



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

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

**REPORT ON THE FIRST GOODHOPE MEETING, HELD AT AWI,
BREMERHAVEN, GERMANY, SEPTEMBER 5 AND 6 2003**

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FORWARD

This document provides a summary of the scientific background and objectives that aim the GoodHop project together with the operational programme for the first phase of the project (years 2004 and 2005) as it was decided during the GoodHope kick-off meeting held in Bremerhaven (Germany) on September 5 and 6, 2003.

Following suggestions and discussions put forward during the Southern Ocean Clivar/CliC Panel (Bremerhaven – Germany, September 8 to 11, 2003), this document also contains a prospective reflection on measurements that will be very profitable for the comprehensiveness of the project and we will try to set up for a future phase of the project.

Sabrina Speich

Brest, 15 January 2004

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1. PROJECT GENERAL INFORMATION

1.1. TITLE

**Good-Hope / Southern Ocean :
Monitoring the Indo-Atlantic connections**

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

1.2. KEYWORDS

Keyword 1: Oceanography
Keyword 2: Ocean/Atmosphere Interactions
Keyword 3: Climate & Climate Variability

Free Word 1: Thermohaline circulation

1.3. START DATE

Intended Start date: January 2004

1.4. THE INTERNATIONAL CONSORTIUM

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1.5. AIMS

While the Southern Ocean dynamics is suspected to have a major role in the global ocean circulation and present day climate, our understanding of its three-dimensional dynamics and variability, and the impact of such variability on the climate system is at best rudimentary. The GoodHope project aims to partially fill in this knowledge gap by periodic observations along a line between the African and Antarctic continents (Fig.1). The objectives are fourfold:

1. A better understanding of Indo-Atlantic interocean exchanges (in terms of water masses, heat and fresh water budgets) and their impact on the global thermohaline circulation and present day climate.
2. A better understanding of the impact of interocean exchanges on the local climate of the African continent.
3. A monitoring of the variability of particular dynamical features of the Southern Ocean (Antarctic Circumpolar Current, frontal systems, ...)
4. A study of the local air-sea heat exchanges and their role on the global heat budget (with emphasis on the intense exchanges in the Agulhas Retroflexion region)

The proposed survey follows the WOCE SR2 transect between Cape Town and the Greenwich Meridian (Fig. 1). This line is very close to the ferry service route from Cape Town and the German Neumayer and the South African Sanae Antarctic stations (Fig. 1).

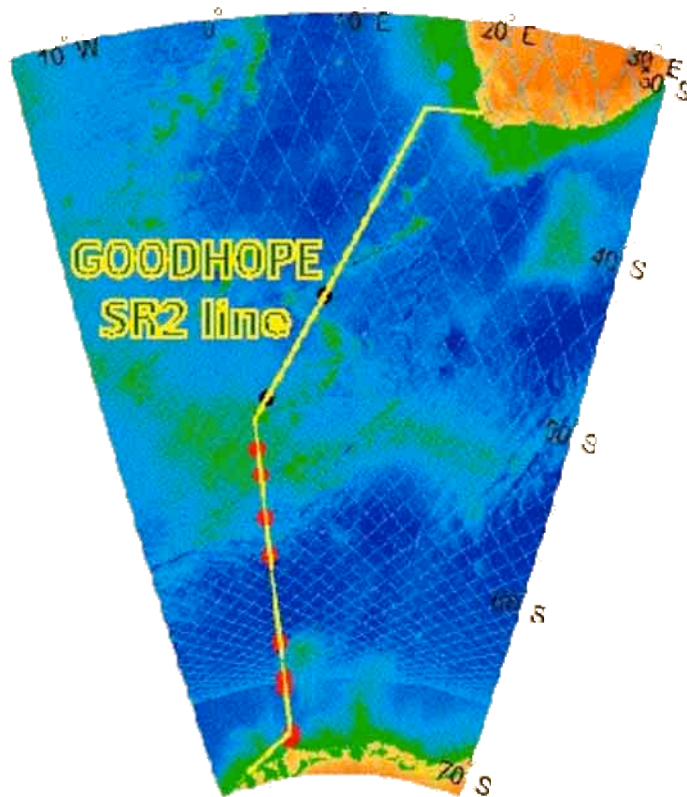


Fig. 1: Map showing the GOODHOPE monitoring line between Cape Town and Neumayer station. This line lies very close to that occupied during WOCE (SR2).

2. SCIENTIFIC BACKGROUND

The Southern Ocean (SO) plays a unique role in coupling the ocean to the atmosphere and the cryosphere. Variations in the mechanisms responsible for this coupling are expected to be linked to the global climate variability.

The most relevant processes are:

- The very intense exchanges of mechanical energy, and heat and fresh-water fluxes between the air, the sea and the cryosphere.
- The variability of the three dimensional structure of the Antarctic Circumpolar Current (ACC, the only current that connects all three major ocean basins, thereby providing an essential heat and fresh water pathway).
- The production of Antarctic Intermediate Water and Subantarctic Mode Water. These spread northward injecting cool low salinity water into and along the base of the main thermocline helping close the hydrological cycle.
- Upwelling of Circumpolar Deep Water poleward of the ACC, which provides a primary mechanism for major venting of deep oceanic heat into the atmosphere.
- The production of cold dense Antarctic Bottom Water.
- The way in which large-scale coherent variability in the atmosphere over the Southern Ocean propagates anomalies across various climate zones (*e.g.* Antarctic Circumpolar Waves, Antarctic Oscillation, ...).

The state of observations and modelling of the Southern Ocean is not as developed as in other regions of the ocean and atmosphere. While major achievements were made during the WOCE/JGOFS era, we still have only a very incomplete “glimpse” of the mean state and variability of the Southern Ocean, its coupling with the atmosphere and cryosphere, and the zonal and meridional fluxes.

SO observations are significantly incomplete in space and time (Fig.2); consequently, further emphasis on exploratory investigations in the Southern Ocean needs to be placed than in better-sampled ocean basins.

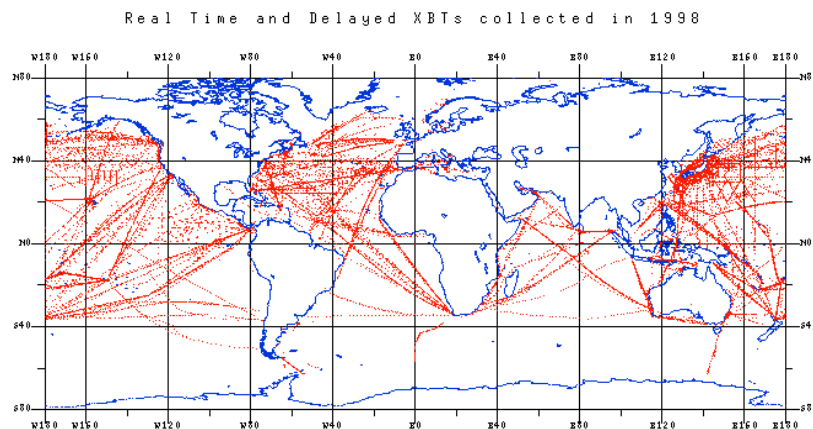
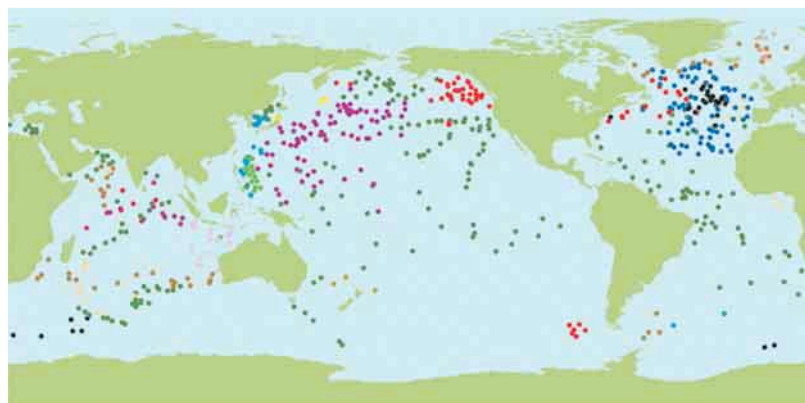


Fig. 2 : The Southern Ocean observational “gap”: a) Spatial distribution of delayed XBTs collected in 1998.



