

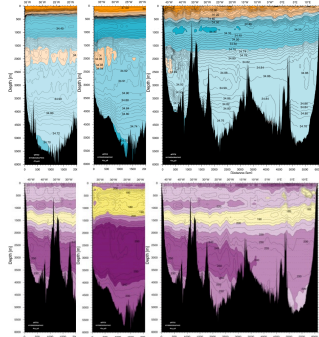
# Tracing the lower limb of the AMOC in the South Atlantic

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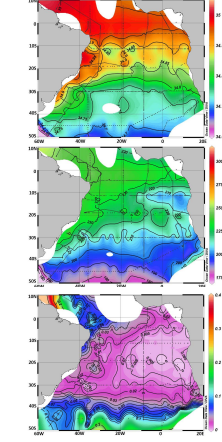
## 1. Water mass properties indicate that LSW crosses the equator and flows into the Atlantic with a distinctive pathway from 10°S to 25°S.

The NADW carried by the lower limb of the AMOC is characterized by low temperature ( $\sim 3^\circ\text{C}$ ), high salinity ( $S > 34.8$  psu), and high levels of dissolved oxygen ( $\text{O}_2 > 5 \text{ ml/l}$ ). This NADW flows southward at neutral density levels between 27.9 and 28.1 in the South Atlantic near  $35^\circ\text{S}$ . Inspection of the CTD sections collected during the WOCE experiment at  $11^\circ\text{S}$ ,  $19^\circ\text{S}$  and  $30^\circ\text{S}$  show that water masses with these characteristics in the South Atlantic are concentrated at the western boundary between 1500 and 3000 m depth (Figure 1).



**Figure 1:** Zonal section of salinity (top) and dissolved oxygen (bottom) from the WOCE Atlas (Koltermann et al. 2011) for lines along  $11^\circ\text{S}$ ,  $19^\circ\text{S}$ , and  $30^\circ\text{S}$ . Water masses with the characteristics of the NADW are seen along the western boundary up to  $30^\circ\text{S}$ . At the eastern boundary (note only the western boundary is shown along  $11^\circ\text{S}$  and  $20^\circ\text{S}$ ) only at  $30^\circ\text{S}$  there is an indication in the salinity of the presence of the NADW (c.f.  $S=34.86$  contour). Adapted from Koltermann et al. (2011).

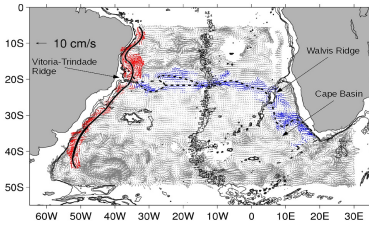
The NADW can also be traced accurately using other tracers. Using the WOCE data era (1992-1997), maps of salinity, dissolved oxygen and chlorofluorocarbon-11 (CFC-11) concentrations have been generated for the South Atlantic (Figure 2) on 34.633  $\sigma_{\theta,5}$ , the level of the upper NADW between 1700 and 2000 m. The maps clearly show water masses with the properties of the NADW spreading southward along the continental slope. The maps also show more diffuse eastward extending tongues of properties between  $10^\circ\text{S}$  to  $25^\circ\text{S}$ . High salinities, which are characteristic of NADW at this depth, are mostly confined west of  $28^\circ\text{W}$  aside from the eastward spreading between  $10^\circ\text{S}$  to  $25^\circ\text{S}$  on the WOCE era map (Figure 2). There is also a tongue of high dissolved oxygen (220  $\mu\text{mol/kg}$  contour) extending eastward along  $10^\circ\text{S}$  to  $25^\circ\text{S}$ .



**Figure 2:** Maps of salinity (top), dissolved oxygen concentration in  $\mu\text{mol/kg}$  (middle) and CFC-11 in  $\mu\text{mol/kg}$  (bottom) on 34.633  $\sigma_{\theta,5}$ , the level of the upper NADW between 1700 and 2000 m, generated from WOCE-era data from 1992 to 1997.

## 2. Argo data

The long-term mean Argo-derived absolute velocity field at 2000 dbar (within the upper layer of the NADW) is shown in Figure 3. South of the Vitória-Trindade Ridge, the flow bifurcates. The dominant branch is a strong southward flow (highlighted in red) along the coast of South America that continues all the way to  $45^\circ\text{S}$ . This flow separates from the boundary at  $38^\circ\text{S}$ , the region of the Brazil-Malvinas Confluence. The Argo velocities also show a less well-defined eastward flow into the interior along roughly  $22^\circ\text{S}$  consistent with the spreading of the NADW towards the center of the basin, which is suggested by the CFC data (Figure 2). However, this pathway (highlighted in blue) is much less well-developed. Eastward of the Walvis Ridge ( $\sim 0^\circ\text{E}$ ), the Argo velocity product produces no clear picture of a continuous flow, likely due to the high degree of mesoscale motion in and northwest of the Cape Basin.



