Mesoscale eddies & their role in the formation & transformation of Indian Ocean mode waters

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Abstract

The **sources and pathways of mode waters** entering the subtropical gyre of the Indian Ocean are examined. A **lagrangian analysis is performed on an eddy resolving model of the Southern Ocean** (DRAKKAR, ¼°Mercator grid), where we trace the subducted mode water's pathways, identify their formation regions, and trace back whether their source waters come from the Atlantic, Pacific or Indian sectors of the Southern Ocean. We also **quantify how the mode water characteristics are modified after subduction, due to internal mixing effects.**

Mode Water Definition

We take a large range for mode waters, defined as below 200m, Potential Vorticity (PV) < 0.2 and potential density in the range 26<σ< 27.4), after Wong (2005). This covers STMW, SAMW and AAIW in the Indian Sector.

Model Validation

The eddy-admitting model is first validated with observations. The model EKE pattern is close to altimetry, although the model misses some of the smaller-scale eddies, and energetic regions are trapped too close to the bathymetry (left). Modelled winter mixed layers are well represented, with strong mesoscale structure, though shifted slightly north (centre) . Vertical sections show very good features, except the model misses some of the warm-salty Agulhas recirculation in the west (right).

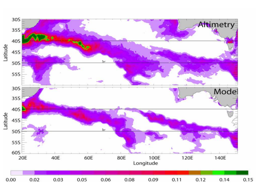


Fig. EKE from altimetry calculated over the period 1993-2007 (top) and from the model over the same period.

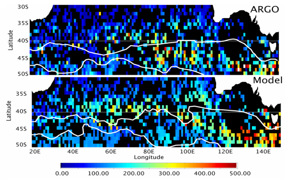


Fig. Winter (July-August) mixed layer depths for the ARGO data (2000-2006) and model data colocated in space and time. Shaded in color are the average MLD over a 1°x1° boxes. Black represent s missing ARGO data during that period. White contours show the STF and the SAF from the model, and from Orsi et al. (1995) for the observations.

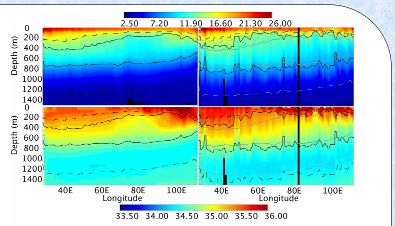


Fig. Vertical sections of temperature (upper panels) and salinity (lower panels) for the model (left) and the observations (right) collocated in time and space for the WOCE I5 section at 32°S in Mar-Apr 2002 . Black dashed and solid contours represent the 27.4, 26.85, 26.4, 26 isopycnals. Grey contour on the observations (right panels) show the same model isopycnals, for comparison. The vertical lines represent missing data.

Pathways and volume transport of mode waters which cross the 30°S line

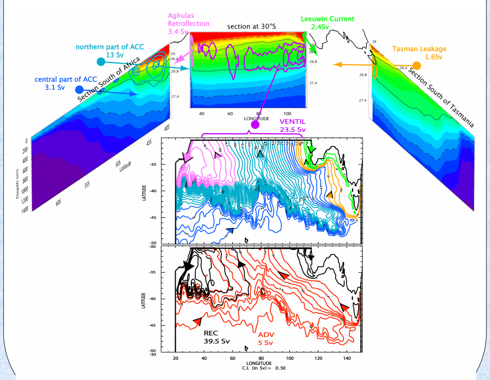
Millions of tiny water mass particles are released within the defined mode waters at 30°S, repeated throughout the time period . We then track the particles back in time and store their changing caracteristics along the route. We identify when they were last in contact with the mixed layer. We stop the integration when they reach the analysis boundaries at 20°E, 150°E or recirculate through 30°S.

