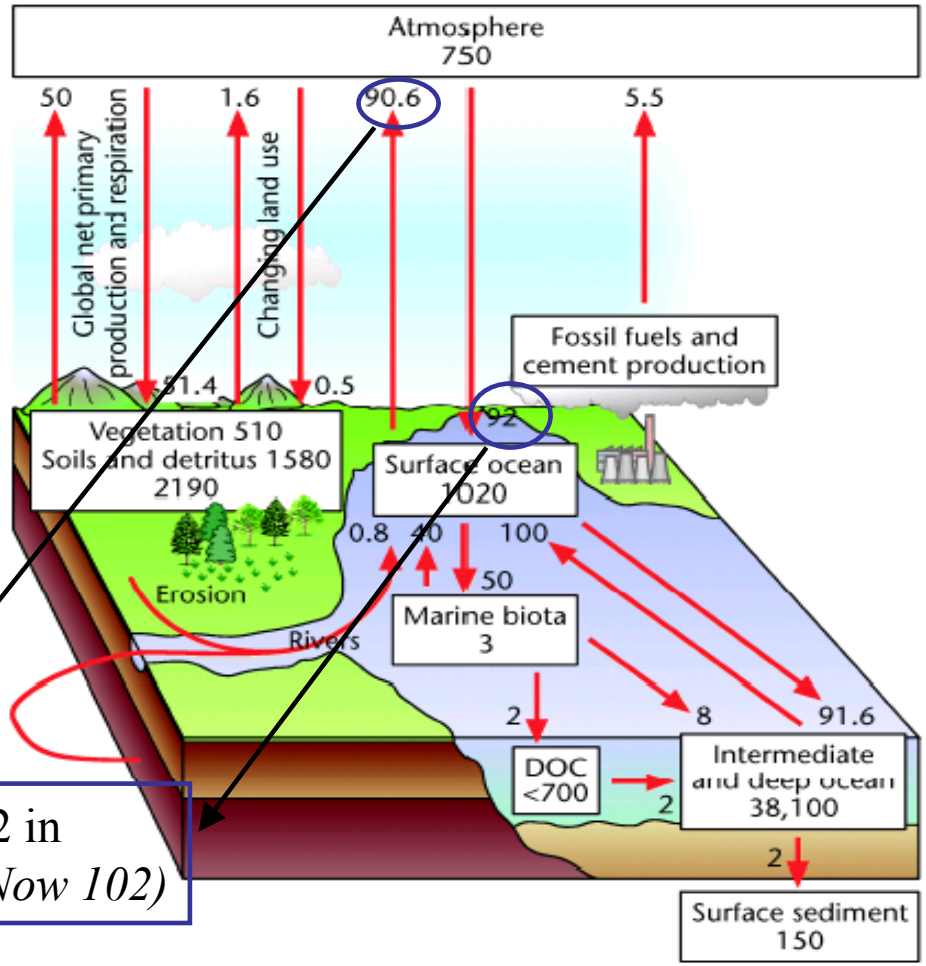
pCO_2 measurements from VOS:
Why do we need high resolution observations?

Rik Wanninkhof NOAA/AOML

The US Carbon Cycle Science Program:
Reduce uncertainties in fluxes between major carbon reservoirs.



90.6 out
(Now 100)

92 in
(Now 102)

Objective of the US Carbon Cycle Science Plan:

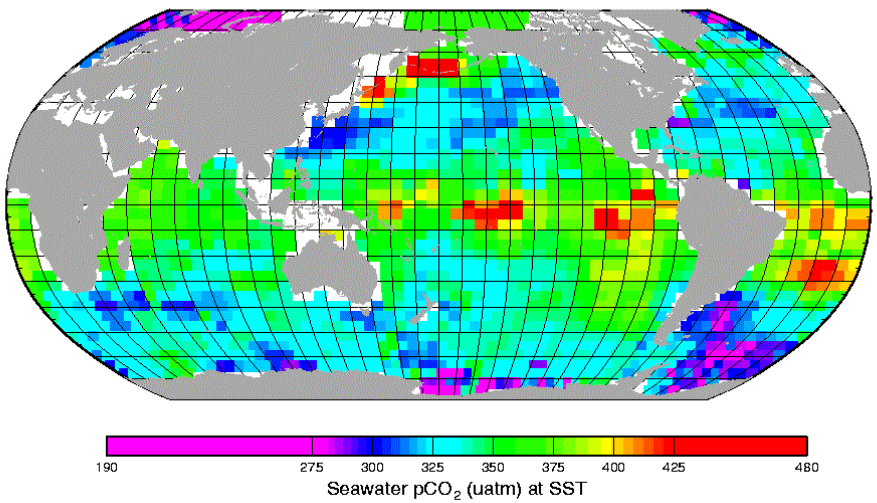
Constrain the exchange of CO_2 between ocean and atmosphere in order to improve prediction of future CO_2 levels

"Determine regional air-sea CO_2 fluxes on seasonal timescales to 0.2 Pg C yr^{-1}"

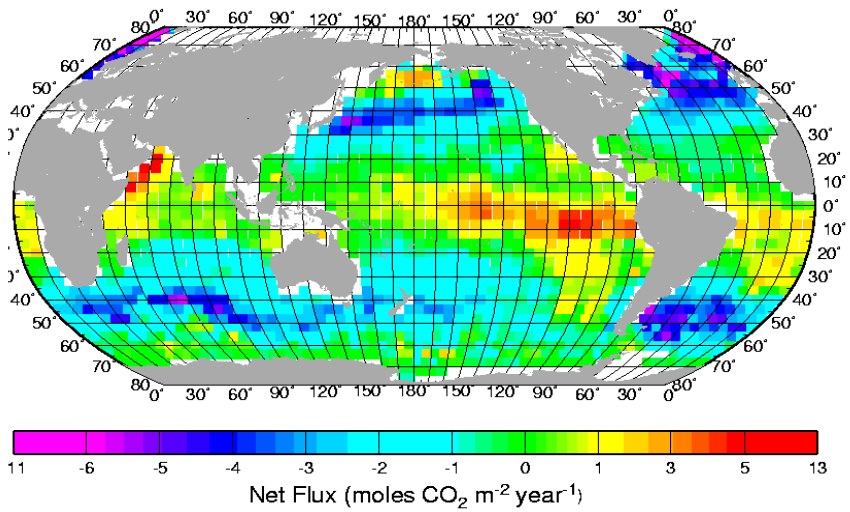
This will require synoptic observations of "driving forces", improved data assimilation, and improved mechanistic understanding of the driving forces.

$$F = k\, s\, (pCO_{2w} - pCO_{2a})$$

(B) Climatological pCO_2 in Surface Water for February 1995



an Annual Air-Sea Flux for 1995 (NCEP 41-Yr Wind, 940K, W-92)



Global fluxes uncertain to about 50 % with a range 1.5 to 2.8 Pg C yr^{-1}

Implementation:

Sustained Ocean pCO_2 Observing network

Determine air-sea fluxes between ocean and atmosphere on basin and seasonal timescales.
"Flux maps"

Goal.- * Quantify Fluxes in North Atlantic and North Pacific in support of NACP
* Fill in observational holes elsewhere (> 30 ˚S Atlantic and Pacific)

NOAA VOS program:

1. NOAA Research Ships and Antarctic supply ships
2. VOS lines

QuickTime™ and a
Photo - JPEG decompressor
are needed to see this picture.

