ROMS simulations to investigate on the Indo-Atlantic Exchange and its influence onto the Benguela Upwelling

Sabrina Speich*, Pierrick Penven◊, and Bruno Blanke*

* LPO/UBO, UFR Sciences, 6 avenue Le Gorgeu, BP 209, 29285 BREST CEDEX FRANCE

◊ IRD, Centre de Bretagne, BP 70, 29280 PLOUZANÉ CEDEX FRANCE, 29200 BREST CEDEX FRANCE

Contact : Sabrina.Speich@univ-brest.fr

Introduction

Interocean exchange of heat and salt around Southern Africa is thought to be a key link in the maintenance of the global overturning circulation of the ocean (Fig. 1). Most of Indian waters leakage to the Atlantic Ocean takes place through large current rings that pinch off from the Agulhas Retroflection. The Agulhas Retroflection and the shedding of large anticyclonic rings have been topic of theoretical and experimental research since more than twenty years. The Agulhas current is the most intense western boundary current of the world ocean and the Retroflection region shows one of the highest signal of kinetic energy. Only recently it is appeared, from intensive Eulerian and Lagrangian observations and satellite data, that interocean exchange South of Africa is dynamically much richer and more complex than previously thought. Almost everywhere, in the Cape Basin region, cyclonic structures develop and interact with the Agulhas Current, Retroflection and rings. More over, the Agulhas Current is thought to strongly influence the dynamics and variability of the South Benguela upwelling systems.

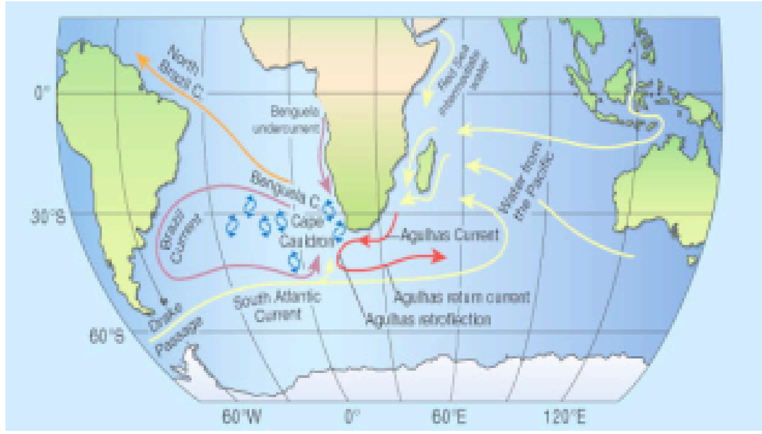

Figure 1: The Agulhas system and associated flow patterns. The Agulhas Current is the western boundary current of the South Indian Ocean. It abruptly turns back towards the Indian Ocean near 20° E. Here, at the Agulhas Retroflection, 'leakage' of water occurs within an array of cyclonic (clockwise) and anticyclonic (anticlockwise) eddies that are injected into

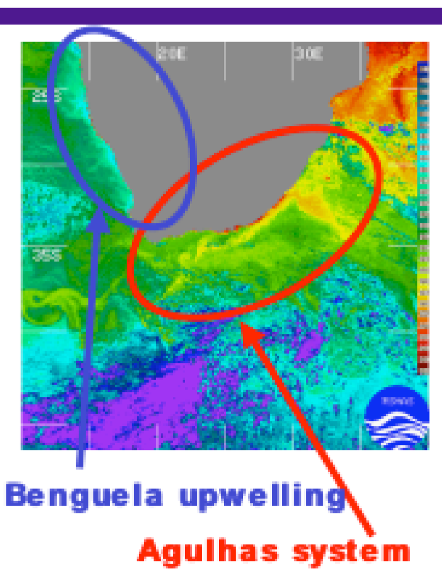

Figure 2: The warm Agulhas and cold upwelling Benguela Sea Surface Temperature systems depicted from the GAC IR satellite imagery on December 31, 2003.

Objectives

In this work we examine the complex dynamics of the Agulhas separation, Retroflection and interocean exchange by using a relatively high-resolution ROMS configuration of the Southern Africa Indo-Atlantic region. Through a hierarchy of sensitivity experiments we investigate the role of

- **the form and steepness of the bathymetry**
- **the influence of the local rate of the Earth's rotation**
- **open ocean and synoptic atmosphere forcings.**

The results are discussed in terms of physical processes inducing or influencing the Agulhas Retroflection, the rings shedding, the general cyclones genesis and dynamics in the region as well as the influence and interactions of Agulhas waters with the upwelling systems.

