Good-Hope / Southern Ocean : A study and monitoring of the Indo-Atlantic connections through the Southern Ocean

An international co-operative project
A process study and a contribution to CLIVAR - Southern Ocean

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1- INTRODUCTION

Interocean exchanges play an important role in global climate in response to variations of local or remote heat and freshwater fluxes via the global ocean circulation. Pathways and mechanisms of oceanic heat and fresh water transports are critical issues in the comprehension of the present climate and its stability. This global ocean transport is coupled to convective overturning, happening essentially in the North Atlantic and in the Southern Ocean, which links the full ocean volume to the climate at decade-to-century time-scales. In the following we will refer to this global circulation with the term of "Meridional Overturning Circulation" (MOC). But what is the MOC structure, and how does it feed back into convective processes and their associated climate phenomena? Because observations are sparse, the detailed global structure of the MOC remains poorly understood.

The Southern Ocean is a critical crossroad for this process as it provides an interocean communication route for heat and freshwater (climate) anomalies, as well as anthropogenic tracers (Sloyan & Rintoul, 2001; Sarmiento et al., 2004). The polar-extrapolar communication of heat and freshwater helps to close the hydrological cycle through the production of Antarctic Intermediate Water and Subantarctic Mode Water (AAIW and SAMW). The Southern Ocean plays also a key role in the global carbon cycle due to unique features involving both dynamical and biological processes (Sabine et al. 2004). In particular, the outcropping of deep-waters as well as formation of AAIW, SAMW and Antarctic Bottom Water provide an important mean of gases such as CO2, to be exchanged between the deep sea and the atmosphere. Also, AAIW and SAMW transfer nutrients northward within the thermocline. Recent hypotheses suggest that this transfer could sustain a large part of the primary and export productions of the world ocean (up to 75%, Sarmiento et al., 2004).

The Antarctic Circumpolar Current (ACC) is by far the largest conduit for interbasin exchanges. Very recent analyses of satellite and *in situ* observations have uncovered that the Southern Ocean is a very turbulent region (Sokolov and Rintoul, 2007a; 2007b; Sallée et al. 2007). This is particular true for the ACC. Indeed, this current that is the most intense of the world ocean is not flowing eastward as an homogeneous wide flow but it is concentrated on a number of quasi-permanent circumpolar jets (Fig.1). These jets are limited by fronts that dynamically separate water masses. Their positions are determined by topographic steering (Gordon et al., 1978; Rintoul et al., 2001) and by the wind stress curl (Nowlin and Klinck, 1986). These frontal systems are thought to be the sites of formation of SAMW and AAIW.

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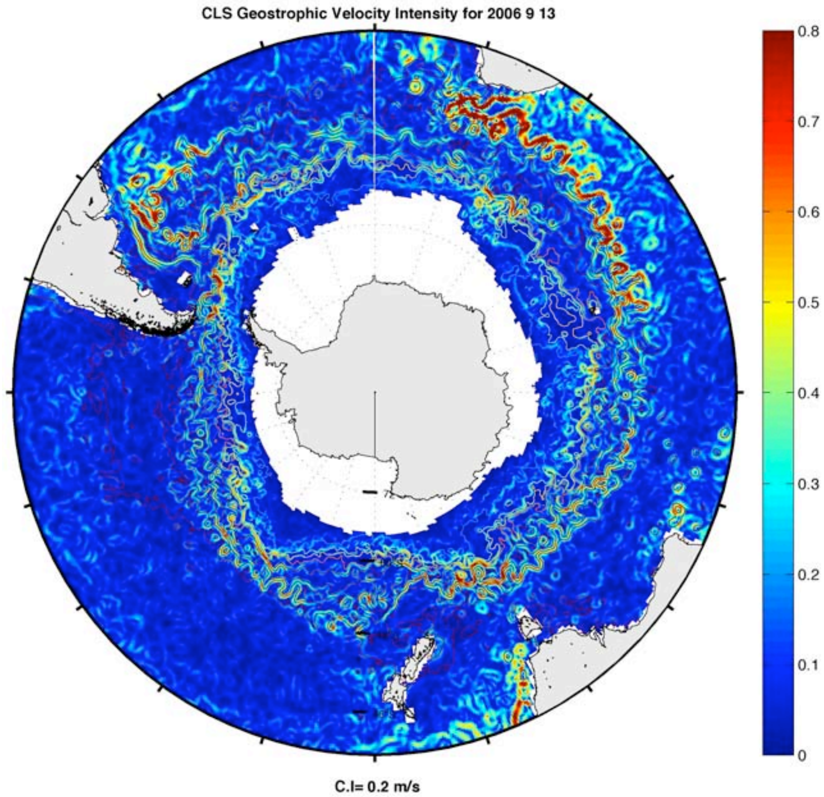


Figure 1 : Intensity of the Southern Ocean geostrophic velocity computed from the CLS altimetry derived Absolute Dynamical Topography for November 11, 2006. The figure shows the existence of multiple intense jets that compose the Antarctic Circumpolar Current (colours are function of the intensity of the velocity. These jets materialize the limit of multiple circumpolar fronts (contours).

Models indicate that the response of the Southern Ocean to global warming will be a critical factor determining the ocean's future uptake of anthropogenic CO2. However the scarcity of direct observations has greatly hampered our understanding of the physical and biogeochemical environment. The challenge of understanding Southern Ocean dynamics and biogeochemistry is exacerbated by the strong link between mesoscale processes and large-scale processes.