Argo Network, as of 20 January 2003 (620 Floats)

● AUSTRALIA (18)	● FRANCE (19)	● NEW ZEALAND (3)
● CANADA (58)	● GERMANY (34)	● NORWAY (3)
● CHINA (16)	● INDIA (10)	● RUSSIAN FEDERATION (3)
● DENMARK (5)	● JAPAN (87)	● UNITED KINGDOM (46)
● EUROPEAN UNION (74)	● KOREA (Rep. of) (26)	● UNITED STATES (218)

Fig. 2b : ARGO profiling floats network as of 20 January 2003.

2.1. INTEROCEAN EXCHANGE

Interocean exchange is thought to be an important part of the present-day global thermohaline circulation, particularly in response to North Atlantic Deep Water (NADW) formation. The Southern Ocean is a critical crossroad for this process. It provides the route for NADW from the source regions to the Indian and Pacific oceans and the routes for the return flow of Intermediate and Central Waters on their way to the North Atlantic after warmer water has been formed in these oceans by upwelling and mixing. South of Africa the Southern Ocean plays a unique role in providing a source for the equatorward flux of heat in the South Atlantic.

The proposed experiment will allow us to better determine the water mass fluxes to and from the western boundary of the South Atlantic, and to link them with transport and properties at the eastern side of the basin. This will in turn provide basic estimates of the mass heat and fresh water fluxes through the open boundaries of the South Atlantic helping to fill the existing observational gap and provide new perspectives for the theoretical modelling.

THE ANTARCTIC CIRCUMPOLAR CURRENT

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, Nowlin and Klinck, 1986). The ACC consists of a number of circumpolar fronts which correspond to water mass boundaries as well as deep reaching jets of eastward flow with the two main fronts – Subantarctic front (SAF) and Polar front (Orsi et al., 1995). The ACC is mainly a zonally flowing current, but large quasi-stationary waves, guided by bottom topography, lead to its latitudinal swing of approximately 1200 km north in the Atlantic; it is found at its southernmost extent in the southwest Pacific (Gordon et al., 1978, Orsi et al., 1995). Mesoscale eddies within the ACC produce oceanic meridional heat and freshwater fluxes that balance much of the ocean-atmosphere exchange south of the ACC.

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). Thus, determining the transport of the ACC has been an observational goal for many years. Our understanding of how and why the ACC transport varies with time, however, is incomplete due to the lack of observations. During the World Ocean Circulation Experiment (WOCE), repeat sections, from which the ACC transport variability could be assessed and monitored, were limited to the three chokepoints between Antarctica and the

southern hemisphere continents. One such section lies across the Drake Passage (SR1), another between Tasmania and Antarctica (SR3) and the last one between the southern tip of Africa and the Antarctica (SR2). While intense and periodic monitoring of the Drake (www.clivar.org/organization/southern/national_reports/uk.htm) and Tasmanian (www.clivar.org/organization/southern/national_reports/australia.htm) sections has been effective since the WOCE period, a regular monitoring line between South Africa and Antarctica is not currently occupied.

THE INDO-ATLANTIC CONNECTION

Undoubtedly, the ACC is the main circumpolar stream of the interocean exchange. However, the regional transport of heat and salt from the subtropical gyre in the South Indian Ocean to the South Atlantic is a remarkable feature of the circulation south of Africa (Fig. 3). The leakage of water or return flow from the South Indian Ocean, presumably through the Agulhas Current, has attracted considerable interest in the past decade. The recent works of Weijer et al. (1999, 2001) suggest that exchanges of heat and salt via the Agulhas leakage could influence the strength and stability of the thermohaline circulation in the Atlantic.

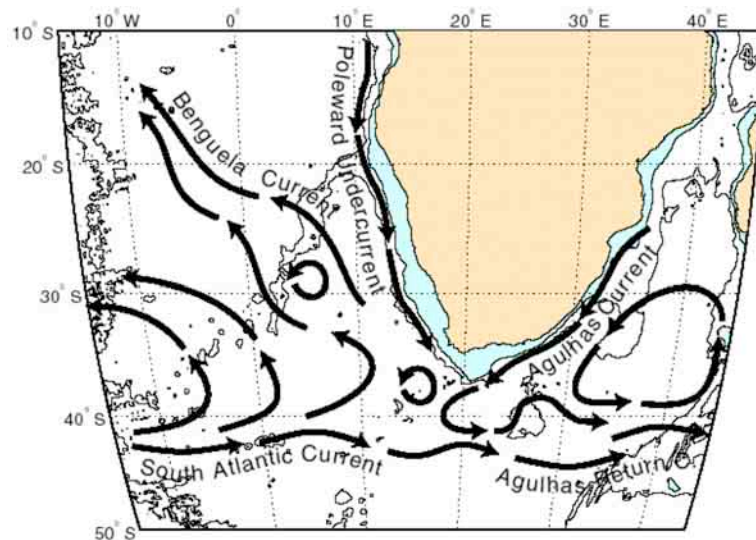


Fig. 3: A scheme for Indo-Atlantic intermediate layers water exchanges (Boebel, *et al.*, 2002)

The sources, pathways and characteristics of this exchange are not well enough established to allow their influence on the climate system to be quantified. Indian Ocean waters are injected into the South Atlantic both by a ring-shedding process at the Agulhas Retroflexion and by intermittent filaments of Indian Ocean water (Lutjeharms, 1996; Byrne, 2000). A key question is the role played by the Mode and Intermediate Waters (SAMW and AAIW respectively) of Indian origins, which move through this region, in the global overturning circulation (de la Heras and Schlitzer, 1999), especially in the light of the recent observed freshening of these waters (Wong et al., 1999). A closely related question is the relative contribution of the surface component into the South Atlantic, which enters south of Africa and via the route south of America.

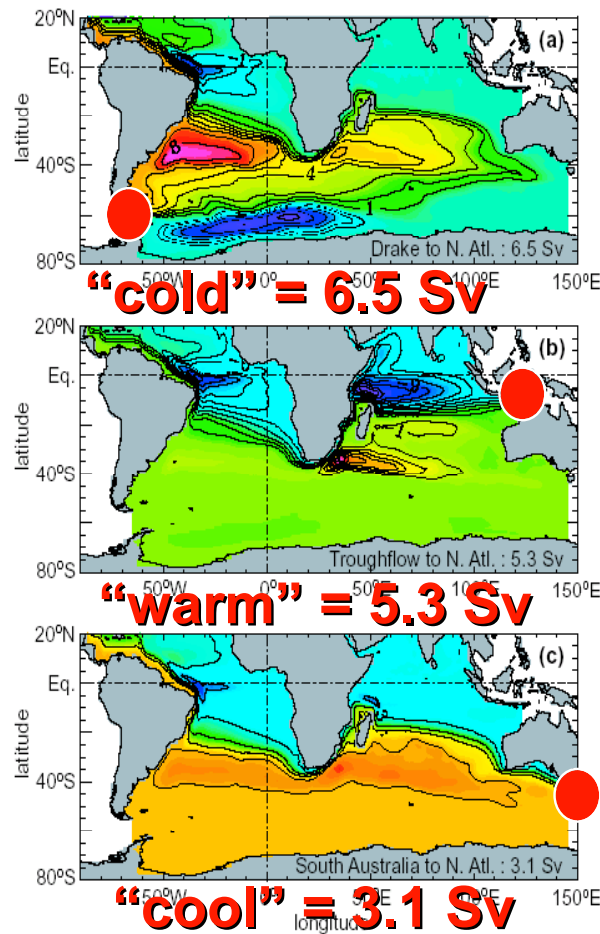


Fig. 4: The three routes (Lagrangian streamfunction) to North Atlantic from Speich *et al.* 2001. Whatever the origin is (Drake Passage, upper panel; Indonesian Throughflow, middle panel; Tasman outflow, lower panel) the Indo-Atlantic exchange is important.