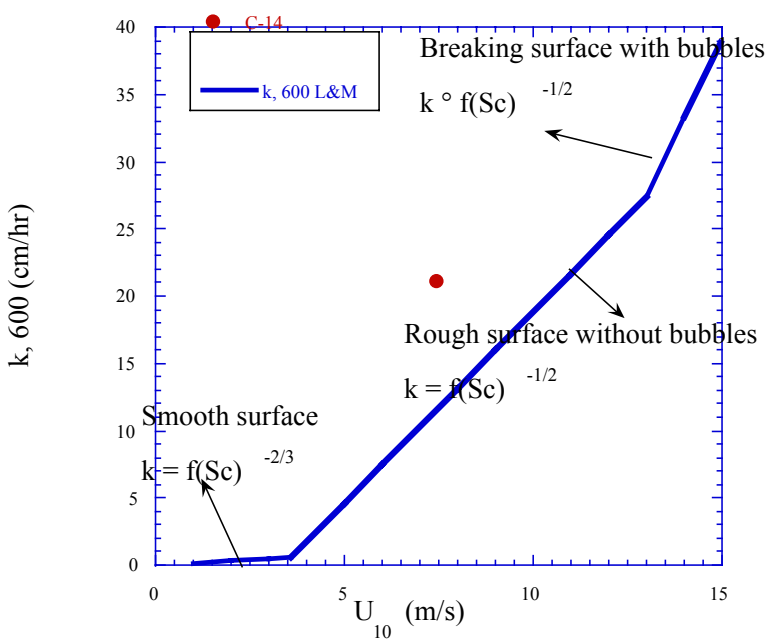
NOAA UW pCO_2 lines in the Atlantic- (funded 2002)

What is needed to determine fluxes:

$$F = k\, s\, (pCO_{2w} - pCO_{2a})$$

Gas transfer velocity
Function of:
Surface turbulence (wind speed)
Physical properties of gas and water
$k = (Sc)^{-1/2} = (\nu/D)^{-1/2}$

Thermodynamic component:
Function of:
Temperature
Biology (photosynthesis/respiration)
Transport (horizontal/vertical)

