Natural and Anthropogenic Carbon Changes in the South Indian Ocean

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N.O. Marion-Dufresne, original painting by Christophe Verdier, January 2004
Observations:

△ INDIGO : 1 cruise conducted in 1985

▲ OISO : 6 cruises conducted between 1998 and 2001
→ interannual variability
Large interannual variability

- associated with the SAF (movement of the front) and
- north of the SAF in the western Indian Ocean (mesoscale feature created by the Madagascar Current and the Agulhas Return Current)

Rodgers et al. (in prep.)
Hydrological fronts and water masses in the South Indian Ocean

Mean position of hydrological fronts (Belkin and Gordon, 1996)

Potential temperature [°C]

Ocean Data View

19-23 may 2008, Gijon, Spain
Hydrological fronts and water masses in the South Indian Ocean

Mode Waters distribution

Hanawa and Talley (2000)

Subpolar MW
Eastern STMW
STMW
SAMW

Potential temperature [°C]

AASW
WW
Upper CDW

STMW
STSW
SAMW

Depth [m]

Ocean Data View
Mode Waters

Mode Waters distribution

Hanawa and Talley (2000)

Subpolar MW
STMW
Eastern STMW
STMW
SAMW

Symposium on Climate Effects on the World’s Ocean 19-23 May 2008, Gijon, Spain
Total Carbon and Anthropogenic Carbon distributions

### Total Carbon Distribution

- **AASW**
- **WW**
- **Upper CDW**

### Anthropogenic Carbon Distribution

- **WW**
- **AASW**

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Anthropogenic Carbon in Mode Waters

Anthropogenic carbon distribution at 500m in the late 1990’s

[\mu\text{mol/kg}]

Anthropogenic carbon calculated from observations (TCO$_2$, TA, O$_2$ and conservative tracers)

Observations:
- OISO 1 to 3 (1998)

Large accumulation of anthropogenic carbon at mid-latitudes (20-40°S) in recently formed Mode Waters
Anthropogenic Carbon in Mode Waters

Anthropogenic carbon distribution at 500m in the late 1990’s

Comparison of recent observations (1998-2001) with historical measurements (1985) to evaluate the decadal change in ocean carbon

Anthropogenic carbon calculated from observations (TCO$_2$, TA, O$_2$ and conservative tracers)

Observations:
- INDIGO 1 (1985)
- OISO 1 to 3 (1998)
Multi-Linear Regression (MLR) technique

**method 1 (only conservative tracers):** 
\[ \text{TCO}_2 = \text{MRL} (S, T, \text{NO}) \]

Multi-Linear Regressions with observations from the first cruise:

**INDIGO (1985):** 
\[ \text{Total Carbon} = 31.86*S - 26.49*T - 0.551*\text{NO} + 1477.7 \]

applied to S, T and NO from the second cruise

\[ \rightarrow \text{Total Carbon in 1985 interpolated on S, T, NO observed in 1998-2001} \]

**Total Carbon change = difference from Total Carbon observed in 1998-2001**
Total Carbon changes

Multi-Linear Regression (MLR) technique

method 1 (only conservative tracers): \( \text{TCO}_2 = \text{MRL} (S, T, \text{NO}) \)

<table>
<thead>
<tr>
<th>Depth [m]</th>
<th>Total Carbon changes (( \Delta \text{TCO}_2 ))</th>
<th>[( \mu \text{mol/kg} )]</th>
</tr>
</thead>
<tbody>
<tr>
<td>50° S</td>
<td>No change</td>
<td>+6±5 ( \mu \text{mol/kg} )</td>
</tr>
<tr>
<td>35° S</td>
<td>No change</td>
<td>-5±3 ( \mu \text{mol/kg} )</td>
</tr>
</tbody>
</table>

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Total and Anthropogenic Carbon changes

Multi-Linear Regression (MLR) technique

**method 1 (only conservative tracers):** \( TCO_2 = MRL (S, T, NO) \)

**method 2 (physical and BGC tracers):** \( TCO_2 = MRL (S, T, O_2, Nut, Alk) \)
When the anthropogenic signal is removed from the total carbon change, the remaining pattern shows

- large decrease in Upper Circumpolar Deep Water (6-12 µmol/kg)
- small decrease in Subantarctic Mode Waters (4-6 µmol/kg)
- no change in subsurface waters and STMW (small increase in newly formed STMW?)
NORTH OF THE POLAR FRONT
Mode Waters transport anthropogenic CO$_2$ from the surface to mid-depths (down to approx. 1000m).

- **In STMW**: The invasion of anthropogenic CO$_2$ explains most of (all) the TCO$_2$ increase (TCO$_2$ increased by 8 (± 3) µmol/kg)
- **In SAMW**: The invasion of anthropogenic CO$_2$ is compensated for by an equal decrease in ocean carbon → No change in TCO$_2$.

SOUTH OF THE POLAR FRONT
No significant change in anthropogenic carbon

- **In WW (200m)**: TCO$_2$ increased by 5 (± 3) µmol/kg
- **In the upper CDW**: TCO$_2$ decreased by 9 (± 6) µmol/kg

Causes and consequences?
What are the mechanisms driving the change in natural carbon
Are these changes representative of the South Indian Ocean?
What will be the evolution in the next decades?
Ocean Carbon Model NEMO2

Components: Ocean Model OPA9 (GM90 and TKE mixed layer scheme), Biogeochemical Model PISCES (NPZD model), Ice Model LIM2

Resolution: 2° x 2° resolution (enhanced at the equator) 31 non-regular vertical levels (19 levels in the upper 500 meters)

Forgings: ERA40 heat fluxes and winds CORE freshwater fluxes (SST and SSS restored to Reynolds SST and Levitus SSS using bulk formulas)

CO₂ scenario: Pre-industrial run keeping atmospheric CO2 constant at 278 ppm Anthropogenic run using the observed atmospheric CO2 values

ANTHROPOGENIC CARBON at 500m (µmol/kg)
DATA / MODEL: Total and Anthropogenic Carbon changes

Total Carbon change (µmol/kg)

Anthropogenic Carbon change (µmol/kg)
DATA / MODEL : ‘Natural’ Carbon changes

Natural Carbon change (µmol/kg)

DATA (ΔTCO₂-ΔCant)

MODEL (CO₂atm = 278 ppm)

Carbon decrease associated with
- Warming
- Oxygen increase
- Nutrients decrease
MODEL: Large scale changes

Natural Carbon changes at 700m [µmol/kg]

Nitrate changes at 700m [µmol/kg]

Oxygen changes at 700m [µmol/kg]

Carbon decrease associated with Nutrients decrease Oxygen increase
To be continued...