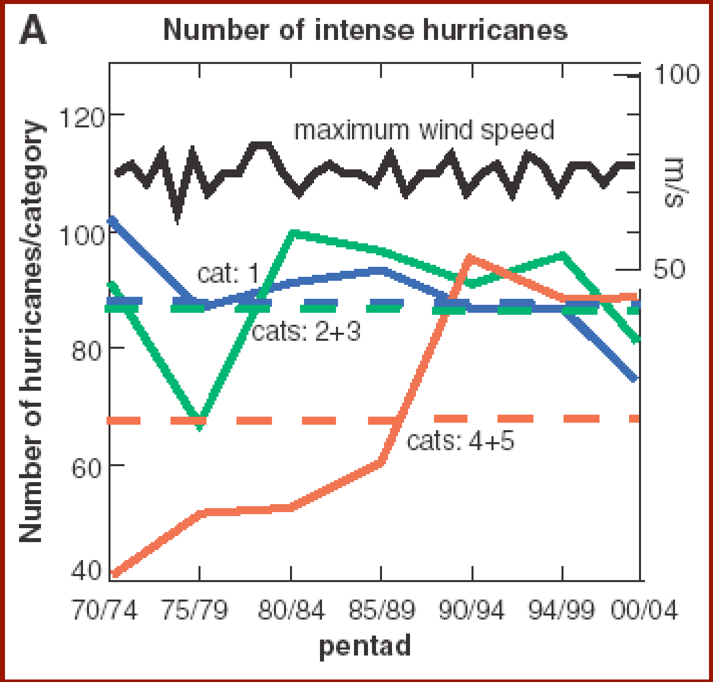
The Earth is in *Very* Big Trouble

Ice and permafrost are melting faster than expected.

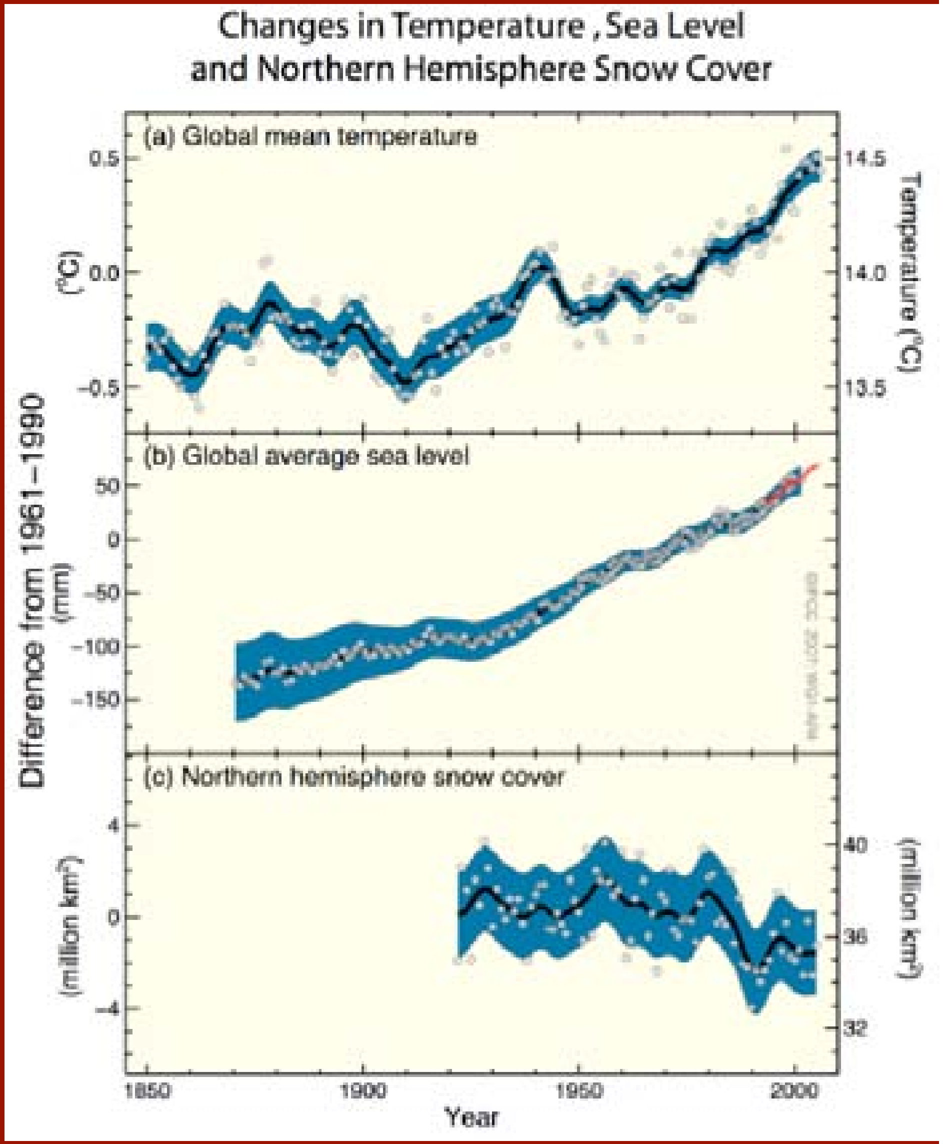
Sea level is rising.

Growing seasons are changing.

Storms seem to be getting more intense.



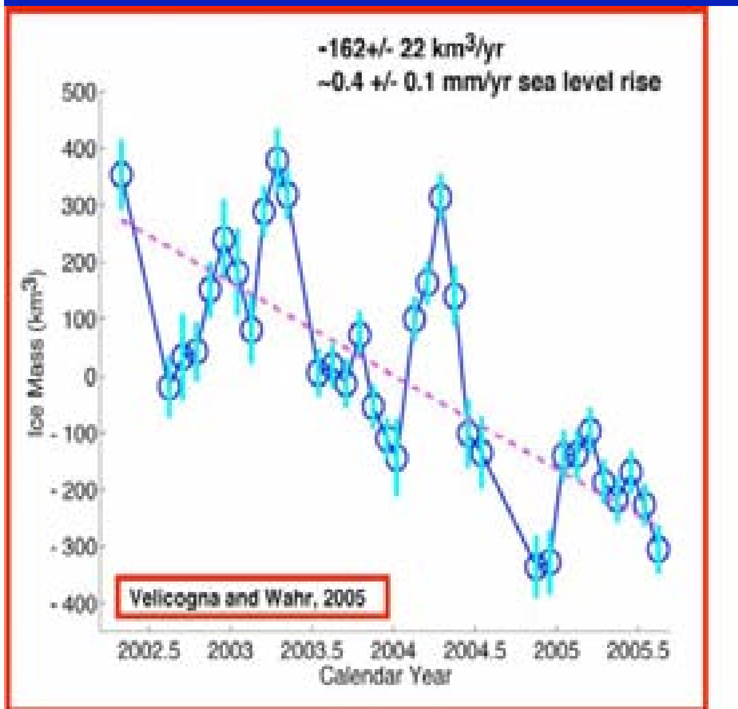
Webster et al., *Science*, *309*, 1844-1846, 2005



IPCC Fourth Assessment Report, Summary for Policymakers, 2007

Ice is melting faster than expected

Greenland Mass Loss – From Gravity Satellite



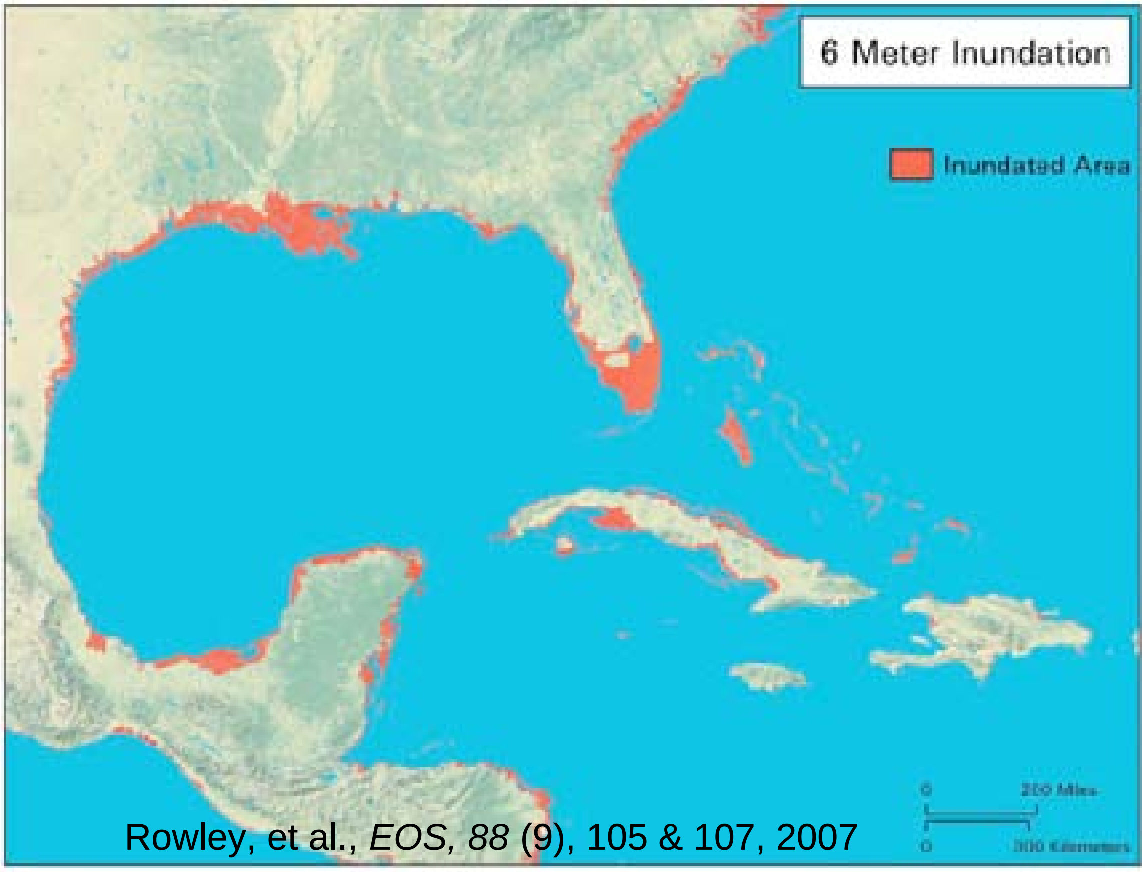
70 meters of thinning in 5 years

Courtesy of Jim Hansen

Surface Melt on Greenland

Source: Roger Braithwaite, University of Manchester (UK)

IPCC, *FAR*: "Paleoclimate information supports the interpretation that the warmth of the last half century is unusual in at least the previous 1300 years. The last time the polar regions were significantly warmer than present for an extended period (about 125,000 years ago), reductions in polar ice volume led to 4 to 6 metres of sea level rise."

