IS THERE A HIGHER $C_{\text{ANT}}$ STORAGE IN THE INDIAN OCEAN?

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IMEDEA, CSIC - UIB, Mallorca, Spain

Gijón, 19-23 May 2008
C\textsubscript{ANT} ALONG CD139 CRUISE (2002) 32°S INDIAN OCEAN

\[
\text{C}_{\text{ANT}} \text{ inventory referred to 1994} = 110 \pm 13 \text{ Pg C}
\]

\begin{itemize}
  \item Indian Ocean contains
  \begin{itemize}
    \item 21\% of the total \text{C}_{\text{ANT}} \text{ inventory}
    \item half of the Atlantic \text{C}_{\text{ANT}} \text{ inventory}
  \end{itemize}
  despite having only 20\% less area
\end{itemize}

(Sabine et al, Science 2004)
Indian Ocean $C_{\text{ANT}}$ vertical distribution $\mu$mol/kg

Red Sea / Persian Gulf Intermediate Water

Antarctic Intermediate Water (AAIW)

AAIW marks the deepest $C_{\text{ANT}}$ penetration in the Subtropical gyre

No $C_{\text{ANT}}$ in deep and bottom waters

(Sabine et al, Science 2004)
**C\textsubscript{ANT} ALONG CD139 CRUISE (2002) 32°S INDIAN OCEAN**

**Hypothesis:**

\[^{\text{C\textsubscript{ANT}}}\text{ penetrates deeper than 1000-1500 m}\]

**How to assess this question:**

- compare different C\textsubscript{ANT} methods -> difficult:
  - every method has high uncertainties
- help: relation of C\textsubscript{ANT} with tracers (CFC\textsubscript{12}, CCl\textsubscript{4})
On board R/V Charles Darwin, CD139 cruise, 1/3 – 15/4/2002, from Durban to Freemantle

P.I.: Harry Bryden (National Oceanographic Centre, Southampton, UK)

Physics: temperature, salinity, ADCP, LADCP

Chemistry: oxygen, salinity, nutrients, CO₂ (pH & TA, TIC), CFCs (11, 12, 113), CCl₄.
C_{ANT} ALONG CD139 CRUISE (2002) 32°S INDIAN OCEAN

Africa  CFC-12 (pmol/kg)  Australia

- SAMW
- AAIW
- NADW
- CDW
- AABW
- CDW

Ocean Depth View

Distance [km]  Distance [km]
C_{\text{ANT}} ALONG CD139 CRUISE (2002) 32°S INDIAN OCEAN

C_{\text{ANT}} TECHNIQUES

1. C_{\text{ANT}} SAB99: method by Sabine et al. (GBC, 1999), using their $\Delta C_{\text{Dis}}$
2. C_{\text{ANT}} LM05: method by LoMonaco et al. (JGR, 2005)
2. Back-calculation technique by Lo Monaco et al. (JGR, 2005): OMP
C\textsubscript{ANT} ALONG CD139 CRUISE (2002) 32\textdegree S INDIAN OCEAN

C\textsubscript{ANT} TECHNIQUES

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2. C\textsubscript{ANT} LM05: method by LoMonaco et al. (JGR, 2005)
3. C\textsubscript{ANT} TrOCA: Touratier & Goyet (Tellus, 2007)
4. C\textsubscript{ANT} TTD
5. C\textsubscript{ANT} from OCCAM model
C\textsubscript{ANT} ALONG CD139 CRUISE (2002) 32°S INDIAN OCEAN

C\textsubscript{ANT} vertical distributions

OCCAM

TTD
Specific $C_{\text{ANT}}$ inventories

<table>
<thead>
<tr>
<th></th>
<th>Total mol C/m²</th>
<th>% Increase</th>
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<tr>
<td>SAB99</td>
<td>21</td>
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<td>LM05</td>
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<td>TTD</td>
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<tr>
<td>OCCAM</td>
<td>24</td>
<td>14</td>
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</table>
Neutral density layers & salinity

Africa

- Surface
- SAMW
- AAIW

Australia

- Deep
- Bottom

CANT ALONG CD139 CRUISE (2002) 32°S INDIAN OCEAN
Specific $C_{\text{ANT}}$ inventories