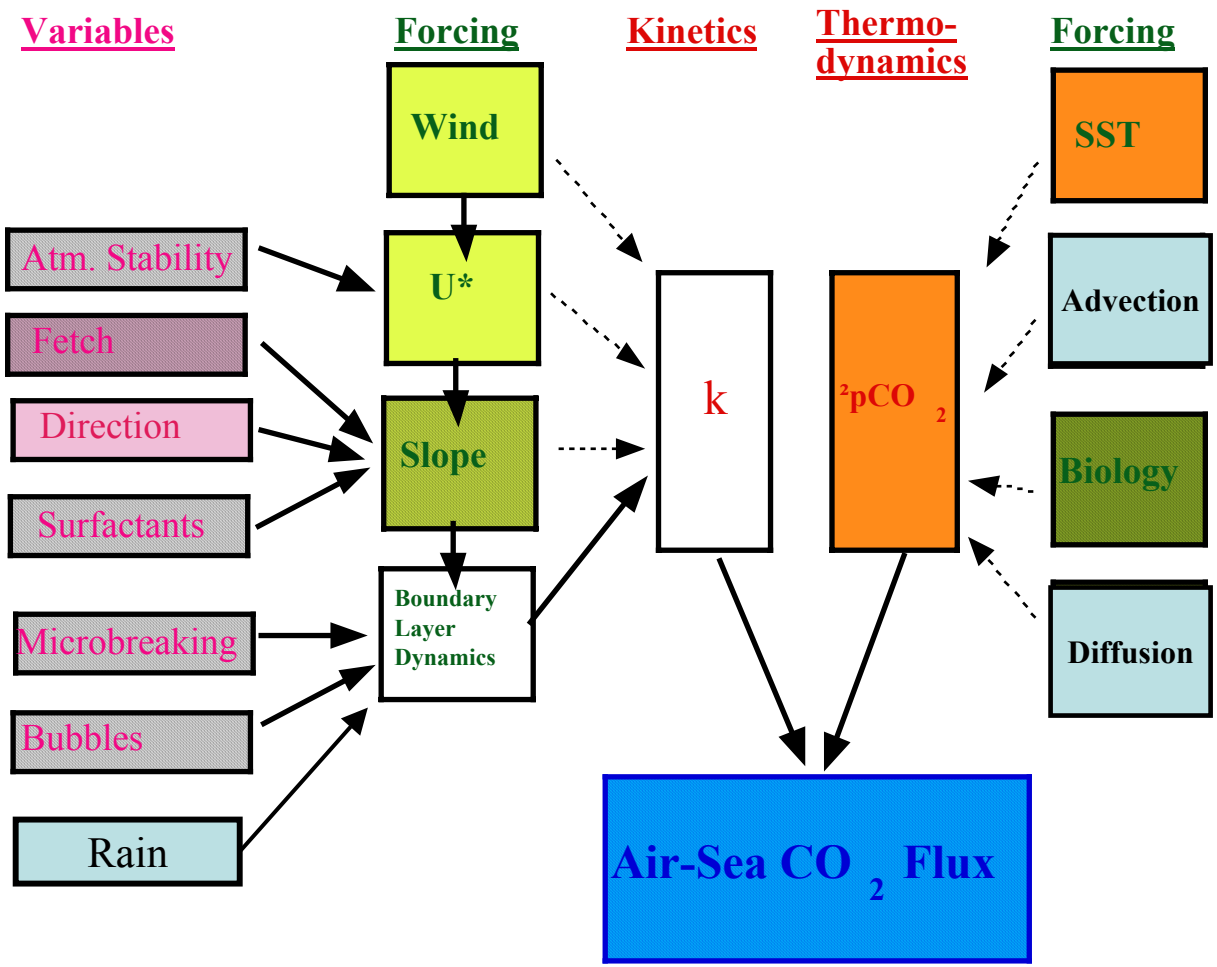


Note, $F_{av} = (k\, s\, \Delta pCO_2)_{av}$

$\neq k_{av}\, \Delta pCO_{2av}$

$= k_{av}\, \Delta pCO_{2av} + (k\, s)'\, \Delta pCO_2'$

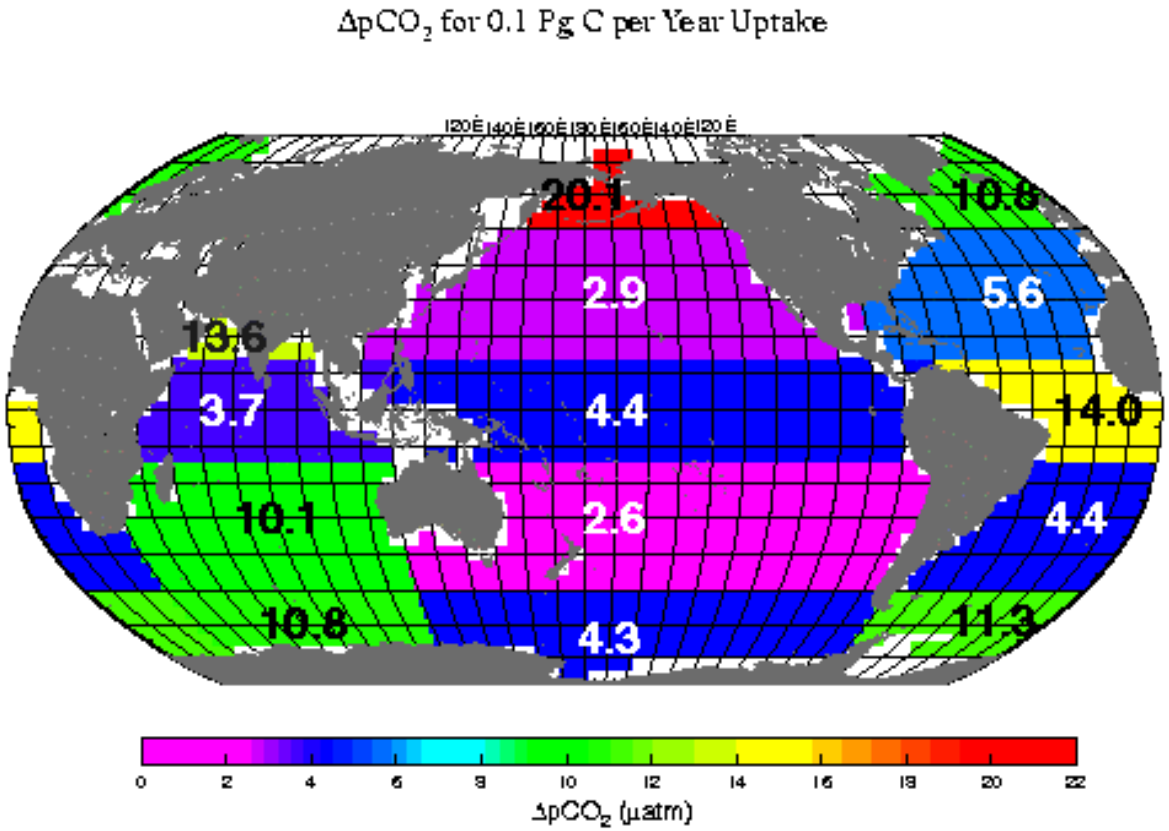
Factors influencing Air-sea CO_2 fluxes



Kinetic forcing:
"High" Frequency
(< day)

Thermodynamic forcing
"Low" Frequency
(> day)

Requirements for Δ pCO_2 measurements

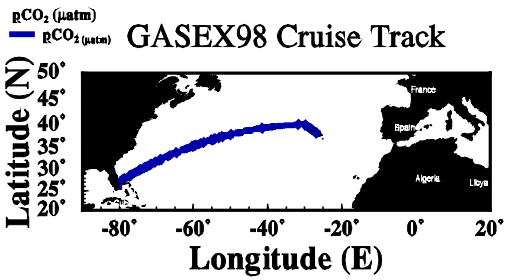


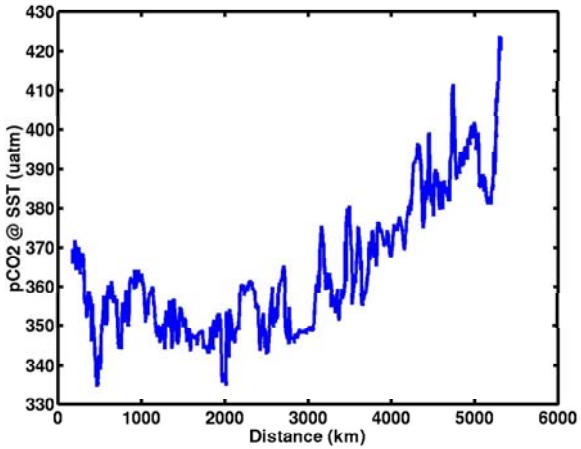
Courtesy of Sweeney

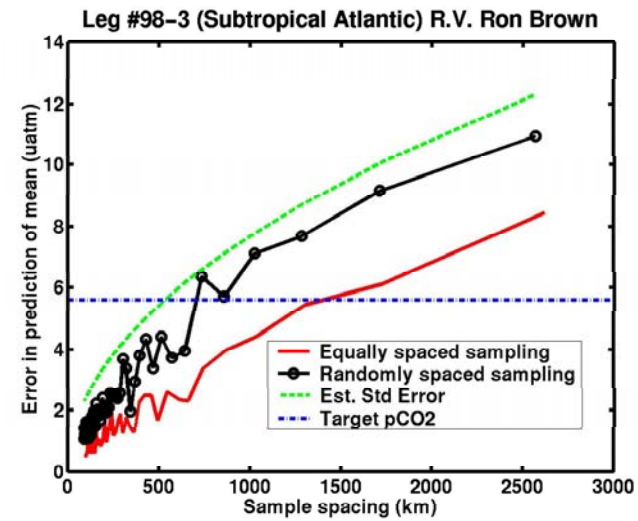
$F = k\, s\, \Delta pCO2$ » $\Delta F = 0.2 / A = \Delta(k\, s\, \Delta pCO2)$ » $\Delta(\Delta pCO2) \propto 0.2\,(U^2 A)^{-1}$

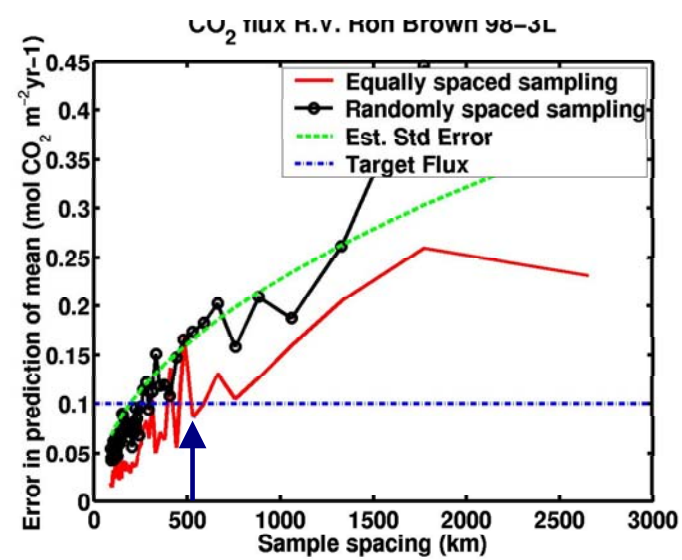
Large Scale Observations: Spacing of observations

Determine decorrelation length scale in order to constrain fluxes to 0.2 Pg C/yr:
Regionally dependent but on average 10^3 km, 6-9 time year, equally spaced,









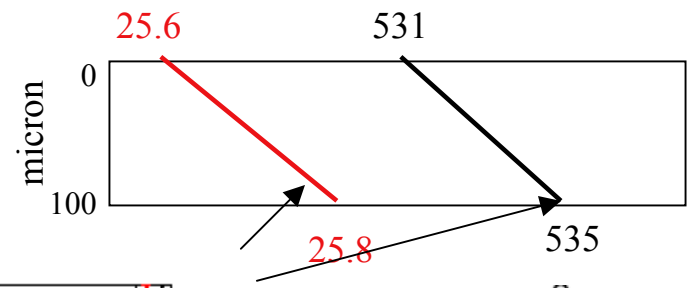
1. A premium on equal spacing
2. Scales for fluxes < 1/3 scales for pCO_2

