The Effect of Changing Wind Speeds on Global Air-Sea CO$_2$ Fluxes

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Changes in wind speed 1987-2015 CCMP-2 winds
Motivation focused on the global carbon cycle

- ≈25% of the anthropogenic CO₂ is sequestered [over time periods] by the ocean
- Changes in Air-Sea CO₂ fluxes can have a profound effect on this uptake and estimates of future atmospheric CO₂ levels/climate mitigation policies (COP-21)
- Gas transfer can effectively be parameterized with wind over the ocean
- Using new quality wind product (CCMP-2) wind speed changes can be assessed at high resolution
- Overall increases in winds should lead to increases in air-sea CO₂ fluxes
Approach

Effect of wind alone, isolating it from the predominant effect of changes in \( \Delta p\text{CO}_2 \)

- \( F = k s \Delta p\text{CO}_2 \)
- \( \Delta p\text{CO}_2 \) monthly 4 by 5° climatology Takahashi centered on 2005 (unpublished) [not time varying]
- \( k_{660} = 0.24 <U_{10}^2> \) or
- \( k_{660} = 3 + 0.1 <U_{10}> + 0.064 <U_{10}^2> + 0.011 <U_{10}^3> \) [“hybrid model”] [Wanninkhof et al., 2009]
- CCMP-2 winds and moments monthly 1 by 1° from July 1987- July 2015 [www.remss.com/measurements/ccmp]
- Focus on long term trends (linear).
- Of note, Climatology shows [low] net uptake \( \approx 1.3 \) Pg C /yr
**Background:** Global Air-Sea CO$_2$ flux patterns

Difference: Net $\approx 0$

Red: $0.24< U_{10}^2 >$ more release/less uptake

Blue: $0.24< U_{10}^2 >$ less release/more uptake

More uptake in Subtropics, more release Eq Pac
Background: Trends

Due to atmospheric CO₂ increase: -0.15 Pg C/yr/decade (increased uptake)
From data based approaches: + 0.2 Pg C/yr/decade (1991-2001);
-0.8 Pg C/yr/decade (2001-2011)

Table 3. Median sea-air anthropogenic CO₂ fluxes for the different approaches centered on year 2000.

<table>
<thead>
<tr>
<th>Approach</th>
<th>Anthr. CO₂ flux</th>
<th>Uncertainty</th>
<th>IAV</th>
<th>SAV</th>
<th>Trend (Pg C yr⁻¹) decade⁻¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>Empirical</td>
<td>-2.0</td>
<td>±0.6</td>
<td>0.20</td>
<td>0.61</td>
<td>-0.15</td>
</tr>
<tr>
<td>OBGCNM</td>
<td>-1.9</td>
<td>±0.3</td>
<td>0.16</td>
<td>0.38</td>
<td>-0.14</td>
</tr>
<tr>
<td>Atmos Inversion</td>
<td>-2.1</td>
<td>±0.3</td>
<td>0.40</td>
<td>0.41</td>
<td>-0.13</td>
</tr>
<tr>
<td>Ocean Inversion</td>
<td>-2.4</td>
<td>±0.3</td>
<td>0.40</td>
<td>0.41</td>
<td>-0.5</td>
</tr>
<tr>
<td>Interior (Green function)</td>
<td>-2.2</td>
<td>±0.5</td>
<td>-</td>
<td>-</td>
<td>-0.35</td>
</tr>
</tbody>
</table>

R. Wanninkhof et al.: Global ocean carbon uptake: magnitude, variability and trends
www.biogeosciences.net/10/1983/2013/

C. Rödenbeck et al.: An ensemble of pCO₂-based sea-air CO₂ flux estimates
Biogeosciences, 12, 7251–7278, 2015
www.biogeosciences.net/12/7251/2015/
Background: The 1: 1: 0.2 rule

Changes due to changes in pCO$_2$ and wind

- 1 µatm increase in $\Delta$pCO$_2$ will cause a 0.2 Pg C increase in global uptake (15 % of net global ocean CO$_2$ uptake)
- A 1 m/s increase in wind speed will increase the uptake by 0.2 Pg C as well

Graphs showing the relationship between global uptake and changes in pCO$_2$ and wind speed.
Global Wind patterns: Higher winds in regions of uptake

Wanninkhof et al., 2009
Trends: Global winds

Trend in global wind (1988-2014):
\[ \langle u \rangle : 0.14 \text{ m/s decade (≈2 %)} \]
\[ \langle u^2 \rangle : \approx 3 \text{ % decade} \]

If 1:1:0.2 “rule” holds:
0.05 Pg C: 1987-1998
0.08 Pg C 1987-2015
Quantitative assessment: the gas exchange coefficient, \((k_s)\)

\[ F = k_s \cdot pCO_2 \]

\(k\) & \(s\) are (opposing) functions of SST through solubility and Schmidt number

\[ k \cdot s = \text{mol/m}^2/\text{yr/atm} \]  
(Also called gas transfer coefficient (Takahashi et al. 2009))

Absolute magnitude of \(k_s\)

Fourfold range over global ocean

\[ k_{660} = 0.24 <U_{10}^2> \]

\[ k_{660} = 3 + 0.1 <U_{10}> + 0.064 <U_{10}^2> + 0.011 <U_{10}^3> \]

Red: \(0.24 <U_{10}^2>\) larger \(k_s\) than hybrid

Blue: \(0.24 <U_{10}^2>\) smaller \(k_s\) than hybrid
Trends: the gas exchange coefficient, $k_s$