- LM05 yields very high $C_{\text{ANT}}$ estimates
- Deeper $C_{\text{ANT}}$ penetration below AAIW
- Significant $C_{\text{ANT}}$ values in deep and bottom waters

TTD & Troca give similar results, higher than SAB99

<table>
<thead>
<tr>
<th>Layer</th>
<th>Troca</th>
<th>TTD</th>
<th>OCCAM</th>
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<td>Surface</td>
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<tr>
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<td></td>
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<tr>
<td>Deep</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bottom</td>
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</table>

mol C / m²
C\text{ANT} ALONG CD139 CRUISE (2002) 32°S INDIAN OCEAN

Surface, SAMW waters and upper AAIW

Revelle = 9

Revelle = 13
Deep and bottom waters

C\textsubscript{ANT} along CD139 CRUISE (2002) 32\textdegree S INDIAN OCEAN

- TrOca
- LM
- SABstr
- TTD
- Model

Deep and bottom waters

C\textsubscript{ANT} umol/kg vs. pCFC-12

C\textsubscript{ANT} umol/kg vs. pCCl\textsubscript{4}

1943 1953 1959 1964

1921 1927 1935

0 2 4 6 8 10 12 14 16 18 20 22 24 26 28 30 32 34 36 38 40 42 44 46 48 50

-10 0 10 20 30 40

-10 0 10 20 30 40
<table>
<thead>
<tr>
<th>Reliability code (subjective)</th>
<th>Upper</th>
<th>SAMW</th>
<th>AAIW</th>
<th>Deep</th>
<th>Bottom</th>
<th>Mean</th>
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<tr>
<td>2- medium</td>
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<tr>
<td>3- low</td>
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<tr>
<td>SAB99</td>
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<td>2</td>
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<td>medium+</td>
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<td>OCCAM</td>
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<td>2</td>
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<td>3</td>
<td>3</td>
<td>medium</td>
</tr>
</tbody>
</table>
Hypothesis:

C\textsubscript{ANT} penetrates deeper than 1000 m (Sabine et al 1999)

seems to be hinted by any other method

How to assess this question:

difficult: every method has uncertainties

absolutely true, no method is perfect

help: relation of C\textsubscript{ANT} with tracers (CFC\textsubscript{12}, CCl\textsubscript{4})

questions still arise, saturation, mixing, etc..

community should combine methods and
time-evolution studies at specially sensitive
regions

OPEN DISCUSSION: KEY REGION ..... THE SO
Back-calculation technique by Sabine et al. (GBC, 1999) to estimate $C_{\text{ANT}}$.

$$C_{\text{ANT}} = \frac{\Delta C^*}{C - \text{AOU}/R_C - \frac{1}{2}(\Delta TA + \text{AOU}/R_N) + 106/104 \cdot N^* - C^{280} - \Delta C_{\text{Dis}}}$$

- $C$ is the current total inorganic carbon
- $\Delta TA = TA - TA^0$, current alkalinity - preformed alkalinity
  $$TA^0 = 378.1 + 55.22 \cdot \text{Sal} + 0.0716 \cdot \text{PO} - 1.236 \cdot Tpot$$
- AOU is the Apparent Oxygen Utilization, assuming oxygen saturation
- $C^{280}$ is the inorganic carbon in equilibrium with the preindustrial atmosphere.
  $$C^{280} = f(Tpot, \text{Sal}, TA^0, pCO_{280})$$ from thermodynamic equations
  $$pCO_{280} = CO_2$$ fugacity at a 100% of water vapor pressure in uatm = $f(Tpot, \text{Sal}, 280)$
  $C^{280}$ in GSS96 $\Rightarrow$ constants by Goyet & Poisson (1989) & a constant $pCO_{280} = 280$ uatm
  linearilized equation:
  $$C^{280} = 2072 - 8.982 \cdot (Tpot - 9) - 4.931 \cdot (\text{Sal} - 35) + 0.842 \cdot (TA^0 - 2320)$$
- $N^* = (0.87 \cdot (\text{NO}_3 - 16 \cdot \text{PO}_4 + 2.9))$ term accounting for the denitrification
\( \Delta C_{\text{Dis}} \) is obtained with own CD139 data using CFC\textsubscript{12} ages and limit at 40 years

a) Old deep waters, \( C_{\text{ANT}} = 0 \Rightarrow \Delta C^* = \Delta C_{\text{Dis}} \)
b) In upper waters, having the age: \( \Delta C_{\text{Dis}} = \Delta C^* t_{\sigma=\text{cte}} \)
   \[
   \Delta C^* = C - C_{\text{Bio}} - C_t \quad \text{where} \quad C_t = f(T_{\text{pot}}, \text{Sal}, TA^0, pCO_2 t) \]
   \( pCO_2 \) in the atmosphere at 2002 – age (t)
c) In between => weighed mean \( \Delta C^* \) and \( \Delta C^* t_{\sigma=\text{cte}} \)

