2. CASO: CLIMATE OF THE ANTARCTIC AND THE SOUTHERN OCEAN

2.1 DECADAL VARIATIONS OF WATER MASS PROPERTIES IN THE ATLANTIC SECTOR

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Objectives

The densest bottom waters of the global oceans originate in the Southern Ocean. Production and export of these dense waters constitute a vital component of the global climate system. The formation of dense water in polar areas is controlled to a large extend by the delicate balance between supply of fresh water through precipitation and melt of continental and sea ice and the extraction of freshwater by sea ice formation and evaporation. Therefore the Southern Ocean's part of the global freshwater cycle links continental and oceanic conditions. It consists in the transport of freshwater from the continent through melting of ice shelf and icebergs and is strongly mediated by redistribution of freshwater through the highly variable and moving sea ice cover on which snow is accumulated as well as by the oceanic circulation. Coupled models predict an intensification of the freshwater cycle in the context of global warming. Observations of the freshening of Subantarctic Mode, intermediate and deep waters suggest that the intensification is ongoing.

Dense waters are produced at several sites near the continental margins of Antarctica. Quantitatively the most important region for dense water formation may well be the Weddell Sea, however other areas provide significant contributions as well. The basic mechanism of dense water generation involves upwelling of Circumpolar Deep Water which is relatively warm and salty into the surface layer where it comes into contact with the atmosphere and sea ice. The newly formed bottom water is significantly colder and slightly fresher than the initial Circumpolar Deep Water which indicates heat loss and the addition of freshwater. Since freshwater input in the upper oceanic layers is prohibitive to sinking through increasing stability of the water column, it has to be compensated by salt gain through fresh water extraction. The upwelled water is freshened by precipitation and melting of glacial and sea ice. Freshwater of glacial origin is supplied from the ice shelves or melting icebergs. Ice shelves melt at their fronts and undersides related to the oceanic circulation in the cavity. Iceberg melting depends highly on the iceberg drift and can supply freshwater to areas distant from the shelves as the Antarctic frontal system. Due to the spatial separation of major freezing and melting areas of sea ice cooling and salt release during sea-ice formation cause the compensation of the freshwater gain and subsequently the density increase which is needed for bottom water formation. Significant parts of the salt accumulation occur on the Antarctic shelves in coastal polynyas. Since extreme heat losses can only occur in ice free water areas, the polynyas are areas of intense sea ice formation. Offshore winds compress the newly formed sea ice and keep an open sea surface in the polynyas. The cold and saline water accumulated on the shelves can descend the continental slope and form deep and bottom waters.

The properties and volume of the newly formed bottom water underlies significant variability on a wide range of time scales, which are only poorly explored due to the large efforts needed to obtain measurements in ice covered ocean areas. As for the atmospheric driving forces, the sea ice and upper ocean layers, seasonal variations are partly known and normally exceed in intensity the other scales of variability. However the spatial distribution pattern of the variability is only poorly resolved e.g. seasonal cycles of sea ice thickness are only available at a few sites. An estimate of the sea ice mass as a baseline to detect change is still not possible due to the missing measurements of sea ice thickness. Longer term variations of the atmosphere-ice-ocean system as the Antarctic Circumpolar Wave, the Southern Hemispheric Annular Mode and the Antarctic Dipole are only poorly observed and understood. Their influence on or interaction with oceanic conditions are only guessed on the basis of models which are only superficially validated due to lack of appropriate measurements.

The extreme regional and temporal variability represents a large source of uncertainty when data sets of different origin are combined. Therefore circumpolar data sets are needed of sufficient spatial and temporal coverage. At present such data sets can only be acquired satellite remote sensing. However, to penetrate into the ocean interior and to validate the remotely sensed data, an ocean observing system is needed, which combines remotely sensed data of sea ice and surface properties with *in situ* measurements of atmospheric, sea ice and oceanic properties.

To achieve further progress significant steps occurred in the development of appropriate technology and logistics. Oceanic properties are measured under the sea ice which required the development of under-ice acoustic ranging and data transmitting systems. To construct from the achievable observations a comprehensive circumpolar view, model assimilations have to be done which require the development of appropriate models.

