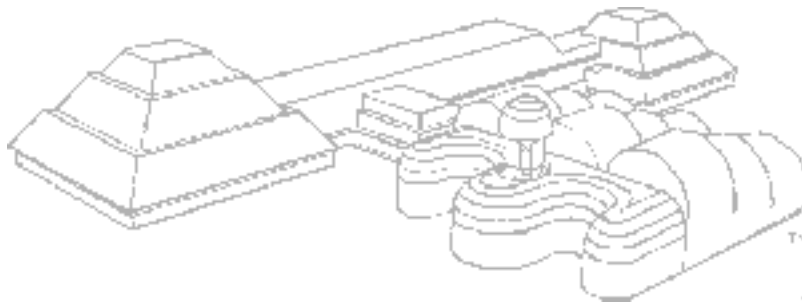


# *iAnZone*

## *International Antarctic Zone*

### *5<sup>th</sup> Coordination Meeting*



Columbia University's  
Biosphere 2 Center  
Oracle, Arizona

December 1-5 1997

*Hosted by  
Lamont-Doherty  
Earth Observatory  
and Biosphere 2 Center*

# TABLE OF CONTENTS

PAGE

1. Introduction
2. Terms of Reference
3. Relationship of iAnZone to Other Programs
4. iAnZone Membership
5. ASPeCT and iAnZone - J. Priddle
6. Progress Report of iAnZone Experiment #2 (1994):  
Antarctic Zone Flux Experiment - AnzFlux (McPhee et al.)
7. Progress Report of iAnZone Experiment #3 (1997):  
Dovetail (Muench)
8. Proposed iAnZone Experiment #4
9. Weddell Quick Response Program (WQRP)
10. Other Southern Ocean Antarctic Zone Programs:
  - A. WCRP-Cryosphere - V. Savtchenko
  - B. CLIVAR D-5
  - C. WOCE Southern Ocean - E. Fahrbach
  - D. CORC - M. Visbeck
11. Next Meeting
12. APPENDICES:
  - A. Agenda
  - B. Attendance List
  - C. National Reports
  - D. Abstracts

## **iAnZone Meeting #5**

Biosphere-2

Oracle, Arizona

1-5 December 1997

The first iAnZone meeting as an affiliated program of SCOR was held at Columbia University's Biosphere-2 facility during the first week of December 1997. In view of the shared research interests, the iAnZone meeting was held in combination with the SCAR ASPeCt program (Steve Ackley chairs that committee).

This report deals only with the iAnZone component of the Biosphere-2 meeting, and may be considered as volume 1 of the Biosphere-2 Meeting Report. It does include an overview of ASPeCt and iAnZone by Julian Priddle.

This is the 5-th meeting of the iAnZone researchers. The previous iAnZone meetings were:

Lamont-Doherty Earth Observatory, Palisades, NY, USA; May 1989

Alfred -Wegener-Institute fur Polar und Meeresforschung, Bremerhaven, Germany; January 1991

University of Helsinki and Finnish Institute of Marine Science, Helsinki, Finland; October, 1993

Universitat Politecnica de Catalunya, Barcelona, Spain, March 1996

**Acknowledgements:** The meeting was hosted by Lamont-Doherty Earth Observatory and Columbia University's Biosphere-2 Center, with contributions from the Scientific Committee on Antarctic Research (SCAR) and the Scientific Committee on Oceanic Research (SCOR).

This report was prepared at Lamont-Doherty Earth Observatory and is Technical Report #98-2.