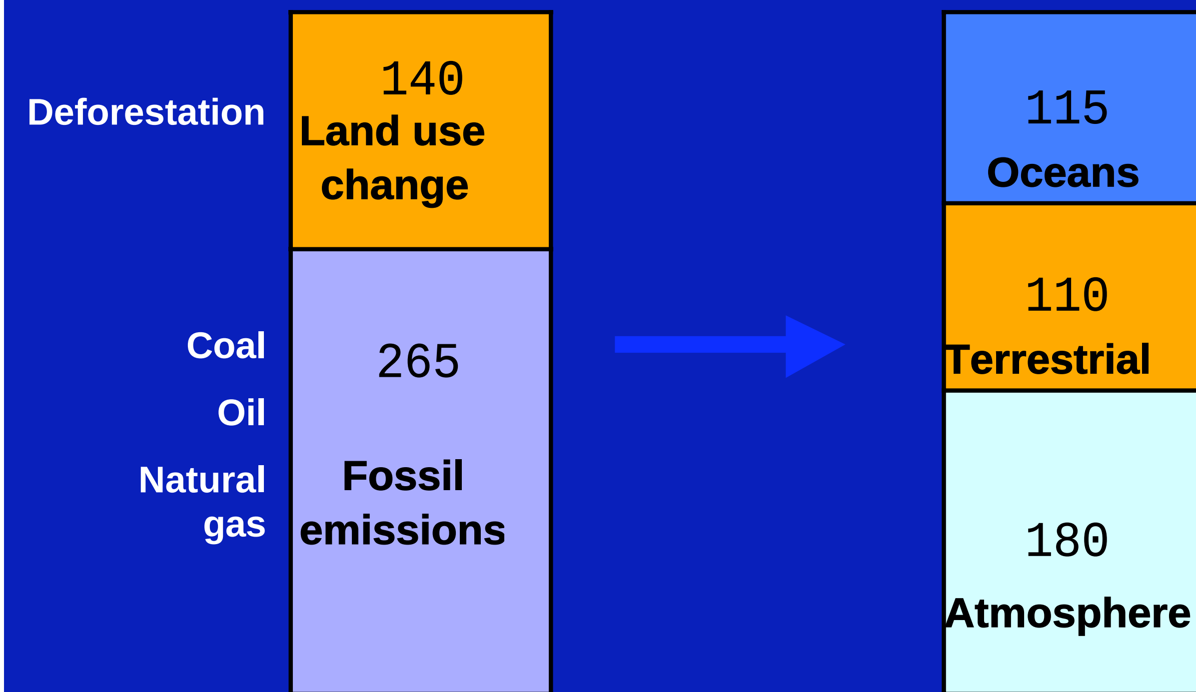


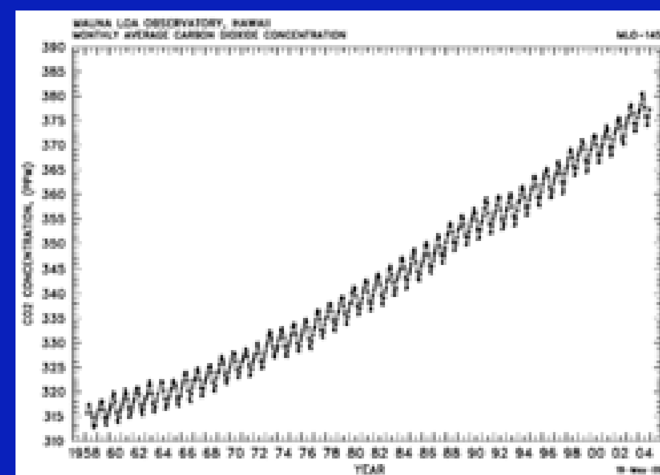
Rowley, et al., *EOS, 88* (9), 105 & 107, 2007

Fig. 1. Inundation of 6 meters (in red) for portions of the southeastern United States, Central America, and the Caribbean. Land cover and shaded relief map from Natural Earth, Tom Patterson, U.S. National Park Service.

CO_2 Emissions and uptakes since 1800 (Gt C)

Presently about 2 Gt C/yr into the oceans

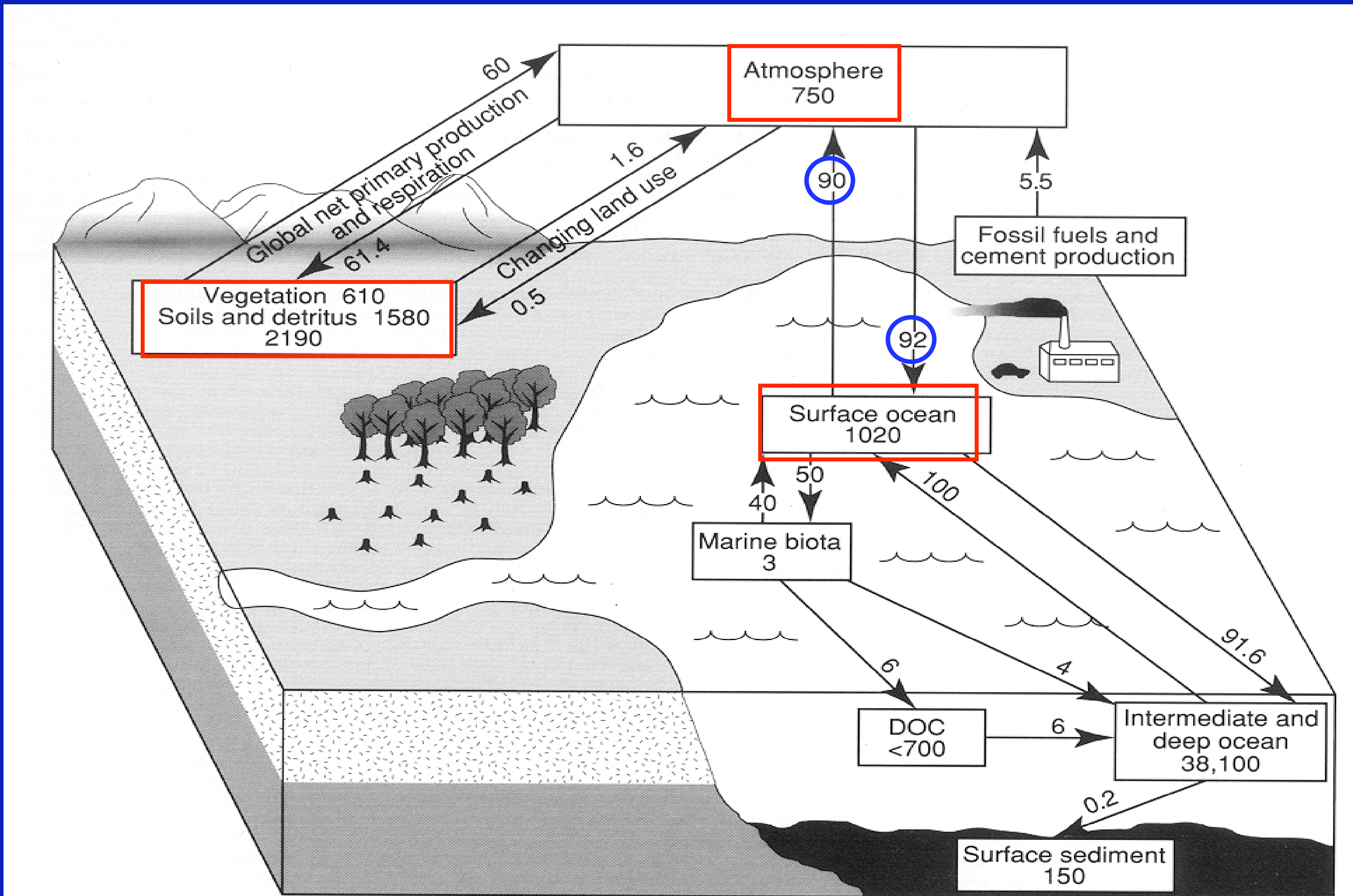




The atmospheric CO_2 concentration is very sensitive to the fraction that is lost to the oceans.

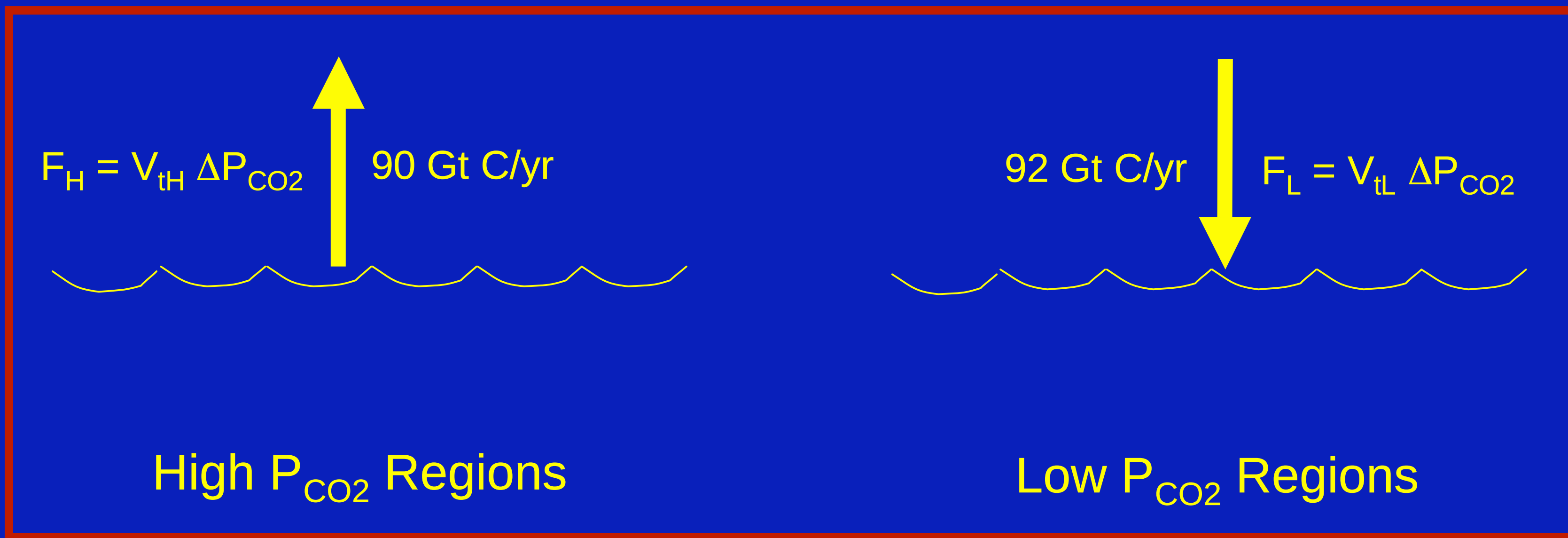
How might this change in a different climate?

Oceanic uptake of CO_2 is a small difference between big numbers, and the exchange *may not change symmetrically*!



Global Carbon Cycle   Reservoirs in Gt C and fluxes in Gt C/yr

Present Global Ocean CO_2 Uptake = 2 Gt C/yr



Nightingale et al., 2000: At most half of the variance in V_t is controlled by wind speed.

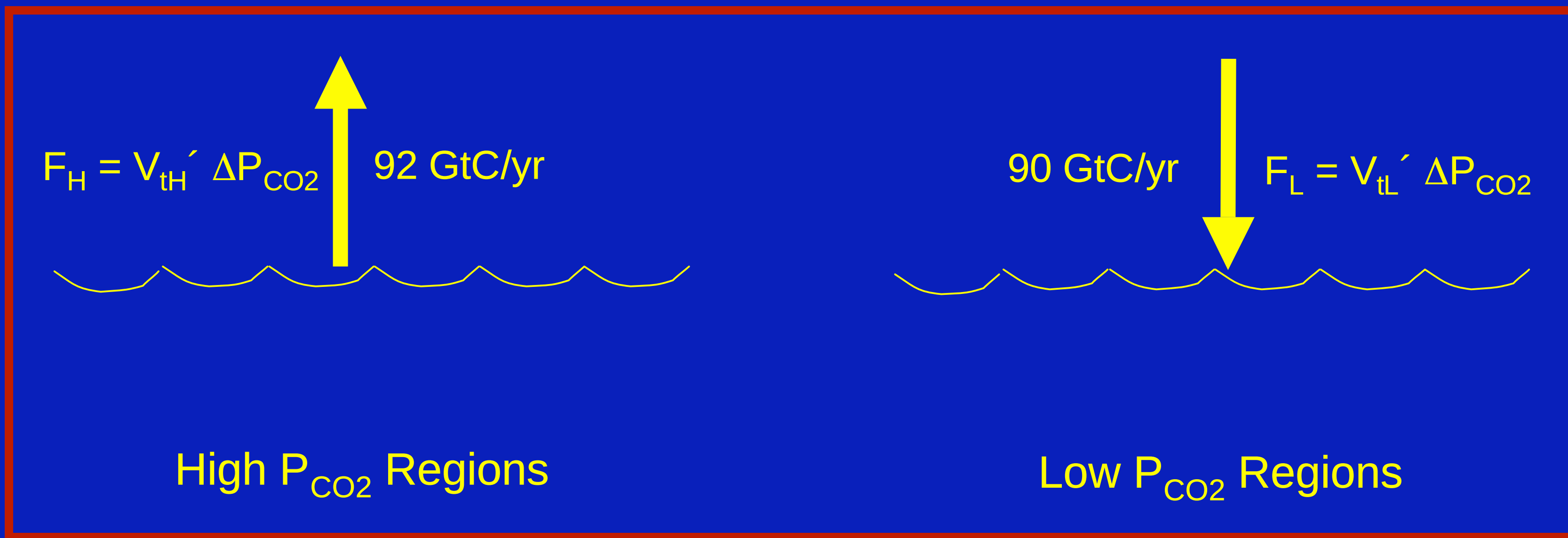
What if those other factors varied in such a way that

V_{tH} Increased by 2% and
V_{tL} decreased by 2%
while P_{CO2} was roughly constant?