Prior to 1990, most of our knowledge of the Southern Ocean was based on detailed measurements in Drake Passage and occasional coarse-resolution hydrographic sections at other locations. The past fifteen years have seen a significant expansion in observations of the Southern Ocean, including circumpolar surveys conducted as part of large international experiments while global ocean and climate models have received an increasing attention. While an intense monitoring effort has been undertaken in Drake Passage and South of Australia, two of the three Southern Ocean chokepoints, the one south off Africa, that is the largest, has been undersampled until 2004 despite its importance in interocean exchanges and MOC structure and stability. Indeed**,** south of Africa, the Southern Ocean plays a unique role in providing the export channel for North Atlantic Deep Water (NADW) to the global ocean and by importing heat and salt from the Indian and Pacific oceans. This region is influenced by the largest turbulence observed in the ocean. In this region the eastward flowing ACC, the South Atlantic Current and NADW meet with the westward injection of flowing Indian waters carried by the Agulhas Current leading to water masses exchanges through jets, meanders, vortex and filaments interactions. These local mesoscale interactions and the derived meridional fluxes constitute perhaps the major link between the Southern Ocean and the MOC by impacting, for example, the transformation and subduction of SAMW and AAIW (Hazeleger and Drijfhout, 2000; Leach et al., 2002; Schmid et al., 2003; Mémery et al., 2005)

2- GOODHOPE PROJECT

Because of the lack of observations in this key region of the world ocean, in early 2003 we decided to initiate an observational project, named GOODHOPE by the Cape of Good Hope, within an International partnership. (Fig. 2). The international partnership is gathering together means (in terms of human, observing platforms, ship time and general financial support) from 11 different institutions and six countries (France, South Africa, United States, Germany, Russia and Spain). The project has been approved in 2003 by the International CLIVAR panel and endorsed by SCAR[2] and CliC[3]. The project aims at studying the full-depth oceanic exchanges between the Indian, Atlantic and Southern oceans, in a latitude band that encompasses the subtropical domain between South Africa and the Subtropical Front (~35°S-40°S), and the ACC (~40°S-55°S). Specific objectives are a better knowledge of the temporal variability of the ACC transport, a study of property modifications experienced by the exchanged waters, an improved understanding of the mechanisms involved in these exchanges throughout the water column and, of course, a long term monitoring of water properties, dynamics and air-sea exchanges in time.

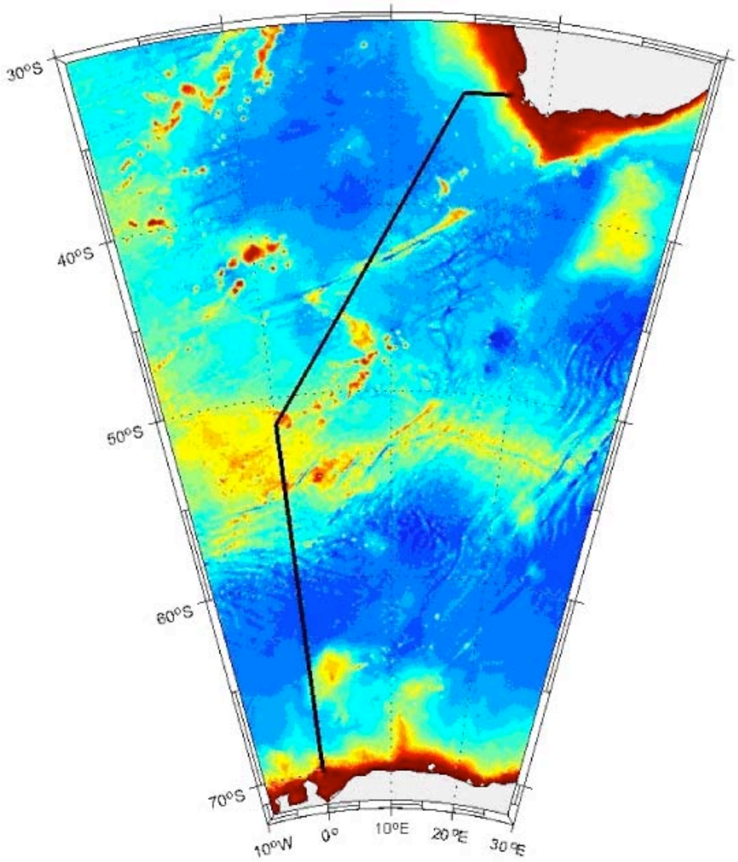


Figure 2: Map showing the GOODHOPE monitoring line between Cape Town and Neumayer station. This line lies very close to that occupied during WOCE (SR2). It has been conceived to follow the closest TOPEX/POSEIDON-JASON1 altimeters flight path (nb 133) and to overlap at its southern end (south of 50°S) with the German WECCON transect which is sampled with full depth hydrology every two years and by a line of moorings since the early 90s.

In the following we present ongoing studies from GOODHOPE data analyses together with syntheses of historical and satellite data and on the ongoing effort of regional modelling and global models analyses.

3- RESULTS

The field activity of the program rests on repeated and high resolution expendable bathythermograph (XBT) samplings (NOAA/Miami, University of Cape Town), on hydrology measurements along the same line (three realizations performed by the Shirshov Institute of Moscow, and a French multidisciplinary one, BONUS-GOODHOPE, planned early 2008 in the framework of the International Polar Year), and on regular launchings of PROVOR/ARGO profilers (LPO/Brest). A first description of water masses and full depth transport observations along the GOODHOPE transect in late 2004 can be found in Gladyshev et al. (2007). Since it starts, GOODHOPE has been one of the major projects in improving the data coverage of the Southern Ocean in terms of number of available monthly profiles (Fig. 3).