Model configuration

We used the UCLA_IRD version of the ROMS code at two different spatial resolutions: 1/6° and 1/10°. While the low resolution configuration gas been used to run numerous sensitivity tests, the highest resolution is used to better quantify the impact and related water mixing and exchanges realized by the mesoscale dynamics.

All the model external forcing are derived from climatologies except for two simulations. At the surface, the model heat and fresh water fluxes are extracted from the COADS ocean surface monthly climatology at 1/2° resolution [Da Silva et al., 1994]. For the wind stress, a monthly mean climatology is computed from QuickSCAT satellite scatterometer data [Liu et al., 1998]. At the three lateral boundaries facing the open ocean, the solution at the boundary is nudged toward cyclic seasonal, time-averaged outputs of the OCCAM global ocean model at 1/4° resolution [Saunders et al., 1999].

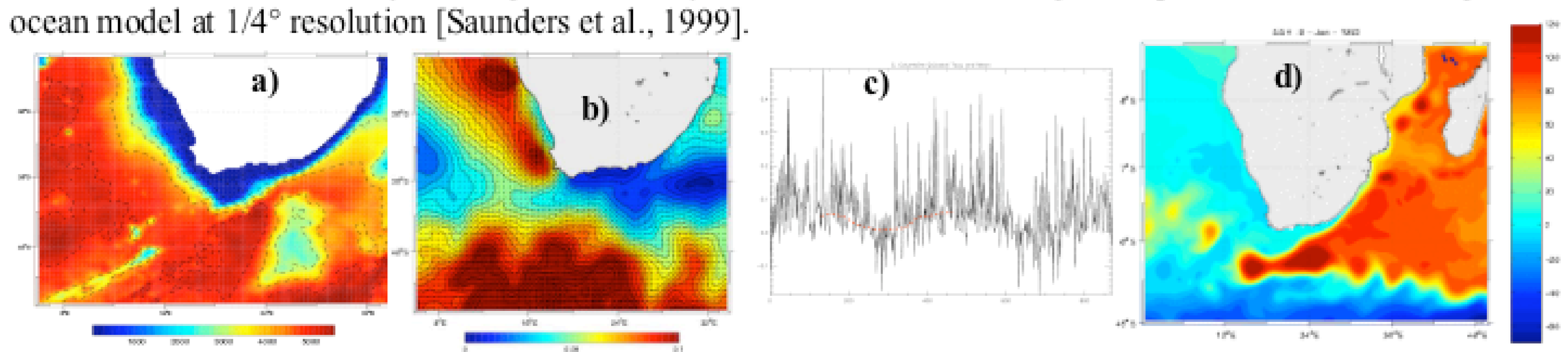

Figure 3: The ROMS simulations. a) The model domain and bathymetry. b) The mean wind-stress structure and intensity derived from QuickSCAT data. c) QuickSCAT wind-stress meridional component near Cape Columbine (west coast of South Africa). Superimposed in red, the derived climatological field. d) OCCAM January Sea Surface Height. We used OCCAM outputs and the derived climatology as initial and open-boundary conditions for the various simulations.

The quantitative Lagrangian diagnostics

Some analyses of our numerical simulation make use of quantitative Lagrangian diagnostics (Blanke and Raynaud, 1997; Speich *et al.*, 2001; 2002) to trace the water masses pathways, inter-current and interbasin connections. Indeed, a natural and convenient way to trace ocean water masses is to follow their pathways. This is something still difficult to achieve with observations, even though there is a true effort of the scientific community to use real floats to track water movements (*e.g.*, for the region south off Africa see Boebel *et al.*, 2003). Ocean models, despite the fact they only approximate reality, compute time-varying three-dimensional velocity fields that can be used for Lagrangian diagnostics. In our approach, individual trajectories are computed with a mass-preserving algorithm [Blanke and Raynaud, 1997; Blanke et al., 1999]. Due to water mass incompressibility, we assume that individual particles conserve their infinitesimal mass along their trajectory. As a current can be entirely determined from the particles composing it, with well-defined characteristics (position, velocity and tracers), the transport of a given water mass can be computed from its own particles and their associated infinitesimal transports. Following Döös [1995], quantitative conclusions are obtained by using a large number of particles, sufficient to insure the numerical stability of the transport estimates. We have used individual transports that are always less than 10^{-2} Sv. It ensures an overall error of the computed water mass transports less than 0.1 Sv. The Lagrangian computations are achieved with both, monthly varying velocity field as the results showed to be sensitive to a time sampling larger than one month and 5 day means.