This is entirely plausible.

If V_{tH} Increased by 2% and V_{tL} decreased by 2%:

Then the Global Ocean CO_2 Uptake = - 2 Gt C/yr



The ocean changes into a net Source of CO_2, rather than a Sink!

(Given our present state of ignorance, this example could just as likely go the other way, making the ocean *take up* more CO_2.)

It is critical that we quantify those other factors controlling V_t, since quite small changes could make large differences in ocean uptake.

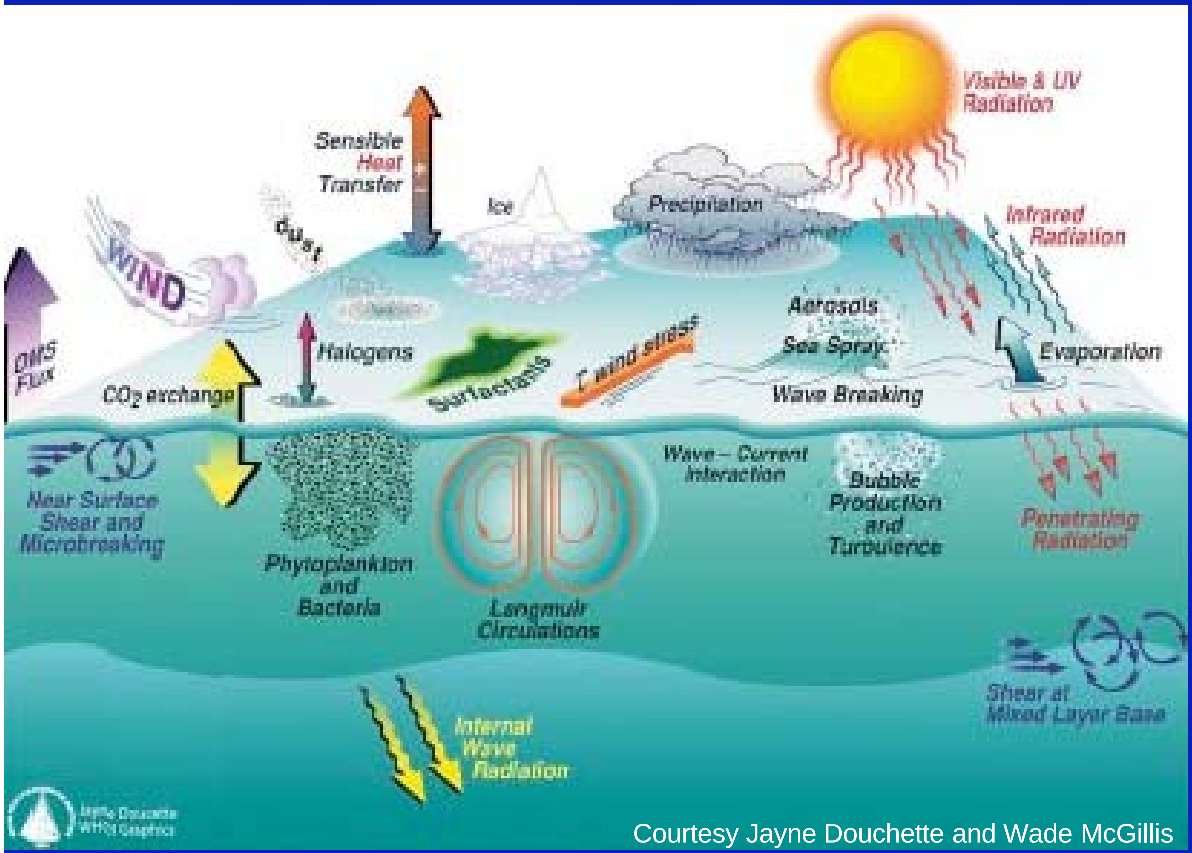
Is it *actually possible* for the net ocean CO_2 uptake to change so radically due to V_t?

What would we need to quantify to find out?

1. What are the quantitative relationships between each controlling factor and V_t?

2. How do those controlling factors vary from one region to another? (Specifically, High vs Low P_{CO2} regions)

3. How would we expect the controlling factors in each region to change under a changed climate?



Courtesy Jayne Douchette and Wade McGillis

Likely controlling factors:

- Wind speed
- Wind stress (turbulence)
- Ocean turbulence
- Bubble spectra
- Mean-square wave slope
- Surfactant films
- Rainfall surface disturbance
- Fresh water lenses from rain
- Temperature, salinity, …

These factors (and probably more) control exchange velocities.

What kinds of studies should SOLAS organize,
to quantify these relationships?

We have some powerful new tools.

What would we need to quantify?

…and what kinds of activities could do so?

1. What are the quantitative relationships between each controlling factor and V_t? [Process studies]

2. How do those controlling factors vary from one region to another? (Specifically, High vs Low P_{CO2} regions) [Surveys]

3. How would we expect the controlling factors in each region to change under a changed climate? [Models]

I'm going to focus on the process studies to quantify

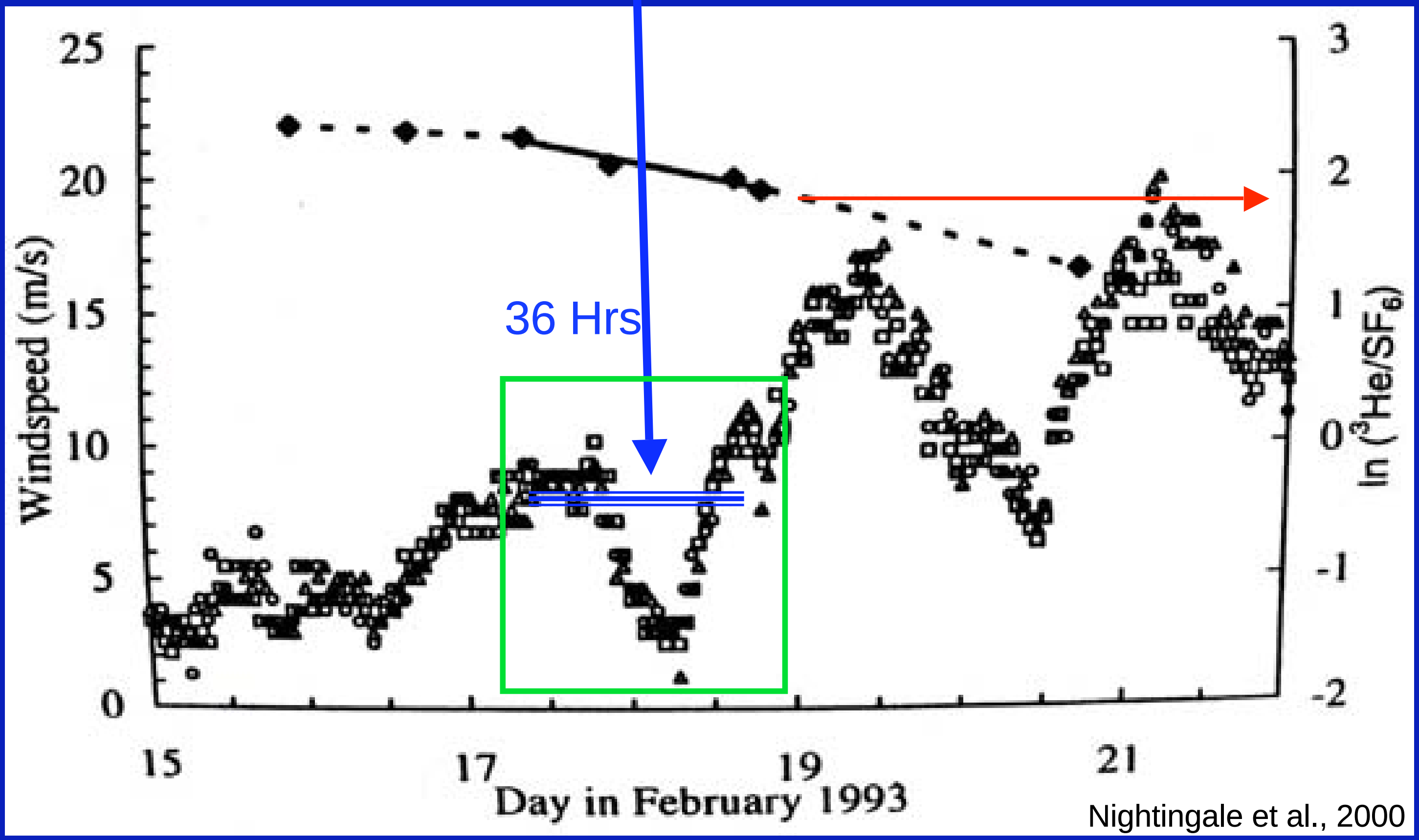
V_t(Controlling Factors).

What is the functionality of each?

What process studies can quantify the functionalities?

First, we need flux measurements on the same time-scales as changes in the controlling factors.

What *was* the wind speed during this interval?



The Vt (flux) measurement time resolution has to be an hour or less.

Eddy correlation is one of the few methods that can operate on this time-scale.

International SOLAS S&IP:

“The development and testing of analytical instruments capable of resolving frequencies of 1-10 Hz in biogenic gas concentration measurements in the atmosphere should be considered a *very high priority*.”