Recent modeling results suggest that the Indo-Atlantic interocean exchanges through the Agulhas system are far more important for the thermohaline circulation than the direct input of water from the Drake Passage (Speich *et al.*, 2001a, 2002, Fig. 4). Numerical results suggest the existence of a dynamical connection between all three wind-driven subtropical gyres in the southern hemisphere (a “supergyre”) that is a very efficient conveyor of SAMW and AAIW (Fig. 5). In agreement with McCartney (1982), the model results 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. Model SAMW freshens as this water is advected along the southern boundary of each subtropical gyre, eventually becoming AAIW. In this “cool water” route SAMW from the Drake Passage transits the South Atlantic and South Indian Oceans via this route, return from the Pacific south of Tasmania, finally re-entering the Atlantic via the Agulhas system.

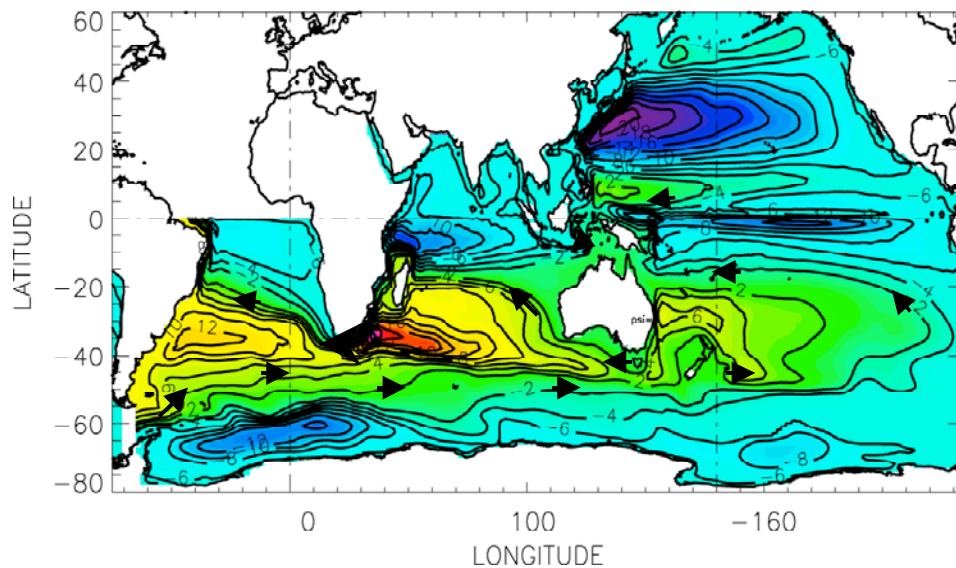


Fig. 5: The total Lagrangian stream function for the upper-branch of the thermohaline circulation. Evident is the Southern Oceans "super-gyre" feature. From Speich *et al.* 2002a

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. If we admit that the SAMW/AAIW are important for the global thermohaline circulation, the quantification, physical understanding and long-term monitoring of the inflow of Indian waters into the Atlantic Ocean becomes unavoidable.

2.2. SCIENTIFIC RATIONALE FOR *AFRICA-ANTARCTICA* SECTION

The GoodHope transect has been chosen to satisfy a number of important oceanographic objectives:

- To provide long-term occupation of SR2 to complement the ongoing monitoring of SR1 and SR3.
- To help fill major gaps in our understanding of the ACC and its role with respect to climate variability in a relatively unexplored region of the Southern Ocean.
- To quantify, understand and monitor the inflow of Indian Ocean waters into the Atlantic Ocean. This will help close the oceanic heat and salt budget and will provide insight into the influence of this energetic region on local and global (atmospheric and oceanic) dynamics and variability, and on the global heat budget.
- To estimate the mass, heat and salt fluxes along the GoodHope section, and to observe their correlation with Atlantic NADW production and export.
- To evaluate the impact of interocean exchange on the local air-sea heat budget and its role in the regional climate of the African continent.

3. OBSERVATIONAL PROGRAMME

3.1. MONITORING STRATEGY FOR *AFRICA-ANTARCTICA SECTION*

The advantages of the GoodHope-SR2 line from Cape Town to the German Antarctic Base station (Fig. 1) are:

- It follows the TOPEX/POSEIDON-JASON1 altimeters flight path (nb 133).
- The southern fraction of this line (south of 50°S) has already been sampled for several years by moorings of the German WECCON project (Fig. 6).
- Its northern part overlaps with the USA ASTTEX programme (Fig. 6), thus linking the Southern Ocean dataset with that collected in the Benguela region.
- Two Pressure Inverted Echo Sounder (PIES) mooring have already been deployed along this line. The data collected during the monitoring programme will support the PIES data set. At least two more PIES mooring are envisaged.
- The monitoring line lies close to the annual “ferry service” of the SA Agulhas from Cape Town to the German Antarctic base Neumayer. No more than an extra day will be required to accommodate this line.

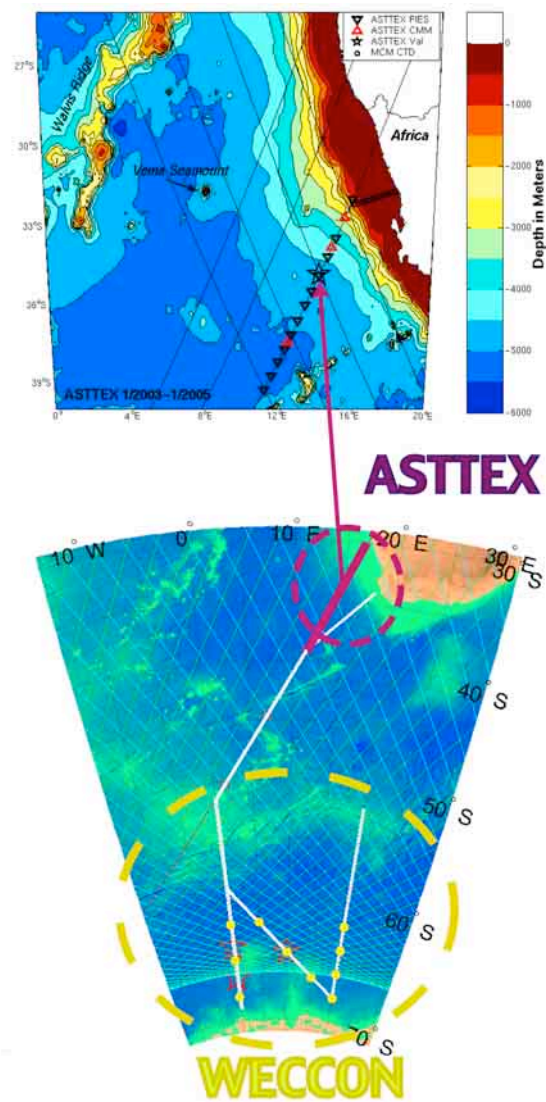


Fig. 6 Location of the WECCON moorings and the ASTTEX array.

The choice to follow a TOPEX/POSEIDON-JASON1 ground track will efficiently increase the spatio-temporal sampling of observations. An example is the study of Goni *et al.* (1997-2002) – Fig. 7.

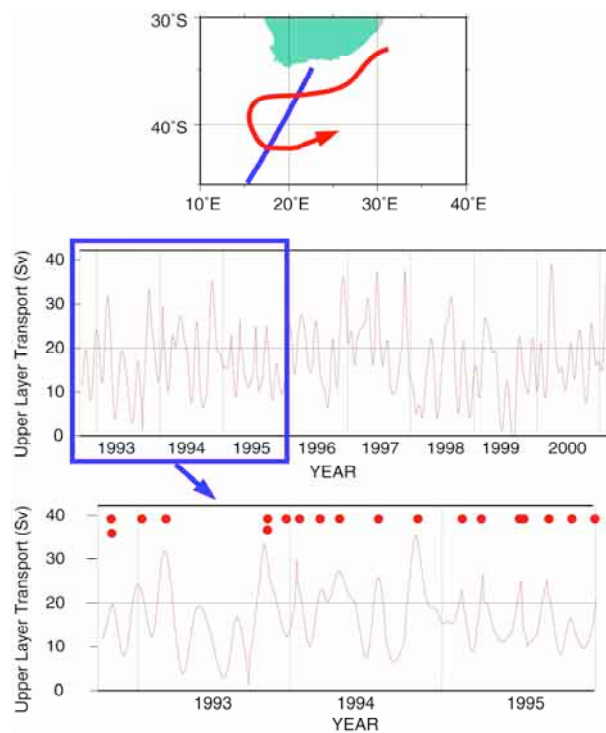


Fig. 7 Schematic of the Agulhas Current retroflexion and Baroclinic transport from the surface to 10°C isotherm across a selected TOPEX/POSEIDON ground track from the coast to 40°S. Red dots are ring shedding events.

