SOUTHERN OCEAN *CHOKEPOINTS*:
Monitoring fluxes associated with water exchanges between the three ocean basins

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This proposal arises from a number of common threads and opportunities of national and international projects that would like to create an efficient synergy to develop a coherent action to be started during the IPY program in the southern hemisphere. This action is an integral part of the more general strategy presented by the CLIVAR/CliC/SCAR Southern Ocean Implementation Panel (*The role of Antarctica and the Southern Ocean in past, present, and future climate: A strategy for the International Polar Year).*

Interocean exchange is thought to be an important part of the present-day global climate particularly in response to variations of local or remote heat and freshwater fluxes via the thermohaline circulation. The Southern Ocean is a critical crossroad for this process as it connects the major ocean basins permitting a global-scale thermohaline circulation and providing an inter-ocean communication route for heat and freshwater (climate) anomalies. Also, the Southern Ocean coupling of the ocean and atmosphere within the subantarctic belt and its polar-extrapolar communication of heat, freshwater and CO2 through the production of Antarctic Intermediate Water and Subantarctic Mode Water, which spread northward injecting cool low salinity water into and along the base of the main thermocline helps close the hydrological cycle.

The Antarctic Circumpolar Current (ACC) is the giant of interocean exchange, carrying about 134 ±13 Sv of polar and subpolar water masses from west to east through the Drake Passage (Whitworth, 1983; Whitworth and Peterson, 1985). The interbasin exchange accomplished by the ACC is an important link in the global overturning circulation (Schmitz, 1995, 1996) and also allows anomalies formed in one basin be carried around the globe, influencing climate in locations remote to the source (White and Peterson, 1996). Changes in the ACC transport (Rintoul *et al.*, 2002; Cunningham *et al.*, 2003; Sprintall, 2003; Sokolov *et al.*, 2004) could be driven by internal variability but also by climate changes (*e.g.*, via changes in the phase of the Annular Mode) and are thought to represent an active chain in a possible positive feedback on large-scale circulation and climate (Hall and Visbeck, 2002; Meredith *et al.*, 2004).

Meridional fluxes across the ACC, which connect the polar region of the Southern Ocean to the global ocean, occur within deep boundary currents, in eddy and isopycnal mixing processes and within the Ekman layer at shallower levels. These meridional fluxes constitute perhaps the major link between the Southern Ocean and the global overturning circulation as they imply the transformation of water masses, driven by air-sea forcing and diapycnal mixing. Much of the conversion of cold to warm water (mode and intermediate waters) that is required to close the North Atlantic Deep Water (NADW) overturning circulation appears to take place in the Southern Ocean, where deep water outcrops and is exposed to air-sea buoyancy forcing (*e.g.*, Döös and Coward, 1997; Rintoul *et al.,* 2001).

Undoubtedly, the ACC is the main circumpolar stream of the southern hemisphere interocean exchange. However, recent modelling studies of the present day ocean (Weijer et al. 1999, 2001, Speich et al. 2001, 2002) and of past periods (Fig. 1), and results from subsurface floats trajectory observations (R. Davies, personal communication) and inverse model calculations (R. Lumpkin, personal communication) suggest an important role played by the Southern Ocean northernmost limits where the subtropical circulation interferes with the subantarctic limb. On one hand, the wind field structure of the Southern Hemisphere and the limited southern extension in latitude of the African and Australian continents permits the three Southern Hemisphere subtropical gyres to be intimately linked. On the other hand, as this linkage happens through dynamical transitions from relatively stable western boundary current regimes to the very unstable eastern boundary ones, the involved water masses exchanges and related interocean fluxes are affected by very intense mesoscale interactions (Boebel *et al.* 2003; Morrow, EGU 2004 and manuscript in preparation; Speich *et al.* EGU 2004, and manuscript in preparation). This southern hemisphere "supergyre" is a very efficient conveyor of SAMW and AAIW. In agreement with McCartney (1982), various global model results (Speich *et al.* 2002) show fresh subantarctic water penetrating into the subtropical ocean at the eastern edge of each of the subtropical gyres, where fronts between the subantarctic and the subtropical circulation are weakest. SAMW/AAIW, identified as the subthermocline salinity minimum in the water column, is present throughout the southern hemisphere and well into the tropical regions of all three oceans. This salinity minimum marks the bottom of thermocline ventilation in the southern hemisphere. It is therefore a major source of fresh water for the World Ocean and hence an important part of the water budget. This has climate implications in that lower salinity waters convert less vigorously at high latitudes than contrasting higher salinity waters. In addition, the wind stress and surface fluxes associated with the development of the "supergyre" are likely to be significantly impacted by the important modes of variability in the Southern Ocean region (Reason *et al.*, 2002 ; Fig. 2). These modes include ENSO (e.g., via the Pacific South America pattern), the Southern Annular Mode, the Antarctic Circumpolar Wave and the semi-annual oscillation. Appropriate model studies can be used to assess the impacts of these modes on the inter-ocean fluxes and water mass formation and exchanges.