During IPY a set of meridional transects will be occupied in one season to provide the first synoptic snapshot of the circulation, stratification and biogeochemical status of the Southern Ocean. At a minimum, each of the “chokepoint” sections between Antarctic and the southern hemisphere continents should be occupied, plus one or more additional lines in each basin. ANT-XXIV/3 will cover the African chokepoint in the Atlantic Sector of the Southern Ocean, the Weddell Sea and Drake Passage. The northern part of the section south of Africa will be covered by BONUS-GOOD HOPE. Of special interest will be the possibility to detect and estimate the transport of newly-formed dense bottom waters flowing westward along the continental slope, to better understand the connections between known deep water sources and the locations where deep water leaves the slopes to flow north. The ANT-XXIV/3 cruise will provide 4 sections (Greenwich Meridian, Kapp Norvegia, Joinville Island, Drake Passage) on which the coastal current has significantly different properties. However, here there are still uncertainties with the ship time. If it will not be available, the present cruise track has to be rediscussed. The African choke point includes measurements with moored Pressure Inverted Echosounders (PIES) which are simultaneously a contribution to the GRACE project. The PIES need to be recovered and redeployed.

The CASO project (*Climate of Antarctica and the Southern Ocean*) takes up work which had started in the WECCON project (*Weddell Sea convection control*). It aims to investigate processes which occur in the Atlantic Sector of the Southern Ocean and Drake Passage in cooperation with the Bjerknes Centre for Climate Research in Bergen, Norway and the British Antarctic Survey (BAS). In the framework of iAnZone, a programme associated to SCOR (*Scientific Committee of Oceanographic Research*) and its IPY SASSI project

(*Synoptic Antarctic Shelf Slope Interactions Study)* observation occur in the area of Maud Rise and the Antarctic Coastal Current. The observations occur jointly with the IPY GOOD-HOPE project which covers the northern part of the Atlantic sector of the Southern Ocean. The global impact of the regional Processes will be considered in the BIAC (*Bipolar Atlantic Thermohaline Circulation*) IPY project. The cruise occurs in the context of the MARCOPOLI programme of the Hermann von Helmholtz Association of German Research Centres (HGF). It is a contribution to the *Climate Variability and Predictability* (CLIVAR) and the *Climate and Cryosphere* (CliC) projects of the *World Climate Research Programm*e (WCRP). The ULS are a contribution to the *Antarctic Sea Ice Thickness Project* (AnSITP). The deployment of floats occurs in the framework of the international *Argo* programme which contributes to the *Global Ocean Observing System (*GOOS).

Work at sea

The *Polarstern* cruise ANT-XXIV/3 will complement the efforts during the International Polar Year 2007/2008 to obtain *in situ* observations in the Atlantic sector of the Southern Ocean in order to allow a circumpolar view. Time series stations with moored instruments will provide measurements in the deep and the surface layers and of ice thickness. For this purpose moorings with current meters, temperature and salinity sensors as well as upward looking sonars will be recovered and redeployed. The cruise concentrates to three major areas: the Greenwich Meridian, the Weddell Sea and Drake Passage.

Ship borne meridional transects are needed to determine water mass properties including tracer concentrations. They will occur along the Greenwich Meridian, across the Weddell Sea and Drake Passage (Fig. 1.1). The ship borne surveys in summer are imbedded in the time series measurements with moorings, drifters and floats to derive the effect of the seasonal variability on transfer processes and to avoid the aliasing effect on longer term observations. Moorings will be recovered (Fig. 2.1) and redeployed (Fig. 2.2). The spreading of floats is able to extend the data from the sections over larger parts of the area.

Profiling floats will be deployed. The float system has to complement *Argo* in ice-fee and under-ice condition to reach a global coverage. Moorings with sound sources for under ice navigation will be recovered and redeployed. The IPY set the goal of achieving at least the 3° X 3° sampling of the global array throughout the southern hemisphere oceans south of 30°S, for the full duration of the IPY (March 2007 to March 2009). Acoustically tracked floats will provide profiles and current velocities from key ice-covered seas. The floats will be programmed to continue to profile and store data beneath ice. Once the floats detect open water, the stored profiles will be transmitted. While the position of the sub-ice profiles is not known without acoustic navigation, the floats can survive the winter and the stored profiles provide a statistical description of winter stratification.