Moreover, the association of hydrology observations, and especially the PIES array with the altimeter measures through the use of a new technique which allows the quantitative estimation of fully depth-resolved salinity and temperature profiles from the combination of acoustic travel time and sea surface height. This method is called GEM-ETTA for Gravest Empirical Mode Enhanced Thermohaline Transport Analysis (developed by Drs. D. Byrne and R. Watts). It uses hydrography and altimetric sea surface height in concert with acoustic travel time to distinguish thermohaline anomalies in the water column (Fig. 8).

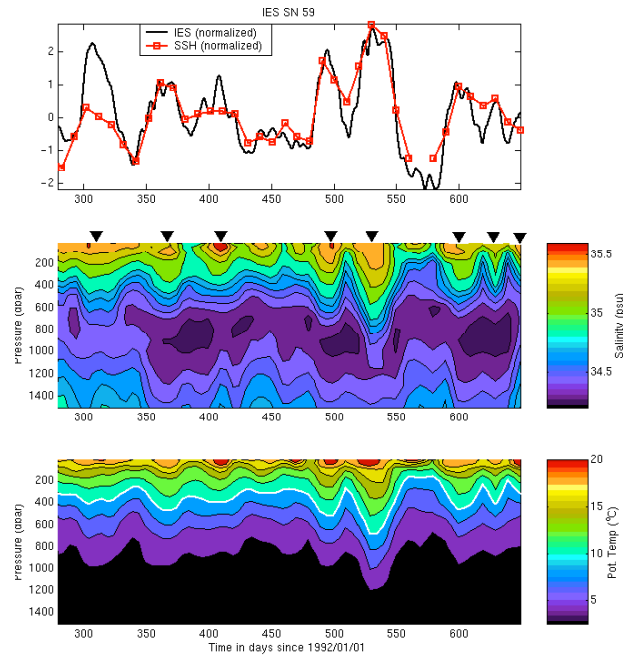


Fig. 8 a) (top) Record of (normalized) sea level and acoustic travel time from a PIES mooring deployed in the South Atlantic Ocean northwest of the Agulhas Retroflection. Peaks indicate the presence of warm Indian Ocean water transiting the mooring. b) (middle) Timeseries of water column salinity structure, inferred from PIES mooring and altimetry data and the GEM-ETTA method. A number of significant thermohaline anomalies were identified by an earlier study (triangles). Intrusions of weakly stratified Indian STMW, and high-salinity Indian AAIW can be seen. c) bottom. Timeseries of water column temperature from PIES, altimetry and GEM-ETTA.

3.2. THE OBSERVING STRATEGY

Due to the extent of the GoodHope section and the need for a long-term commitment, this project is conducted as a collaborative of various scientific institutes of different countries. To be quantitative, the observations should meet the WOCE standards.

Monitoring the GoodHope transect will be accomplished using a combination of the following observational tools: Altimetry, high density XBTs, XCTDs, profiling floats, subsurface floats, drifters, thermosalinograph; *in situ* sampling for oxygen, nutrients, and chlorophyll. Complete CTD sections (hydrography and biogeochemistry) will be carried out every 2 to 5 years. In particular:

- **Repeat high density XBT sampling** will provide measurements of changes in upper ocean heat content on seasonal and interannual time scales. In addition, by exploiting the relationship between upper ocean temperature and dynamic height, XBTs can be used to infer baroclinic velocities and transports (Rintoul and Sokolov, 1999). In this way XBT sections can be used to estimate changes in the heat carried by the interocean exchanges and their variability. Twice a year, high-density XBT transects will be conducted using XBTs provided essentially by NOAA-AOML. Eventually we also plan to use XCTDs to evaluate freshwater fluxes in the upper ocean.
- **Inverted Echo Sounder** moorings equipped with **Bottom Pressure sensors (PIES)**. Bottom moored echo sounders measure the vertical acoustic travel time, which has been shown to be a regionally robust estimator of $T(z)$ and $S(z)$ (Watts *et al.*, 2001;

Byrne, 2000). The PIES bottom pressure sensors are used to infer the deep (barotropic) velocity field (possibly in conjunction with deep current meters as is the case in ASTTEX). The pressure sensor also provides an accurate tidal record for use in correcting altimetric Sea Surface Height. Deployment of an increased number of PIES along the transect is being planned in order to increase the sampling of the ACC region.

- **Profiling floats:** In remote regions such as the Southern Ocean, monitoring upper ocean temperature and salinity is only possible using drifting platforms. Profiling floats with temperature and salinity sensors provide a cost effective means of making such measurements. The floats also provide a measure of the absolute velocity field.
- **CTD sections:** While repeat XBT sections across the Southern Ocean chokepoints provide a cost-effective way to monitor changes in upper ocean heat content and the transport of volume and heat, they are not able to measure changes in the freshwater flux, in deep ocean properties, or in the transport. For this purpose, full-depth CTD sections are required. Such sections will include tracer measurements that will help resolve the time scales of interocean communication. To avoid aliasing such signals as the southern hemisphere internal modes, annual sampling is required on at least one of the three Southern Ocean chokepoints; currently this requirement is being satisfied by Drake Passage monitoring programs. The sections will be repeated approx. every 3-5 years across each chokepoint and are not expected to be incorporated into the “ferry service”. Eventually, we hope to extend the program to include CTD transects in other seasons. In the meantime, summer-summer comparisons will provide our first measure of interannual variability.
- **Atmospheric observations:** To provide additional information regarding the atmospheric transports and forcing for models, standard atmospheric observations will be made during each occupation of the section. Most important are measurements of the heat and moisture, wind velocity, sea level pressure, and cloudiness.
- **Altimetry:** Altimetry plays a particularly important role in the Southern Ocean because other aspects of the observing network are so sparse. In the context of long-term monitoring, altimetry provides year-round sampling (over ice-free areas), while XBT and CTD sections are likely to be limited to the summer season. Altimetry provides the only measurement which samples the entire Southern Ocean, allowing the propagation of signals to be determined. The altimeter also of course measures a different quantity than the XBT/CTD sections - it includes the barotropic as well as the baroclinic signals. And while aliasing of high-frequency modes in the sea level signal is a problem on shorter timescales, especially in the Southern Ocean, it is quite suitable for the measurement of large-scale, seasonal-to-interannual variability.
- **SST Surface Drifters:** Satellite sensors will provide the primary means of measuring SST. However, *in situ* observations are needed to remove biases in the satellite measurements. The most practical way to measure *in situ* SST over large areas of the Southern Ocean is by surface drifters.
- **SLP:** Measurements of surface pressure from drifters is crucial to improve analyses produced by operational atmospheric models. Such models are likely to provide the best estimates of wind stress, and (perhaps) the air-sea flux of heat and freshwater we can get over the Southern Ocean. These fluxes are needed to drive ocean models and to validate coupled climate models. For this reason, maintaining an array of surface drifters in the Southern Ocean is important to attaining the goals of CLIVAR.

- **SSS**: Sea surface salinity is very poorly known over most of the Southern Ocean, yet it is the primary controller of surface density south of 60°S. Climate models indicate that the dominant global warming signal is not SST increase, but SSS decrease, and that this freshening could be important for climate stability. Thermosalinographs are installed on almost all Antarctic research and supply vessels. Such sections would provide some indication of the variability and trends in SSS.
- **Chl**: Total Chlorophyll, Nutrients (Nitrites, Nitrates, Phosphates and Silicates) and dissolved oxygen will be analysed in order to study the productivity of this chokepoint region and to correlate to SEAWIFS ocean colour imagery.