In order to close the SO water budget and to quantify the SO contribution to the global water cycle, its sensitivity to climate change and variability, and to identify the impact of changes in the high latitude on the rest of the globe, the interocean connections need to be monitored. During the IPY, a focused effort will be undertaken with a combination of observations carried out along the three Southern Ocean chokepoints where the meridional spread of the Southern Ocean dynamics is constrained and where the transport measurements and interocean exchanges can be accurately monitored.

Specific modelling studies will accompany the observational effort.

IPY SO *chokepoints* observational strategy/ideas

We would like to reinforce the ongoing observational effort with the already undertaken strategy of using a combination of observing tools (CTD, tracers, XBTs, XCTDs, ARGO floats, altimetry, etc.) but improving the coverage strategy (simultaneous coverage of the three sections, better sampling of the seasonal cycle if not higher resolution with mooring, focus on frontal regions, eastern boundary dynamics, southern limb covered most of the time by sea-ice, etc …). The various programmed actions (that still need to be approved for financial support in some cases) are:

- **<u>Drake Passage</u>**
    - Regular CTD United Kingdom survey and (in the framework of) the "South Atlantic Box" plan (SOC and UEA – United Kingdom);
    - Continue with deployments of Bottom Pressure Recorders (BPRs) on either side of Drake Passage. Combined with the Antarctic tide gauge network, they provide a good means of monitoring circumpolar transport variability on timescales from days up to interannual (POL/BAS – United Kingdom) ;
    - XBTs, XCTD and ADCP USA regular line (Scripps-USA);
    - the CTD, ADCP and XBTs from the Shirshov (cf. Interocean Exchange project of GoodHope with the Atlantic Ocean A17 repeated) (Shirshov – Russia);
    - the DRAKE mooring project (LODYC -France, Argentina, Univ. Bremen - Germany, and POL/BAS - United Kingdom);
    - the ARGAU-Canopo project (LBCM - France, Argentina and ENEA - Italy).
    - Brazil-to-Antarctica line (XBTs, Low Cost Drifters: FURG – Brazil, NOAA-AOML – USA, and Argentina);
    - Repetition of the WOCE A17 and SR1 legs with full depth CTD and Carbon measurements (IIM-CSIC – Spain).
- **<u>Sector south of Africa</u>**
    - GoodHope along ASTTEX and WECCON (LPO and Coriolis - France, AWI and Univ. Bremen - Germany, KNMI and Univ. Utrecht - Netherlands, Shirshov and AARI - Russia, UCT, MCM, Rhodes Univ. and Univ. Pretoria - South Africa, IICM - Spain, SOC - United Kingdom, NOAA and Univ. Maine - United States of America);
    - Repetition of I6 in the framework of the United Kingdom "South Atlantic Box" plan (SOC and UEA - United Kingdom).

- **<u>Region south of Australia</u>**
    - Repetition of SR3 CTD section (CSIRO - Australia);
    - SURVOSTRAL regular XBTs section (CSIRO - Australia and France);
    - New Zealand to Antarctica (P14S and 170W) regular XBTs section (UNIPARTHENOPE and CNR-ISMAR - Italy).