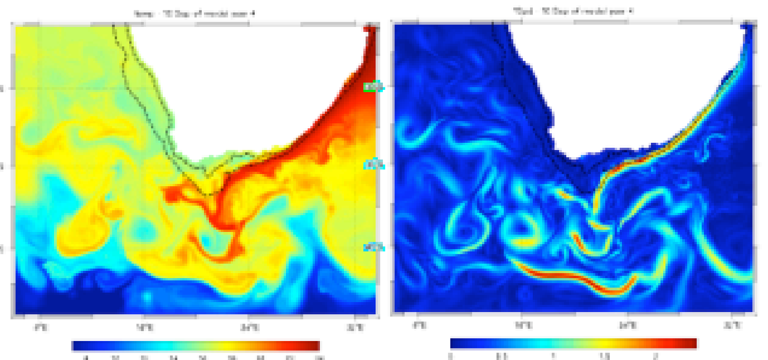

Figure 8; A 5-day mean snapshot of SST and surface velocity intensity showing the simulated high mesoscale activity in the Cape basin region (South-West off Africa). From observations, this region has been renamed Cape Cauldron by Boebel et al. (2003) because of this huge mesoscale mixing activity. Our simulations shows a similar behaviour as the observations.

Agulhas separation, slope steepness and curvature and current inertia

Effects of slope steepness

With a first set of sensitivity simulations we have investigated the influence of bottom topography on the Agulhas Current separation, Retroflection and eddy shedding mechanisms.

The simulations proved to be crucial in assessing the importance of the slope steepness and steepness along-flow variations on the separation mechanism and Indian Ocean water intrusion in the South Atlantic basin. The results can be summarized as follow:

- **The steepest the slope, the western boundary current becomes more narrow and intense, and, as consequence, the current inertia increases (Fig. 4);**
- **More the current gets intense and its inertia increases, less is able to follow the slope contours, when these change suddenly direction (sharp corner at the southern-west tip of the South African slope). As a result the Agulhas current overshoot in the open ocean (Fig. 4, 5 and 6).**
- **This overshooting and the consequent current separation for steep slope configurations, acts on the quantity of Agulhas water entering the South Atlantic basin (Fig. 6, fourth column for direct quantitative Lagrangian estimates for Agulhas Current transmitted transports). The steepest the slope, the less important is the Agulhas water penetration into the Atlantic.**

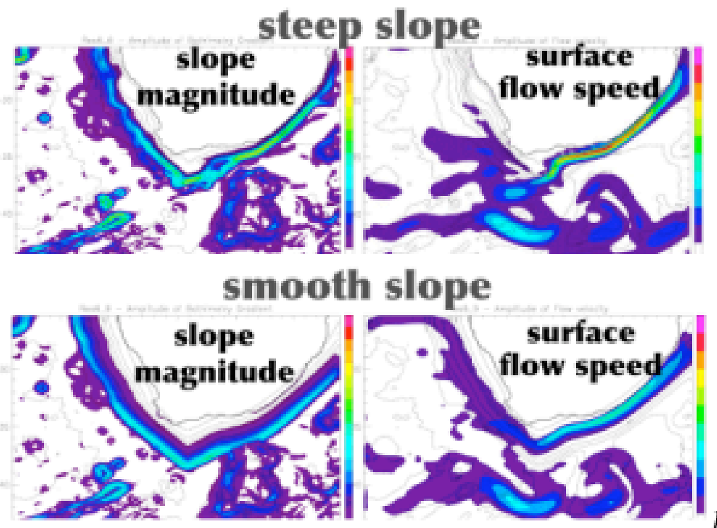

Figure 4: Topographic steepness (left column) and intensity of surface flow speed (right column) for a steep slope (upper figures) and a smooth slope (bottom figures).