The nature of this proposal is thus to routinely survey the SR2 transect with a high resolution XBT deployment using the SA Agulhas as a monitoring platform during its contracted “ferry service”. Underway surface samples will be collected at 15’ intervals. A number of drifters, floats and profiling floats aimed at capturing regional dynamics and the large-scale thermohaline structure of the upper 2000 m of the water column will be deployed during each transit. The intended line will also take full advantage of WECCON and ASTTEX observations. In addition a full depth CTD section is planned for every three to five years and will complement the routine XBT surveys that will be established in a few months’ time. In particular, the related INTAS-NIS *Interocean Exchange* project will undertake (if approved) the first SR2 CTD section at the end of 2004 (*cf.* section 3.5). Lastly, the position of the selected transect will permit us to take full advantage of available satellite altimetry coverage.

3.3. THE XBTS TRANSECTS

The first GoodHope transect will take place during the transit of the SA Agulhas to the German Antarctic base Neumayer during February-March 2004. During this first transect we will sample the upper ocean with Sippican T-7 XBT probes with the spatial resolution of ~35 km (higher near frontal structures), surface drifters with a spatial resolution of ~300 km and we will deploy 15 Argo PROVOR floats. Underway SSS, Chl and standard atmospheric measurements are planned. This XBT/float section will be repeated at least once a year in February-March on the annual transit of the SA Agulhas.

3.4. EXISTING MOORING ARRAYS

In this section we briefly describe the two existing mooring arrays that are already sampling the hydrology and dynamics of a portion of the GoodHope section.

WECCON : Weddell Sea Convection Control

Large scale processes and long-term variations of convection in the Weddell Sea

A contribution to **CLIVAR** and **iAnzone#4** Convection in the Weddell Sea

E. Fahrbach (PI), O. Boebel, M. Schroeder, M. Hoppema, AWI, Germany

A major contribution of the global deep and bottom water occurs in the Weddell Sea. **WECCON** aims to investigate processes which occur in the Weddell Sea to form deep and bottom water in the framework of **iAnZone # 4** – Convection in the Weddell Sea and the

influence of variations of the Antarctic Circumpolar Current in the Atlantic sector on water mass modifications in the Weddell Sea.

Science Goals

The objectives of the project are:

- To determine the variation in water mass properties in the convective area north and west of Maud Rise
- To determine the variability in characteristics and amount of the inflowing Circumpolar Deep Water
- To determine the effect of variations in the elements of the fresh water budget as sea ice transport and iceberg melt on the stability of the water column
- To estimate the effect of topographic features like Maud Rise to intensify vertical transports
- To determine the potential of remote and local effects to induce variability in the atmosphere-ice-ocean interaction
- To estimate the contribution of open ocean convection in the Antarctic zone to the ventilation of the global ocean
- To estimate the potential of abrupt changes.

Method

The observational program contains the following components (Fig. 9):

- A moored observing system is maintained since 1996. Current meter moorings were exchanged in 1998, 1999, 2001 and 2003. The moorings are equipped with current meters, temperature and conductivity sensors to measure the vertical distribution of the currents and water mass properties to determine the stability of the water column.
- In the area of the Weddell Front three sea level recorders were deployed in 1999 to detect variations in the location of the front as an indicator of changes of the inflow of Circumpolar Deep water into the Weddell Sea.
- The inflow is regularly tracked by APEX floats which are deployed in the northern Weddell gyre and southern ACC.
- Upward looking Sonars in 150 m depth are installed on six moorings in the framework of the WCRP Antarctic Sea-Ice Thickness Project (AnSITP) to determine the sea ice transports (<http://www.awibremerhaven.de/Research/IntCoop/Oce/ansitp/index.html>).
- Regularly, icebergs are marked by satellite transmitters to determine their tracks from the Antarctic coast into the melting area.

To measure the near surface layers and to increase the horizontal resolution, ship-borne measurements are regularly performed (1996, 1998, 1999, 2001, 2003). From the water samples, measurements of the following tracers are carried out: CFCs (Freon-11 and Freon-12, Freon-113, CCl₄), tritium, ³He, He, and Ne. A repeat of this transect is planned for 2005. Norway has deployed a mooring on top of Maud Rise with current meters and with an ULS.

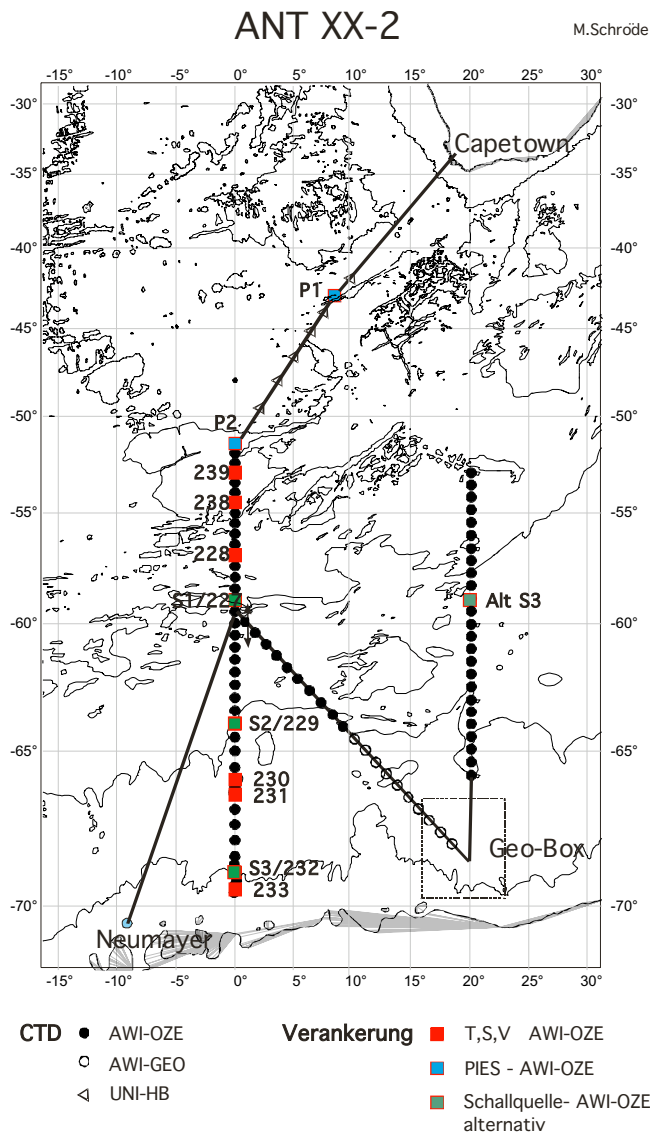


Fig. 9: Map showing the WECCON mooring array and the CTD stations sampled during the austral summer 2002-2003 WECCON section.

ASTTEX : Agulhas-South Atlantic Thermohaline Transport Experiment

Deirdre Byrne (PI), Neal Pettigrew (CO-PI) (U. of Maine, USA)
 Randolph Watts (CO-PI), U. of Rhode Is. USA, Donna Witter (CO-PI), Kent State U. USA
 Christopher M. Duncombe Rae (CO-PI) (MCM, South Africa)

Science Goals

ASTTEX examines the fluxes of heat, salt and mass entering the South Atlantic Ocean via the Agulhas Retroflection. The goal of the experiment is to provide a quantitative, multi-year Eulerian measurement of the strength and characteristic scales of Agulhas-South Atlantic

mass and thermohaline fluxes, which contain a strong mesoscale component, resolving those fluxes on density horizons. While it has been estimated that up to half of the Agulhas-South Atlantic exchange is contained in mesoscale rings and eddies [Byrne, 2000] and the strength of the mesoscale fluxes could potentially vary a great deal in time, this has yet to be confirmed by a single, consistent set of observations -- principally for want of a method with which to make the measurement. Ship-based surveys lack the temporal resolution required and the only prior mooring deployment that spanned the Cape Basin (conducted as part of the Benguela Sources and Transport experiment) was not at eddy-resolving resolution. An additional element of uncertainty is added by the extreme variability in size, strength and thermohaline signature of individual Agulhas eddies, which are dissimilar enough that some were at one time ascribed an origin in the Brazil Current (e.g., Smythe-Wright et al., [1996]).

Methods

The core of the ASTTEX field component is a 24-month deployment of sixteen moorings that monitor the transports of Indian Ocean water into the South Atlantic via the Agulhas Current at eddy-resolving resolution (70 - 80 km). The moored array consists of twelve Pressure sensor-equipped Inverted Echo Sounders (PIES) three near-bottom current meters (CM), and one validation mooring with six recording conductivity-temperature (CT) sensors (Fig. 6). All of the moorings are deployed along a Topex-Poseidon/Jason satellite altimeter groundtrack (n. 133). The mooring deployment was completed on January 16, 2003.