In addition, we would strive to build an implementation plan that includes some of the following ideas:

- **IDEA 1**

Have all three sections more or less sampled at the same time (synoptical *view*). Ideally, the observations would be accomplished by at least one full depth CTD line and three high-resolution XBT transects for the other seasons and for each chokepoint. The best strategy is to have them following a Jason-1 ground track line to better make use of altimetry for extrapolating quantitative transports and variability.

- **IDEA 2**

Have the southern limb sampled with as many under-ice floats as possible (with tracking acoustic) in order to recover full year data for the southern limb.

- **IDEA 3**

Try to have a mooring array that could cover time scales from high-resolution variability (daily if not higher) and last for a few years in order to get trends. One ideal array that is more viable than others in term of cost is a combination of Pressure Inverted Echo Sounders (PIES) and bottom current meter deployed along altimeter ground track (and use of Byrne-Watts GEM-ETTA statistical technique as for the ASTTEX array).

- **IDEA 4**

Have *ad hoc* observations on the north-eastern corner of these chokepoints to try to measure the highly energetic Cauldron-type dynamics happening during the transition between western to eastern boundaries current regimes with the related transition in the Subtropical Convergence. This transition is thought to be important in relation with the advection of SAMW/AAIW into the south Equatorial Current of the different SH basins. For example, we could think of relatively short transects in a perpendicular direction to the chokepoint sections with high density observations performed with instruments such as Gliders or similar type of devices, as well as deployment of a number of profiling floats and drifters in particular dynamical features (cyclonic and anticyclonic eddies).

- **IDEA 5**

Zonal/diagonal sections in the SH oceanic basins in order to close the fresh-water (and mass and heat) budgets. Probably the most viable idea granting an efficient outcome is a diagonal line that crosses the South Equatorial Current once (Arnold Gordon suggestion). This could be suggested to Bacon *et al*. (SOC-UK) for the South Atlantic in the framework of their idea of a closed box with a two ships action, and with a repetition of SR1 and I6.

- **IDEA 6**

Ideally, the establishment of several monitoring line such as between Falklands - South Georgia - Antartica and between Concepcion to Amundsea Sea coast of Antarctica would permit to look more in detail at the ENSO - PSA driven impact on AAIW and AABW exchanges as well as the ACC advection of signals from the Pacific to Atlantic sector. The Amundsen – Bellinghausen Seas region is, for example, where one often sees the largest anomalies in the atmospheric forcing which may be teleconnected to climate variability signals in Australasia, South American, southern Africa, etc.

- **IDEA 7**

Increase the number of mini-CTDs tagged seals (*cf*. POL/BAS and SMRU – UK and CEBC/CNRS – France activity), and in general, on other marine animals.

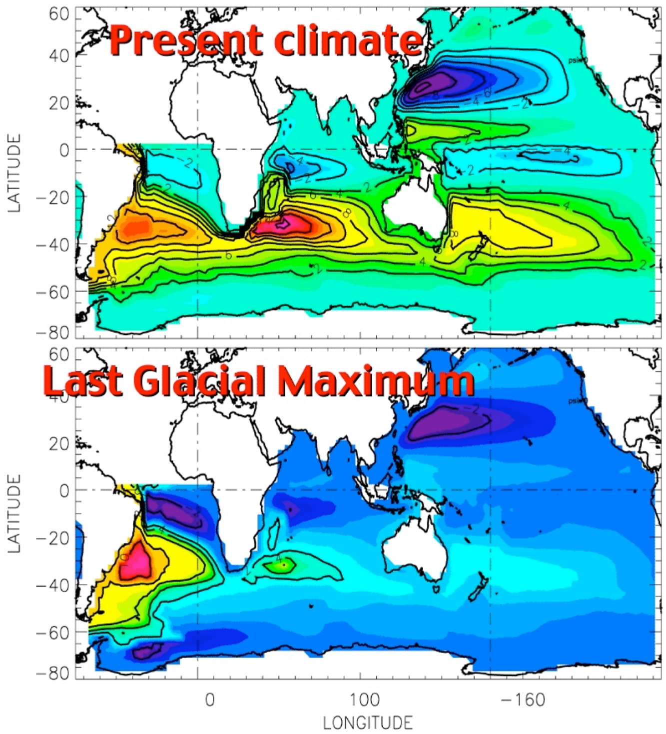

Figure 1: Visualization of the THC upper branch through a Lagrangian stream function computed from the ORCA2 model of the world's oceans and depicting the path of water particles reaching the North Atlantic from the Southern. It shows the different behaviour of the ocean response to the present climate forcing (upper panel) compared to one close to the Last Glacial Maximum (LGM) conditions (lower panel). The most striking feature is the existence of a three-oceans subtropical super-gyre connection for the present climate and its absence for the LGM. From Speich et al. (2004).