[2] SCAR : Scientific Committee on Antarctic Research (http://www.scar.org/)
[3] CliC : Climate and Cryosphere (CliC) Project (http://clic.npolar.no/)

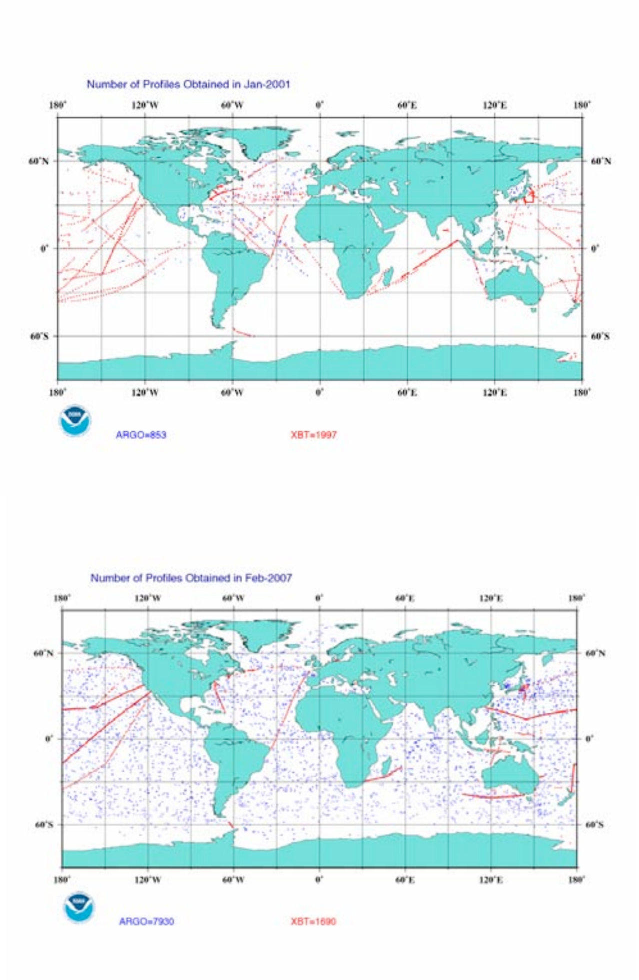


Figure 3: Number of XBTs, ARGO floats or CTDs monthly profiles for a) July 2001 and b) for February 2007. Courtesy of NOAA-AOML

Out of 48 PROVOR floats launched since early 2004 in the framework of GOODHOPE, 37 were still active in June 2007, and a total of about 2800 hydrology profiles down to 2000 m had been gathered through the CORIOLIS data centre (Fig. 4). This data base has proven to be a very important source of new quantitative information for the region. For example, these data proved to be very successful to describe the surface mixed layer seasonal variations that has not been possible to achieve with any other available data set. Displayed on Fig. 5 are the annual cycles of the mixing layer depth in the subtropical and subantarctic zones, for the longitudes interval 0°W-40°E. The allotment of a profile to a given zone was done on the basis of its surface dynamic height value (referenced to 1500 m), a value of this parameter having previously been ascribed to the Subtropical Front from neighbouring historical and the more recent GOODHOPE hydrological data. For both regions that are shown in Figure 5, the mixing layer depth shows a pronounced seasonal cycle with depths of the order of 200 m.

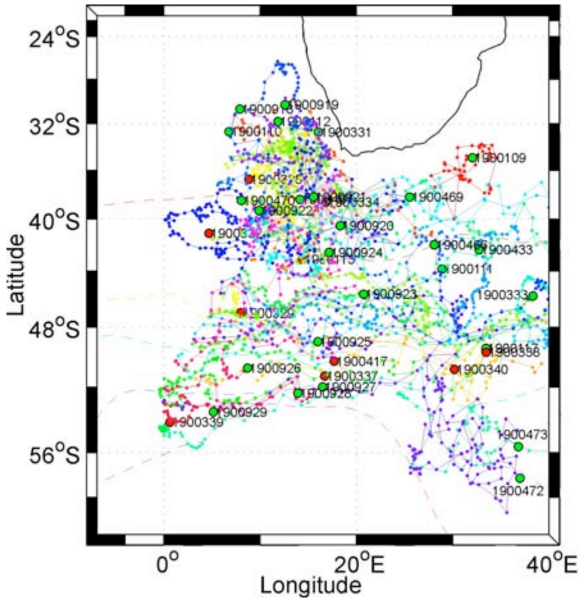


Figure 4: Trajectories and profile locations of GOODHOPE ARGO floats (years 2004 to 2007, here limited to 0°W-40°W). Green (red) dots mark floats that were active (no longer active) in June 2007. Climatological ACC fronts locations (derived from Orsi et al. 1995) are also shown : red dashed line is the position of the Subtropical Front; yellow dashed line show the Subantarctic Front; the green dashed line shows the location of the Polar Front; the blue dashed line show the Southern ACC front and the violet one the Southern Boundary.

With the relatively important number of deployed profiling floats we can try to assess the influence of thermohaline properties exchanged south of Africa. One of the most important aspects concerns the ventilation of the South Atlantic thermocline. This ventilation occurs through waters that have been recently in contact with the atmosphere. How this happens and what are the water masses that penetrate the thermocline and from where they come from. A question that was often arising is the direct ventilation of the South Atlantic from ACC waters. The Southern Ocean Atlantic sector has long been known as a weak contributor of SAMW to lower latitudes (McCartney, 1977). Although annual cycles of the mixed layer depth stand out in both zones, low average winter values around 130 m in the subantarctic zone confirm this weak contribution (Fig. 5). The pronounced scatter of the winter mixed layer depths around their average values reflects significant exchanges across the Subtropical Front. Parcels of relatively fresh Subantarctic Surface Water shed into the subtropical domain are associated with thin mixed layers. On the other hand, eddies of subtropical water penetrating the subantarctic zone may, owing to their saline nature, favour convection reaching downward to ~300 m.