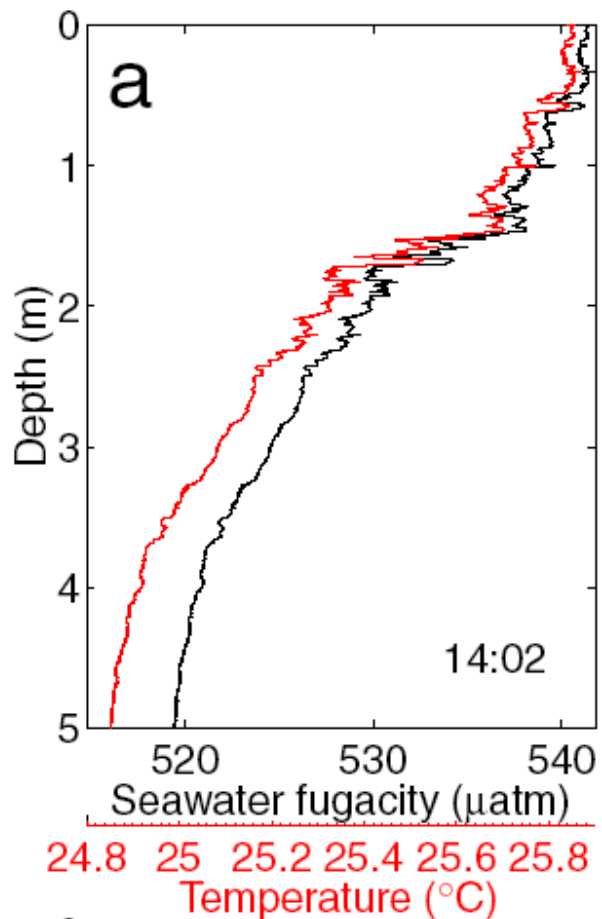
Courtesy Colm Sweeney, Princeton

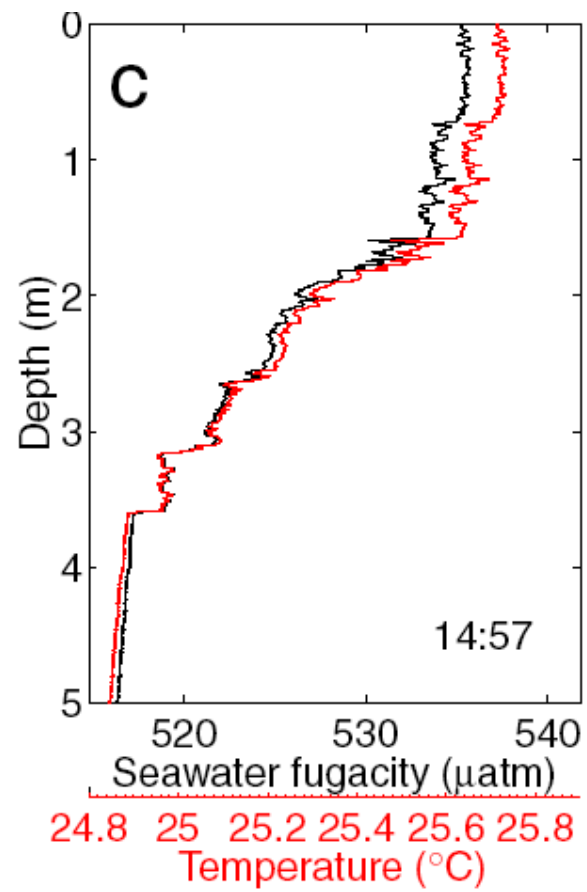
High resolution measurements ΔpCO_2- **temperature** : $dpCO_2/dT = 0.0423$

pCO_2: cool skin temperature and warm layer effects- timescale hours

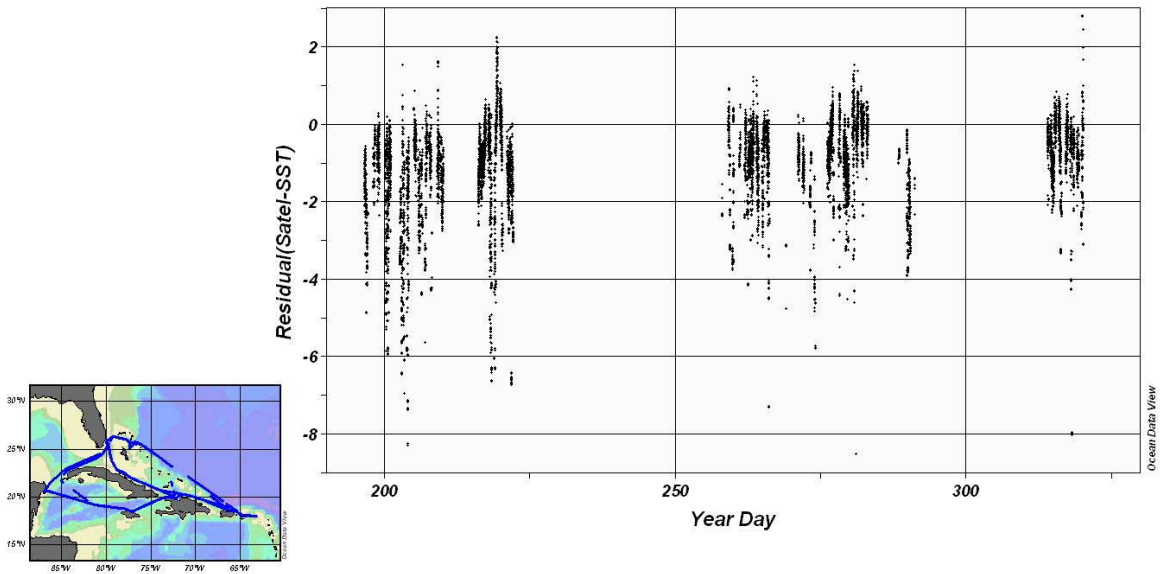
Effect of cool skin
0.7 to 0.2 pG C/yr
Bias towards greater uptake



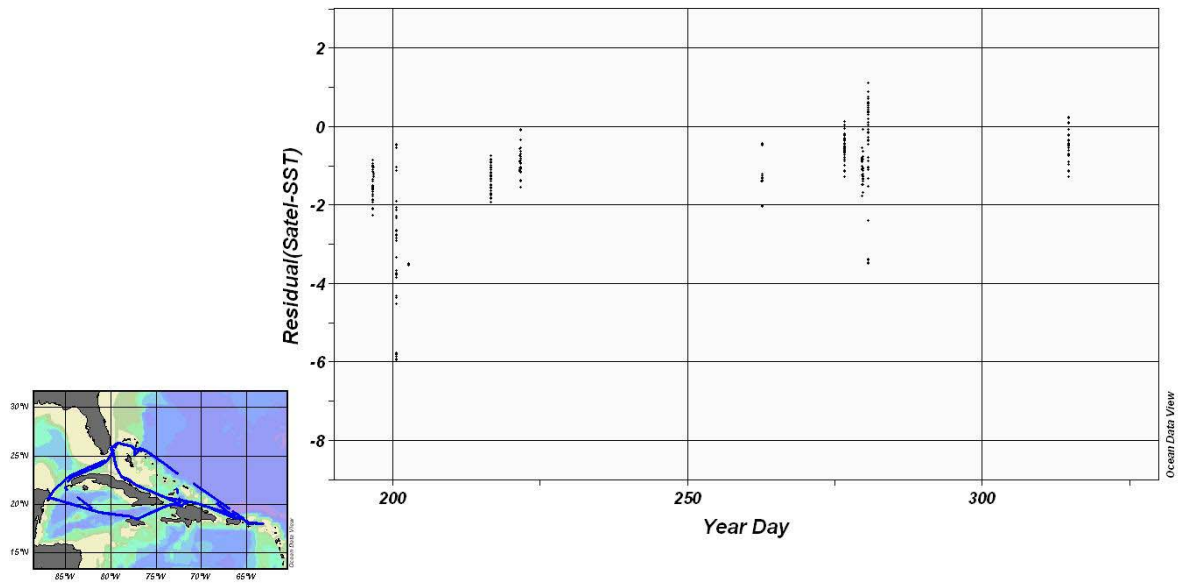




High resolution measurements ΔpCO_2- **temperature** : validation of remotely sensed T