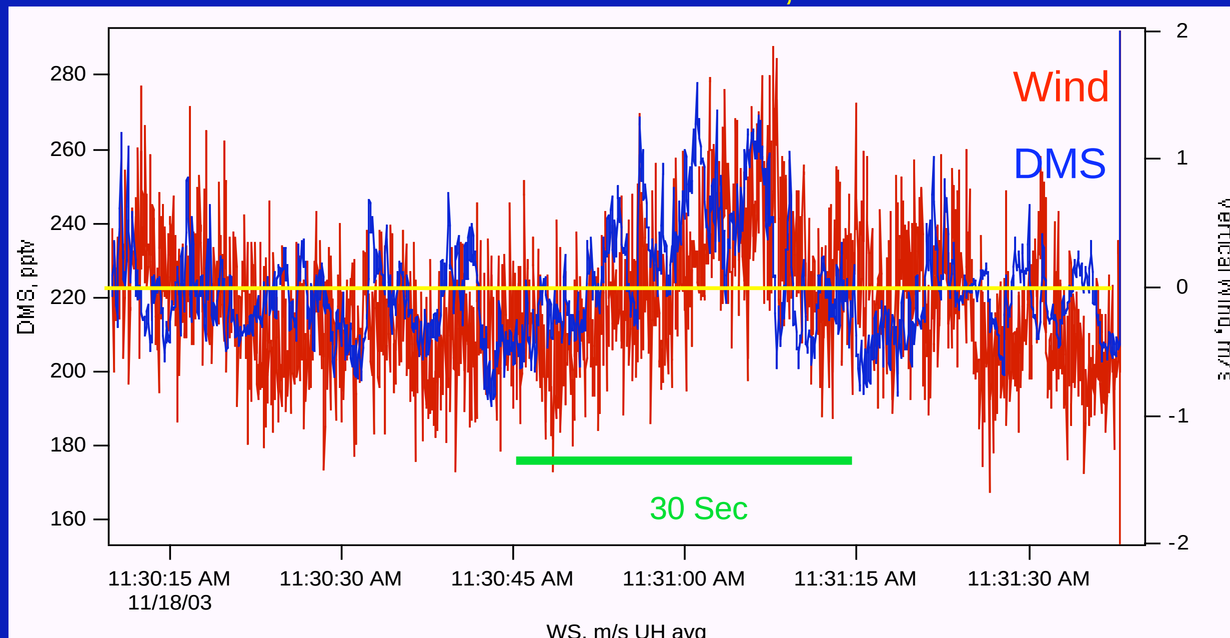
“These direct EC flux measurements can be made on the same time (20-30 min) and spatial (tens of km) scales as changes in the physical forcing processes.”

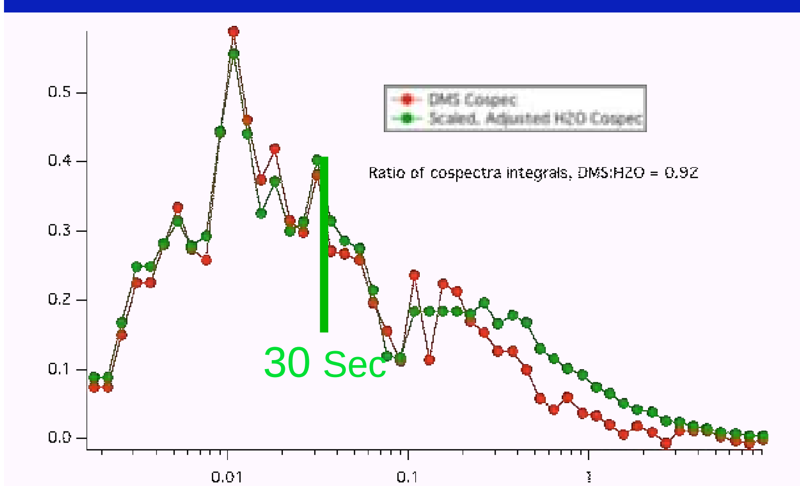
Note that it does not specify *which* gas, since controlling factors can be studied with any one.

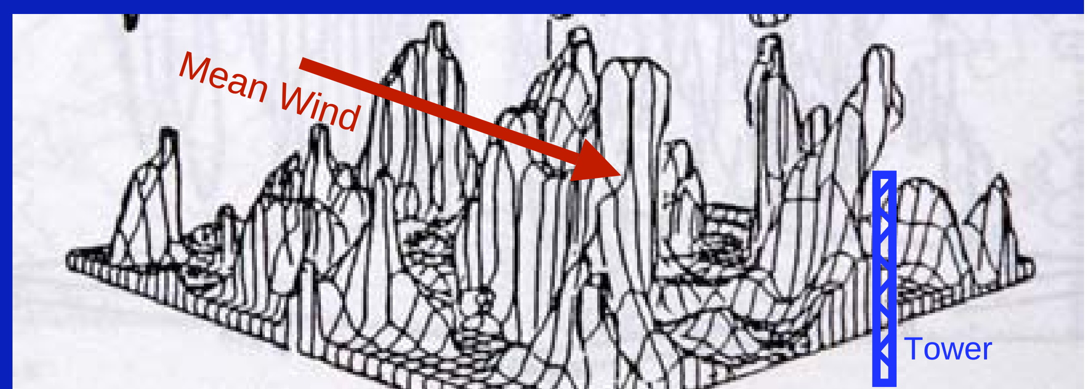
$$F_i = \overline{c_i'\omega'} = V_t \Delta c$$

For Eddy Covariance, the chemical measurement must resolve ~1 Hz

90 seconds of Vertical wind and DMS, Oct 03 TAO cruise

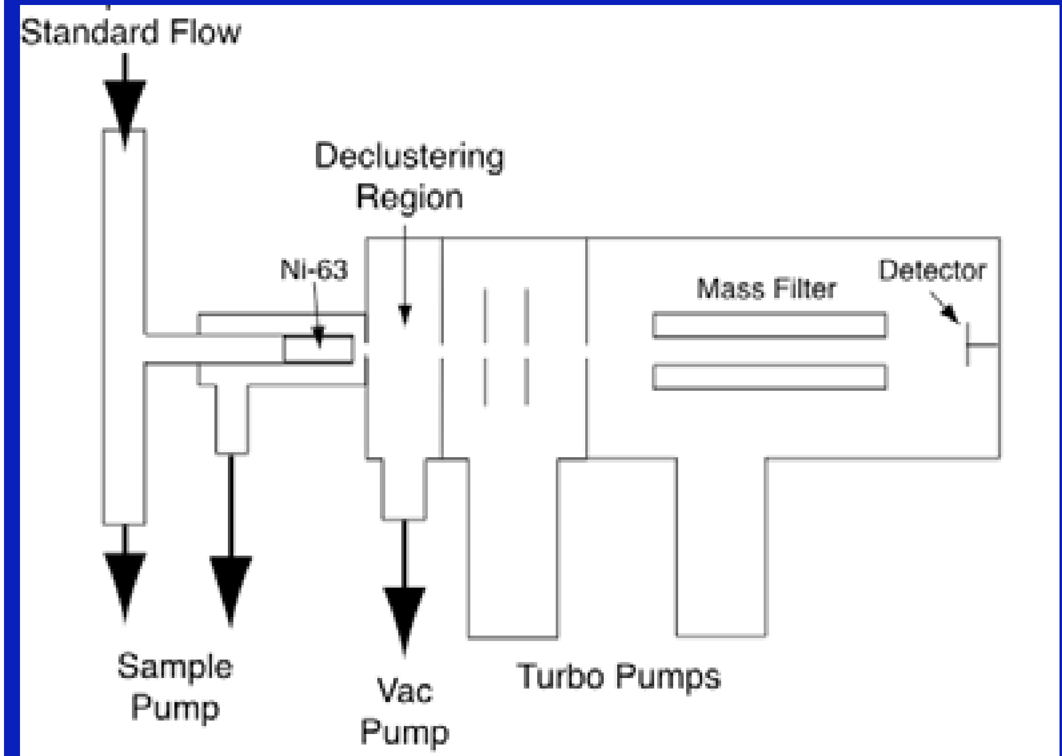






Fluxes must be averaged over many updrafts, >20 min

Atmospheric Pressure Ionization Mass Spectrometry (APIMS) can now make ~1 Hz measurements of DMS



Bandy, et al., *JGR*, *107*, 4743, 2002.

APIMS-ILS uses an Isotopically-labeled internal standard

APIMS-ILS is useful for DMS, SO_2 and probably CO_2, so we can make ~1 Hz concentration measurements to measure gas fluxes using Eddy Covariance.

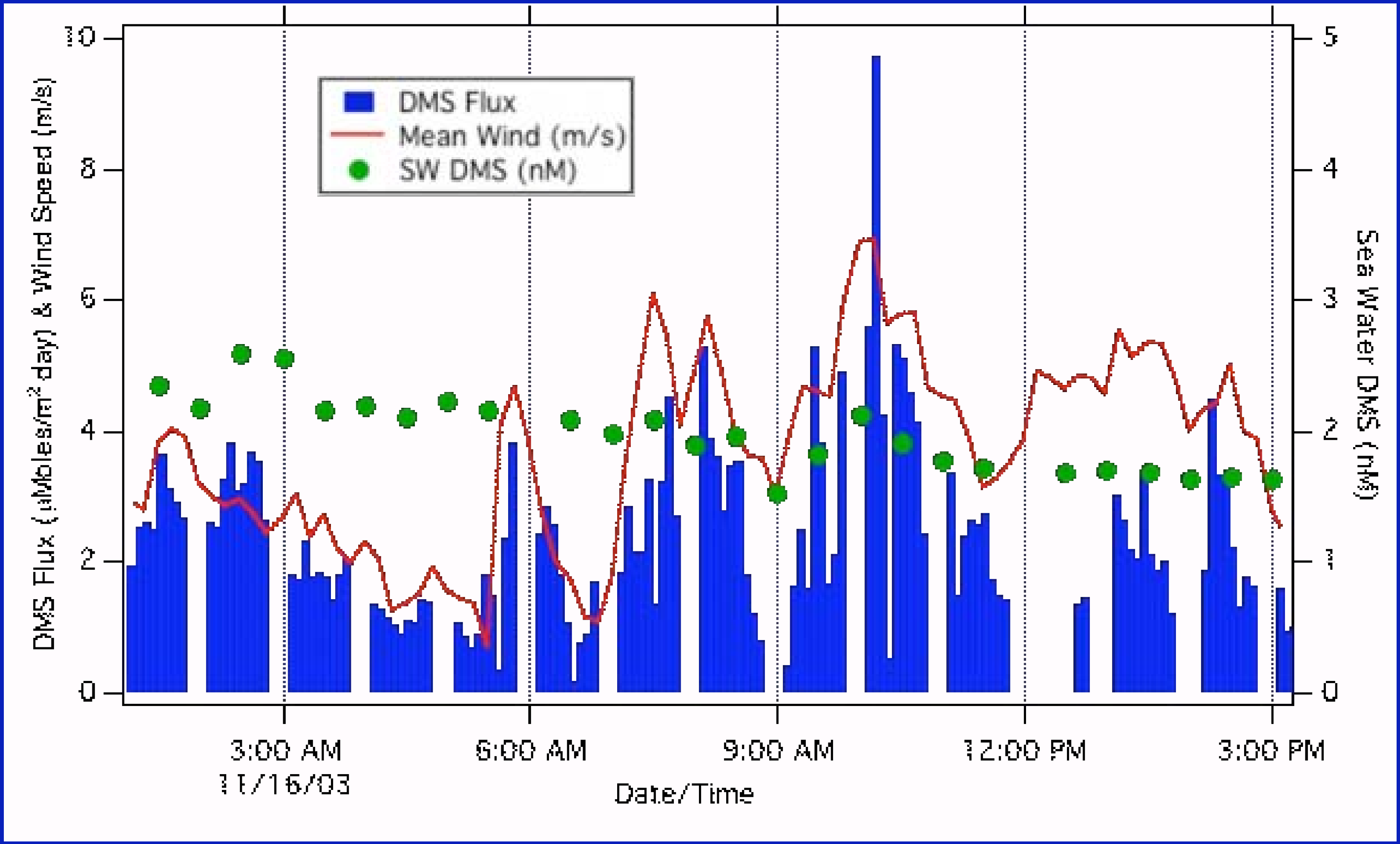
$H_3O^+ \bullet (H_2O)n$ + DMS (ambient) $\Rightarrow$ $\underline{DMS \bullet H^+}$ + $H_2O(H_2O)n$

$H_3O^+ \bullet (H_2O)n$ + D_3-DMS (spike) $\Rightarrow$ $\underline{D_3\text{-}DMS \bullet H^+}$ + $H_2O(H_2O)n$

The use of an *internal standard* means that every analysis has a built-in standard, 20 times a second.