Hence, the winter mixing-layer depth assessed from the GOODHOPE-ARGO floats profiles shows that the rate of formation of SAMW is relatively low in the region. Nonetheless, observations from these same ARGO floats and CTD data from GOODHOPE cruises suggest strong winter convection in some Agulhas rings. This accounts for a production of a local variety of Mode Water that is injected in the Atlantic through rings propagation. This local Mode Water is different from the classic SAMW inflowing from the Indian Ocean and the Agulhas Current.

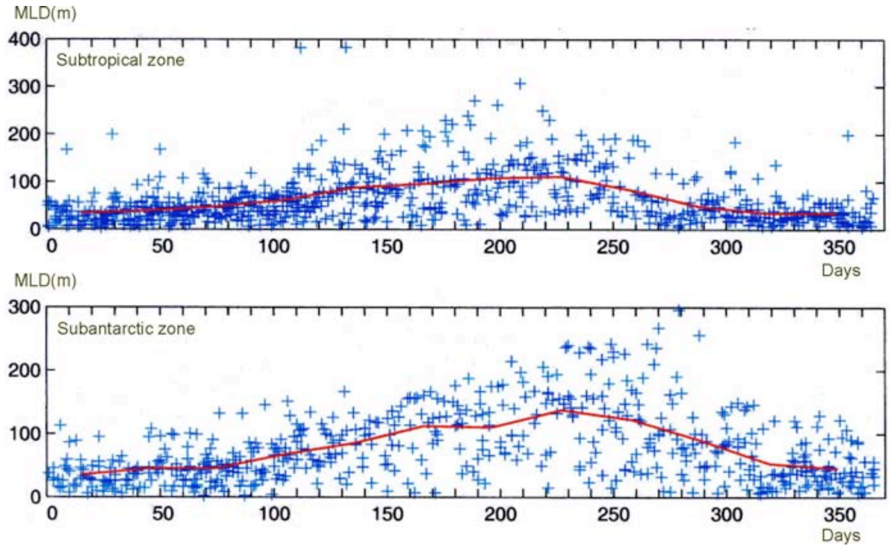


Figure 5: Depth of oceanic mixed layer from ARGO-PROVOR profiles south of South Africa in the subtropical (upper) and subantarctic (lower) domains

Relatively deep convection happens in this region in the core of southern advected Agulhas rings. Figure 6 illustrates an extreme case where convection reached 390 m. The lower panels showing the float locations superimposed onto concomitant maps of absolute sea surface height (SSH: Ducet et al., 2000, Rio and Hernandez, 2004) confirm that this deep convective event occurred in an eddy of subtropical water shed in the subantarctic zone. Previous occasional samplings of eddies with a subsurface homogenized core in the Cape Basin (e.g. Arhan et al., 1999) suggested a formation of these structures in the subantarctic zone, before their northwestward propagation and subduction beneath lighter Atlantic subtropical waters. The present observation by ARGO floats in the formation region complements the previous ones. An altimetric tracking of these vortices shows that they originate in the subdivision of newly-spawned Agulhas rings encountering the Agulhas Ridge. Intense cooling and convection of the eddy core waters may occur during autumn or winter transit through the subantarctic domain, leading to the formation of vertically homogenized water with temperatures that may reach downward to about 12°C. This locally ventilated water has higher oxygen concentrations than the remotely formed SAMW (of Indian Ocean origin) present in the Agulhas retroflection (Gordon et al., 1987). The ongoing study aims to better evaluate the amount and role of this water in the ventilation of the Atlantic Ocean thermocline and understand the behaviour of the eddies that convey it.

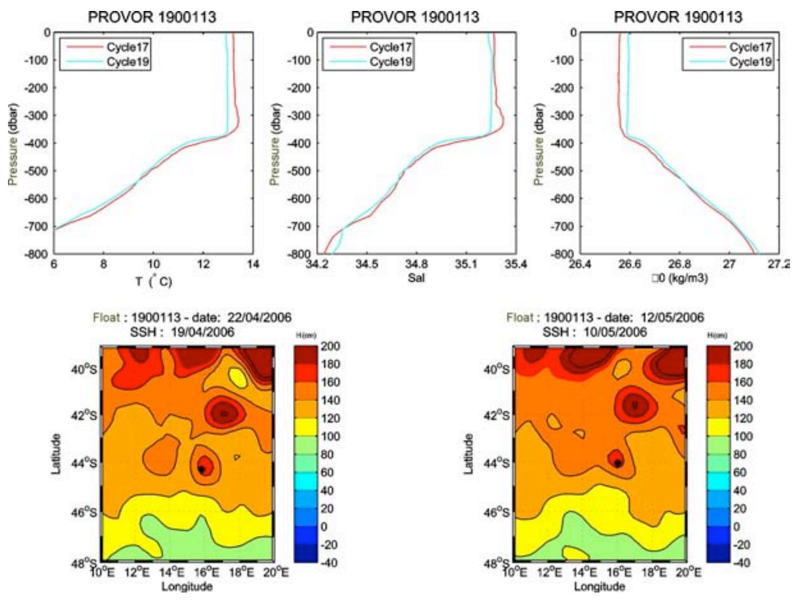


Figure 6: Upper: Deep (390 m) homogenized core water of an eddy in the ACC subantarctic zone south of South Africa. Lower: SSH maps showing the eddy and positions of the PROVOR float which was trapped in it for more than 20 days.

