What can global simulations of transient tracers tell us about quadratic vs. cubic formulations for air-sea CO2 exchange?
Outline

- Background, Objectives:
- Model & simulations
- Results: model-data & model-model comparison
  - CFC-11
  - Bomb C-14
  - Anthropogenic CO2
- Do we know wind speeds well enough?
- Winds and predicted oceanic CO2 uptake
- Conclusions
Tool: Ocean General Circulation Model (OGCM)

OPA-ORCA Model (LODyC-IPSL)
- Resolution: 2° (nominal)
- Resolution higher in tropics (0.5°)
- Diff. Isopycnal & GM
- TKE Model
- Ice Model (LIM)

Forced mode
- Paleo (LGM)
- Preindustrial
- Industrial era
- Variability
- Future

Coupled mode (w/ atmosphere)
⇒ Simulations Industrielle (± 200 ans)

Validation?
Simulations (follow lead of OCMIP-2*)

- Circulation Tracers
  - CFC-11 and CFC-12
  - Natural C-14 and Bomb C-14 (but we use perturbation approach)
  - Mantle He-3 and He-4

- Carbon
  - Preindustrial:
    - Abiotic
    - Common Biogeochemistry ($\sum$CO$_2$, Alk, PO$_4^{3-}$, O$_2$, DOM)
  - Preindustrial to Present (Anthropogenic carbon, perturb. approach)
  - Future (two IPCC scenarios: IS92a, S650)
  - Sequestration (7 sites, 3 depths, 2 scenarios)

*See [http://www.jcim.jussieu.fr/OCMIP](http://www.jcim.jussieu.fr/OCMIP)
JGOFS/WOCE survey data. Pacific meridional section (Sabine et al., 2002)

Fossil fuel signal has penetrated to > 1000m. Surface concentrations reach 50 \( \mu \text{mol/kg} \).

The global inventory estimated from data is 118\(\pm\)19 Pg C in 1994 (Sabine et al, 2004). We have disposed of ~430 billion tons of CO\(_2\) in ocean waters.

Global surface ocean CO\(_2\) disposal is now about 20 million tons per day, i.e., ~4 kg / (person * day)
Provided a framework for comparing & improving models
CFC-11 data provides some hard constraints
Inventory: the importance of area

Global

Zonal Mean Inventory

Zonal Integral Inventory

Pacific

Zonal Mean Inventory

Zonal Integral Inventory
Zonal Mean [CFC-11]: model vs. data

Global

Pacific

Data (GLODAP)

Quadratic

Cubic
New ORCA05 model shows promise

Global

Zonal Mean Inventory

Zonal Integral Inventory

- Data (GLDASAF)
- Quadratic (LIM ice, NCEP wind)
- Cubic (LIM ice, NCEP wind)
- Quadratic (GCMIP-2 ice, NCEP wind)
- Cubic (GCMIP-2 ice, NCEP wind)
- ORCA05 (LIM ice, clim wind)

Pacific

Zonal Mean Inventory

Zonal Integral Inventory

- Data (GLDASAF)
- Quadratic (LIM ice, NCEP wind)
- Cubic (LIM ice, NCEP wind)
- Quadratic (GCMIP-2 ice, NCEP wind)
- Cubic (GCMIP-2 ice, NCEP wind)
- ORCA05 (LIM ice, clim wind)
OCMIP-2 Bomb C-14
(Global Zonal Mean, 1994)

\[ K = a u^2 \left( \frac{Sc}{660} \right)^{-1/2} \]
Can we calibrate “a” with the spatial pattern of observed inventories?

\[ K = a u^N (\text{Sc/660})^{-1/2} \]
GasEx calibration: adjust “a” to reach GEOSECS Inventory

<table>
<thead>
<tr>
<th>Field</th>
<th>N</th>
<th>astd</th>
<th>amod</th>
<th>Δ</th>
<th>1975s</th>
<th>1975m</th>
<th>1994s</th>
<th>1994m</th>
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<tbody>
<tr>
<td>NCEP</td>
<td>2</td>
<td>0.31</td>
<td>0.3332</td>
<td>+7%</td>
<td>231.3</td>
<td>244.8</td>
<td>302.9</td>
<td>325.3</td>
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<td>0.0370</td>
<td>+31%</td>
<td>196.9</td>
<td>244.3</td>
<td>273.8</td>
<td>329.1</td>
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<td>ERA40</td>
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<td>1.0</td>
<td>0.7878</td>
<td>-21%</td>
<td>294.3</td>
<td>245.8</td>
<td>380.5</td>
<td>328.8</td>
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<tr>
<td>ERA40</td>
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<td>0.31</td>
<td>0.2503</td>
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<td>289.0</td>
<td>245.6</td>
<td>378.8</td>
<td>331.6</td>
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<tr>
<td>ERA40</td>
<td>3</td>
<td>0.028</td>
<td>0.0225</td>
<td>-20%</td>
<td>291.9</td>
<td>245.9</td>
<td>387.5</td>
<td>336.4</td>
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</table>

\[ K = a u^N (Sc/660)^{-1/2} \]