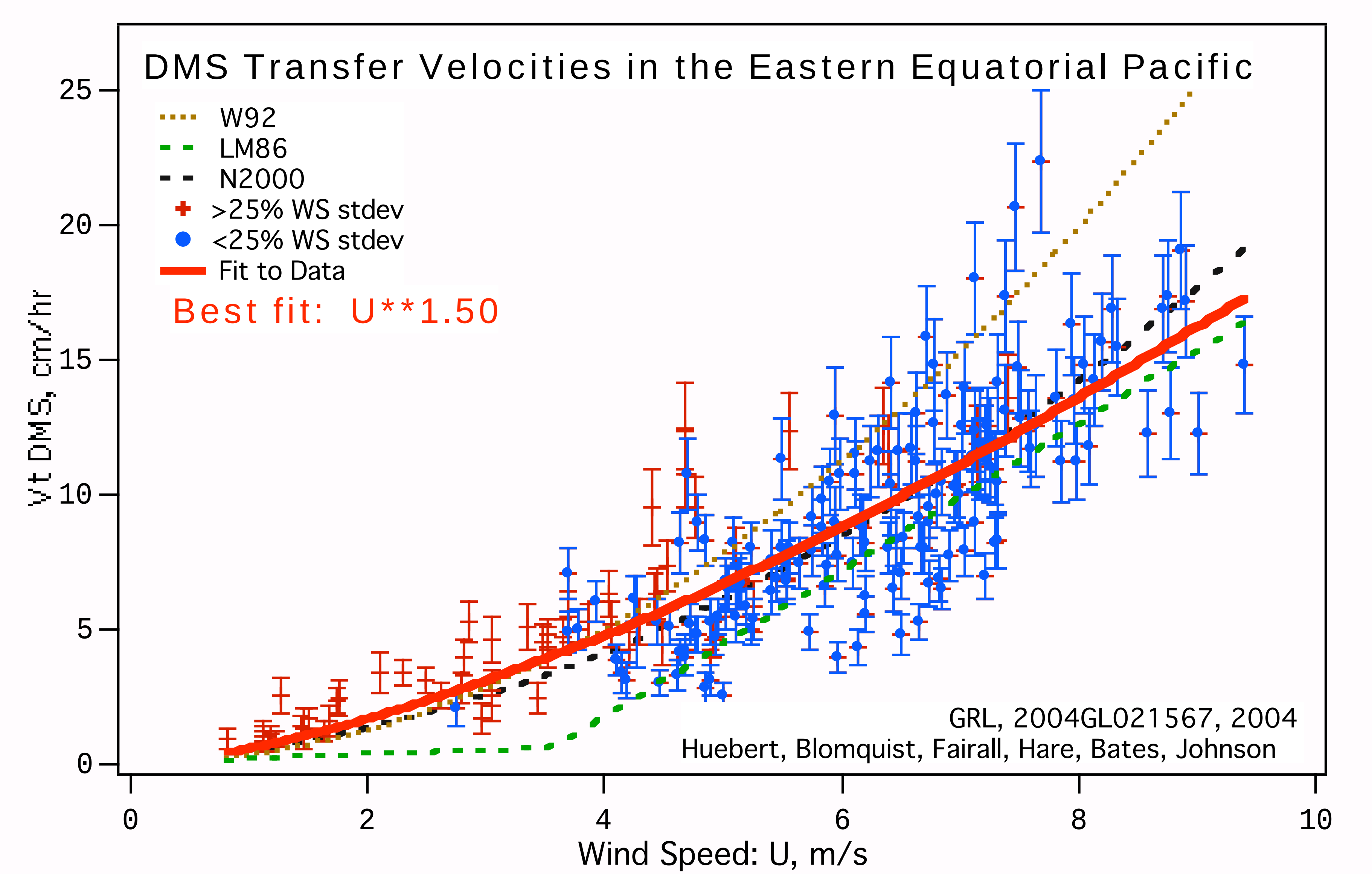
APIMS-ILS has made it possible to measure DMS fluxes by EC, with accuracies ~15% and times ≥ 20 minutes.

Huebert, et al., *GRL*, *31*, doi:10.1029/2004GL021567, 2004.



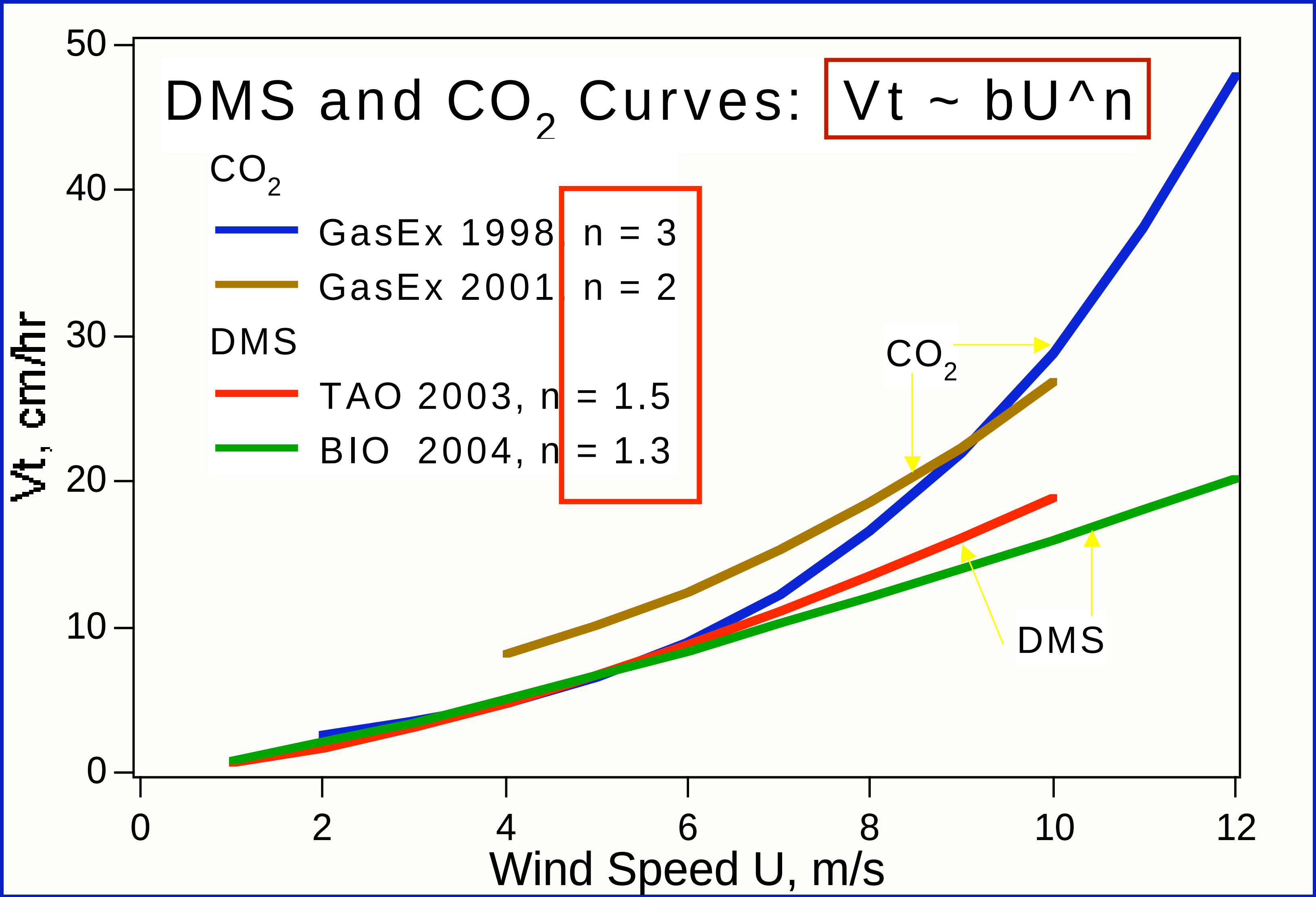
The DMS flux can respond very rapidly to wind speed changes…
…but not always. Clearly other factors also have some influence.

Our 2003 cruise DMS Exchange Velocities were *less* dependent on wind speed than quadratic.



On our next cruise, the curve was even flatter.

Different high-WS behavior changes the *shape* of V_t curves.

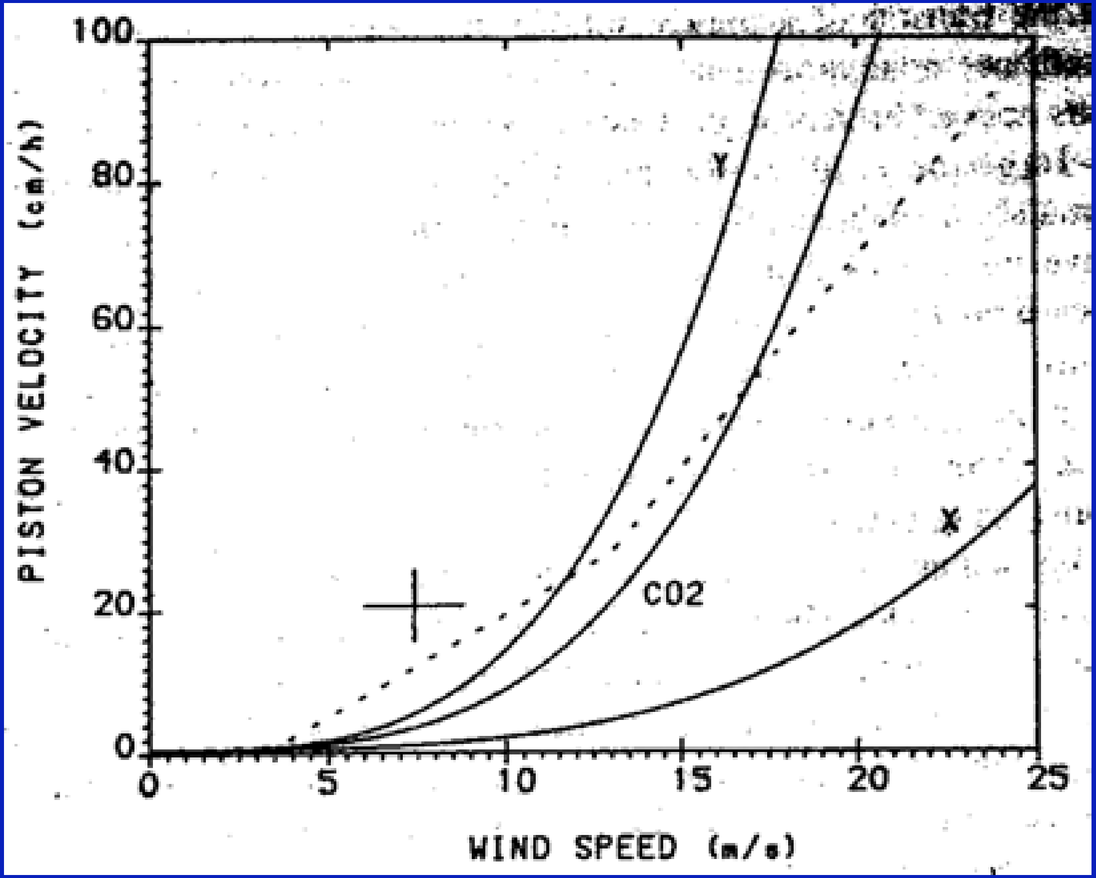


None of the WS-only parameterizations (LM87, W92, N2000) can predict these different curve-shapes for different gases.

Woolf (93) predicted exactly this difference, based on bubble-mediated transfer and solubility.

Woolf argued that the DMS curve would be much flatter than that for CO_2, due to the higher solubility of DMS.