Waters ventilated in the Indian Sector (top panels)

23 Sv of mode waters are ventilated in the Indian sector of the model, and then exit into the subtropical gyre crossing the 30°S l ine. Of these waters, the major branches come from the Agulhas Retroflection and the northern ACC (19.5 Sv – in pink and blue). There is a small recirculation of Leeuwin Current waters (2.4 Sv – green), and from the Tasman Leakage (1.6 Sv – yellow).

Non-ventilated mode waters crossing 30°S (bottom panel)

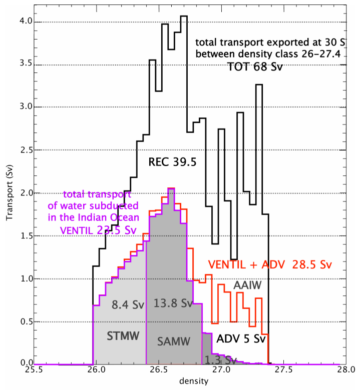
44.5 Sv of mode waters exiting at 30°S in the Indian Ocean are non-ventilated – either advected from the Pacific or south Atlantic (5 Sv) or in deeper recirculation cells (mainly eddies at 30°S).



Density distribution of mode waters which cross the 30°S line

Waters ventilated in the Indian Sector

Of the 23 Sv of mode waters ventilated in the Indian sector of the model, which then exit into the subtropical gyre crossing the 30°S line, 8.4 Sv are in the STMW density class, 13.8 Sv are in the SAMW class, and only 1.3 Sv in the AAIW density class. **Most of the AAIW which cross 30°S are advected at deeper levels from the Atlantic and Pacific Oceans, and are not ventilated in the Indian sector.**

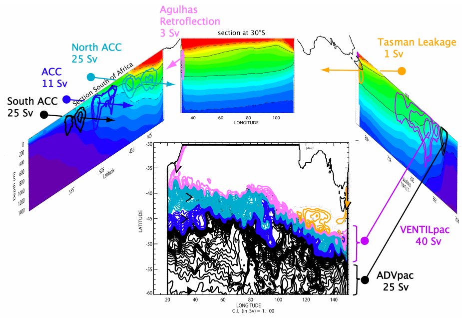


Pathways and volume transport of mode waters which exit into the Pacific at 150°E

Waters ventilated in the Indian Sector (VENTILpac)

40 Sv of mode waters are ventilated in the Indian sector of the model, which then exit into the Pacific Ocean crossing the 150°E lin e. Of these waters, the major branches come from the Agulhas Retroflection and the northern ACC (39 Sv – in pink and blue). There is a small recirculation of Tasman Leakage waters (1 Sv – yellow).

25 Sv of denser and deeper mode waters transit the Indian Ocean from the Atlantic to the Pacific without touching the surface mixed layer (ADVpac).



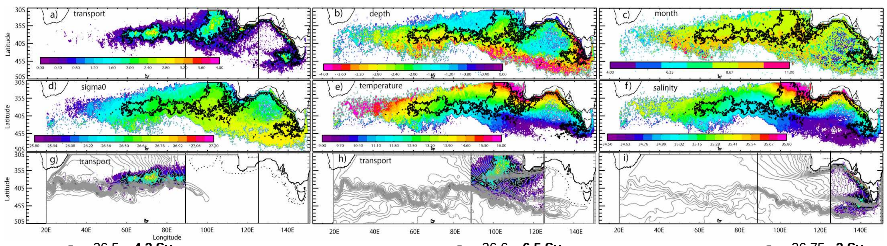
SAMW properties at the last ventilation site in the Indian Ocean

Lagrangian particle analysis of SAMW (density class 26.4 – 26.8) for waters formed in the Indian sector of the Southern Ocean, which then exit north at 30°S in the Indian Ocean. These maps show the SAMW characteristics at the location where these waters were last ventilated (properties at the base of the mixed layer). a) volume transport of particles in 10^{-4} m²/s, b) mixed layer depth, in 10²m, c) month, d) potential density in kg.m³/s, e) temperature in °C, f) salinity. Lower panels show the upstream and downstream lagrangian pathways for these source waters formed between g) 20-90°E, h) 90-125°E, and i) 125-155°E.