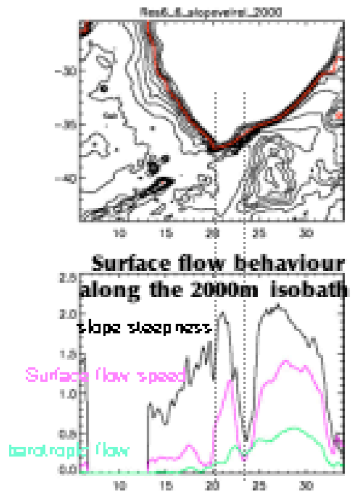

Figure 5: Bottom topography (upper figure) and (bottom) slope steepness (in black) and surface current behaviour.

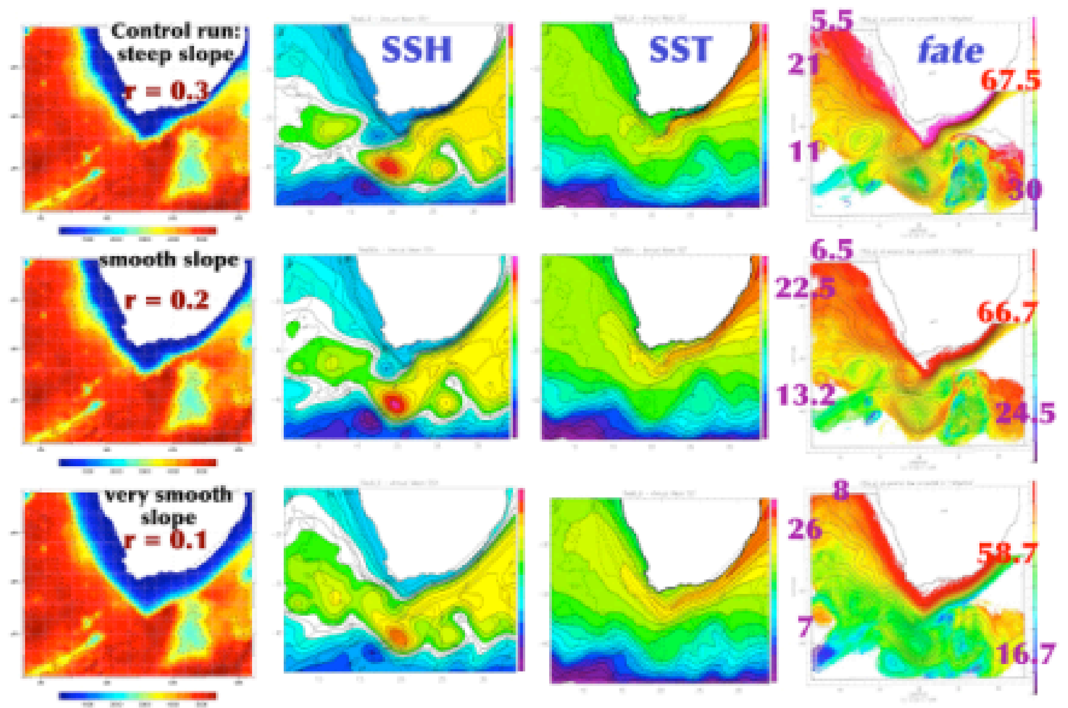

Figure 6; bottom topography (left), mean annual sea surface height, SST and Lagrangian Agulhas water transport connections for a steep slope (upper row), a smooth slope (central row) and a very smooth slope (bottom row).

Effects of the Agulhas Plateau

A major topographical feature in the oceanic region South off the African Continent, is the Agulhas Plateau. After the Retroflection, the Agulhas "return" current encounters the Agulhas Plateau at approximately 1500 m. The interaction of the currents with the plateau creates a large quasi-stationary meander in the current around the topographical feature and a quasi-stationary eddy practically sitting on it (Fig. 7). By removing this large topographical feature in one of our simulations, we were able to assess that, in the model, the Agulhas Plateau has an influence on the intensity of the Retroflection recirculation in addition and relation with the disappearence of the meandering of the current and the narrowing of the corridor between the African shelf and the Agulhas Plateau, through where normally the current flows.