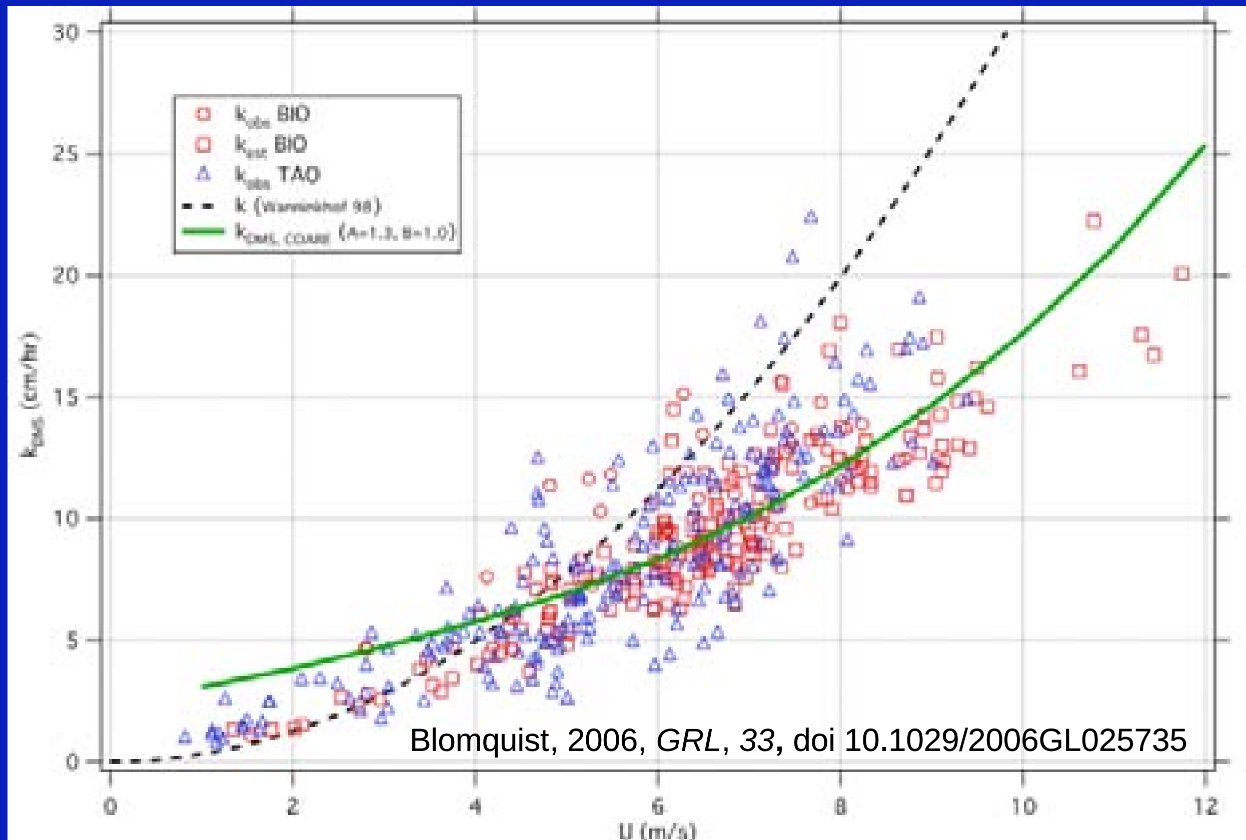
Woolf, *Atmosphere-Ocean*, *31*, 517-540, 1993.



" Gas X" has Schmidt # = 600, but the solubility of DMS.

Bubbles are more effective for less soluble gases.

The NOAA/COARE model (including Woolf's function for bubbles and gas solubility) predicts the right shape for k_{DMS} (and for k_{CO2}).

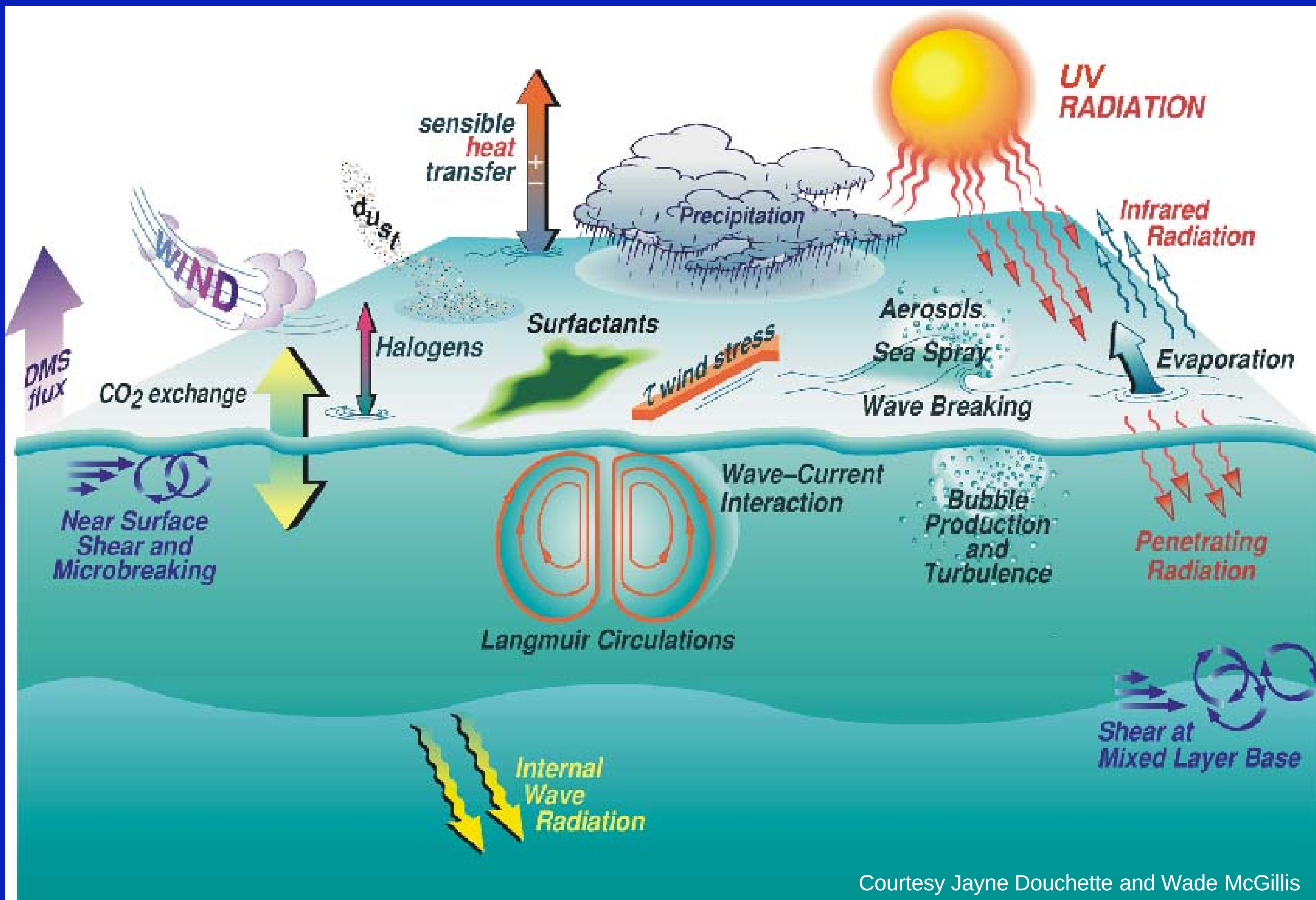


So one useful approach is to

1. use lab experiments and theory to guess at the right functionality, and then
2. compare models including those processes with in situ data.

A better approach is to measure transfer velocities while *directly measuring the controlling factors*.

The same factors will affect DMS, CO_2, N_2O, CH_3I, CH_4, …



Approach A (Adequate):

1. use lab experiments and theory to guess at the right functionality, and then
2. compare models including those processes with in situ data.

Approach B (Better):

measure the controlling factors and look for correlations between V_t and the changing factors.

Your cruise should therefore include measurements of fluxes, $[C]_{sw}$ and $[C]_{air}$, and

Wind speed

Wind stress

Ocean turbulence

Bubble spectra

Mean-square wave slope

Surfactant films

Rainfall

Fresh water lenses

Temperature, salinity, …

Approach C: *Intercompare* flux measurement methods, to validate less costly approaches and assess their accuracy.

- Eddy correlation by APIMS-ILS
- Atmospheric gradient methods
- Nighttime DMS increase
- Daytime photochemical DMS loss
- Thin-film methods (LM87, W92, N2000, etc.)
- Ozone and CO_2 eddy correlation
- *Multiple groups with similar methods*

Method comparisons are virtually always informative, even when the results aren't pretty.

Experiments using Approaches A, B, and C are being planned:

DOGEE, Deep Ocean Gas Exchange Experiment, North Atlantic in June/July 2007, on the UK R/V *Discovery (Rob Upstill-Goddard)*

Will work in and out of a bloom, deploy a deliberate surfactant layer, and measure DMS and CO_2 fluxes and several controlling factors
http://web.pml.ac.uk/solas/dogee/dogee.htm

GasEx-III, NOAA Gas Exchange Experiment, South Atlantic in March 2008, on NOAA's *R/V Ronald H. Brown (David Ho)*

Will compare multiple methods for CO2 fluxes and our DMS APIMS-ILS, while measuring many controlling factors in a high-wind area.
http://www.climate.noaa.gov/cpo

VOCALS-REx, VAMOS Ocean Cloud Atmosphere land Study, SE Pacific in October 2008, on NOAA's *Ronald H. Brown (Rob Wood)*

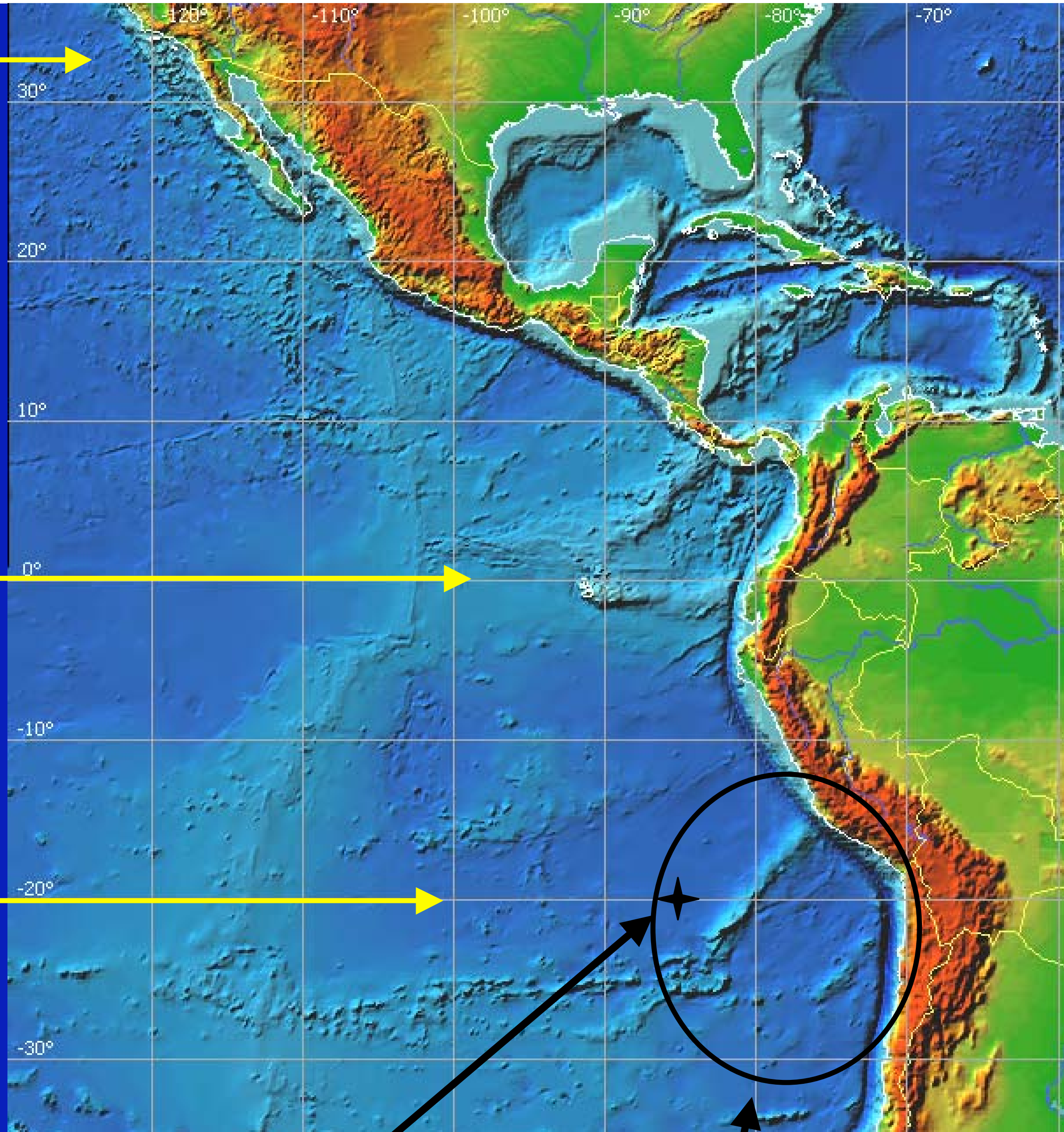
Fluxes will be measured in the context of an aerosol/cloud/DMS study, along with precip, sea state, and other controlling factors.
http://www.eol.ucar.edu/projects/vocals/