ASTTEX uses a new technique, which allows the mapping of fully depth-resolved salinity and temperature profiles from the combination of acoustic travel time and sea surface height. This method is called GEM-ETTA for Gravest Empirical Mode -- 3D. GEM is a technique developed by Dr. Watts and some of his current and former students, and uses historic hydrography and acoustic travel time as proxies for vertically resolved in situ thermohaline profiles. A similar technique, ETTA (Enhanced Thermohaline Transport Analysis) was developed by Dr. Byrne in her doctoral thesis and uses historic hydrography and altimetric sea surface height in concert with acoustic travel time to distinguish thermohaline anomalies in the water column. ASTTEX has provided a context in which to integrate these two independently-developed methods as GEM-ETTA. Fig. 10 shows the flowchart of how the information collected will be used to address the scientific goals of the project.

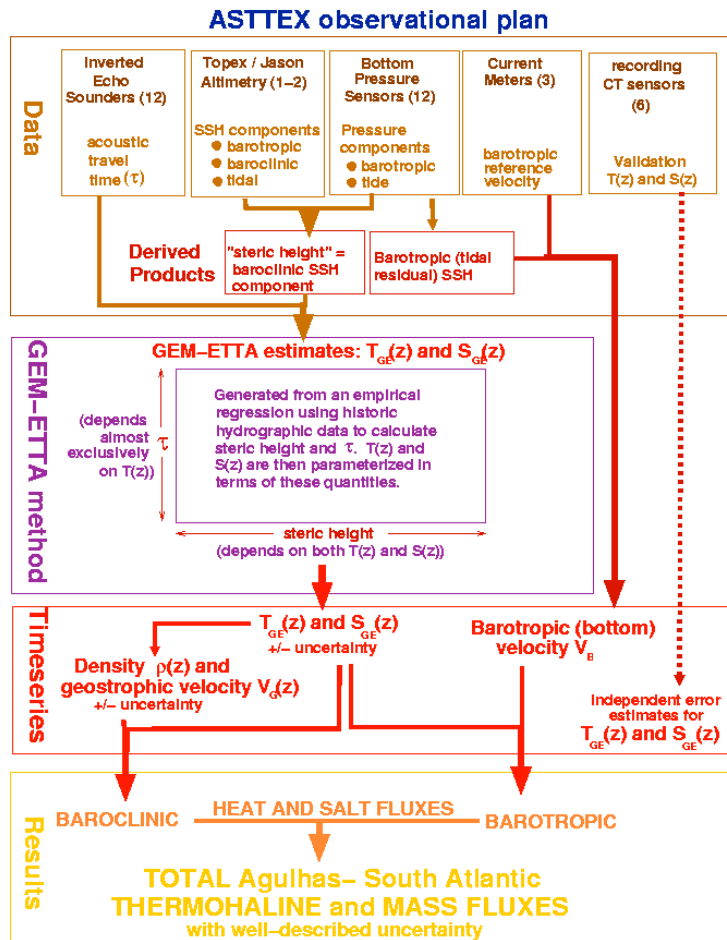


Fig. 10: Flow chart for the ASTTEX mooring data implementation and analysis.

3.5. FLOAT DEPLOYMENT STRATEGY

Argo profiling floats will be deployed over the entire section. In the northern part (north of 40°S), an array most appropriate for monitoring the injection into the Atlantic of Agulhas waters and their changes will be designed. We will deploy 20 ARGO/Provor floats in 2004 and possibly again in 2005. The French Argo floats will sample the region between Africa and the southern boundary of the ACC. The German Argo floats will cover the southern region of the transect. 13 Coriolis floats will be deployed along the SR2-GoodHope line (Fig. 6) from Cape Town to 55°S in February 2004. Due to their expected rapid displacement in the ACC, and in order to be able to sample the intraseasonal variability, four (4) additional floats will be deployed along the GoodHope line, between 40°S and 55°S in August-November 2004. The floats deployed in the subtropical region (north of ~40°S) might slowly drift northwestward. Nevertheless, due to the strong dynamics of the region (Agulhas current, retroflection, and eddies in the northern part of the line and the ACC in the central and southern parts), it is expected that in a year, the floats will have drifted away from their initial position, therefore the deployment strategy will be possibly repeated in 2005. The Coriolis floats will be parked at 1900 m of depth to reach the less intense water movement of the region. To help choose the optimal deployment locations, the statistics of Lagrangian particles in several ocean general circulation models are being analyzed.

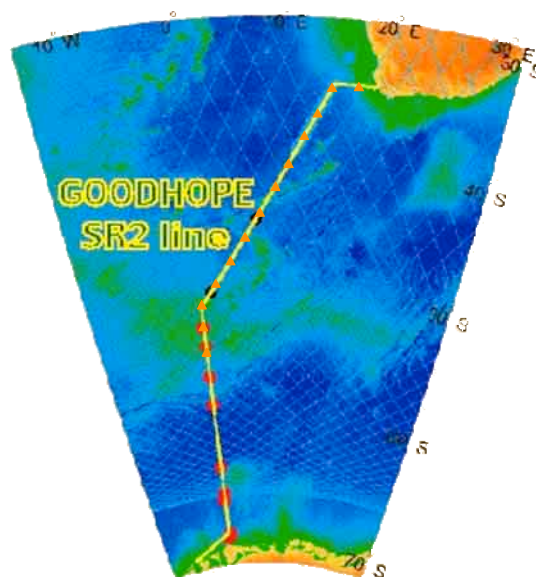


Fig. 11: Deployment position for the first 13 PROVOR-CORIOLIS Argo floats in the framework of GoodHope.

The remaining three (3) floats will be used more specifically to study strong property changes often experienced by the Indian Ocean subtropical water *en route* for the Atlantic. As most of this water is conveyed by Agulhas rings, the floats will be launched in such newly formed structures, preferentially during the austral fall-early winter, in order to observe a likely effect of winter cooling. An April 2004 cruise of the RV Agulhas is presently envisaged for the launching of these floats in the area 15-18°E, 38-41°S. These profilers will have a shallow parking depth of 400-500 m to favour their trapping in the rings during the first months. As this portion of the GoodHope profiler programme will rely on the (uncertain) presence of a newly spawned ring during the launching cruise, a different deployment platform will be used should appropriate conditions not obtain in early 2004. A number of other research programmes in the area have indicated their willingness to cooperate by launching these floats for GoodHope.

Additional floats provided by the UK MeteoOffice, by the US (NOAA/AOML and University of Washington) and Russia will be deployed along the return transect of the first XBTs line, along the Russian CTD line (December 2004) along the transect from 60°S 0°E to Ushuaia, along the different transit of the S.A. Agulhas to Gough Islands and Marion Islands as well as along the regular “ferry service” of the Russian “Akademik Fedorov” at 20°E between December 2004 and April 2005.

3.6. THE FIRST GOODHOPE CTD SECTION AND THE RELATED INTEROCEAN EXCHANGE PROJECT

During October-November 2004, full-depth measurements of water properties (CTD, CO₂ and nutrients) and velocity profiles (LADCP), will be accomplished by Russian and Spanish scientists (Shirshov Institute and Moskow University, Russia and *Instituto de Investigaciones Marinas* of Vigo, Spain) on board of the Russian research vessel “Akademik Vavilov”. The calibration for salinities and oxygens will be performed in the container laboratory from the French *Laboratoire de Physique des Océans*. The group will sample the GoodHope section at WOCE standard resolution till the sea ice. In March 2005, the German researcher from AWI, on board of the German research icebreaker “Polarstern”, will overlap the Russian transect south of 50°S and reach the Antarctic continent.

The Russian effort is coupled to a cruise along the WOCE/CLIVAR A16-A17 section and across the Drake Passage (SR1 line, slightly different from the UK because the Russians start from Ushuaya, Argentina) performed in October-December 2003 (Fig. 11). The A17-18 section will be tentatively repeated in 2005.