Western section (g) – 4.3 SV of lighter SAMW are ventilated just north of the deepest winter mixed layer (b), with a density ~ 26.5 kg/m3. Their source waters are in the Agulhas Retroflection.

Central section (h) – 6.5 SV of SAMW are ventilated to the SW of Australia in a region spanning the STF (e,f), with a density ~ 26.6 kg/m3. Their source waters are varied : the Agulhas Retroflection, Antarctic Surface waters, and Leeuwin Current waters.

Eastern section (i) – 3 SV of denser SAMW are ventilated SW of Tasmania with a density ~ 26.75 kg/m3. Their source waters come from the ACC, from the Tasman Leakage and the Leeuwin Current.



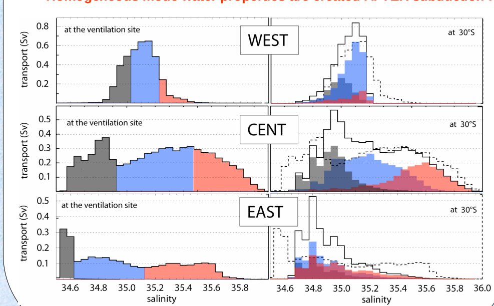
σ_0 ~ 26.5 **4.3 Sv** σ_0 ~ 26.6 **6.5 Sv** σ_0 ~ 26.75 **3 Sv**

Modification of mode water properties by internal (eddy) mixing AFTER subduction

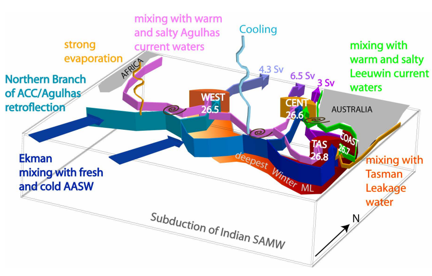
This figure shows the salinity distribution of the mode waters at each of the main ventilation site (LEFT) at the moment of ventilation and (RIGHT) when they exit at 30°S. The initial salinity distribution is c olour coded. At 30°S, the salinity distribution has been spread over neighbouring bins. The new total salinity distribution at 30°S (solid black line) is narr ower than the original distribution (dashed line) – the extremities have been eroded.

⇒The bi-modal or tri-modal structure at the ventilation site has become more homogeneous through eddy mixing.

=> Homogeneous mode water properties are created AFTER subduction !



Summary and Conclusions



Koch-Larrouy et al., 2009. **Origin and mechanisms of SAMW formation and transformation in the southern Indian Ocean.** *Ocean Dyn.* (submitted).

The major conclusions of this study are :

1) We have quantified that **only one third of the water exported at 30°S between 26 and 27.4 is subducted locally** in the Southern Indian Ocean.

2) **AAIW exported across 30°S in the Indian Ocean are not ventilated in the South Indian Ocean** but are advected from other oceans.

3) **Three main ventilation sites for SAMW have been found in the Indian Ocean**:
- WEST : 4.3 Sv of lighter SAMW, north of Kerguelen
- CENT : 6.5 Sv SW of Australia
- EAST : 3 Sv SW of Tasmania

4) The model highlights **new important ventilation sites for the deepest and densest SAMW** in the TAS and COAST sites.

5) **This study modifies the classical vision of MW ventilation.** We find that the **last ventilation** "leaving the ML" occurred on the **adjacent downstream side of the deep WML,** & mainly due to horizontal advection

6) **Winter re-emergence can occur many years after waters leave the deep WML north of the SAF.**

7) **Eddies play an important role in the formation of these SAMW.**
- Firstly, **upstream** of the last ventilation site, eddies can contribute to mixing different branches together,
- Secondly, at the **last ventilation site,** the model shows **isolated deep mixed layers** (chimneys), mainly created by mesoscale activity.

8) Finally, this study shows that **eddies are crucial AFTER the last ventilation in homogenising the T,S properties.**

Further Information

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