Another water mass that is of very particular interest for South Atlantic thermocline ventilation is the AAIW. The penetration of this water in each southern hemisphere basin is still under debate. Does it come from particular regions of the subantarctic belt or does it spreads northward homogeneously from the entire circumpolar region? This question is of particular importance for the Atlantic sector and its fresh-water budget. The ARGO data set proves to be suitable also to investigate about this question. Indeed, while data from the Southern Ocean are usually concentrated along particular hydrographic sections, ARGO profiling floats spread large oceanic regions giving access to an unprecedented vertical and horizontal distribution. This is particular true for the GOODHOPE ARGO data. Deployed along the GOODHOPE transect they have spread eastward and northward giving a satisfactory sampling of the Southern Ocean region south of Africa. These data are used to evaluate the South Atlantic AAIW ventilation from the Southern Ocean south of Africa. Their analyses suggest a direct inflow from the Indian Ocean and a weak contribution from the water locally ventilated. Indeed, the collected ARGO salinity profiles show a well defined zonality of the salinity minimum values. No meridian exchanges are evident connecting directly the subantarctic region with the subtropics in the south-east Atlantic just west off Africa, while the figure shows a clear inflow of Indian Ocean salinity minimum waters into the South-East Atlantic (Fig. 7).

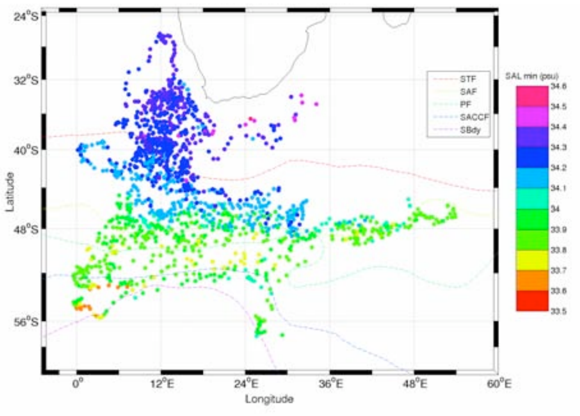


Figure 7: Vertical salinity minimum for AAIW. Values are from the GOODHOPE ARGO profiling floats deployed since early 2004 in the region. Salinity values greater 34.3 are characteristic for water masses inflowing from the Indian Ocean. Salinity values lower than 34.3 are typical for waters recently ventilated in the Southern Ocean.

Despite the increased hydrographic effort and the ARGO programme, Southern Ocean sampling is limited in terms of time series. Indeed, *in situ* data are useful to get both, a climatology or surface and subsurface seasonal variability of the large-scale circulation. It is far to be enough to uncover higher scales of variability (spatial and in particular temporal) and still insufficient to monitor interannual to inderdecadal large-scale variations. For this reason, the development of proxy methods could provide an attractive alternative to evaluate ocean dynamics. In the framework of the GOODHOPE project we are using and further developing such a kind of approach for the ACC dynamics already initiate partially south of Australia (Rintoul et al., 2002; Sokolov and Rintoul, 2007a) and in the Drake Passage (Sokolov et al. 2004). This method relies on the fact that variations in the potential energy and geopotential height at the sea surface reflect changes in the baroclinic structure of the water column with depth.

A first study estimated the 2500 db ACC baroclinic transport south of Africa from historical XBTs data that makes use of an empirical relation between mid-depth temperature and potential energy (Legeais et al. 2005). Recently we expanded our study to dynamic height instead of potential energy derived from repeat, high-density GOODHOPE XBT casts (Fig. 8). In both studies extensive variability in the transports was found in the northern domain of the ACC and is likely caused by the intrusion of Agulhas Rings, shed off by the Agulhas Retroflection, across the Sub-Tropical Front (STF). Thanks to the increased resolution of the XBTs casts, the new study gave better results as for distinguishing and evaluating the baroclinic transport for each frontal region. South of the STF, the majority of the baroclinic transport falls into relatively neat pockets for each ACC fronts defined by Orsi et al. (1995). Each of these fronts turns out to be made of multiple jets. The Sub-Antarctic Front (SAF) and Antarctic Polar Front (APF) are responsible for the largest percentage of such a transport for the ACC's in the GOODHOPE region, with 29% and 25% contributions, respectively (Swart et al., 2007).

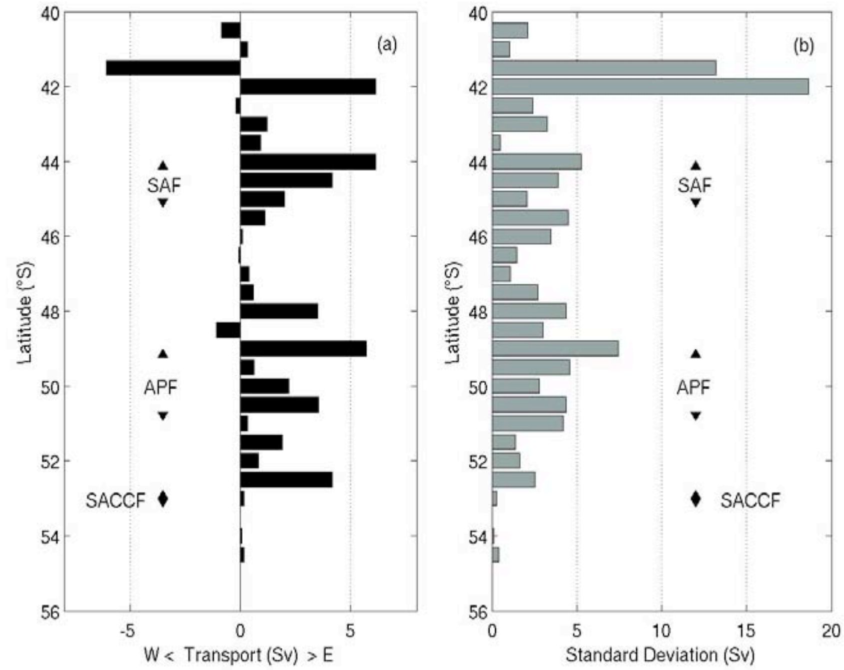


Figure 8: (a) Mean baroclinic transport, relative to 2500 dbar, per half degree latitude for five XBT occupations along the GOODHOPE transect. (b) The respective standard deviation for the baroclinic transports. Arrows represent the mean latitudinal positions of the three inner ACC fronts from the five hydrographic sections. From Swart et al. (2007).