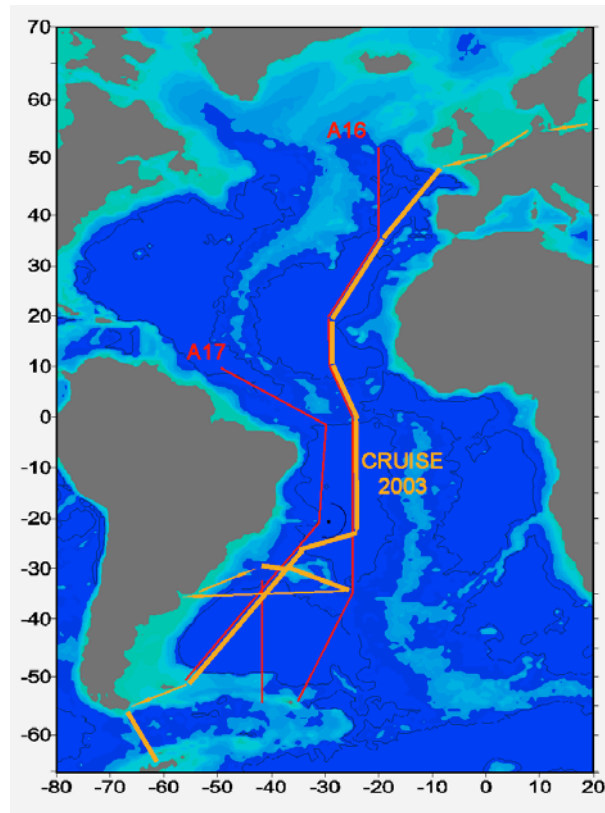


Fig. 11: The *Interocean Exchange* project planned A16, A17 and SR1 sections (to be undertaken end of 2003 and 2005 by the Shirshov Oceanographic Institute and the Moscow University)

The sampling of these sections at the opposite east-west boundaries of the South Atlantic will help to estimate the magnitude and impact of mass, heat and salt fluxes associated with the Indian Ocean compared to those entering the South Atlantic from the Pacific sector through Drake Passage. In particular, we will focus on:

1. To evaluate the correlation of these fluxes (e.g., of NADW from the WBCS to the Southern Ocean and that of relatively "warm" waters *via* the South Equatorial Current into

the WBCS) with the outflow and inflow of water masses across the Eastern open boundary of the South Atlantic, namely the SR2 section;

2. To determine how the ACC is modified in the Atlantic sector, in terms of transports and water mass content.
3. To calculate the mass, heat and fresh-water budgets of the South Atlantic by combining present measurements with all available historical data.

3.7. GENERAL COMMITMENTS

Due to the magnitude of the intended observational task and in order to be as quantitative as possible, the work of the program will rely heavily on different contributions undertaken separately by the international partners of the projects. Tentatively, the tasks and related costs will be distributed as follow :

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Name of involved scientists	Scientific Tasks	Field Work	Funds for	Origins of funding
Sabrina Speich	Indo-Atlantic exchanges, thermohaline circulation, diagnostics on atmosphere/ocean models	Profiling floats,, XBTs atmospheric/ocean modelling, salinities & oxygen calibrations	Profiling floats,, XBTs atmospheric/ocean modelling, salinities & oxygen calibrations	French ARGO, IFREMER, CNRS, UBO
Michel Arhan	Agulhas rings, Indo-Atlantic exchanges			
Isabelle Ansonge	Ring dynamics	Underway samples XBT, SSS, SST, nutrients, Oxygen Remote sensing.	S.A. Agulhas ship time	SANAP, NRF, UCT
Johann Lutjeharms	Indo-Atlantic exchanges, Remote sensing.		XBTs, manpower	
Chris Reason	Diagnostic of regional climate variability and atmosphere/ocean modelling	Atmosphere/ocean modelling		
Mathieu Rouault	Agulhas current & rings, remote sensing, meteorology	Agulhas current & rings, remote sensing, meteorology		
Howard Waldron	Nutrients diagnostics	Nutrients analyses		
William Froneman	Biogeochemical analyses	Underway chlorophyll/ plankton samples		
Eberhard Fahrbach	AABW formation and variability	WECCON moorings	S. A. Agulhas ship time, WECCON moorings, floats, XBT	AWI, WECCON, German ARGO, MERSEA.
Olaf Boebel	AAIW formation, subsurface circulation	PIES, profiling floats, RAFOS floats	PIES, profiling floats, RAFOS floats	
Michael Schroeder	Variations of inflowing Warm CDW of the Weddell Gyre	WECCON moorings		
Mario Hoppema	Carbon cycle	Water samples, underway measurements		
Deirdre Byrne	Indo-Atlantic exchanges	ASTTEX moorings	ASTTEX project (PIES, CMM, moored CT)	NSF, NASA
Silvia.Garzoli	Indo-Atlantic water mass exchanges	Profiling floats, XBTs, drifters	Drifters, HD XBTs, profiling floats	NOAA, US-CLIVAR
Gustavo Goni	Agulhas and rings dynamics	Altimetry		
Alexander Klepikov	XBTs South. Ocean line at 20°E, Southern Ocean modelling	XBTs , XCTDs	XBTs, XCTDs, Academic Fedorov Ship-time	AARI
Alexey Sokov	Full depth hydrology of A16, A17, SR1 (Ru) and SR2	CTD Hydrography (every 3 to 5 years)	CTDs Akademik Vavilov Ship-time	Shirshov Institute
Sergey Gladyshev				
Eugene Morozov				
Sergey Dobroliubov	Mass, heat and fresh water fluxes and their variability in the South Atlantic	Historical CTD data analysis	CTD data analysis	MSU
Hannes Rautenbach	Air-sea heat fluxes, atmospheric dynamics and variability over the Southern Ocean	Atmospheric observations, measurements of heat fluxes Atmospheric modelling	Atmospheric observations and modelling	University of Pretoria, SANAP
Marta Alvarez Rodriguez	Full depth tracers fluxes and budget for SR1 and SR2	Full depth tracers measurements	Tracers measurements	IIM-CSIC
Fiz Fernandez Perez				
Brian King	ACC transport and variability, relationship with SR1(UK) and SR1(Ru)	Full depth hydrology and tracers along SR1 (UK)	SR1(UK) full depth CTD-tracers line	SOC, NERC, UK Argo, INTAS-NIS
Peter Jan van Leeuwen	Indo-Atlantic interocean exchange	Ocean modelling, data assimilation	Ocean modelling, data assimilation	IMAU
Sergey Dobroliubov	Indo-Atlantic interocean exchange, mesoscale activity	Ocean modelling analyses, analytical studies	Ocean modelling analyses and theoretical studies	KNMI

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		Austral Summer 2003-2004		Austral Summer 2004-2005					
Instrument	Usage	Feb 2004 RV <i>Agulhas</i> full GH section 15' spacing	Apr 2004 RV <i>Agulhas</i> Marion Island Cruise – Agulhas Ring experiment	Nov 2004 <i>Aka. Vavilov</i> CT – ice 30' spacing ~ 60 stations	Dec 2004 RV <i>Agulhas</i> SANA E	Dec 2004 <i>Aka.</i> Fedorov CT – AA, 20°E Return April	Jan 2005 RV <i>Polarstern</i> ice – AA 30' spacing ~ 50 stations	Feb 2005 RV <i>Agulhas</i> full GH section	Feb. 2005 US ASTTEX–42°S
<i>Pls</i>		<i>Ansorge</i>	<i>Ansorge</i>	<i>Gladyshev</i>	<i>Ansorge</i>	<i>Klepikov</i>	<i>Fahrbach</i>	<i>Speich</i>	<i>Byrne</i>
XBT	upper ocean GEM frontal position	UCT 220 NOAA XBTs 120 AWI XBTs high res. @ fronts	UCT 48 CORIOLIS XBTs	-	220 NOAA XBTs ?	AARI 108 XBTs 108 for return ? (April)	-	UCT/NOAA 220 XBTs	-
CTD	deep GEM	-	-	SIO	-	-	AWI	-	UM/Byrne
Oxygen	for CO2 Analysis	-	-	LPO container UCT students	-	-	AWI UCT	-	UM/Byrne
I ADCP		-	-	SIO	-	-	AWI	-	UM/Byrne
s ADCP		-	-	SIO	-	-	AWI	-	UM/Byrne
ARGO floats	upper ocean GEM	13 PROVOR LPO	3 PROVOR LPO	5 LPO/ 3 SIO 5 UK to the west	6 UK / Met Office	ARGO floats by AWI (south of 55°S)	10, AWI	20 LPO?	
Drifters		10 NOAA	5 NOAA		SAWS			10 NOAA	
PIES		-	-	-	-	-	AWI 2+2	-	Redeployment?
tall moorings		-	-	-	-	-	AWI	-	-
Chlorophyll		Rhodes	Rhodes	Rhodes U		-	UniHamb	Rhodes	?
Nutrients		UCT - Surface	UCT - Surface	SIO/UCT		-	UCT	surface	?
CO2		-	-	IICM		-	AWI	-	-
zooplankton		Rhodes	Rhodes	Rhodes U		-	UniHamb	Rhodes	-
CFCs / Helium / Tritium		-	-	M. Rhein M. Warner R. Fine		-	M. Rhein	-	-
Atmosphere		UPretoria/SAWS	UPretoria/SAWS	UPretoria/SAWS	SAWS	standard	standard	UPretoria/SAWS	standard
Jason	GEM-ETTA	NRL/AVISO+Orsi Climatology / Goni							