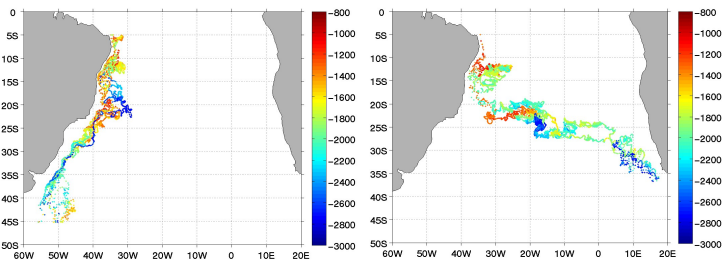
**Figure 3:** Velocity field at 2000 dbar derived from the Argo data. Red highlights the strong southward flow along the western boundary; blue indicates the eastward velocity originating near the Vitória-Trindade ridge. Isotherms: 2000, 2500 and 3000 m. Solid curves highlight the pathway of the DWBC along the South American coast. Dashed lines indicate regions where the pathway is less well developed as it moves to the interior of the basin.

## 3. Analysis of the OFES products

### 3.1 Lagrangian pathways

In a recent study, van Sebille et al., (2012) examined the pathways of NADW in the South Atlantic in the OFES model using Lagrangian pathways generated by integrating 27-years of OFES model output velocities forward in time. Float deployments are simulated along a grid at  $5^\circ\text{S}$  whenever the local instantaneous transport within the grid cell is southward. For a total of 5 years, one simulated float is released every 3 days. The vast majority of these floats are within the NADW layer. In their experiment they focused the analysis on the connectivity between the DWBC and the Cape Basin and concluded that the pathway for NADW zonally across the subtropical South Atlantic lies directly below the Agulhas Ring corridor transporting 3.6 Sv of NADW from the DWBC at  $25^\circ\text{S}$  eastward toward the southern tip of Africa.

Further analysis of the Lagrangian simulation is performed here, analyzing the pathways of the DWBC based on lessons learned from the hydrographic and tracer observations, with a focus along the continental shelf of South America. The Lagrangian model results indicate that, while some flow does cross the South Atlantic interior near  $20^\circ\text{S}$ , the dominant pathway of the DWBC is along the continental slope of South America. Approximately 13.2 Sv crosses southward  $5^\circ\text{S}$  in the depth range where the float simulations are started. This result is in agreement with the value obtained from the hydrographic data collected along the WOCE A07 line (12.6 Sv southward between neutral densities 27.9 to 28.1). Lagrangian particle back-tracking from points further south indicates that most of this southward and southeastward flow originates west of  $30^\circ\text{W}$  along  $5^\circ\text{S}$  (90% of the total virtual floats). Approximately 71% of the synthetic Lagrangian floats move along the continental shelf of South America forming the main branch of the southward DWBC. Approximately 21% of the simulated floats in the NADW layer flow eastward into the interior Atlantic and continue towards the Cape Basin directly beneath the Agulhas Ring corridor.



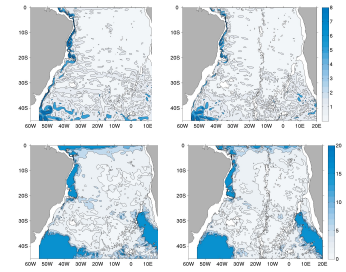
**Figure 4:** Examples of the two main pathways for the NADW derived from the synthetic floats. The top panel shows example trajectories of the 71% of the synthetic floats flowing along the western boundary; the bottom panel shows example trajectories of the 21% of floats heading towards the Cape Basin. The color shading indicates the depth of the float in meters.