The interest of using dynamic height comes from the possibility to extend time and space coverage by using satellite derived altimetry. We did so, using the satellite altimetry available along the GOODHOPE transect (whose largest fraction goes over the altimeter 133 ground-track). To obtain a dynamic height series, we combined the altimeter Mean Sea Level Anomaly (MSLA) data with the mean sea surface height computed from repeated CTD sections along GOODHOPE. By applying the tight empirical relationships we developed for XBTs, we derived a weekly time series for the baroclinic transport referenced to 2500 db. More over, we applied to the dynamical eight time series another empirical relationship we built by correlating dynamic height values with Temperature and Salinity profiles obtained from both historical and GOODHOPE CTDs in the region and at homogeneously sampled depth. This method, known as the Gravest Empirical Mode (GEM: Sun and Watts, 2001), allows us to reconstruct a weekly time series of Temperature and Salinity profiles for the first 2500 m of the water column along the ACC portion of the GOODHOPE section. Such a time series can now be analysed to better understand the varying structure and transport of the ACC and its related heat and salt contents as it is illustrated in Figure 9. In the upper panel of this figure (Fig. 9a) a Hovmüller diagram shows the weekly varying heat content anomaly along the GOODHOPE section for the ACC latitude band during the Topex/Poseidon-Jason1 satellite missions. The highest variability happens between the subtropical and subantarctic region (the uppermost part of the diagram), where the dynamics is characterized by eddies. The SAF (43.5°S – 45°S) shows relatively low frequency variability that appears clearly peaking around a six-year period when the heat content is summed up for the entire frontal region (Fig. 9b). The variability of APF (around 50°S) seems to be very different, peaking at higher frequency and suggesting a high decorrelated behaviour for the two regions.

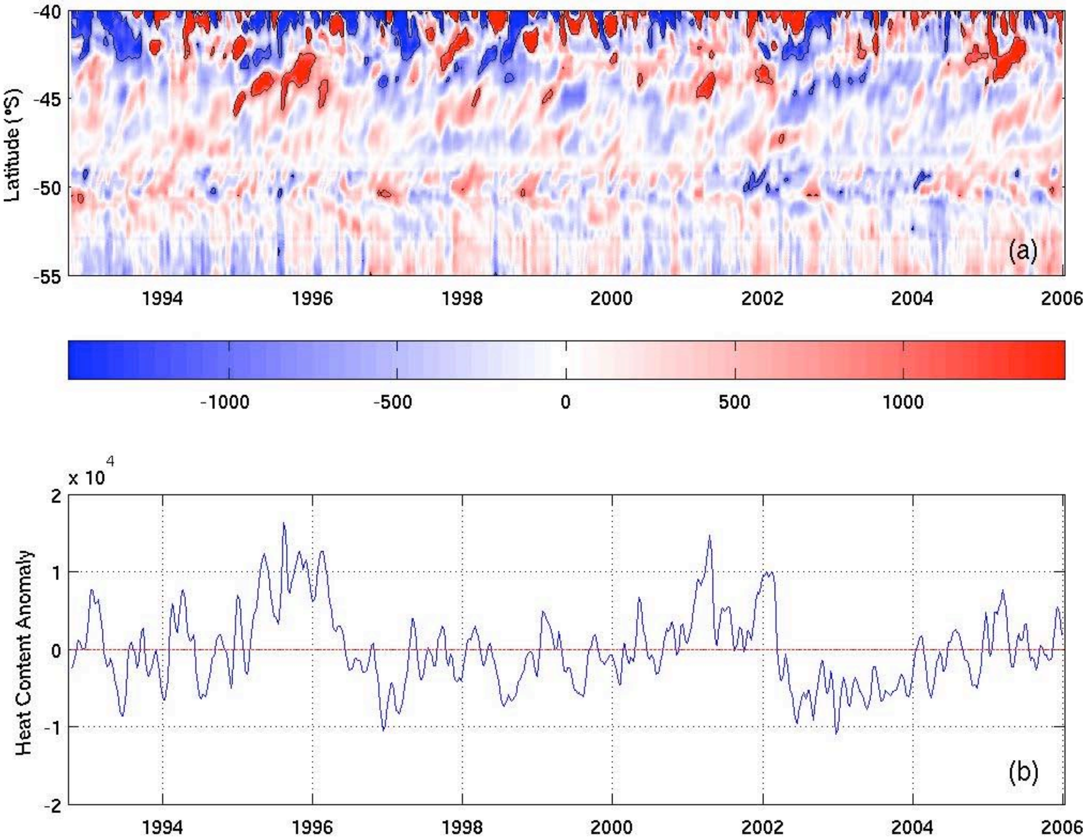


Figure 9: (a) Heat content anomaly occuring along the GOODHOPE transect as derived from satellite altimetry, for the period October 1992 to the end of 2005. (b) The heat anomaly is summed over the SAF (between 43-45.5°S) revealing a ~6 year signal. This varying trend may be related to Antarctic Circumpolar Wave or Southern Antarctic Mode.