We are planning an IFO in October 2008

DYCOMS-II

TAO-EPIC

EPIC2001-Sc



WHOI Buoy

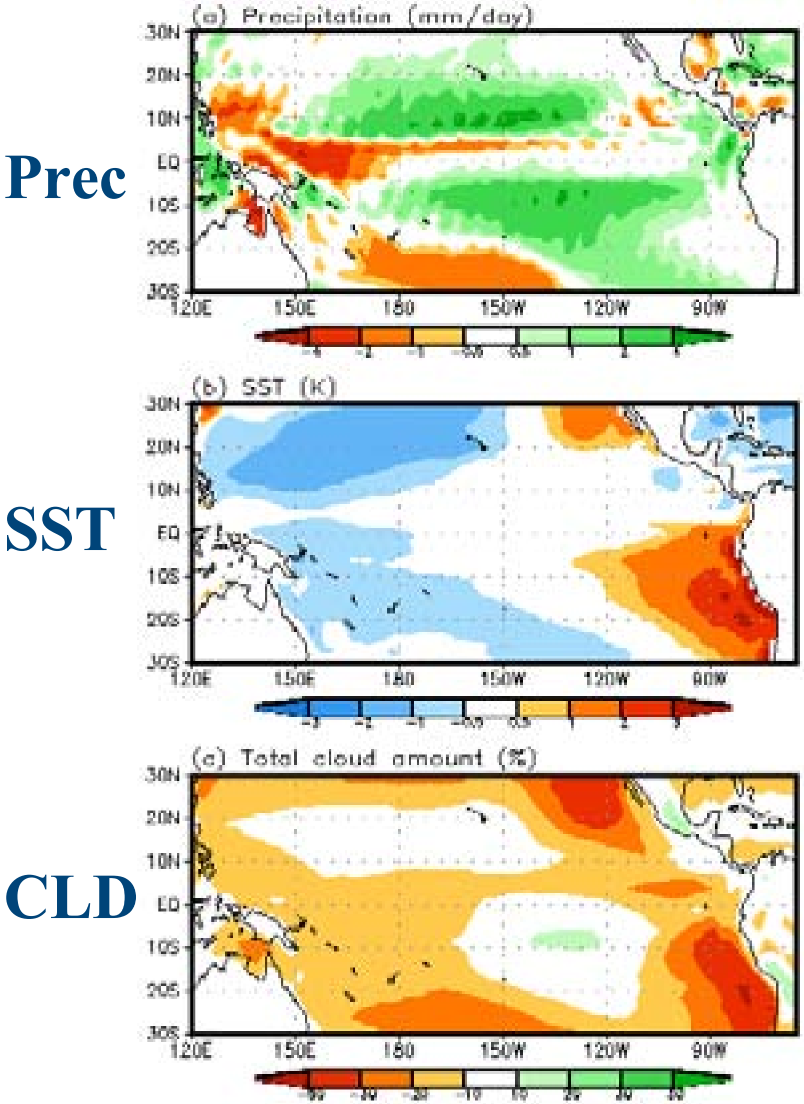
VOCALS Region

The VOCALS motivation:
Large CGCM Errors

- The NCEP CFS model has significant errors in the SE Pacific (also GFDL, NCAR…)
- There is a meridional shift in ITCZ (top), a warm SST bias (middle) and insufficient stratocumulus cloud cover, (bottom)
- These errors adversely affect the skill of CFS climate forecasts (ENSO).

VOCALS addresses the model developments required to alleviate these systematic CGCM errors

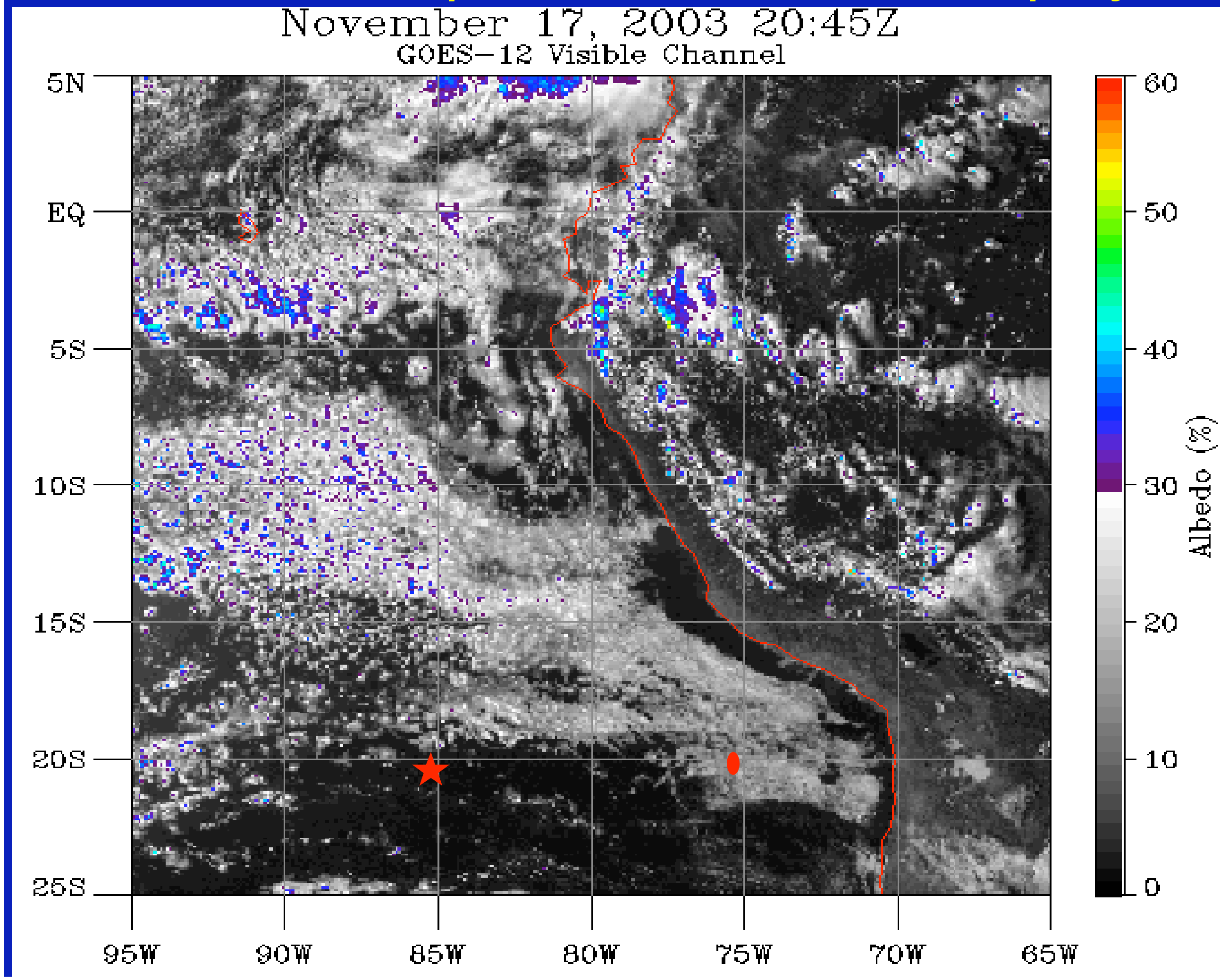
CFS Errors



What role do aerosols play in creating these pockets of open cells, POCs? Drizzle removal? Refilling?

To improve models of this region, we need to quantify the factors controlling clouds and radiation.

http://www.eol.ucar.edu/projects/vocals/



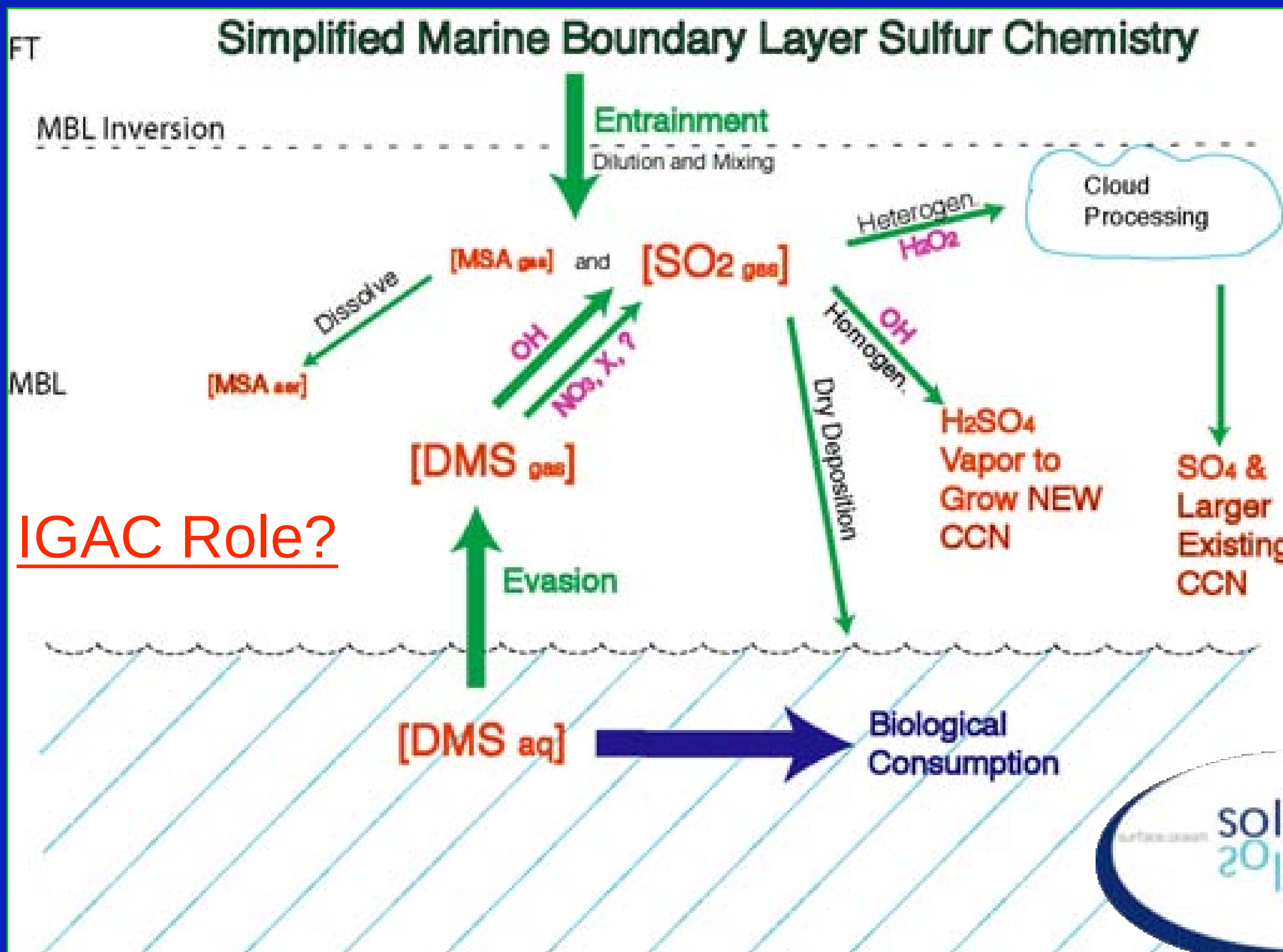
2-300 Wm^{-2} Difference!