12 hours/25 km

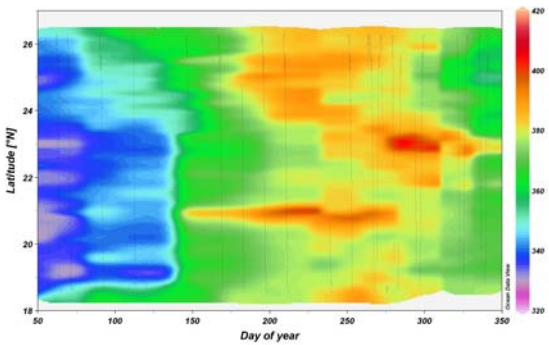


1 hours/25 km

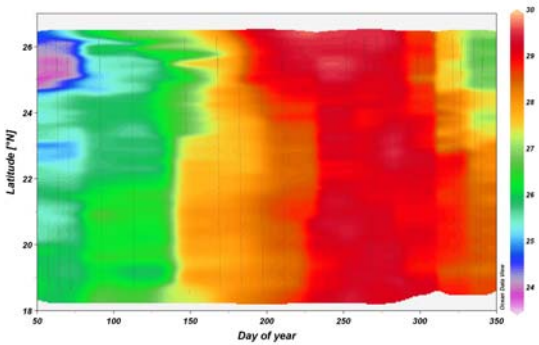
Example of use of SST to determine pCO_2

Air-Sea CO_2 Fluxes in the Caribbean Sea Using In Situ Observations and Remote Sensing

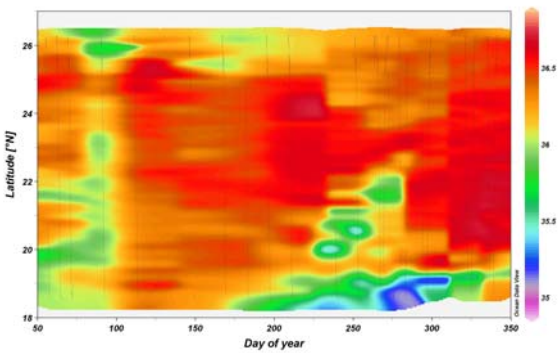
Observations



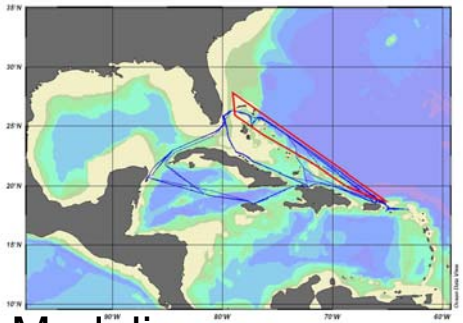
pCO_2



Temperature

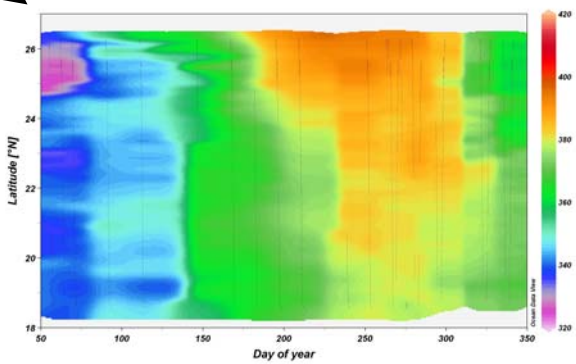


Salinity

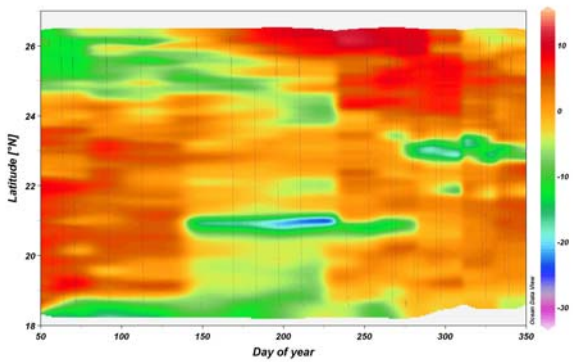


Modeling

pCO_2 = 10.8 SST + 1.4 latitude + 0.12 longitude



pCO_2 computed

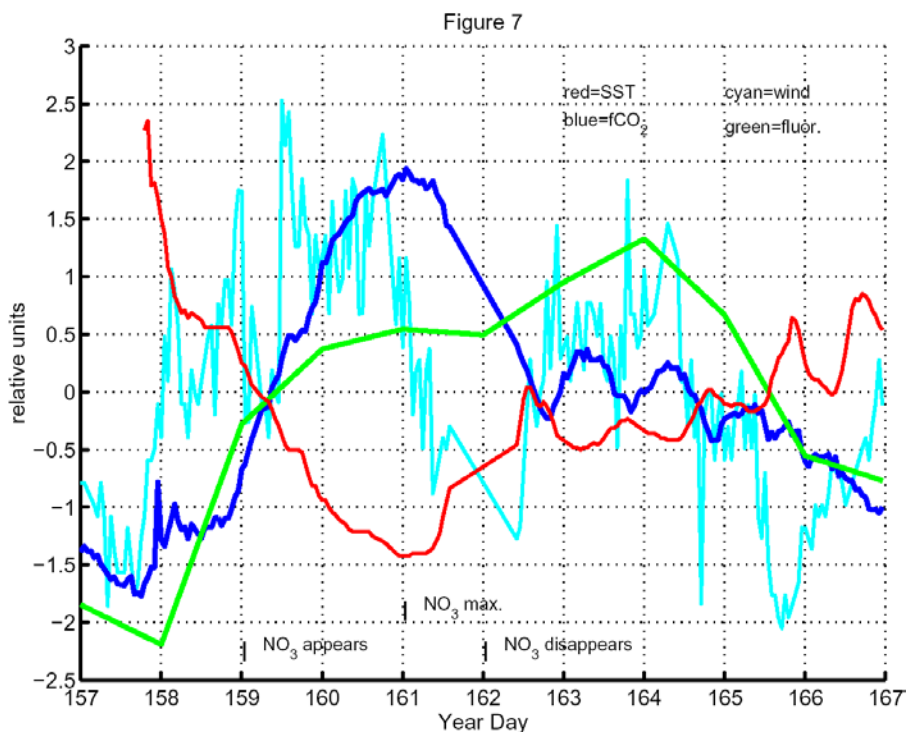


Residual (model-obs)