The international *Argo* programme aims at observing global ocean upper temperature and circulation by means of free floating *Arg*o floats. Globally, approximately 2800 of such regularly undulating platforms are in operation. During the past years, the AWI pushed technological developments to extend the operational rage of Argo floats into seasonally ice-covered regions. To this end and with additional support by the EU project MERSEA and the BMBF Project German *Argo* the so-called NEMO float (Navigating European Marine Observer) was developed and tested, which are now fully operational. During ANT-XXIV/3, up to 18 NEMO floats and an overhauled APEX floats will deployed in the Weddell Sea. In

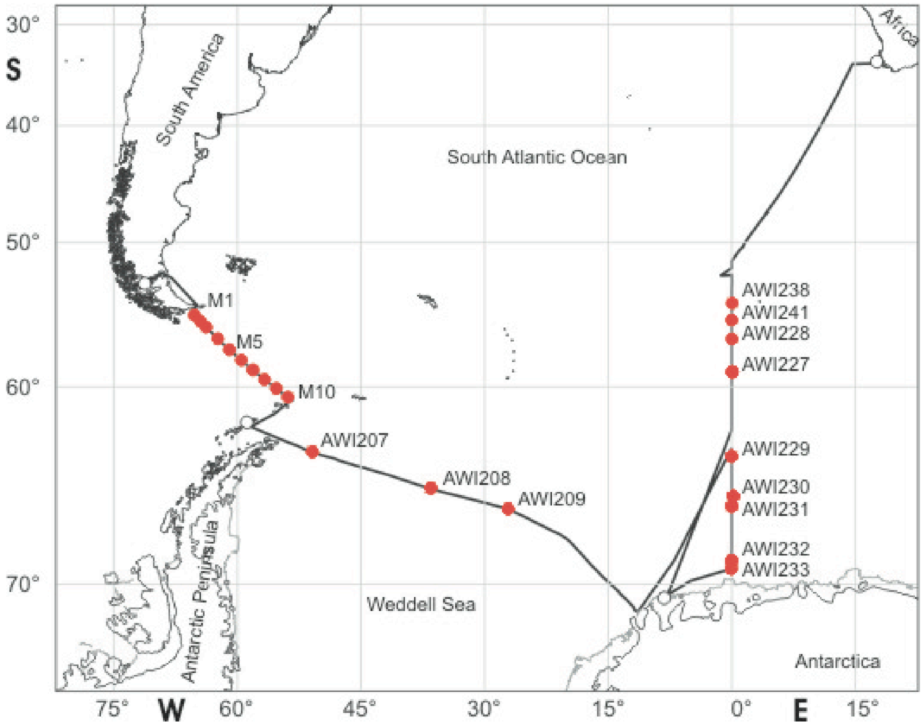

Fig. 2.1: The locations of moorings to be recovered during ANT-XXIV/3

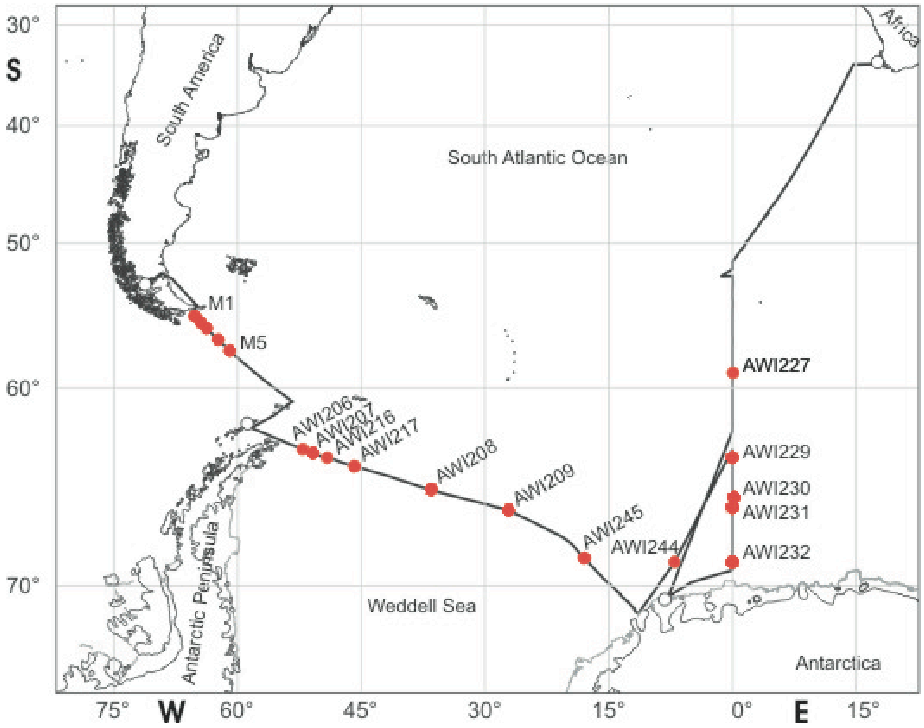

Fig. 2.2: The locations of moorings to be deployed during ANT-XXIV/3

addition, on request of Steve Riser, University of Washington, we will deploy up to 40 additional APEX floats along the ships transect.