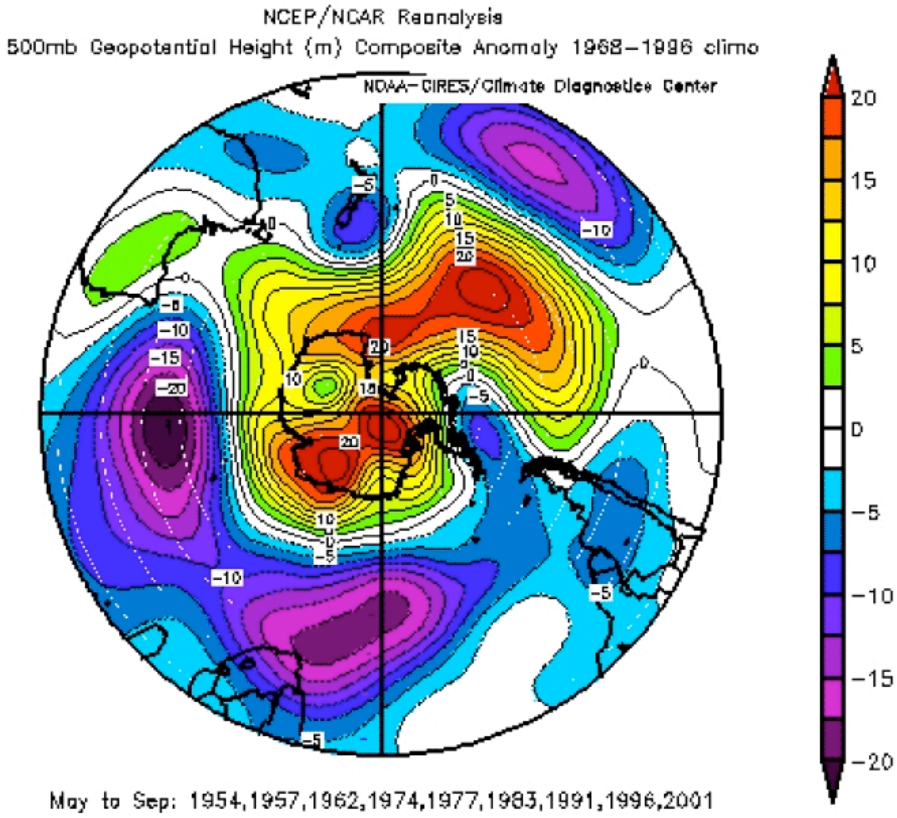

Figure 2: 500 hPa anomalies for wet SW South African winter composite (Reason et al., 2002).

References

Boebel O.; Lutjeharms J.; Schmid C.; Zenk W.; Rossby T.; Barron C., 2003 : The Cape Cauldron: a regime of turbulent inter-ocean exchange. *Deep Sea Res*., 50, 57-86(30)

Döös K. and A.C. Coward 1997: The Southern Ocean as the major upwelling zone of the North Atlantic Deep Water. WOCE Newsletter, No. 27, July 1997, 3-17.

Cunningham, S. A., S. G. Alderson, and B. A. King, 2003: Transport and variability of the Antarctic Circumpolar Current in Drake Passage. *J. Geophys. Res.*, *108*, 8084, doi:10.1029/2001JC001147.

Hall, A. and M. Visbeck, 2002: Synchronous variability in the southern hemisphere atmosphere, sea ice, and ocean resulting from the annular mode. Journal of Climate, **15**(21): 3043-3057.

McCartney, M., 1982: The subtropical recirculation of mode waters. *J. Mar. Res*., **40 (supp),** 427-464.