\( \Delta C_{\text{Dis}} \) is obtained with own CD139 data using CFC\textsubscript{12} and CCl\textsubscript{4} ages

a) \( T_{\text{pot}} < 3^\circ \text{C} \), (assumed 100% saturation) deep waters, \( \Delta C_{\text{Dis}} = \Delta C^* t_{\text{CCl4} \sigma=\text{cte}} \)
   \[
   \Delta C^* = C - C_{\text{Bio}} - C_t \quad \text{where} \quad C_t = f(T_{\text{pot}}, \text{Sal}, TA^0, pCO_2 t_{\text{CCl4}}) \]
   \( pCO_2 \) in the atmosphere at 2002 – age CCl\textsubscript{4}(t)
b) In upper waters, having the CFC age: \( \Delta C_{\text{Dis}} = \Delta C^* t_{\text{CFC12} \sigma=\text{cte}} \)
   \[
   \Delta C^* = C - C_{\text{Bio}} - C_t \quad \text{where} \quad C_t = f(T_{\text{pot}}, \text{Sal}, TA^0, pCO_2 t_{\text{CFC12}}) \]
   \( pCO_2 \) in the atmosphere at 2002 – age CFC\textsubscript{12} (t)
c) In between => weighed mean a & b
Back-calculation technique by Lo Monaco et al. (JGR, 2005):

\[ C_{\text{ANT}} = C_T - C_{\text{Bio}} - C_T^{0\text{obs}} - (C_T - C_{\text{Bio}} - C_T^{0\text{obs}})^{\text{REF}} \]

- \( C_T \) = measured TIC
- \( C_{\text{Bio}} = 0.73 \cdot (O_2^0 - O_2) + 0.5 \cdot (TA - TA^0) \)
  \( TA^0 \) = preformed TA
- \( O_2^0 = O_2^{\text{sat}} - \alpha \cdot K \cdot O_2^{\text{Sat}} \)
  \( \alpha O_2 = 12\% \) undersaturation
  \( K = \) mixing ratio of ice-covered water (OMP)
- \( C_T^{0\text{obs}} \) = preformed TIC
  currently observed in the formation area water masses
- \( \text{REF} \) = reference water where no \( C_{\text{ANT}} \) should be detected.
C\textsubscript{ANT} ALONG CD139 CRUISE (2002) 32ºS INDIAN OCEAN

Back-calculation technique by Lo Monaco et al. (JGR, 2005)

\[
\begin{align*}
\text{TA}^0 &= k(S) \text{TA}^0(S) + k(N) \text{TA}^0(\text{NADW}) \\
\text{C}^{0,\text{obs}} &= k(S) \text{C}^{0,\text{obs}}(S) + k(N) \text{C}^{0,\text{obs}}(\text{NADW})
\end{align*}
\]

southern relationships:

winter surface data from the Atlantic and Indian oceans (WOCE and OISO cruises)

\[
\begin{align*}
\text{TA}^0(S) &= 0.0685 \text{PO} + 59.787 \text{S} - 1.448 \theta + 217.15 \\
&\quad \pm 5.5 \text{ µmol/kg, } r^2 = 0.96, n = 243 \\
\text{C}^{0,\text{obs}}(S) &= -0.0439 \text{PO} + 42.79 \text{S} - 12.019 \theta + 739.83 \pm 6.3 \text{ µmol/kg, } r^2 = 0.99, n = 428
\end{align*}
\]
	northern relationships

subsurface data from the North Atlantic and Nordic Seas (WOCE and KNORR cruises)

\[
\begin{align*}
\text{TA}^0(N) &= 42.711 \text{S} + 1.265 \theta + 804.6 \\
&\quad \pm 9.3 \text{ µmol/kg, } r^2 = 0.92, n = 297 \\
\text{C}^{0,\text{obs}}(N) &= 10.69 \text{S} + 0.306 \text{NO} + 1631.6 \pm 9.2 \text{ µmol/kg, } r^2 = 0.79, n = 364
\end{align*}
\]

mixing ratios of southern and northern waters:

\[k(S) + k(\text{NADW}) = 1\]
determined from OMP analysis
Back-calculation technique by Lo Monaco et al. (JGR, 2005):

