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

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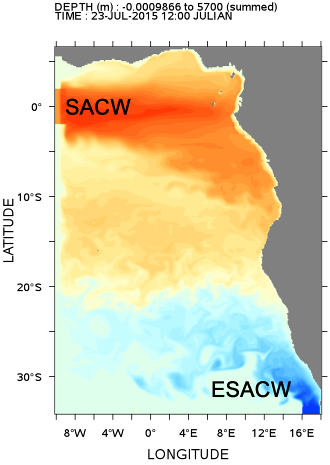
South Atlantic - Central Water masses



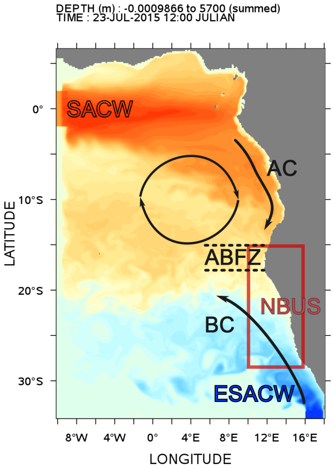
ESACW + SACW

- 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

South Atlantic - surface currents

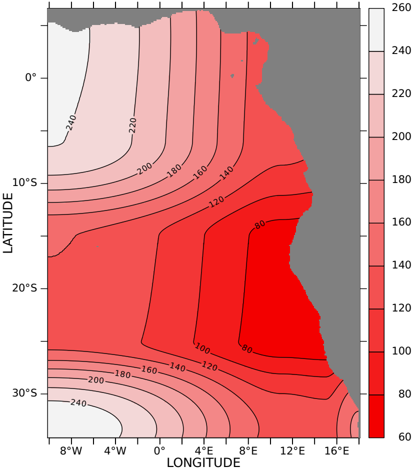


ESACW + SACW

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

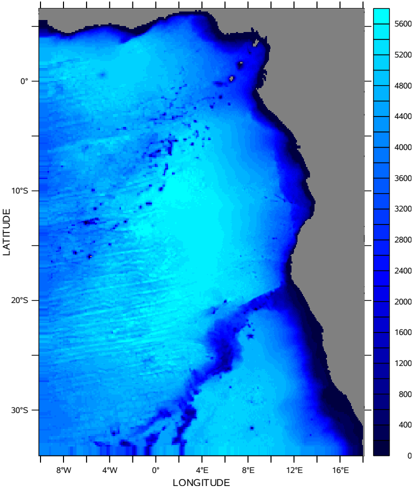
Regional circulation model



Grid cell area $[\mathrm{km}^2]$

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

Regional circulation model



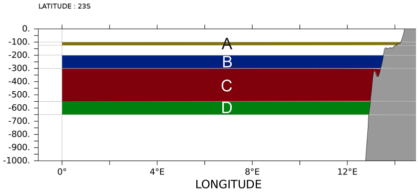
Model topography [m]

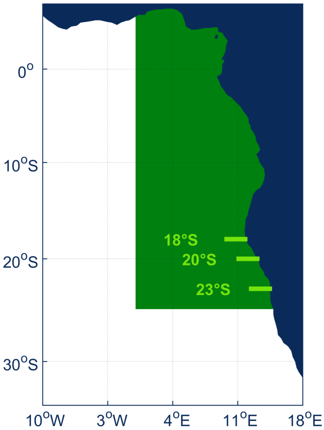
- corrected GEBCO topography
- model output: $5\,\mathrm{d}$ averages
- passive tracers:
  - dimensionless
  - between 0 and 1 (at release region)
  - following advection & diffusion
  - no impact on hydrographic fields

Upwelling depth

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

Hart & Curie, 1960:
$\rightarrow 200\ \mathrm{m}$ to $300\ \mathrm{m}$ (CTD)
Toggweiler (submitted):
$\rightarrow$ signature of AAIW (Δ^{14}C)





