Origin of upwelled water in the Benguela system: source region, upwelling depth and propagation pathways

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Introduction

South Atlantic - Central Water masses

- Central water masses feed upwelling
- Determine hydrographic conditions
- SACW: oxygen-depleted, nutrient-rich
- ESACW: oxygen-rich, nutrient-poor

Modelled mixing of tracers injected
- In the equatorial undercurrent (SACW, orange)
- Near the Cape of Good Hope (ESACW, blue)
- After about 16 years of model integration
- Summed over depth
Surface and near-surface currents and frontal zones. Simplified from Hardman-Mountford et al. (2003)

**NBUS** Northern Benguela Upwelling System

**AC** Angola Current

**ABFZ** Angola-Benguela Frontal Zone

**BC** Benguela Current
Methods

Regional circulation model

- based on Modular Ocean Model
- horizontal resolution: minimum grid cell size is about 8x8 km in the Namibian coastal region
- grid stretches towards model boundaries (18 km)
- vertical grid resolution: 3 m up to 500 m
- boundary values for sea-level and tracer concentration: cube92 product from the ECCO consortium
- atmospheric data: NCEP reanalysis and scatterometer data (QuikSCAT / ASCAT)
Model topography [m]

- corrected GEBCO topography
- model output: 5 d averages
- passive tracers:
  - dimensionless
  - between 0 and 1 (at release region)
  - following advection & diffusion
  - no impact on hydrographic fields

Upwelling in Benguela system

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To study the upwelling depth 4 passive tracers are designed which represent horizontal cross sections through the South Atlantic.

Hart & Curie, 1960:
\[ \rightarrow 200 \text{ m to } 300 \text{ m (CTD)} \]

Toggweiler (submitted):
\[ \rightarrow \text{signature of AAIW (}\Delta^{14}\text{C)} \]
### Upwelling Time

<table>
<thead>
<tr>
<th>Passive tracer</th>
<th>18°S</th>
<th>20°S</th>
<th>23°S</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>180 m</td>
<td>0 m</td>
<td>200 m</td>
</tr>
<tr>
<td>A</td>
<td>⋮</td>
<td>5 d</td>
<td>⋮</td>
</tr>
<tr>
<td>B</td>
<td>⋮</td>
<td>70 d</td>
<td>⋮</td>
</tr>
<tr>
<td>C</td>
<td>240 d</td>
<td>720 d</td>
<td>275 d</td>
</tr>
<tr>
<td>D</td>
<td>5385 d</td>
<td>–</td>
<td>1060 d</td>
</tr>
<tr>
<td></td>
<td>(14 a 275 d)</td>
<td>(2 a 330 d)</td>
<td></td>
</tr>
</tbody>
</table>

**Table:** Time span until tracer concentration exceeds 0.01 at shelf / surface

- **tracer from 100 m:** several days to surface
- **tracer from 200 m:** 1 to 2 months to surface
- **tracer from 300 m:** 1 to 2 years to surface
- **tracer from 550 m:** only at 23°S to surface
- **tracer from 550 m:** at 20°S only at shelf but NOT at surface
Source region - passive tracers

Composite of two passive tracers

Release region

after 1 model year (21 July 2000)

after 16 model years (23 Jul 2015)
Time to reach the upwelling cells

How long does SACW need to reach the upwelling cells?

<table>
<thead>
<tr>
<th>position</th>
<th>date</th>
<th>number of days since model initialisation</th>
</tr>
</thead>
<tbody>
<tr>
<td>9°W, 2°S</td>
<td>Jul 1999</td>
<td></td>
</tr>
<tr>
<td>11.4°E, 18°S</td>
<td>Feb 2001</td>
<td>570 d</td>
</tr>
<tr>
<td>12.2°E, 20°S</td>
<td>Mar 2002</td>
<td>960 d</td>
</tr>
<tr>
<td>14.5°E, 23°S</td>
<td>Apr 2003</td>
<td>1365 d</td>
</tr>
</tbody>
</table>

How long does ESACW need to reach the upwelling cells?

<table>
<thead>
<tr>
<th>position</th>
<th>date</th>
<th>number of days since model initialisation</th>
</tr>
</thead>
<tbody>
<tr>
<td>16°E, 34°S</td>
<td>Jul 1999</td>
<td></td>
</tr>
<tr>
<td>14.5°E, 23°S</td>
<td>Jun 2000</td>
<td>315 d</td>
</tr>
<tr>
<td>12.2°E, 20°S</td>
<td>Aug 2001</td>
<td>765 d</td>
</tr>
<tr>
<td>11.4°E, 18°S</td>
<td>Jul 2002</td>
<td>1085 d</td>
</tr>
</tbody>
</table>
To study propagation pathways several passive tracers are designed which represent 3 cross sections in the South Atlantic.

