pCO$_2$ measurements from VOS: Why do we need high resolution observations?

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

Constrain the exchange of CO₂ between ocean and atmosphere in order to improve prediction of future CO₂ levels

“Determine regional air-sea CO₂ 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.

\[ F = k_s (pCO_{2w} - pCO_{2a}) \]

Global fluxes uncertain to about 50 % with a range 1.5 to 2.8 Pg C yr⁻¹
Implementation:

Sustained Ocean pCO₂ 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

NOAA UW pCO₂ lines in the Atlantic- (funded 2002)
What is needed to determine fluxes:

\[ F = k_s (p_{CO_2w} - p_{CO_2a}) \]

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,
\[ F_{av} = (k_s \Delta p_{CO_2})_{av} \neq k_{av} \Delta p_{CO_2av} \]
\[ = k_{av} \Delta p_{CO_2av} + (k_s)' \Delta p_{CO_2}' \]
Factors influencing Air-sea CO$_2$ fluxes

**Variables**
- Atm. Stability
- Fetch
- Direction
- Surfactants
- Microbreaking
- Bubbles
- Rain

**Forcing**
- Wind
- U*
- Slope
- Boundary Layer Dynamics
- SST
- Advection
- Biology
- Diffusion

**Kinetics**
- k

**Thermodynamics**
- $pCO_2$

**Air-Sea CO$_2$ Flux**

Kinetic forcing: “High” Frequency (< day)

Thermodynamic forcing: “Low” Frequency (> day)
Requirements for $\Delta pCO_2$ measurements

\[ \Delta pCO_2 \text{ for } 0.1 \text{ Pg C per Year Uptake} \]

\[ F = k s \Delta pCO_2 \quad \Rightarrow \quad \Delta F = 0.2 / A = \Delta (k s \Delta pCO_2) \quad \Rightarrow \quad \Delta (\Delta pCO_2) \propto 0.2 \ (U^2 A)^{-1} \]
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 $\Delta pCO_2$ - 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 $\Delta p\text{CO}_2$ - temperature: validation of remotely sensed T

12 hours/25 km

1 hours/25 km
Example of use of SST to determine \( p\text{CO}_2 \)

Air-Sea \( \text{CO}_2 \) Fluxes in the Caribbean Sea Using In Situ Observations and Remote Sensing

\[ p\text{CO}_2 = 10.8 \text{ SST} + 1.4 \text{ latitude} + 0.12 \text{ longitude} \]

Observations

- \( p\text{CO}_2 \)
- Temperature
- Salinity

Modeling

- \( p\text{CO}_2 \) computed
- Residual (model-obs)
High resolution measurements $\Delta p_{CO_2}$-mixing: $dp_{CO_2} = f(\sum CO_2, Talk)$

Timescale $\approx$ day

$\Delta p_{CO_2}$ change on daily time scales even in energetic environments

Hood et al.
The Kinetic Forcing:
Effect of variable winds

- Bi-modal winds
  - $0.39 U^2$

- Global winds
  - $0.31 U^2$

- Steady winds
The effect of wind speed variability

\[ k = a U^x \]
\[ = a (f(u)) U_{av}^x \]

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

Rayleigh (Weibull) Distribution

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

-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

k = 0.31 U_{10}^2

-2.1 Pg C /yr

k = 0.39 U_{10}^2

-3.3 Pg C /yr

k = 0.0283 U_{10}^3

-2.6 Pg C /yr

k = 0.39 U_{10}^2
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

![Graph showing different parameterizations of $k_{660}$ vs. wind speed $u$.](image)
“Wind Statistics”

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

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<thead>
<tr>
<th></th>
<th>$U_{av}$</th>
<th>$\sum U^2/U_{av}^2$</th>
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<td>s.d</td>
<td>1.30</td>
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$k_{660} = 0.31 \ U^2$ -Global

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<td>average</td>
<td>7.6</td>
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$k_{660} = 0.0283 \ U^3$ SoFex

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<td>s.d</td>
<td>4.31</td>
<td>1.09</td>
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Can satellite observations replace high resolution *in situ* observations?

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

*Revelle and QSCAT wind compare*

*Revelle and QSCat wind compare*

*Revelle and QScat wind compare*
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