Upwelling time

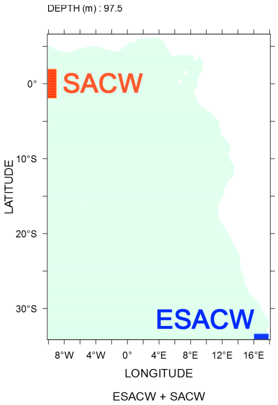
Passive tracer	18°S 200 m	18°S 0 m	20°S 200 m	20°S 0 m	23°S 340 m	23°S 140 m	23°S 0 m
A	...	5 d	...	10 d	...	...	15 d
B	...	70 d	...	35 d	...	15 d	50 d
C	240 d	720 d	275 d	415 d	...	300 d	370 d
D	5385 d (14 a 275 d)	–	1060 d (2 a 330 d)	–	175 d	5150 d (14 a 40 d)	5175 d (14 a 65 d)
	shelf	surface	shelf	surface	outer shelf	inner shelf	surface

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

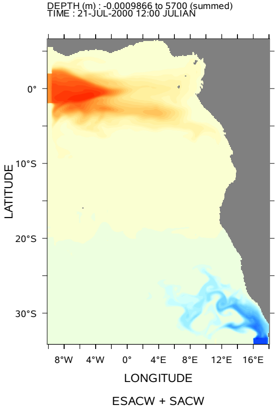
- tracer from 100 m: several days to surface
- tracer from 200 m: 1 to 2 months to surface
- tracer from 300 m: 1 to 2 years to surface
- tracer from 550 m: only at 23°S to surface
- tracer from 550 m: at 20°S only at shelf but NOT at surface

Source region - passive tracers

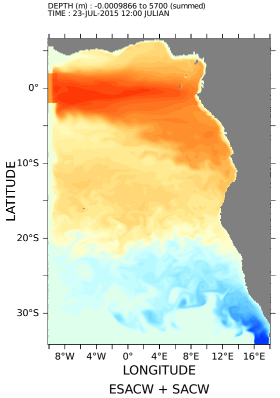
Composite of two passive tracers



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?

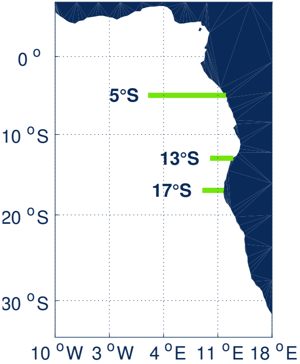
position	date	number of days since model initialisation	
9°W, 2°S	Jul 1999		
11.4°E, 18°S	Feb 2001	570 d	
12.2°E, 20°S	Mar 2002	960 d	↓ 390 d
14.5°E, 23°S	Apr 2003	1365 d	↓ 405 d

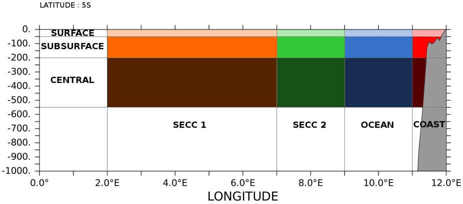
How long does ESACW need to reach the upwelling cells?

position	date	number of days since model initialisation	
16°E, 34°S	Jul 1999		
14.5°E, 23°S	Jun 2000	315 d	
12.2°E, 20°S	Aug 2001	765 d	↓ 450 d
11.4°E, 18°S	Jul 2002	1085 d	↓ 320 d.

Propagation pathways

To study propagation pathways several passive tracers are designed which represent 3 cross sections in the South Atlantic.