The *supply* of DMS and its *oxidation mechanisms* limit the rates of new particle nucleation and growth.

These processes probably control the re-filling of POCs with clouds.

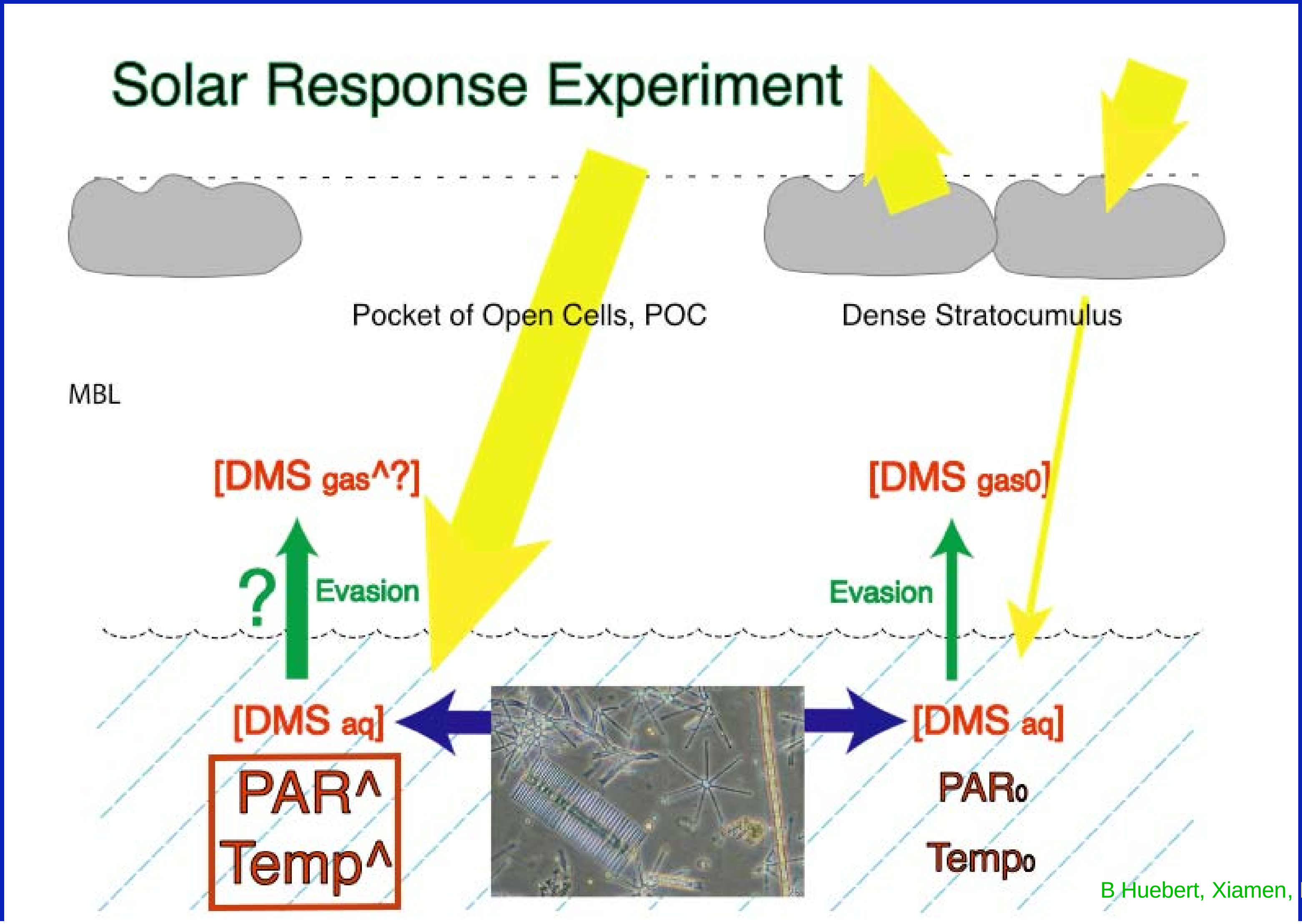
Photochemistry, iodine, ammonia, and <u>organics</u> may also play a role.

SOLAS is planning to study S chemistry from both ship and aircraft.



POCs should change irradiance (and thus SST) enough to allow a test of the light / temp > biology > DMS emissions parts of the CLAW Hypothesis.

A separate SOLAS experiment along these lines might be proposed for 2009 or later. Discussion group this afternoon.



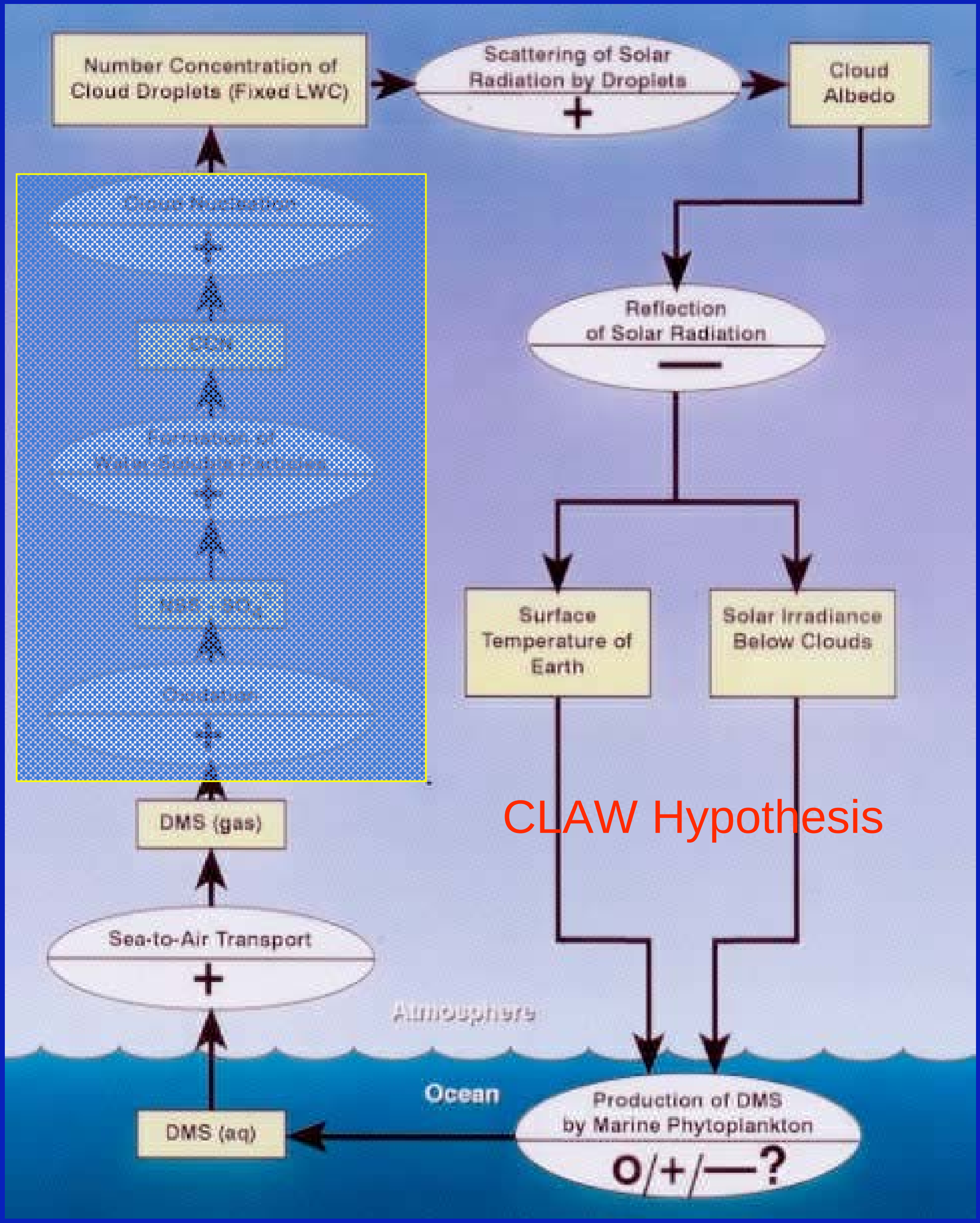
B Huebert, Xiamen, Mar 2007

This is an excellent natural laboratory to test parts of the CLAW Hypothesis

Possible experiments include examining the impact of POC-driven irradiance changes on SST, productivity, and DMS fluxes, all the unshaded parts of this diagram.

Testing the DMS_{gas} to CCN parts would require Lagrangian observations.

Nature, *326*, 655-661, 1987.



Summary

- DMS (and other) fluxes can be measured rapidly and accurately with APIMS-ILS, making it possible to measure fluxes on hour (or less) time-scales for deriving V_t.

- These rapid flux (V_t) measurements can be made alongside measurements of the factors controlling V_t, to look for correlations.

- In some cases, physically-based models can be used to test the functionality of controlling factors.

- Method Intercomparisons are critical to test flux methods.

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- DMS (and other) fluxes can be measured rapidly and accurately with APIMS-ILS, making it possible to measure fluxes on hour (or less) time-scales for deriving V_t.
- These rapid flux (V_t) measurements can be made alongside measurements of the factors controlling V_t, to look for correlations.
- In some cases, physically-based models can be used to test the functionality of controlling factors.
- Method Intercomparisons are critical to test flux methods.

- Controlling factor measurements should be added to flux experiments with geophysical objectives, to look for functionalities.

- These experiments must be done in many different regimes, where the variation of each relevant controlling factor can be quantified.

- Physically-based models should replace wind-only models of Vt, so controlling factor functionalities can be included.

- The net ocean uptake of CO_2 could increase or change sign under a changed climate, due to its high sensitivity to exchange velocity dependencies.

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I did not intend to suggest that CO_2 source or sink regions were homogeneous entities. Rather, if all the estuaries and rivermouths changed in a particular way, the many Equatorial upwelling areas might change in the opposite way.

Since the net C uptake is a small difference between large numbers, any coherent change could make a proportionally much larger change in the net uptake number and sign. Is that a sensible argument?

I guess it only makes sense if surface exchange is limiting in the long term. Andy Watson speculated that perhaps the exchange velocity wasn't the most critical factor of concern here: if the net loss of atmospheric CO_2 is controlled largely by how fast physical or biological carbon pumps operate, are there any areas where the exchange coefficient matters? We're back to serial resistances, again. In what circumstances would a change in our understanding of exchange velocities change flux estimates, as opposed to carbon pumps? Someone in JGOFS must have addressed that.

Barry, 20th March 2007

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