OMP analysis modified from Lo Monaco et al. (JGR, 2005)

Endmembers:
- AAIW
- NADW-E
- NIDW
- Indian Water
- WDS/CDW
- ISW Weddell

Variables:
- Sal
- Tpot
- SiO2
- NO

Diagram showing the relationships between Tpot, Salinity, SiO2, and NO with different water masses represented.
C ANT ALONG CD139 CRUISE (2002) 32°S INDIAN OCEAN

Back-calculation technique by Lo Monaco et al. (JGR, 2005): OMP

\[
\begin{array}{cccc}
Tpot, & Sal, & SiO_2 & NO \\
STD Res. & 0.0481 & 0.0051 & 1.3 & 3 \\
R^2 & 0.9979 & 0.9967 & 0.9973 & 0.9611 \ (n=1299)
\end{array}
\]
Back-calculation technique by Lo Monaco et al. (JGR, 2005):

\[ C_{\text{ANT}} = C_T - C_{\text{Bio}} - C_T^{0 \text{ obs}} - (C_T - C_{\text{Bio}} - C_T^{0 \text{ obs}})_{\text{REF}} \]

REF = NADW = reference water where no \( C_{\text{ANT}} \) should be detected.

Applied to samples with more 50% NADW from OMP analysis

\[ (C_T - C_{\text{Bio}} - C_T^{0 \text{ obs}})_{\text{REF}} = -54.4 \pm 1.4 \text{ umol/kg} \]

(LoMonaco JGR2005 -51 umol/kg)

\[ C_{\text{ANT}} = C_T - C_{\text{Bio}} - C_T^{0 \text{ obs}} - (-54.4) \]
**C\textsubscript{ANT} ALONG CD139 CRUISE (2002) 32°S INDIAN OCEAN**

\textbf{C\textsubscript{ANT} TrOCA, Touratier et al (Tellus B, 2007):}

\[ \text{TrOCA} = O_2 + a \cdot (C_T - \frac{1}{2} \cdot TA) \quad a = \frac{\psi_{O2}}{[\psi_{CO2} + \frac{1}{2} \cdot (\psi_{H^+} - \psi_{HPO2^{4-}})]} \]

\[ C\textsubscript{ANT} (\text{TrOCA}) = (\text{TrOCA} - \text{TrOCA}_{280}) / a \]

\[ C\textsubscript{ANT} = (O_2 + 1.279 \cdot (C_T - 0.5 \cdot TA) - \exp(7.511-0.01087 \cdot \theta - 781000/TA^2))/1.279) \]
4. $\text{C}_{\text{ANT}}$ TTD (Waugh et al., 2004; 2006; Tanhua et al., 2008):

- each water sample has its own “age”, i.e. time since it was last in contact with the atmosphere. The sum of all these ages makes the TTD of a water sample

- the mean age ($\Gamma$) and the width of the TTD ($\Delta$) are assumed to be of equal magnitude: realistic assumption of the relation between advective and diffusive transport in the Ocean

- $\text{C}_{\text{ANT}}$ is an inert passive tracer where air-sea disequilibrium hasn’t changed over time.
5. C\textsubscript{ANT} OCCAM

- global, medium-resolution, primitive equation ocean general circulation model (Marsh et al., 2005).

- OCCAM's vertical resolution is 66 levels (5 m thickness at the surface, 200 m at depth), with a horizontal resolution of typically 1 degree.

- Advection is 4th order accurate, and the model is time-integrated using a forward leapfrog scheme with a 1 hour time-step.

- Surface fluxes of heat and freshwater not specified but are calculated empirically using NCEP-derived atmospheric boundary quantities (Large and Yeager, 2004).

- OCCAM incorporates a NPZD plankton ecosystem (Oschlies, 2001; Yool et al., 2007) which drives the biogeochemical cycles of nitrogen, carbon, oxygen and alkalinity.