Despite the increased data sampling brought with the onset of GOODHOPE and the availability of proxy Temperature and Salinity time series, many question on the detailed regional dynamical processes and interocean exchanges remain open. Numerical general circulation ocean models represent an alternative, even if they only approximate reality. Indeed, numerical models not only provide varying 3D fields, they also can be used to test hypotheses on physical processes. This is why we choose to approach the dynamical understanding of this region of the world ocean by various modelling approaches. We used global ocean models for the present-day climate to fully reconstruct the North Atlantic related MOC (Fig. 10: Speich *et al*., 2007). This same approach is used together with recently developed diagnostic techniques (Iudicone *et al*., 2007) to investigate the air-sea and ocean dynamics coupling in coupled models of the present, past and future climate (PMIP2 and IPCC simulations). The large number of available simulations represents an optimal set to reach a sufficient number of experiments for results being quasi-statistically qualified.

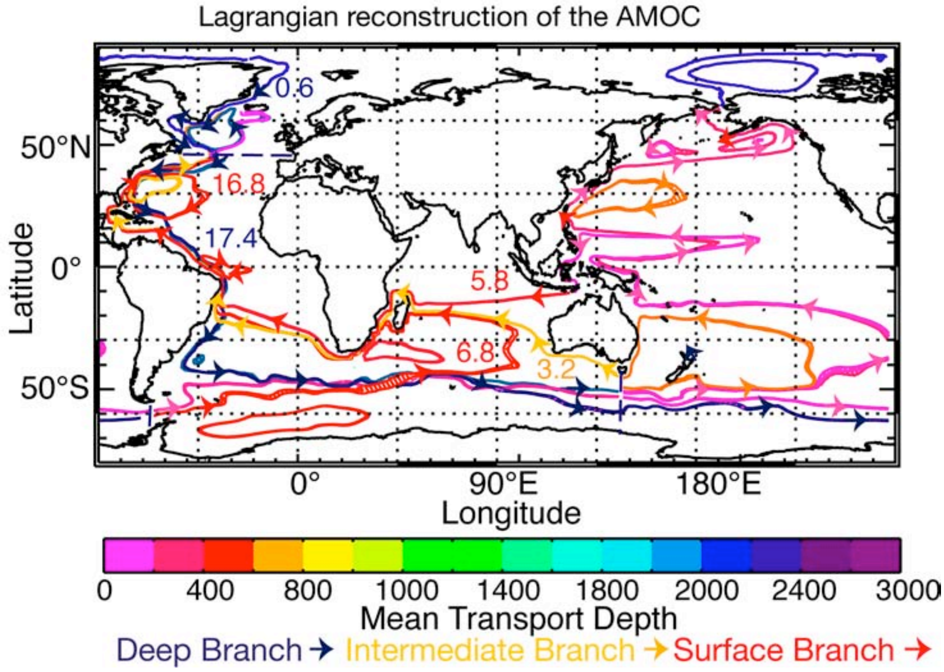


Figure 10: Lagrangian derived reconstruction of the global AMOC. Its structure is shown as median pathways between successive oceanic sections crossed by water particles. The colors indicate the mean depth of the transfer between two given sections. The AMOC is defined here as the thermocline waters (in orange, red and pink) transformed into NADW (blue) in the North Atlantic sector. Pathways show the upper and lower branches of the AMOC. Numbers quantify the mass transfers between control sections (transports are expressed in Sverdrups 1 Sv = 10^6 m s^{-1}). 17.4 Sv of NADW flow southward from the North Atlantic and are replaced by 0.6 Sv from the Pacific Ocean through Strait of Bering and 16.8 Sv of thermocline water flowing northward from the equator.

A regional modelling approach is then used to increase the ocean model resolution compared to that of the global ocean models, in order to simulate the highly nonlinear character of the local dynamics. Also, because of their limited cost, they can be run efficiently. This makes possible to obtain a large number of sensitivity tests on various parametrizations, forcings and processes. For example, through a hierarchy of experiments we investigate the role of the shape and steepness of the bathymetry as well as of open ocean and atmospheric forcings and model resolution. The dynamical links and the water mass origins and exchanges are analysed with Lagrangian quantitative diagnostics. The results are discussed in terms of physical processes inducing or influencing the Agulhas Retroflection, the rings shedding, and the general cyclone genesis and dynamics in the upwelling region (Fig. 11; Speich et al., 2006). These numerical experiments show that the net Indo-Atlantic interocean exchange is very sensitive to the topography and geometry (the steepness of the South-African continental slope, the small radius of deformation of the continental slope at the southern tip of the continent, the presence of a large Agulhas Bank, the narrowing induced by the existence of the Agulhas Plateaus well as to the specific mid-latitude location of the Agulhas Retroflection and to the mean thermohaline ocean structure. This last point shows how interocean exchange can be affected by slight modifications of the mean ocean state: in a warmer and slightly fresher upper 1500 m ocean, the interocean exchange is enhanced. Moreover, it is shown that variations in the Indo-Atlantic thermohaline structure and interocean exchanges affect significantly the waters transferred across the slope along the Agulhas Bank and the efficiency of the Southern Benguela upwelling.