### 3.2 Eulerian analysis

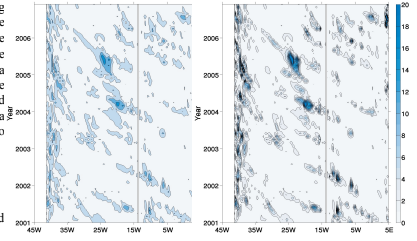
The mean speed and eddy kinetic energy (EKE) in the model were calculated at different depths within the NADW layer: 1700 m (the upper boundary of NADW), 2500 m (the NADW core depth), and 3600 m (the lower boundary of NADW) (Figure 5). The mean speed fields show a steady and strong flow following the coast of South America both at 1700 m and 2500 m. The very energetic flow variability entering the South Atlantic from the tropics is fairly tightly confined along the western boundary (e.g. near  $5^\circ\text{S}$ ). Traveling southward, the region of flow variability extends a little further offshore beginning around  $8^\circ\text{S}$ , consistent with the observations indicating that the DWBC breaks up into rings at this latitude. When this flow reaches the Vitória-Trindade Ridge at approximately  $20^\circ\text{S}$  the region of high variability stretches even further offshore, which is consistent with the flow becoming even more energetically eddy-dominated due to the interaction with the topography. In agreement with the Lagrangian analysis, there is a signature of enhanced variability stretching eastward across the basin towards the Walvis Ridge in the EKE maps (Figure 5), suggesting that these eddies may carry part of the flow towards the interior of the basin. The EKE maps also show a narrow tongue of higher variability close to the southern side of the Vitória-Trindade Ridge and continental slope to the south, consistent with a more stable and stationary DWBC flow returning to the continental slope moving southward.

Animations of the flows in the South Atlantic at all three levels indicate that energetic mesoscale features propagating westward are prevalent in the South Atlantic basin. In particular, signals generated in the Agulhas Current region propagate northwestward into the interior along the model ring corridor and in some cases reach the western boundary.

To look at the westward component of the propagation of the mesoscale signals in the basin, speed and EKE were plotted for different latitudes and at different depths. An example of this westward propagation can be seen in a Hovmöller diagram of the speed and the EKE along  $25^\circ\text{S}$  at 2500 m from 2001 to 2006 (Figure 6). The westward propagation has the characteristics of a Rossby wave-like feature with estimated speeds of about 5 to 7  $\text{cm/s}$ . The feature is consistent with previous satellite and in situ observations of first baroclinic mode Rossby waves.



**Figure 5:** Examples of the speed in  $\text{cm/sec}$  and eddy kinetic energy in  $\text{cm}^2/\text{sec}^2$  calculated from the OFES fields. Top panels show the annual mean of the speed and the lower panel the EKE for two different depths: the upper boundary of the DWBC (1700 m, left) and the core of the DWBC (2500 m, right).



**Figure 6:** Hovmöller diagrams of the speed in  $\text{cm/sec}$  (left) and eddy kinetic energy in  $\text{cm}^2/\text{sec}^2$  (right) calculated from the OFES fields across  $25^\circ\text{S}$  and at 2500 m depth from 2001 to 2006.

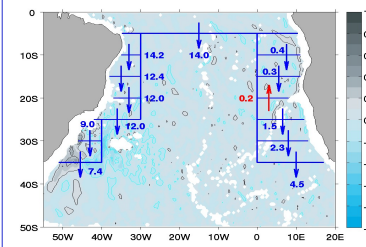
Volume transport	Neutral density 27.9 to 28.1 ( $\sim 1700$ to $3000$ m)	By depth 1000 to 3500 m	Floats deployed between 1000 to 3500 m
<b>From model results from coast to coast at <math>5^\circ\text{S}</math>.</b>	<b>-14.0 Sv</b>	<b>-16.8 Sv</b>	<b>-13.2 Sv</b>
<b>From CTD and Argo observations from coast to coast at <math>5^\circ\text{S}</math>.</b>	<b>-12.6 Sv</b>	<b>-21.4 Sv</b>	<b>n/a</b>
<b>Model results at <math>34.5^\circ\text{S}</math> from <math>44.5^\circ\text{W}</math> to the coast</b>	<b>-7.4 Sv</b>	<b>-14.0 Sv</b>	<b>-10.2 Sv</b>
<b>From PIES observations at <math>34.5^\circ\text{S}</math></b>	<b>-10.9</b>	<b>-16.7</b>	<b>n/a</b>
<b>From combined observations at <math>-35^\circ\text{S}</math></b>	<b>-9.6</b>	<b>-19.7</b>	<b>n/a</b>
<b>Model results at <math>34.5^\circ\text{S}</math> from <math>40.0^\circ\text{W}</math> to the coast</b>	<b>-10.0 Sv</b>	<b>-16.3 Sv</b>	<b>-11.1 Sv</b>
<b>From observations at <math>30^\circ\text{S}</math></b>	<b>-8.2 Sv</b>	<b>-14.5 Sv</b>	<b>n/a</b>
<b>From combined observations at <math>-35^\circ\text{S}</math></b>	<b>-9.0</b>	<b>-19.5</b>	<b>n/a</b>
<b>Model results at <math>34.5^\circ\text{S}</math> from <math>0^\circ\text{E}</math> to coast</b>	<b>-4.5 Sv</b>	<b>-2.8 Sv</b>	<b>-3.0 Sv</b>
<b>From combined observations at <math>30^\circ\text{S}</math></b>	<b>-4.0 Sv</b>	<b>-3.5</b>	<b>n/a</b>