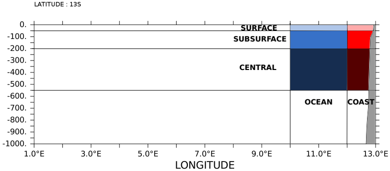


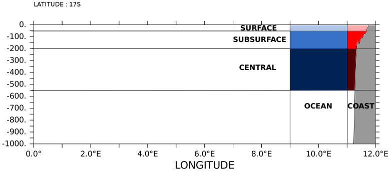


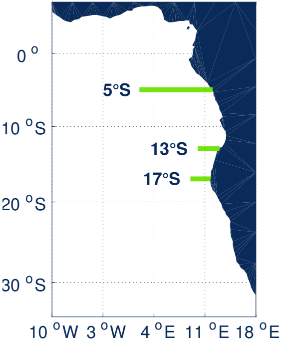
<u>5°S</u>

- mouth of Kongo river
- 3 vertical boxes
- 4 zonal boxes

Propagation pathways





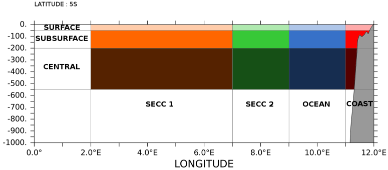


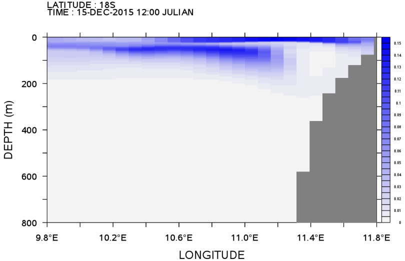
<u>13°S and 17°S</u>

- 3 vertical boxes
- 2 zonal boxes
- 13°S: near Lobito, change in coastline direction
- 17°S: Kunene river, upwelling cell

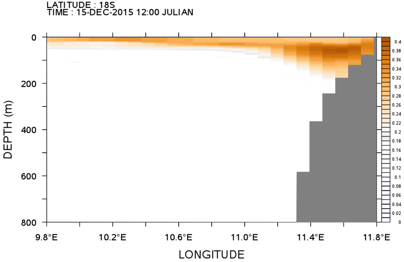
Upwelled water in Kunene Cell (18°S)

12 tracers released at 5°S

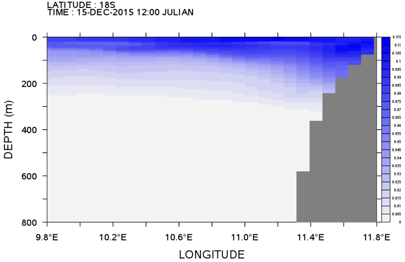




OCEAN surface



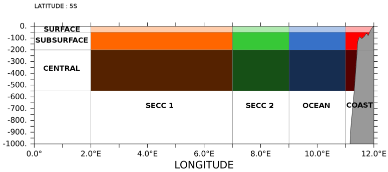
SECC 1 subsurface



OCEAN subsurface

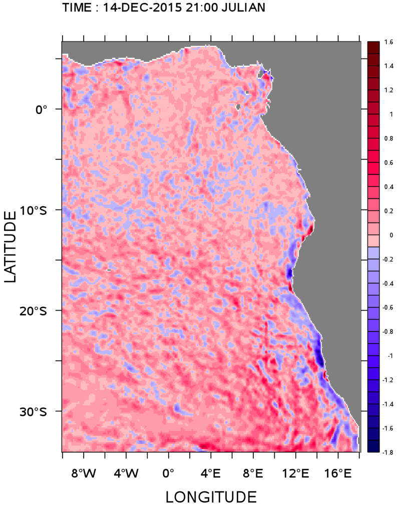
Upwelled water in Kunene Cell (18°S)

12 tracers released at 5°S



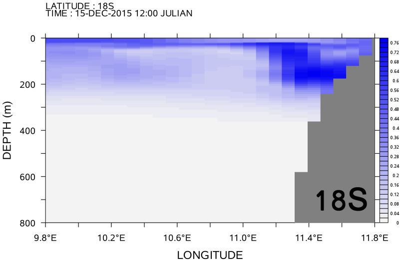
- both tracers are released offshore at 5°S
- surface water is not significantly vertically mixed
- tracer from the open ocean is advected onto the shelf

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

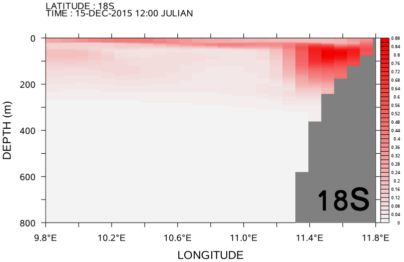


Wind stress curl

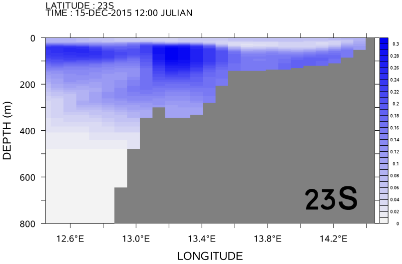
Kunene (18°S) and Central Namibian Cell (23 °S)