Greatest trend:
Equatorial Pacific
40 °S in Southern Ocean
Western boundary currents

Largest difference in trends:
Equatorial Region: quadratic larger trend in $k_s$
Southern Ocean: hybrid larger trend in $k_s$

Red: $0.24 <U_{10}^2>$ larger trend than hybrid
Blue: $0.24 <U_{10}^2>$ smaller trend than uptake
**Trends:** Global Sea-Air CO$_2$ Fluxes (Spatial distribution)

Areas of efflux: more release over time
Areas of uptake: more sequestration

Trend in Sea-Air CO$_2$ Flux: $0.24 < U_{10}^2$

Trend in Sea-Air CO$_2$ Flux: Polynomial

Red: $0.24 < U_{10}^2$  more release/less uptake
Blue: $0.24 < U_{10}^2$  less release/more uptake
Changes: global sea-air CO$_2$ fluxes by year

Global Ocean Trend in Sea-Air CO$_2$ fluxes due to changes in winds: 0.015 ±0.009  Pg C decade (slightly less uptake)
Cause of small trend: Balance of effluxes and influxes

Efflux: 0.071 ±0.009 Pg C decade

Net Flux: 0.015 ±0.009 Pg C decade

Influx: -0.05 ±0.01 Pg C decade
Patterns of Trends: Zonal distribution of Fluxes
Patterns of Trends: Zonal distribution of Fluxes

Climatological sea-air CO₂ flux

Regional fluxes (0.24 <u²>) 1988-2014

Regional fluxes (Hybrid) 1988-2014
Patterns: Zonal distribution of annual trends in Fluxes

\[ k_{660} = 0.24 \langle u_{10}^2 \rangle \]

\[ k_{660} = 3 + 0.1 \langle u_{10} \rangle + 0.064 \langle u_{10}^2 \rangle + 0.011 \langle u_{10}^3 \rangle \]
**Trends:** winds for the Equatorial Pacific
(14 °N-14 °S, 130 °E, 80 °W)

Changes in $<u>$
1988-2014: 0.28 m/s/decade (4.5 %/decade)
1993-2011: 0.38 m/s/decade (6.1 %/decade)

Changes in $<u^2>$
1988-2014: 3.5 (m/s)$^2$/decade (7.7%/decade)
1993-2011: 4.6 (m/s)$^2$/decade (10%/decade)
Trends: Fluxes and ks from the Equatorial Pacific

(14N-14S, 130 E, 80 W)

Changes in ks
1988-2014 (quadratic) ≈ 7% decade
1993-2011 ≈ 11% decade
Hybrid: changes 29 % less

Changes in Flux
1988-2014 (quadratic) ≈ 8% decade
1993-2011 ≈ 12% decade
Hybrid changes: 31 % less
**Trends: Effluxes from the Equatorial Pacific (Local)**

**Tropics (169.5 W, 5.5.N)**

- Wind speed increase: 0.5 (m/s)/decade
- Variability Decrease $\langle u^2 \rangle / \langle u \rangle^2 \approx 1\%$ decade)

**Eq Pac Warm Pool**

- $ks: \approx 10\%$/decade
- Flux: 9%/
decade
- Quadratic 25 % greater change than hybrid
Trends: Changes in winds for the North Atlantic (> 50 °N)

Changes in <u>
1988-2014: 0.06 m/s/decade (0.5 %/decade)

Changes in <u^2>
1988-2014: 1.4 (m/s)^2/decade (1 %/decade)

No significant decadal changes in wind
CO₂ Influx into the North Atlantic
(> 50 °N)

Changes in ks
1988-2014 (quadratic) ≈ 1% decade
(Hybrid) ≈ 1.5 % decade
Hybrid changes: 46 % greater

Changes in Flux (greater uptake)
1988-2014 (quadratic) ≈ -1% decade
(Hybrid) ≈ -1.6 % decade
Hybrid changes: 46 % greater
**Trends**: Changes in winds for the Southern Ocean (50 °S- 62 °S)

Changes in $<u>$
1988-2014: 0.1 m/s/decade (1 %/decade)

Changes in $<u^2>$
1988-2014: 2.7 (m/s)$^2$/decade (2 %/decade)
CO₂ Influx into the Southern Ocean  
(50 °S – 62 °S)

Changes in ks  
1988-2014 (quadratic) ≈ 2% decade  
(Hybrid) ≈ 2.7 % decade  
Hybrid changes: 36 % greater

Changes in Flux (greater uptake)  
1988-2014 (quadratic) ≈ -3% decade  
(Hybrid) ≈ -3.7 % decade  
Hybrid changes: 25 % greater

Southern Ocean (50-62 °S: significant trends, small magnitude of fluxes)
Conclusions

The effect of changing winds using a constant monthly pCO$_2$ climatology

- Global winds in the CCMP-2 product have increased by about 0.4 m/s over 26 years (1988-2014)
- Largest regional change is in the Equatorial Pacific with an increase of 0.7 m/s
- Change in global air-sea CO$_2$ fluxes relatively small due to compensation of increases with decreases
- Difference in quadratic and polynomial parameterizations has a small effect on trend in global scale fluxes with quadratic showing an increase in efflux and hybrid model showing no trend
- Effect of changes in wind is generally much smaller than impacts of changing ΔpCO$_2$ on fluxes with the direction of the trend (≈0.015 Pg C/decade being opposite and much smaller than the trend caused by changes of ΔpCO$_2$ (-0.15- 0.35 Pg C decade)