To obtain position for the CTD profiles collected by the abovementioned floats during the winter season, the installation of a RAFOS sound source array is necessary. The travel time of sound signals of moored sound sources (1- 12) will be recorded by the free drifting floats. Using times of arrival of signals of two or more sources, the position of the receiver, i.e. the float, may be determined retrospectively.

The present state of planning for the installation of the RAFOS array is displayed in figure 2.3. At this time, sound sources at positions 01, 02, 03, 04, 05, 06, 07, und 08 are deployed. During ANT-XXIV/3, sound sources at positions 01, 02, 04, 05 und 06 shall be recovered, while sound source deployments will occur at positions 01, 02, 09, 11, 04, 10 und 06.

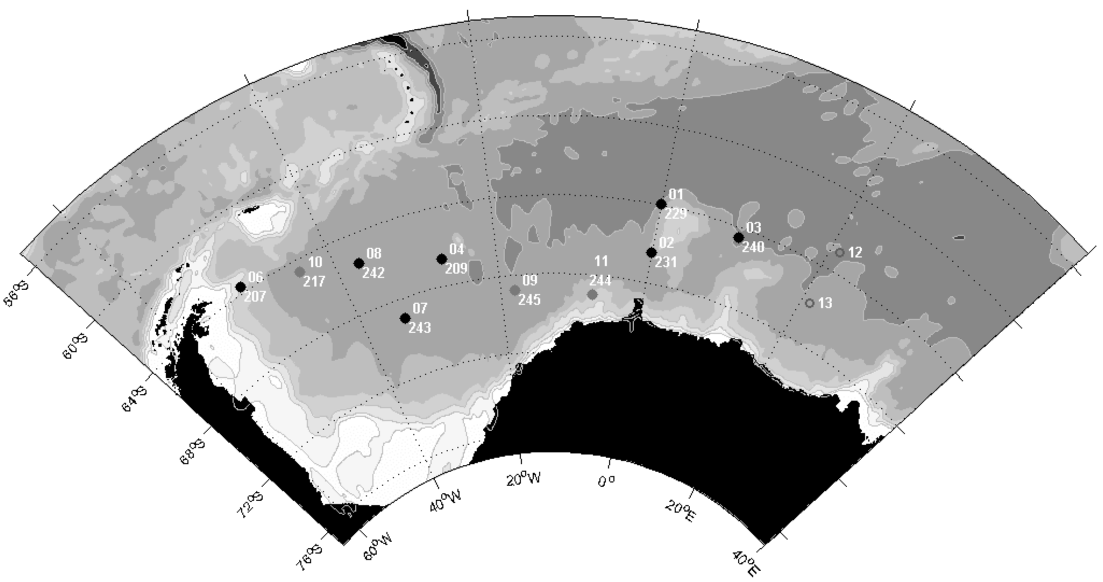

Fig. 2.3: Planned sound source array. Numbers next to the dots indicate sound source codes and corresponding mooring numbers.

Additional work will be probably executed concurrently during a Norwegian cruise onboard *G.O. Sars*. During that cruise, sound source 03 shall be recovered, and new sound source mooring shall be deployed at positions 03, 12, und 13.

Since 2002, the GRACE satellite mission has observed the gravity field of the Earth with unprecedented accuracy. Gravity field products provided by the GRACE Science Data System allow assessing both the static geoid, as well as time-varying signals associated with changes of global water mass distribution.

To detect temporal variability of oceanic currents and mass transports, it is critical to validate the space-born GRACE data by both observed and modelled Ocean Bottom Pressure (OBP) time series. In the framework of a joint BMBF (German Ministry for Education and Research) project, an OBP database is established by the Alfred Wegener Institute (AWI) to collect all available observations of OBP recorders deployed at the sea floor.