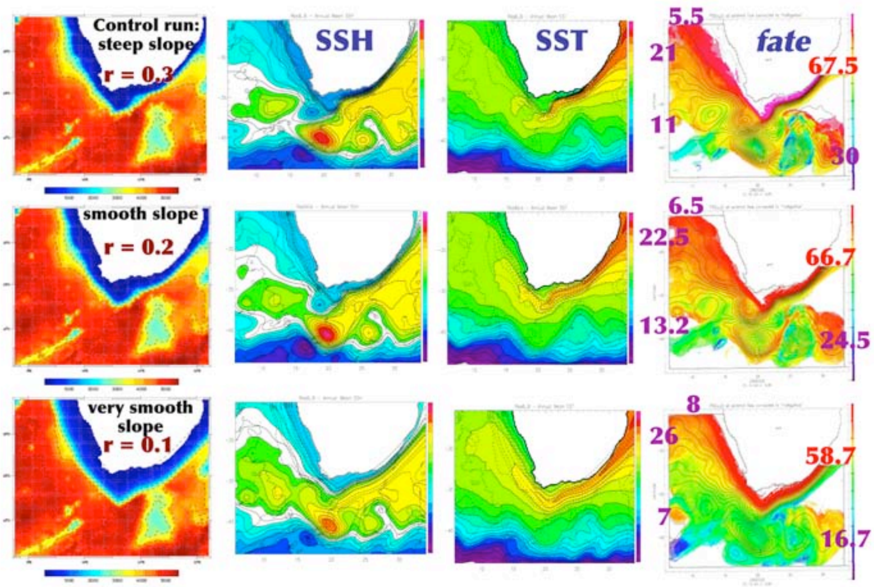
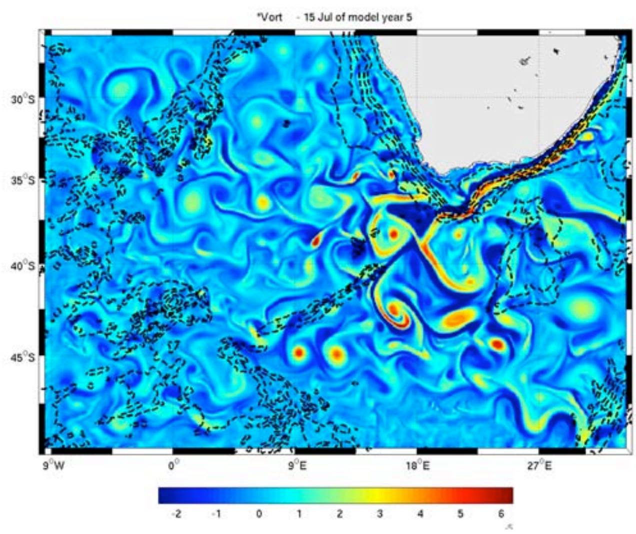


Figure 11: Bottom topography (left), mean annual sea surface height, SST and Lagrangian Agulhas water transport connections for a steep slope (upper row), a smooth slope (central row) and a very smooth slope (bottom row) resulting from regional simulations achieved with the ROMS UCLA-IRD community model.

Eulerian and Lagrangian observations, satellite data and numerical models have already shown the complexity of the turbulent interocean exchanges between the Southern, Indian and Atlantic oceans. While *in situ* and satellite observations allow a rough evaluation of the transport and thermohaline characteristics of this highly variable oceanic region, they are not sufficient to fully understand and evaluate the turbulent processes that control the local mass, heat and fresh-water exchanges. On the other hand, the recently developed statistical and Lagrangian analyses of eddies simulated by regional ocean models offers promising bases for the development of more robust estimates of the conservation and propagation of eddy properties. In this framework, we have developed a technique based on wavelet decomposition to identify coherent structures in models and to follow water mass properties along their tracks. We applied this technique successfully to our ROMS simulations. This diagnostic tool complemented with a Lagrangian dissemination of numerical particles in selected cyclones and anticyclones made possible to diagnose the 3D eddies varying properties, to track their remote origins in term of water masses. By this technique it was also feasible to evaluate the mass transfers associated to the eddies and to detect local mixing processes (Fig. 12: Speich et al. 2006; Doglioli et al. 2006; 2007).



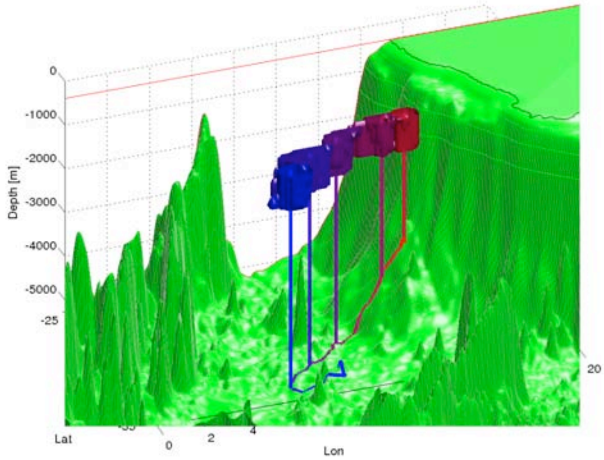


Figure 12: Regional models coupled to newly developed analyses have been applied to the GOODHOPE oceanic region to deepen our understanding of mesocale and submesoscale role in interocean exchanges south of Africa. a) the rich dynamics of the subtropical-subantarctic zones of the GOODHOPE region as it is reproduced by a regional simulation at 1/10° of resolution performed with the ROMS-IRD-UCLA model (in the figure it is shown a snapshot of the relative vorticity field); b) tracking in time of a cyclone developing on the Benguela slope in the regional model via a wavelet diagnostics (Speich et al. 2006; Doglioli et al. 2006; 2007).

4- CONCLUSION

All these preliminary results illustrate how rich this oceanic sector is in terms of dynamics and physical processes. All this dynamical processes need to be better understood in order to improve our knowledge on the role of the Southern Ocean as a driving factor of the MOC and global climate. The adventure continues early 2008 in the framework of the International Polar Year through the BONUS-GOODHOPE multidisciplinary action (www.univ-brest.fr/IUEM/BONUS-GOODHOPE/).

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