- 5°S
  - mouth of Kongo river
  - 3 vertical boxes
  - 4 zonal boxes
13°S and 17°S

- 3 vertical boxes
- 2 zonal boxes
- 13°S: near Lobito, change in coastline direction
- 17°S: Kunene river, upwelling cell
Upwelled water in Kunene Cell ($18^\circ$S)

12 tracers released at 5$^\circ$S
12 tracers released at 5°S

- both tracers are released offshore at 5°S
- surface water is not significantly vertically mixed
- tracer from the open ocean is advected onto the shelf

Role of negative wind stress curl for meridional transport (Sverdrup balance)?
Propagation pathways

Kunene (18°S) and Central Namibian Cell (23 °S)

Tracer released at 13°S

Upwelling in Benguela system
Propagation pathways

Kunene (18°S) and Central Namibian Cell (23 °S)

- structure of the shelf determines position of poleward undercurrent
- shelf waves: maximum above shelf edge
- coastal Kelvin waves: maximum at coast
Upwelling in the Northern Benguela upwelling system must be treated in 4 dimensions.

On shorter time scales upwellled water originates in depths smaller than 550 m.

On decadal time scales even Intermediate Water feeds upwelling.

Water from the EUC (SACW) takes 1.5 years to reach the northern Benguela upwelling system.

Poleward transport of tropical water (SACW) does not only take place inside the coastal wave guide but to a substantial amount also in the open ocean.

It is confirmed that the poleward undercurrent is located close to the coast or above the shelf edge in the northern Benguela upwelling system.
Acknowledgement

Thank you for your attention!

Thanks to

my co-author, supervisors
and colleagues

Thank you for your attention!
Passive tracer released in EUC - SACW

shall represent SACW

Source region:
- \( \lambda < 9^\circ W \)
- \( |\varphi| < 2^\circ \)
- \(-200\ m < z < -50\ m\)

area of investigation: northern Benguela upwelling system

on \( \sigma_0 = 26.2\)-level (Mercier 2003)
upwelling in the Northern Benguela upwelling system must be treated in 4 dimensions

- poleward undercurrents can be found near the coastline in subsurface waters or deeper offshore above the shelf edge
- coastal jets and poleward undercurrents determine the meridional (North-South) transport near the coast, their strength varies seasonally depending upon the strength of the local wind patches
- its location varies seasonally and depends on shelf structure
- cross-shore Ekman transport takes place in the surface layer
- between 10°S and 30°S mesoscale eddies contribute to cross-shore transport
- export of equatorial waters to the BUS is not only controlled by advection on the inner shelf but by offshore advection of water
- surface water in the upwelling cells is only partly locally upwelled but also determined by water advected onto the shelf (e.g. through meridional transport of water)
- water from the EUC takes approximately 1.5 years to reach the Kunene Cell
- once it has reached the northern BUS it takes 390 d to reach the Northern Namibian Cell (20°S) and further 450 d to the Central
### Table: Characteristics of upwelling cells in the northern Benguela upwelling system

<table>
<thead>
<tr>
<th>Upwelling Cell</th>
<th>Geographical features</th>
<th>Forcing</th>
<th>External input</th>
<th>Hydrographic features</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kunene Cell</td>
<td>18°S narrow, steeply sloping shelf, shelf edge at 610 m depth, 50 km wide, pronounced shelf edge, change in orientation of coastline</td>
<td>Kunene wind cell permanent</td>
<td>river Kunene year-round water bearing</td>
<td>southern branch of Angolan gyre deflection of currents to the west</td>
</tr>
<tr>
<td>Northern Namibian Cell</td>
<td>20°S gently sloping shelf, shelf edge at 246 m depth, 100 km wide, hardly pronounced shelf edge</td>
<td>wind patch parallel to coast</td>
<td>seasonally variable run-off</td>
<td>linkage between tropical and subtropical Atlantic</td>
</tr>
<tr>
<td>Central Namibian Cell</td>
<td>23°S double shelf structure, first shelf: linearly sloping, shelf edge at 150 m depth, second shelf: sea mount, second shelf edge at 350 m depth, in total: 141 km wide</td>
<td>wind patch parallel to coast</td>
<td></td>
<td>filaments</td>
</tr>
</tbody>
</table>
## Passive tracers A, B, C and D

<table>
<thead>
<tr>
<th>Passive tracer</th>
<th>Source depth</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>100 ... 120 m</td>
</tr>
<tr>
<td>B</td>
<td>200 ... 300 m</td>
</tr>
<tr>
<td>C</td>
<td>300 ... 550 m</td>
</tr>
<tr>
<td>D</td>
<td>550 ... 650 m</td>
</tr>
</tbody>
</table>