During ANT-XXIV/3, up to 6 PIES will be deployed (ANT-3,5,7,9,11, and 13). Optionally 2 - 3 of these will be equipped with up to 2 PopUp modules for early data transmission (after 1 year).

2.2 MONITORING THE ACC TRANSPORT THROUGH DRAKE PASSAGE

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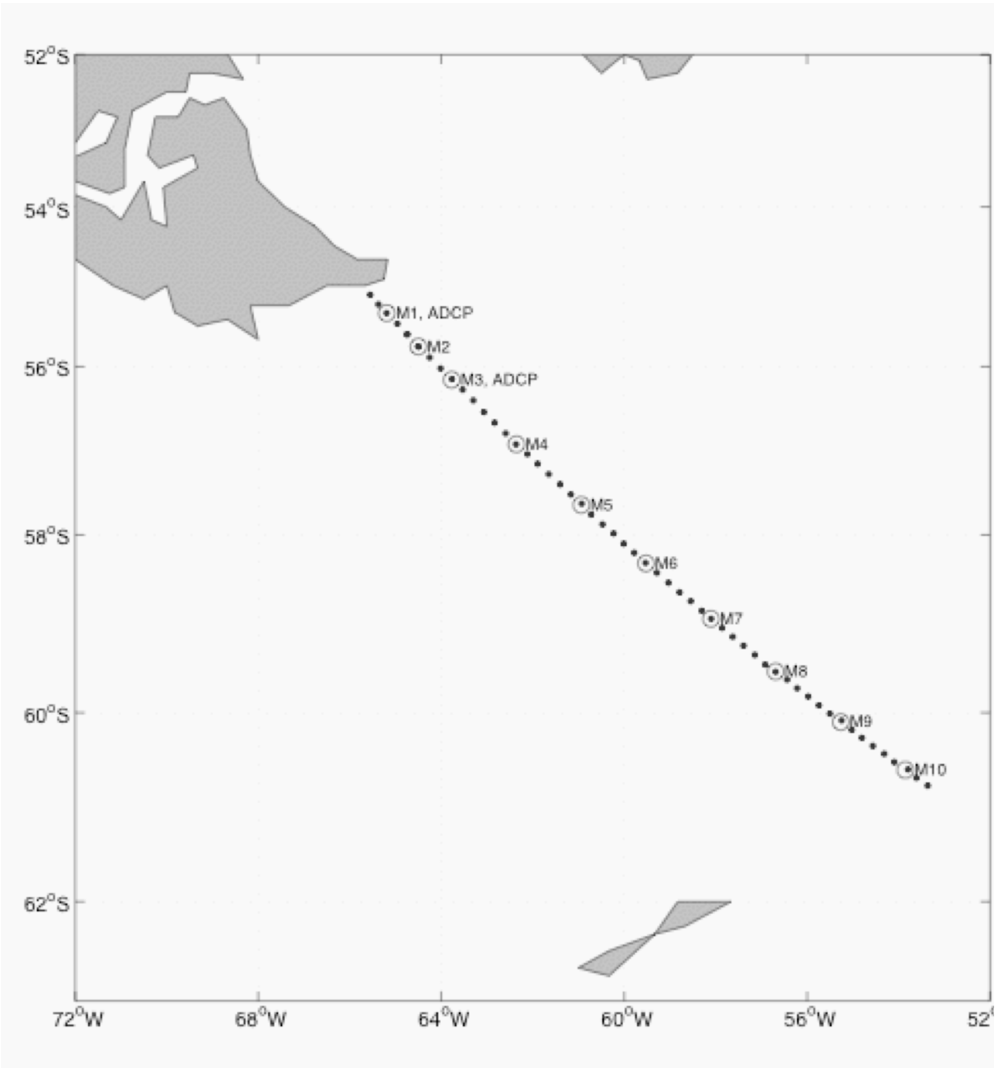

Fig. 2.4: Planned route and station locations for Drake cruise. M1 to M10 are mooring locations. Dots are planned hydrological stations. The final number of hydrological stations will be adjusted to the progress of work. Time losses due to unexpected events or slower progress than expected will be buffered by a reduction of station time.