High resolution measurements ΔpCO_2- mixing : $dpCO_2 = f(\sum CO2, Talk)$

Timescale ≈ day

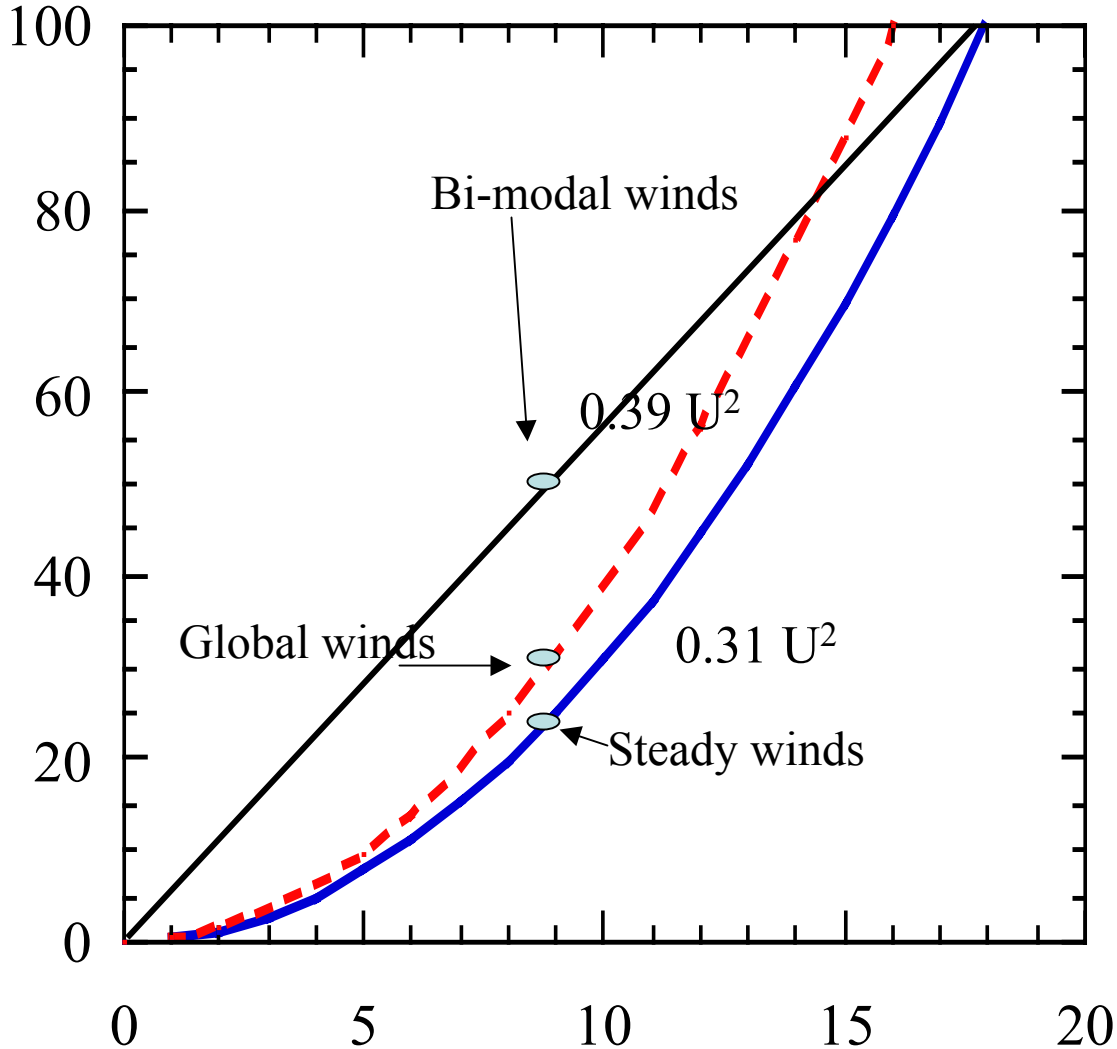
ΔpCO_2 change on daily time scales even in energetic environments



Hood et al.

The Kinetic Forcing:

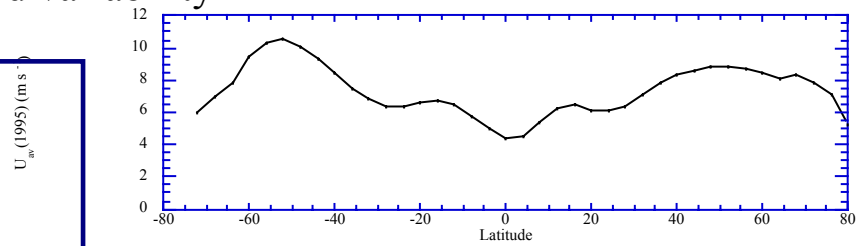
Effect of variable winds



The effect of wind speed variability

$k = a\,U^x$
$= a\,(f(u))\,U_{av}^{\,x}$

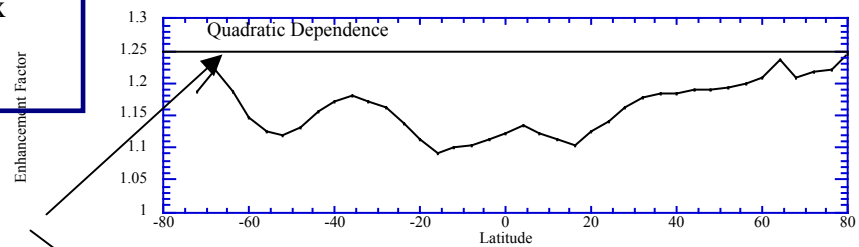
f(u) = wind speed probability/distribution function = $\sum U^x / U_{av}^{\,x}$



12

$k = 0.39\,U_{10}^2$
-2.2 Pg C /yr
$k = 1.09\,U_{10} - 0.333\,U_{10}^2 + 0.078\,U_{10}^3$
-3.3 Pg C /yr