Meredith, M. P., P. L. Woodworth, C. W. Hughes, and V. Stepanov, 2004 : Changes in the ocean transport through Drake Passage during the 1980s and 1990s, forced by changes in the Southern Annular Mode. *Geophys. Res. Lett.*, submitted.

Morrow, R., 2004 : Meridional propagation of ocean eddies and their role in the ocean heat budget. EGU 1st General Assembly, 25-30 April 2004, Nice, France.

Reason, C.J.C., M. Rouault, J.-L. Melice and D. Jagadheesha, 2002: Interannual winter rainfall variability in SW South Africa and large scale ocean-atmosphere interactions. *Met. Atmos. Phys*., Special Issue on Atmosphere-surface interactions, 80 (1-4), 19-29.

Rintoul, S. R., C. W. Hughes, and D. Olbers, 2001: The Antarctic Circumpolar Current System. In: *Ocean Circulation and Climate*. G. Siedler, J. Church, and J. Gould (eds.), Academic Press, 271-302.

——, S. Sokolov, and J. Church, 2002: A 6 year record of baroclinic transport variability of the Antarctic Circumpolar Current at 140°E derived from expendable bathythermograph and altimeter measurements. *J. Geophys. Res.*, *107*, 3155, doi:10,1029/2001JC000787.

Schmitz, W. J., 1995 : On the interbasin-scale thermohaline circulation. Rev. of Geophys., **33**(2):151-173.

——, 1996 : *On the World Ocean Circulation: Volume I* (Woods Hole Oceanographic Institution Technical Report WHOI-96-03).

Sokolov, S., B. A. King, S. R. Rintoul, and R. L. Rojas, 2004: Upper ocean temperature and the baroclinic transport stream function relationship in Drake Passage. *J. Geophys. Res.*, *109*, C050001, doi:10.1029/2003JC002010.

Speich, S., B. Blanke, P. de Vries, K. Döös, S. Drijfhout, A. Ganachaud, and R. Marsh, 2002a : Tasman Leakage: A new route for the global conveyor belt. *Geophys. Res. Letters,* **29***, 10.*

——, D. Iudicone, G. Madec, 2002b: Pathways and ventilation of salinity minimum waters at 32°S as derived from an OGCM. Proceedings of *WOCE2002,* San Antonio, Texas, 17-22 October.

——, B. Blanke, and G. Madec, 2001 : Warm and cold water paths of a GCM thermohaline conveyor belt. *Geophys. Res. Lett.*, **28**, 311-314.

——, P. Penven, B. Blanke, 2004 : On the Cape Cauldron dynamics : some physical insights on the turbulent Indo-Atlantic exchange and impact of Agulhas waters in the Southern Africa upwelling region from a hierarchy of regional numerical simulations. EGU 1st General Assembly, 25-30 April 2004, Nice, France.

——, O. Marti, B. Blanke, 2004: Thermohaline circulation changes in global ocean simulations for the modern and the Last Glacial Maximum climates. *Geophys. Res. Lett.,* to be submitted.

Sprintall, J (2003), Seasonal to interannual upper-ocean variability in the Drake Passage, J. Marine Res., 61, 27-57.

Weijer,W., W. P. M. de Ruijter, and H. A. Dijkstra, 2001: Stability of the Atlantic overturning circulation: Competition between Bering Strait freshwater flux and Agulhas heat and salt sources. *J. Phys. Oceanogr.,* **31**, 2385-2402.

——, W. P. M. de Ruijter, H. A. Dijkstra, and P. J. van Leeuwen, 1999: Impact of interbasin exchange on the Atlantic overturning circulation. *J. Phys. Oceanogr.,* **29**, 2266-2284.

White, W. B., and R. Peterson, 1996: An Antarctic circumpolar wave in surface pressure, wind, temperature and sea ice extent. *Nature*, **380**, 699-702.

Whitworth, T. III, 1983: Monitoring the transport of the Antarctic Circumpolar Current at Drake Passage. *J. Phys. Oceanogr.*, *13*, 2045-2057.

——, and R. G. Peterson, 1985: Volume transport of the Antarctic Circumpolar Current from bottom pressure measurements. *J. Phys. Oceanogr.*, *15*, 810-816.

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