Objectives
Monitoring the Antarctic Circumpolar Current (ACC) transport is essential for understanding the coupling of this major current with climate change. The main objective of the expedition is to monitor the magnitude and variability of the ACC through Drake Passage. Therefore one of the main task of the expedition is the deployment of a mooring array below track 104 of altimetric satellite Jason-1 for at least two years.

The *in situ* time series of currents through the Passage coupled with the satellite altimetric observations should provide estimations of variations of the mass transport on time scale from month to interannual. We should be able to produce a continuous time series of transport through Drake Passage starting in 1992. Then we shall examine the mechanisms responsible for the variability of the transport. Hopefully the comparison of this 16-year-long time series with the time series obtained by ISOS at the end of the 1970 will provide information on the changes in 30 years.

A proper use of the altimetric data requires a better understanding of the altimetric signal in these high latitudes. Therefore an important technical objective is a precise validation of the altimetric signal. In particular, the rough sea state and atmospheric conditions require a precise examination of the corrections to be applied for the ocean response to the atmospheric pressure and the sea state effects on the altimetric measurements.

High frequencies and transients: Another difficulty resides in the fact that time scales are small in the ACC. The satellite time sampling (10 days) may lead to serious aliasing problems. We shall therefore estimate potential aliasing (from the *in situ* data) and combine several satellites (to improve the time resolution) and use data assimilation models. Another objective is to document eddies and transient structures to improve our understanding of their interactions with mean current and their role for the transport of properties across the current.

Water masses: Water masses enter Drake Passage where they undergo substantial modifications. Our objectives concerning water masses are the following:

- identify precisely water masses, their sources and trajectories,
- quantify mixing by small scale structure analysis (CTD Thorpe method, LADCP shear method) and multiparameter analysis,
- Study climate change in water masses.

Work at sea
The 10 subsurface current meter moorings (M1 to M10) deployed during ANT-XXII/3 will be recovered. 5 new moorings will be installed at locations M1 through M5. Each mooring carries 3 current meters and seacats. M1 and M3 carry an upward-looking ADCP on top.

A proper use of the altimetric data requires a validation of the altimetric signal. For that the upward-looking ADCPs on moorings M1 and M3 will provide valuable data for validation.

Another technical objective is the improvement of our knowledge of the geoid in the area. For that gravimetric measurements will be performed using *Polarstern* gravimeter.

To complement the mooring array, we shall perform a high resolution CTD/LADCP station section.The distance between adjacent stations will be less than 20 km with a closer spacing in the frontal regions. The hydrographic stations will gather water samples at different levels for tracers.

Temperature, salinity and ocean currents will be measured with the thermosalinographs and acoustic Doppler profiler from the moving vessel. During the whole cruise, the ship-borne gravimeter KSS-31 and GPS will be operated.

Expected Results

The data to be gathered will provide

- new information on the velocity field at Drake Passage (time scales, vertical structure, transients, mean flow) 30 years after ISOS (from currentmeters and full depth LADCP),
- new full depth high resolution hydrography with tracers 16 years after last similar cruise (METEOR A21) thus information on variability in water mass characteristics,
- a better understanding of the altimetric signal in the Drake Passage,
- an improvement of the geoid in the area,
- a precise documentation of the mass and volume transport through DRAKE on the mean and variability,
- new estimates of mixing.

2.3 DYNAMICS AND TRANSPORT OF THE ANTARCTIC CIRCUMPOLAR CURRENT IN DRAKE PASSAGE

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Objectives

The Southern Ocean is especially sensitive to climate change, responding to winds that have increased over the past 30 years and warming significantly more than the global ocean over the past 50 years. The ACC is the pulse of the Southern Ocean, and the Drake Passage choke point is not only well suited geographically for measuring its time-varying transport, but observations and computer models suggest that dynamical balances which control its transport are particularly effective through the Drake Passage. This project contributes to the International Polar Year (IPY) through its transport line monitoring of the ACC in Drake Passage. The observations will resolve the seasonal and interannual variability of the total ACC transport, its vertical structure partitioned between barotropic and baroclinic components, and its lateral structure partitioned among the multiple jets comprised by the ACC. Moreover, Drake Passage is a region of high mesoscale variability. The mesoscale eddies are thought to play a mediating role in transferring momentum from the circumpolar winds that drive the ACC, down through the water column to the seafloor, where topographic form stresses regulate its long-term transport. Measurements in the local dynamics array will quantify eddy exchanges with the mean current and density structure, and they will quantify the mean vorticity balance in order to test hypotheses regarding the dynamical balances that govern the ACC.