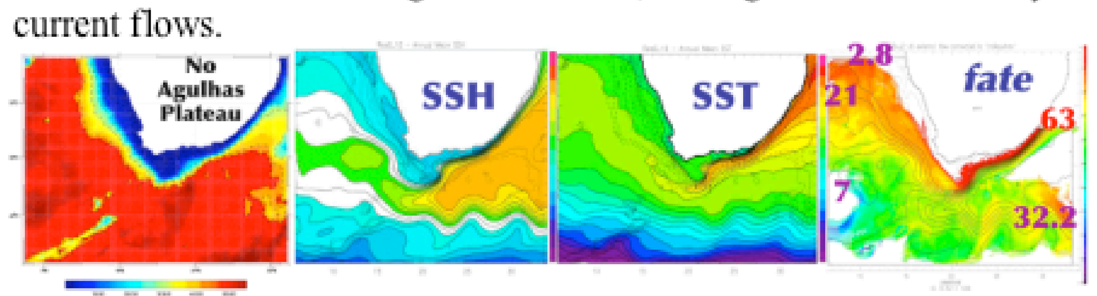

Figure 7; bottom topography (left), mean annual sea surface height, SST and Lagrangian Agulhas water-transport connections for a simulation with the Agulhas Plateau topographic feature removed.

Simulated Agulhas eddy shedding and *Cape Cauldron* dynamics

Agulhas Rings, which carry the relatively warm and salty waters of the Indian Ocean, are shed from the Agulhas Retroflection. From there they drift north westward into the Cape Basin and subsequently into the interior South Atlantic. It is a commonly held view that once in the Cape Basin, the rings are embedded in the rather unenergetic Benguela drift. This, in combination with the rings' intrinsic potential vorticity barrier, is thought to facilitate the preservation of the rings property anomalies for extended period of times and prevent mixing with the surrounding Atlantic water. This view is now challenged by in-situ velocity measurements from the KAPEX float program (Boebel *et al.*, 2003) and by our numerical results. In agreement with the sparse KAPEX observations, the model simulations show highly energetic field of anti-cyclonic and cyclonic eddies in the southern half of the Cape Basin (the *Cape Cauldron* from the definition of Boebel *et al.*, 2003). The data and our numerical results (Fig. 8) suggest extensive interactions between these eddies. Agulhas Rings, for example, are observed to merge and split, to reconnect to the Agulhas Retroflection and to assume shapes other than circular. This vigorous stirring process results a) in an increase of temperature and salinity of the intrinsically cold and fresh Atlantic water while b) a rapid loss of salt and heat is observed for Agulhas Rings.

Our simulations show that a large quantity of cyclonic structures are generated at the South African western and southern slope (where the water is relatively cold and fresh), and this even in the absence of the Natal Pulse events, previously claimed as essentials in both, the Agulhas ring shedding and Retroflection as well as for cyclonic eddy source. The most energetic source of cyclonic eddy vorticity is the south-eastern part of the South African shelf, where the shelf enlarges suddenly and shear-edge cyclonic vorticity is generated.

A dynamical insight on eddy shedding and current retroflection mechanisms

In all our simulations, the Agulhas Current sheds eddies in the South Atlantic. We explored the mechanisms governing the eddy shedding and Agulhas Retroflection numerically. We found that the major mechanism driving these phenomena resides in the occurrence of a dynamical transition to which the Agulhas current undergoes. This current flows south as a western boundary current along the Indian side of the African slope. At the southern tip of the continental margin, while the Agulhas current is transported by inertia into the open ocean, it is constraint to leave its western boundary along which it was flowing as a stable western boundary current. Once in the open ocean, this current partly retroflects as consequence of potential vorticity conservation and in relation with the position of the zero wind-curl (and becomes the southern branch of the wind-driven subtropical gyre of the South Indian Ocean). The rest intrudes in the South-East Atlantic where it becomes unstable and forms the Agulhas rings. The explanation to this dynamical behaviour is, according to our results and the suggestions found in some very recent bibliographic references is the following:

- **While poleward Western Boundary Currents (WBC) are stabilized (*i.e.*, accelerated) by the concurrent effect of:**
  - **the geographical β effect**
  - **the slope steepness (the topographical β effect)**
- **For Eastern Boundary Currents (EBC) flowing equatorward the β effect counteracts the current stability (Marshall and Tansley, 2001). The flow (that originally flows back towards the slope on the Eastern Boundary) gets unstable and detaches from the slope definitively.**
- **Rossby waves mechanism is the most natural way for our ocean to transmit information across a basin from in the East-West direction. We think that the fraction of Agulhas water that detach from the South African eastern Boundary, in search of a dynamical equilibrium, start to travel westward to reach a western boundary as Rossby waves. Because of the relatively high latitudes compare to the tropics, these Rossby waves experience baroclinic instabilities (Lacasce and Pedlosky, 2004) and eventually form eddies.**

This is supported by a numerical simulations for which we imposed $\beta = 0$, and in which all the Agulhas Current water retroflects and goes back to the Indian Ocean (Fig. 9).