Global Inventory in RCU
(10^{26} atoms C-14)
GEOSECS: Zonal Inventory
Std & Adjusted “a” coefficient (1975)

Bomb $\Delta^{14}C$ in ORCA2 Perturbation Runs
Global Inventory (1975): Standard $a$

Zonal Mean, Vertical Ratio Integral

Zonal Mean, Vertical Mass Integral

Zonal Integral, Vertical Mass Integral

Bomb $\Delta^{14}C$ in ORCA2 Perturbation Runs
Global Inventory (1975): Adjusted $a$

Zonal Mean, Vertical Ratio Integral

Zonal Mean, Vertical Mass Integral

Zonal Integral, Vertical Mass Integral
GEOSECS: Inventory, Surface level, Penetration Z
with Standard & Adjusted “a” (1975)
Station Inventories with Std & Adjusted “a”
(W. Indian GEOSECS Section, 1978)

Bomb $\Delta^{14}C$ in ORCA2 Perturbation Runs
West Indian GEOSECS Section (1978): Standard a

Bomb $\Delta^{14}C$ in ORCA2 Perturbation Runs
West Indian GEOSECS Section (1978): Adjusted a
Station Inventories with Std & Adjusted “a”
(W. Pacific GEOSECS Section, 1974)
**Inventory, Surface level, Penetration depth w/ Std. & Adj. "a" (WOCE, 1994)**

**Bomb $\Delta^{14}C$ in ORCA2 Perturbation Runs**

**Zonal Mean (Global, 1994): Standard a**

- **Inventory**
  - Vertical integrated (permil ± 1)

- **Surface $\Delta^{14}C$**
  - Data-based
  - NCEP (3)
  - ERA40 (3)
  - NCEP (1.5)
  - ERA40 (1.5)

- **Penetration Depth**
  - Mean penetration depth (m)

**Bomb $\Delta^{14}C$ in ORCA2 Perturbation Runs**

**Zonal Mean (Global, 1994): Adjusted a**

- **Inventory**
  - Vertical integrated (permil ± 1)

- **Surface $\Delta^{14}C$**
  - Data-based
  - NCEP (3)
  - ERA40 (3)
  - NCEP (1.5)
  - ERA40 (1.5)

- **Penetration Depth**
  - Mean penetration depth (m)
Reanalyzed winds differ in magnitude and variability.
Reanalyzed 10-m Wind Speed (m s\(^{-1}\))

- **Interannual variability**
  - NCEP: little variability
  - ERA40: big variability
    - Tropics: ± 1 m s\(^{-1}\)
    - S. Ocean: ± 1.5 m s\(^{-1}\)
    - Global: ± 0.5 m s\(^{-1}\)

- **Magnitude**
  - ERA40: much larger in S. Ocean
  - NCEP: small

- **Large differences**
  - S. Ocean \(\Delta = 1.0\) to 4.5 m s\(^{-1}\)
  - Global \(\Delta = 0.5\) to 1.5 m s\(^{-1}\)
NCEP underpredicts WOCE shipboard 10-m wind speeds

*Smith, Legler, & Verzone, *J. Climate, 14*, 4062-4072, 2001
Simulated Anthropogenic DIC Inventory: Little sensitivity

- Consistent with previous work (Sarmiento et al., 1992)
  - @ 2 x Kg \(\rightarrow\) only +10% increase
  - Little sensitivity for constant vs. quadratic
  - But this is an “old” OGCM with only annual-mean forcing (neglects seasonal, interannual changes in advection, mixed-layer depth, etc.)
Flux from data-based pCO2 maps

\[ pCO_2^{sw} \]
Climatological pCO2 in Surface Water for February 1996

\[ pCO_2^{sw} \]
Climatological pCO2 in Surface Water for August 1995

Fluxes with NCEP wind in 1995

<table>
<thead>
<tr>
<th>Wind</th>
<th>n=2</th>
<th>n=3</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.995 sigma (~40 m)*</td>
<td>2.22</td>
<td>3.72</td>
</tr>
<tr>
<td>10-m wind (~ 1 m s(^{-1}) lower)</td>
<td>1.64</td>
<td>2.34</td>
</tr>
</tbody>
</table>

Takahashi et al., DSR II, 49, 1601-1622, 2002.

Takahashi et al., revised, 2003

Implications of uncertainties in wind speed for predicting air-sea $CO_2$ fluxes?

- **No problem:** for OGCM (model)-based predictions
  - Sarmiento, Orr, & Siegenthaler (JGR, 1992)
  - This study

- **Big problem!** for fluxes from data-based $\Delta pCO2$ maps
Conclusions

- What can global simulations of transient tracers tell us about quadratic vs. cubic formulations for air-sea CO$_2$ exchange? **Not much**

- For $K = a \, u^N \,(Sc/660)^{-1/2}$ when simulating bomb C-14 uptake
  - Magnitude of $a$ (dominates)
  - Spatial pattern $N$ (small 2$^{\text{nd}}$ order effect)

- Do we know wind speeds well enough?
  - Not for flux estimates from data-based pCO$_2$sw maps