Work at sea

This study will deploy a transport line and local dynamics array of Current Meters and Pressure-recording Inverted Echo Sounders (CPIES) moored for a period of 4 years to quantify the transport and dynamics of the Antarctic Circumpolar Current (ACC) in Drake

Passage. Data will be collected annually by acoustic telemetry, leaving the instruments undisturbed until recovered.

2.4 MEASUREMENT OF TRACE GASES (CFCS, HELIUM ISOTOPES, NEON)

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Objectives

The Weddell Sea is the main supplier for Antarctic Bottom Water (AABW) to the World Ocean. Weddell Sea Deep and Bottom Water are formed by interaction of mid-depth water masses with several shelf water masses (e.g. glacial melt water or Ice Shelf Water) and by entrainment of external water masses. Changes in its formation rates - caused by environmental changes, e.g. the decay of ice shelves or warming mid-depth water - could modify the strength and variability of the Meridional Overturning Circulation (MOC) and, thus, affect climate and climate change. Changes in the AABW formation process and in the amount of AABW formed might also influence the anthropogenic carbon uptake of the deep ocean.

The deep and bottom water formation in the Weddell Sea and its variability will be studied by using time series of CFC inventories inferred from this cruise and from historical data. The combined hydrographic, CFC and noble gas data will allow to distinguish different source water masses, that contribute to deep and bottom water formation, and how they reflect changing environmental conditions. Further insight in the variability of the export of deep and bottom water out of the Weddell gyre across the Greenwich Meridian and through the South Scotia Ridge system as well as the import of easterly sources is expected from the continuation of the CFC time series in 2008. The role of the Southeast Pacific Deep Slope Water in the transport of the Atlantic Circumpolar Current will be studied through a noble gas/CFC and lADCP repeat through Drake Passage.

Methods

Chlorofluorocarbons (CFCs) are gaseous, anthropogenic tracers that enter the ocean by gas exchange with the atmosphere. The evolution of these transient tracers in the ocean interior is determined by their temporal increase in the atmospheric and by the formation and mixing processes of intermediate, deep and bottom water.

The applied methods using CFCs as age tracers and include transit time distributions (TTDs, or age spectra). By applying a “mean age” and a “width of the age”, this dating method accounts for advection and mixing, other than the “concentration age” approach, which accounts - as a first approach - for advection only. Additionally, a tracer free dilution can be applied. This improves the estimates of ventilation rates significantly. Necessary to derive the parameters of the TTDs is to use different transient tracer observations, i.e. different observed age tracers or/and tracers at different observation times (i.e. time series).

The total inventories of CFCs in deep and bottom water reflect the accumulation of CFCs carried by its surface near source water masses. Together with the known atmospheric CFC evolution, CFC inventories and their changes allow estimating the renewal or formation rates of recently formed bottom water. Furthermore, with the available time series from various sections allows to investigate its variability and, possibly, its relation to changing environmental (boundary) conditions (ice shelf decay, surface water warming, etc.).

Using stable tracers like helium isotopes and neon, additional to temperature and salinity, allow one to carry out a Optimum Multiparameter (OMP) analysis to estimate the contributions of the parent source water masses to the formation of deep water masses. Herein helium and neon are ideal tracers for glacial melt water or ISW, and the 3He/4He isotope ratio is a tracer for deep water from the Pacific.

Work at sea

About 1,500-2,000 CFC samples are planned for the three subsections of the cruise. Water samples from the rosette system will be stored in glass ampoules. Either they will be analyzed directly on board or they will be sealed off after a CFC free headspace of nitrogen has been applied. In both cases the CFC measurement uses a purge and trap sample pre-treatment followed by gas chromatographic (GC) separation on a capillary column and electron capture detection (ECD).

Approximately 500 samples for helium isotopes and neon are planned for the cruise to guarantee a sufficient vertical and horizontal resolution. The samples will be taken in the Drake Passage (~200) to determine the South Pacific Deep Slope Water signal and at special locations at the section across the Weddell Sea (~300) to determine the relative contributions from the various bottom water sources. The samples for helium isotopes and neon are stored in sealed copper tubes (50 ml). The noble gas samples are analysed in the IUP Bremen mass spectrometry lab afterwards with a sector field and quadrupole mass spectrometer system.