### Volume Transport

Analysis of the model trajectories indicates that after crossing  $34.5^\circ\text{S}$ , a small amount (about 1 Sv) of NADW flows towards the east at the latitude where the Malvinas Current turns offshore. The rest of the flow continues south to approximately  $45^\circ\text{S}$  where it joins with the eastward flowing the ACC. Eulerian volume transport estimates indicate that about 2 Sv of NADW does not leave the South Atlantic as NADW. This is consistent with previous modeling and observational results which found that in the Brazil-Malvinas Confluence region approximately 2.6 Sv of water is transformed from NADW to AAIW.

**Table 1:** Volume transport in Sv ( $1 \text{ Sv} = 10^6 \text{ m}^3/\text{sec}$ , negative indicates southward), estimated from the OFES velocity field between neutral densities 27.9 and 28.1 (Column 1) and between 1000 and 3500 m (Column 2). Column 3 values are from the Lagrangian trajectory field for floats deployed between 1000 and 3500 m. Values in red are obtained from observations: CTD and Argo observations at  $5^\circ\text{S}$ , combined observations at  $30^\circ\text{S}$  and  $-35^\circ\text{S}$ , and a line of PIES (inverted echo sounder and pressure sensors) moorings along  $34.5^\circ\text{S}$ .

From the model velocity fields, meridional volume transports at different latitudes are obtained. Comparisons between results obtained here from the different methods and the available observations across the basin at  $5^\circ\text{S}$  and at the boundaries are shown in Table 1. An overall NADW schematic flow along the boundaries is illustrated in Figure 7.



**Figure 7:** Volume transports between neutral density levels 27.9 and 28.1 corresponding to NADW, and obtained from the OFES velocity fields. The color shading shows the zero-lag correlation between meridional velocity at any given location in the South Atlantic at a depth of 2500 m with the DWBC meridional volume transport at that depth along  $34.5^\circ\text{S}$  near the western boundary. The color scale is the correlation value (r) from -1.0 to 1.0.

## Summary and conclusions

Lagrangian and Eulerian analysis of the OFES model, validated against hydrographic, tracer, Argo and PIES data, provides a description of the pathways of the DWBC as it moves through the South Atlantic, carrying NADW southward as the lower limb of the AMOC. Re-analysis of the WOCE-era hydrographic data collected along  $5^\circ\text{S}$  in conjunction with the modern Argo drift velocity field indicates that 90% of the southward flow at  $5^\circ\text{S}$  originates west of  $30^\circ\text{W}$ . The DWBC carries NADW along the coast of South America and breaks into rings near  $8^\circ\text{S}$ , a region where the flow is mostly "non-stationary." This "ring-dominated" flow continues southward to the Vitória-Trindade Ridge (near  $20^\circ\text{S}$ ) where preservation of potential vorticity results in a branching of the flow in this area. From the western boundary, about 20% of the water flows eastward into the interior South Atlantic. It is hypothesized that this southeastward spreading of properties could result from a combination of the mechanism of eddy-thickness flux divergence due to Agulhas ring decay, and enhanced mixing caused by the clearly very-energetic eddy field at the Vitória-Trindade Ridge.

The most prevalent motion noted in the ocean model velocity fields at three depths is a strong northwestward propagation consistent with the westward propagation characteristics of Rossby Waves. This westward propagation interacting with the mean circulation field may be the reason why southward of the Vitória-Trindade Ridge most of the flow ( $\sim 71\%$  in the model) returns to the continental slope, as a more steady flow, forming the main branch of the DWBC south of the ridge. Based on the available observations and the model analysis, we conclude that the DWBC, and the NADW that it carries, follows two different pathways south of  $5^\circ\text{S}$ . The main pathway is as the DWBC flowing along the coast of South America. A smaller portion flows towards the interior of the basin.