Enhancement factor, U^2



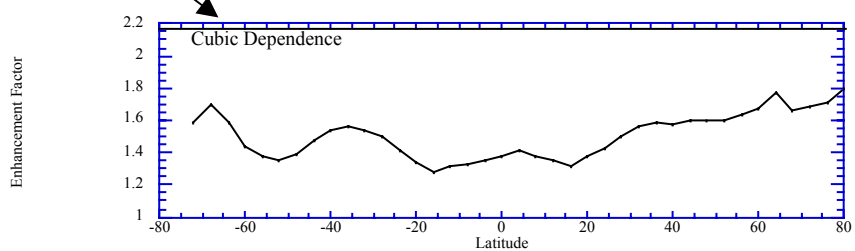
1.3

1

$k = 0.31\,U_{10}^2$
-2.1 Pg C /yr

Rayleigh (Weibull) Distribution

Enhancement factor, U^3



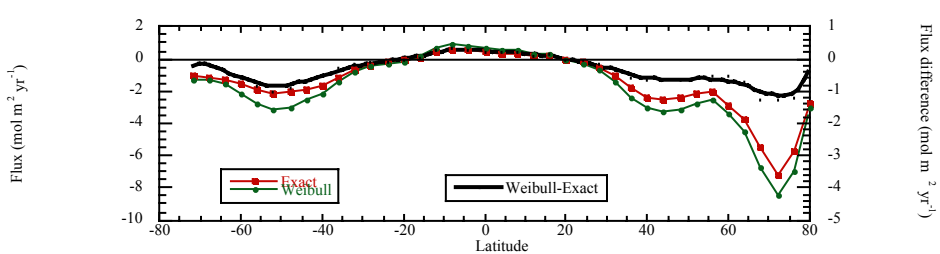
2.2

1

$k = 0.0283\,U_{10}^3$
-2.6 Pg C /yr

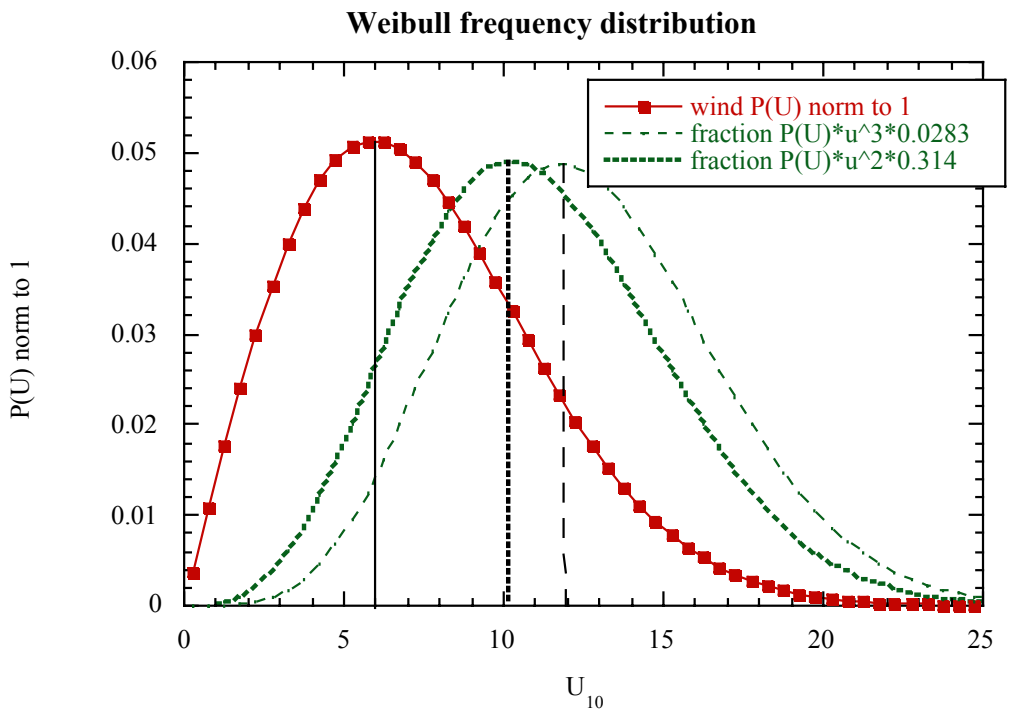
-90 0 90

The greater the non-linear dependence, The more important the need for high res. winds



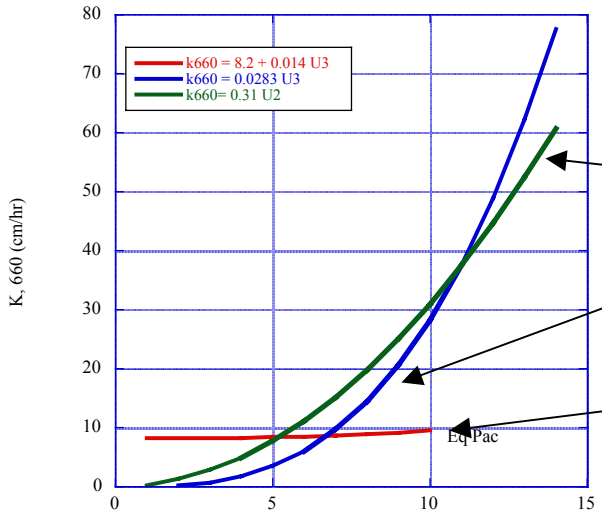
Approaches to determine f(u) :

- Use climatological mean
- Assume a climatological distributions
- Use real winds (e.g. remote sensing)
- Use real winds plus statistics on distribution



Note, the importance of high wind events gets great with stronger dependencies of wind

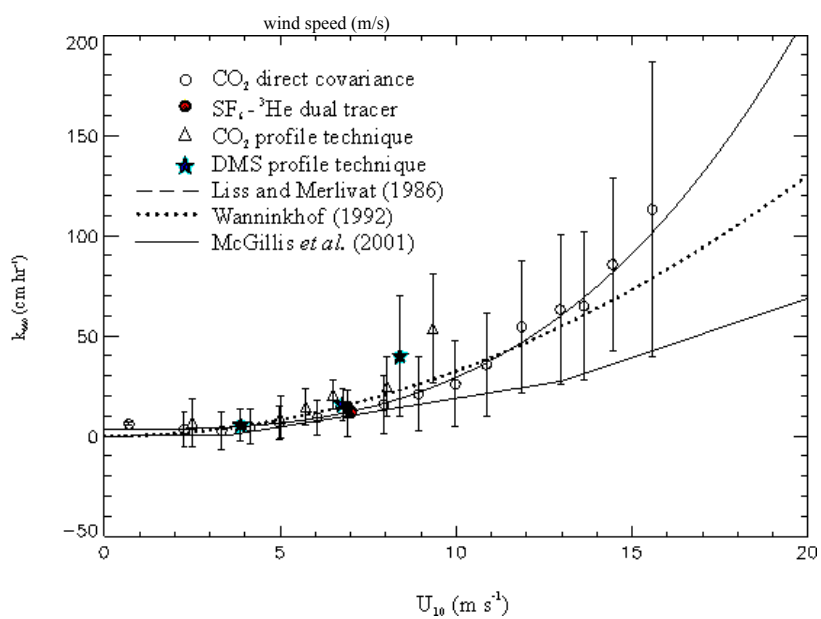
High resolution measurements k: k = F(u) different k vs. u parameterizations

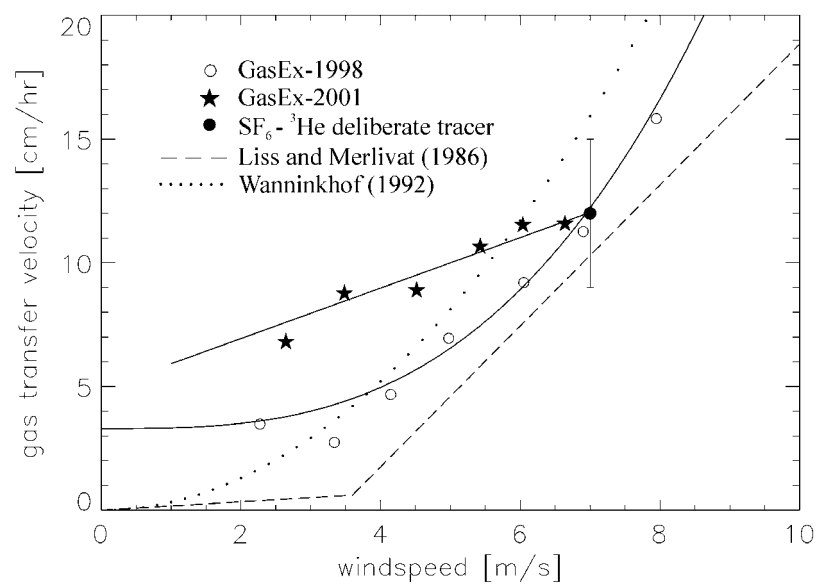


$k_{660} = 0.31\ U^2$ - Global

$k_{660} = 0.0283\ U^3$ - high latitude SoFex & Gas Ex

$k_{660} = 8.2 + 0.014\ U^3$ - Eq Pac



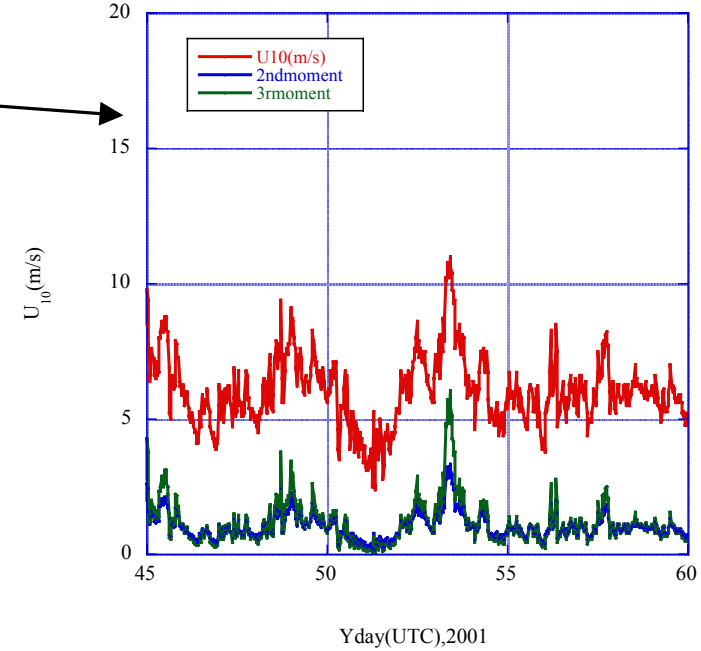


Courtesy W. McGillis, WHOI

"Wind Statistics"