13S OCEAN subsurface

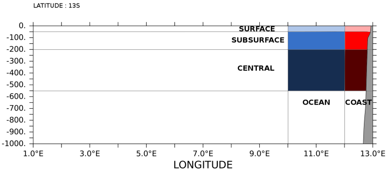


13S COAST subsurface

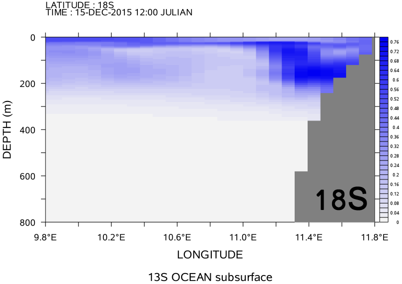


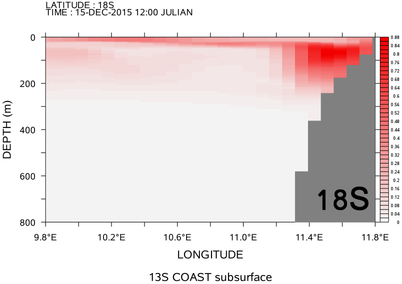
13S OCEAN subsurface

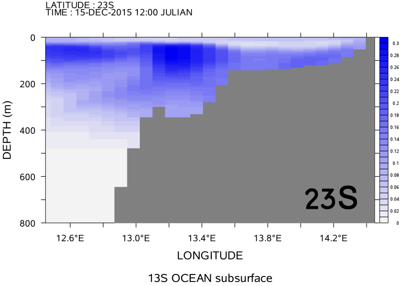
Tracer released at 13°S



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

Summary

- Upwelling in the Northern Benguela upwelling system must be treated in 4 dimensions.
- On shorter time scales upwellled water originates in depths smaller than $550\ \mathrm{m}$.
- 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

SACUS Spaces

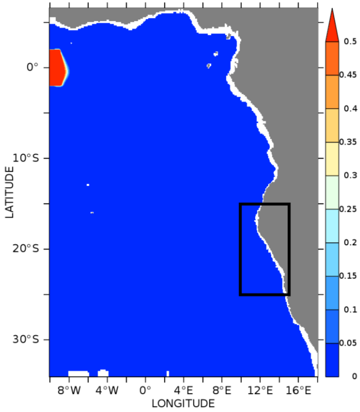
Bundesministerium für Bildung und Forschung

Thanks to

my co-author, supervisors and colleagues

Thank you for your attention!

Passive tracer released in EUC - SACW



- shall represent SACW
- Source region:
  - λ <9°W
  - $|\varphi| < 2°$
  - $-200 \text{ m} < z < -50 \text{ m}$
- area of investigation: northern Benguela upwelling system
- on $\sigma_0 = 26.2$-level (Mercier 2003)

Summary - additional points

- 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 $390\ \mathrm{d}$ to reach the Northern Namibian Cell (20°S) and further $450\ \mathrm{d}$ to the Central

Upwelling Cells - characteristics

Upwelling Cell	Geographical features	Forcing	External input	Hydrographic features
Kunene Cell	18°S narrow, steeply sloping shelf shelf edge at 610 m 50 km wide pronounced shelf edge change in oritentation of coastline	Kunene wind cell permanent esp. strong in Nov	river Kunene year-round water bearing seasonally variable run-off	southern branch of Angolan gyre deflection of currents to the west linkage between tropical and subtropical Atlantic
Northern Namibian Cell	20°S gently sloping shelf shelf edge at 246 m wide 100 km hardly pronounced shelf edge	wind patch parallel to coast		filaments
Central Namibian Cell	23°S double shelf structure first shelf: linearly sloping first shelf edge at 150 m depth second shelf: sea mount second shelf edge at 350 m depth in total: 141 km wide	wind patch parallel to coast		filaments

Table: Characteristics of upwelling cells in the northern Benguela upwelling system

Passive tracers A, B, C and D

Passive tracer	Source depth
A	$100 \ldots 120$ m
B	$200 \ldots 300$ m
C	$300 \ldots 550$ m
D	$550 \ldots 650$ m