3.9. PERSPECTIVE CONSIDERATIONS

Some points on future observational implementations needed for a more efficient monitoring arose from the discussions occurred during the first Kick-off GoodHope Meeting and the Southern Ocean Clivar/CliC Panel Meeting.

General remarks

The major lines of the discussions were:

- I. Temporal resolution of XBT sections. One section a year will not be sufficient to resolve accurately the seasonal and intraseasonal variability, with the consequence of possible aliasing in the signal when the aims is to resolve the interannual and lower frequency variability.
- II. Need of deeper XBT measurements along the “subtropical” region of the transect. This point arises because of the huge variations in isotherm depths from the southern part (polar) of the transect to the northern part (subtropical) and with the XBT-7 we will have to deal with different isotherm instead as just one as a proxy for the sea Surface Height. Also with this kind of XBTs we will be close to the base of the thermocline in the subtropical region, but we will not be able to pick up the Intermediate Water layer.

- III. Need of salinity measurements. Salinity will be measured always at the sea surface and in the ocean interior only during the full depth CTD lines or ARGO floats profiling and drifting. In the Southern Ocean the salinity signal is of capital importance (due to the low temperature and sea-ice formation/melting in the south and the contrast between Indian and Atlantic water masses in the north) and a higher temporal sampling (comparable to that of temperature) would be really suitable.
- IV. Underway measurements of PCO₂. In the context of the global CO₂ budget and its monitoring and the scarcity of data in the Southern Ocean, a regular monitoring of this quantity would be really precious.

We first considered points I-III. It is clear that a period of increased observations is necessary to prevent of the seasonal aliasing of the signal. Due to the large extent of the section (the Southern Ocean south of Africa is more an ocean by-itself than just a choke-point), performing repeated CTD lines in the four different seasons is completely utopistic, even for a brief period (one or two years). On the contrary, a period of increased expandable observations can be envisaged for the future. We are therefore thinking to implement a period of two years with four XBT transects. During this period, we are thinking to implement deeper XBTs in the northern part of the transect and to use some XCTDs to capture some of the salinity signal. This item is still under discussion.

Extension of ASTTEX moorings

The Southern Ocean sector South of Africa is characterized by strong environmental contrasts and intense mesoscale activity. As consequence, the vertical stratification and composition of the water column can vary drastically over time or can change sharply across a synoptic section. An accurate knowledge of the ocean's vertical structure is a first step on the path to making accurate estimates of the larger scale property of heat and salt fluxes. At the same time, it is evident that to understand and monitor the role of the ocean in climate, long-term measurements are required. To resolve both the short and long term time variability the GEM-ETTA technology combining altimetry, bottom pressure and vertical acoustic travel time (measured by the PIES) demonstrates to be the best and unrivalled strategy. The combination of these three data streams allows temporal and spatial changes in bulk salinity to be distinguished from those in temperature. Combined with a database of high-quality regional hydrography, such contrasts can be associated with statistically significant modes of variability in the stratification, water mass composition, and associated properties (Fig.8). GEM-ETTA allows for accurate estimation of large-scale (baroclinic) interocean fluxes. With the addition of a reference bottom current, barotropic transports can also be computed and thus the total fluxes. With an adequate density of PIES moorings, as it is the case for ASTTEX, it is possible to sample effectively the mesoscale spatial variability. The large-scale analysis of regional sea surface height (SSH) anomaly fields during the field will provide a large-scale, low-frequency context for the experiment.

Therefore, efficiency of the GoodHope project to observe and monitor interocean fluxes of mass, heat and salt depends essentially on:

- **A deployment of the ASTTEX moorings extended in time.**
- **A deployment of an increased number of PIES along the transect is considered in order to cover the gap between ASTTEX and WECCON to include accurate high frequency observations of the ACC region.**

4. A POINT ON MODELLING

Despite the fact that models only approximate reality they offer a unique tool in permitting the integration of very sparse (in both space and time) information from the real world, such as those derived from observations in the Southern Ocean. During the GOODHOPE project we will make efforts also to integrate collaborations and constructive exchanges with teams involved in global and regional oceanographic and atmospheric modelling.

Our initial strategy is to use available coupled ocean/sea ice global general circulation models at different resolutions and appropriate diagnostics to evaluate volume, heat and salt transports, interbasin exchanges, frontal system dynamics and their variability.

The modelling activity will also consider process studies and regional models. This will permit to isolate particular dynamical regimes and investigate the physical processes involved. A dedicated high resolution (1/12 - 1/16) numerical study on the oceanic region South of Africa is in implementation since October 2003 through a collaboration between the *Laboratoire de Physique des Océans*, the IDYLE group of *Institut de Recherche pour le Développement* and the University of Cape Town. This particular study is intended to better evaluate the role of mesoscale activity in the general circulation of this particular zone. The Dutch groups (IMAU and KNMI) have already experience in process studies and regional simulation with data assimilation.

Coupled atmospheric/oceanic/sea ice models (such as the OPA-LMDz-CLIO and OPA-ARPEGE models) and forced high resolution atmospheric models over Southern Africa will help us to evaluate the climatic impact of observed and modelled oceanic variability. The AARI group will be also involved in a regional modelling of the Southern Ocean.

A meeting to better coordinate the modelling effort will be organized during 2004.

5. INTERNATIONAL COLLABORATIONS

In addition to the international partners that will be participating actively in the GOODHOPE project, various other collaborations have already been established or proposed to make the most of measurements.

The SR2 line will be the last Southern Ocean chokepoint monitoring programme to become operational. An essential and effective collaboration with the working teams on the other two chokepoints will be established. This includes (among others) Stephen Rintoul and Serguei Sokolov (CSIRO, Australia), Rosemary Morrow (CNES, France), and Brian King (SOC, UK).

Other collaboration are through the French national CLIVAR programme, namely the BILBO project that includes an integration of observation analyses and global modelling tasks (among others Gervan Madec, Frédéric Vivier, LODYC), the FLOSTRAL and OISO projects (Rosemary Morrow, CNES, and Nicolas Metzl, LBCM), and the DRAKE project (Christine Provost, LODYC).

The GOODHOPE project, lying at the connection of the South Atlantic and Indian basins, will interact with scientific teams involved in past, present and future programmes in these oceans. These include: the Benguela Source and Transport Experiment (BEST) and the Benguela Current Experiment (Silvia Garzoli, NOAA-AOML, USA); the Agulhas - South Atlantic Thermohaline Transport Experiment (ASTTEX, Deirdre Byrne, University of Maine, USA); the South Atlantic high density AX8 and AX18 XBT lines project (Gustavo Goni, NOAA-AOML, USA); the subsurface floats programme Kap der guten Hoffnung Experiment (KAPEX, Olaf Boebel, AWI, Germany, and Johann Lutjeharms, UCT, South Africa); the Indian Ocean 32°S repeated section (Harry Bryden, SOC, UK); the Agulhas Undercurrent Experiment (Lisa Beal, Miami, USA); the long term monitoring programme in the Mozambique Channel (Herman Ridderinkhof, NIOZ, The Netherlands).

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