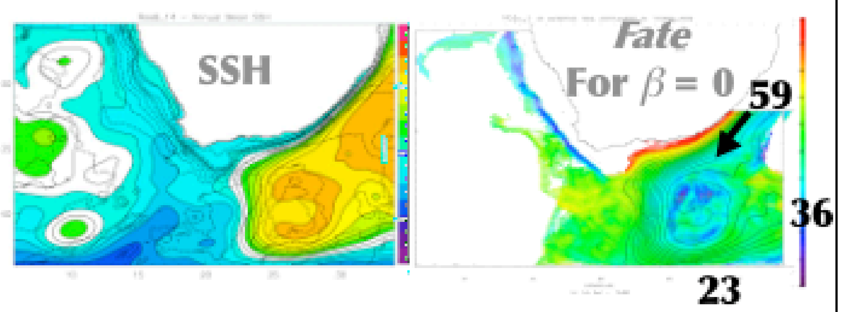

Figure 9; Mean annual sea surface height, and Lagrangian Agulhas water-transport connections for a simulation with $\beta = 0$. All the Agulhas water retroflects back into the Indian Ocean and none enters the South Atlantic.

REFERENCES Blanke, B., S. Speich, G. Madec and R. Maugé, 20021: A global diagnostic of interior ocean ventilation. Geophys. Res. Lett. - Boebel, O., Lutjeharms J. R. E., Rossby H. T., C. Schmid, W. Zenk, T. Rossby, and C. Barron, 2003: The Cape cauldron: A regime of turbulent interocean exchange. *Deep-Sea Res.*, **50**, 57-86. - Da Silva, A. M., C. C. Young, and S. Levitus, 1994: Atlas of surface marine data 1994, vol. 1, algorithms and procedures, *Tech. Rep.*, U. S. Department of Commerce, NOAA. - Gordon, A. L. Interocean exchange of thermocline water. *J. Geophys. Res.*, *91*, 5037-5046, 1986. - Gordon, A. L., Interocean Exchange. In: *Ocean Circulation and Climate*, G. Siedler, J. Church and J. Gould Eds., 303-314, 2001.- Gordon, A. L., R. F. Weiss, W. M. Smethie Jr., and J. Warner, Thermocline and intermediate water communication between the South Atlantic and Indian Oceans. *J. Geophys. Res.*, *97*, 7223-7240, 1992 - Marchesiello, P., J. C. McWilliams, and A. Shchepetkin, 2001: Open boundary condition for long-term integration of regional oceanic models, *Ocean Modelling*, 3, 1–21.- Penven, P., C. Roy, J. R. E. Lutjeharms, A. Colin de Verdière, A. Johnson, F. Shillington, P. Fréon, and G. Brundrit, 2001: A regional hydrodynamic model of the Southern Benguela, *S. Afr. J. Sci.*, *97*, 472–476.- Saunders, P. M., A. C. Coward, and B. A. de Cuevas, 1999: Circulation of the Pacific Ocean seen in a global ocean model (OCCAM), J. Geophys. Res., 108, 18,281–18,299 - Speich, S., B. Blanke, O. Marti, 2004: The structure of the oceanic thermohaline circulation for present climate and the last glacial maximum from models. To be submitted. - Speich, S., B. Blanke, P. de Vries, K. Döös, S. Drijfhout, A. Ganachaud, and R. Marsh, 2002 : Tasman Leakage: A new route for the global conveyor belt. *Geophys. Res. Letters*, 29, 10. - Speich, S., B. Blanke, and G. Madec, 2001 : Warm and cold water paths of a GCM thermohaline conveyor belt. *Geophys. Res. Lett.*, 28, 311-314.