$k_{660} = 8.2 + 0.014\ U^{3-}$ Eq Pac

	U_{av}	$\square\sum U^2/U_{av}^2$	$\sum U^3/U_{av}^3$
average	6.03	1.05	1.15
s.d.	1.30	0.46	0.81

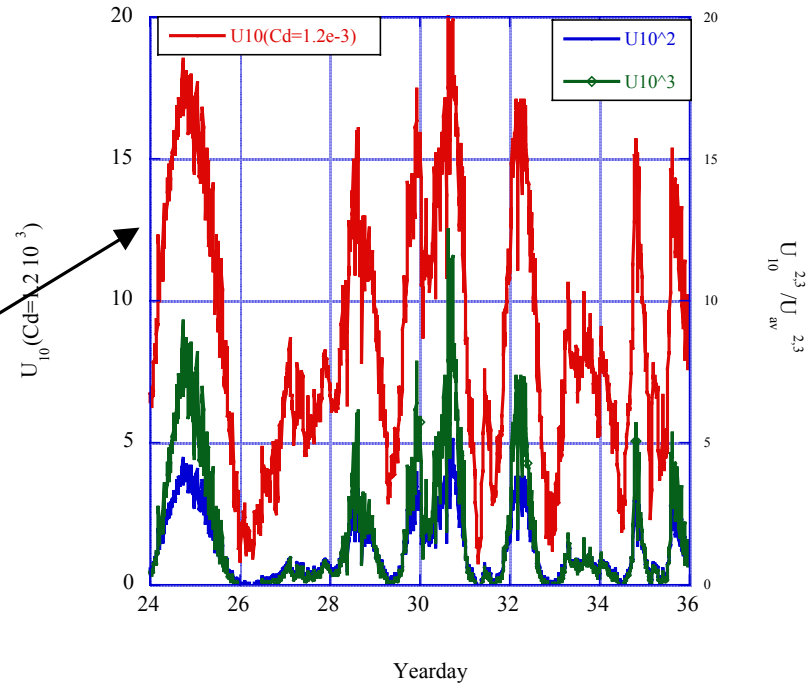


$k_{660} = 0.31\ U^2$ -Global

	U_{av}	$\square\sum U^2/U_{av}^2$	$\sum U^3/U_{av}^3$
average	7.6	1.24	2.21

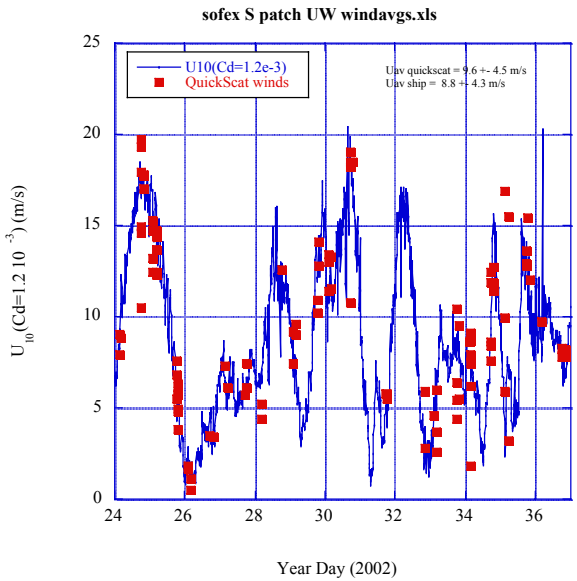
$k_{660} = 0.0283\ U^3$ SoFex

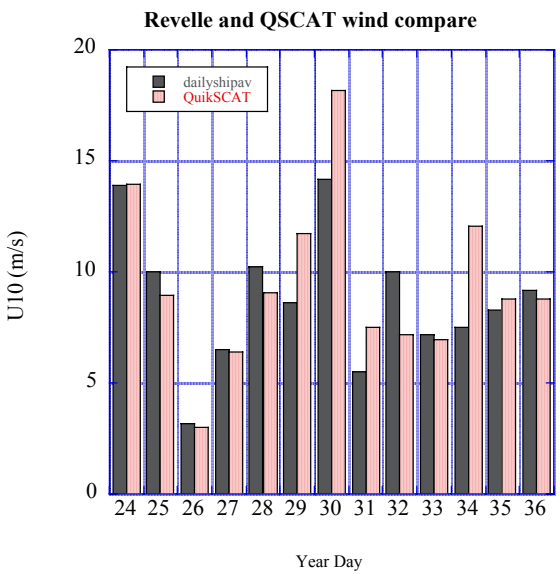
	U_{av}	$\square\sum U^2/U_{av}^2$	$\sum U^3/U_{av}^3$
average	8.79	1.24	1.76
s.d	4.31	1.09	2.15

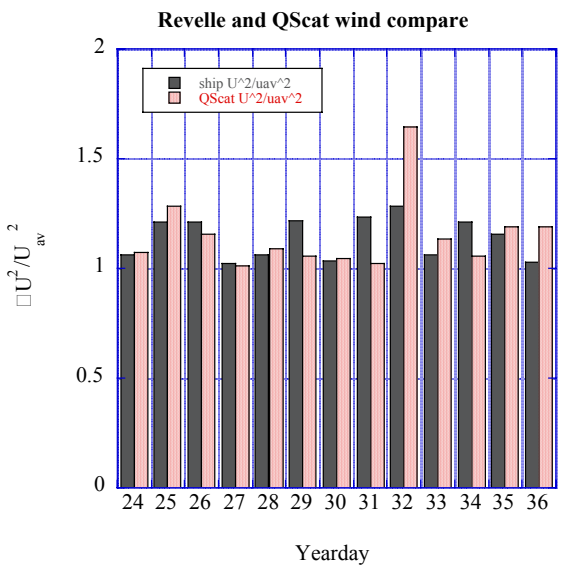


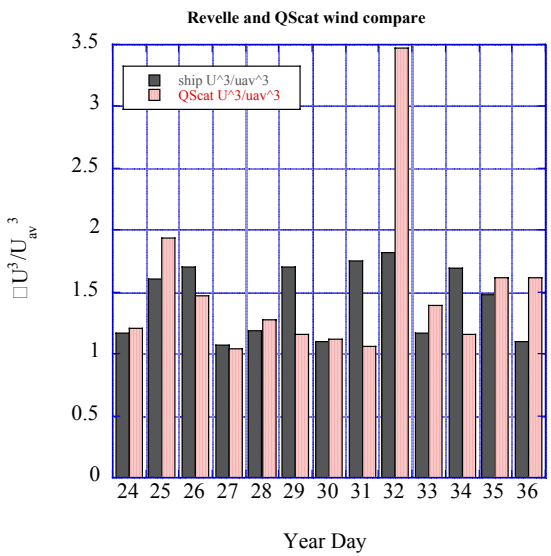
Can satellite observations replace high resolution *in situ* observations?

Winds: 2 time day- substitute temporal variability by spatial variability?









Closing comments:

- To convert pCO_2 measurement to fluxes the following high resolutions measurements are desirable:
  1. Bulk SST
  2. Wind
  3. Skin SST
  4. T,S profiles (mixed layer depth)
  5. Salinity
  6. Chlorophyll

- There is significant merit to have high resolution CO_2 measurements co-located on ships with CO_2 observations
  - For interpolation
  - Validation

- We need higher resolution observations than remote sensing can offer to determine the effect of variability on calculated CO_2 fluxes