Visit the iAnZone website at: <http://www.ldeo.columbia.edu/physocean/ianzone>

Arnold L. Gordon

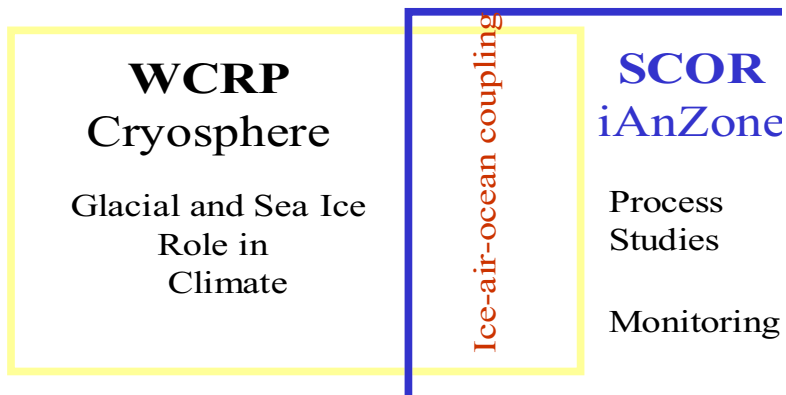
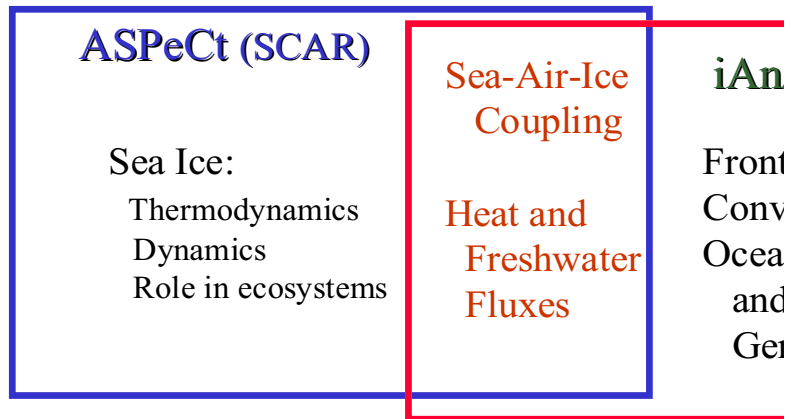
31 March 1998

## **International Antarctic Zone Program**

### **iAnZone**

- **AnZone Goal:** Through development and coordination of observational and modeling programs, to advance our quantitative knowledge and modeling capability of climate relevant processes, their seasonal cycle, their inter-annual and decadal variability, within the Southern Ocean's Antarctic Zone (region poleward of the Antarctic Circumpolar Current), with emphasis on ocean and atmosphere coupling in regions influenced by sea ice, and to the link between the Antarctic Zone and the global ocean and climate system.
  
- **Terms of Reference:**
  1. To identify, develop and coordinate research projects which address the iAnZone goal.
  2. To provide a forum for the exchange of iAnZone research plans, results and data.
  3. To assist in the coordination of Antarctic Zone research with global climate research programs and with other Southern Ocean programs.
  4. To advise SCOR on the development of appropriate observing system (e.g. for GOOS, GCOS), data sets and modeling strategies needed to understand the scales and mechanisms of climate variability within the Antarctic Zone.

iAnZone Interactions with other Programs



## **iAnzone Membership:**

A Steering Committee will consist of approximately 15 members who will set up the bi-annual (objective is to have meetings at roughly 18 month intervals) meetings, promote actions recommended at those meetings and foster coordination between meetings. All Steering Committee appointments are for three years, staggered appointments are envisioned to promote continuity. The co-chairs will interact with the SCOR Executive in assigning periods of service and appointment of replacement members.

### Initial Steering Committee:

1-	A. Gordon	(USA)	Co-chair
2-	E. Fahrback	(Germany)	Co-chair
3-	R. Muench	(USA)	
4-	K. Heywood	(UK)	
5-	A. Piola	(Argentina)	
6-	J. Launiainen	(Finland)	
7-	P. Schlosser	(USA)	
8-	M. Garcia	(Spain)	
9-	M. Wakatsuchi	(Japan)	
10-	A. Klepikov	(Russia)	
11-	C. Garcia	(Brazil)	
12-	G. Spezie	(Italy)	
13-	N. Bindoff	(Australia)	
14-	H. Hellmer	(Germany)	

Working with the SCOR executive, we are seeking a member from: South Africa (Lutjeharms declined), China and India.

The iAnZone co-chairs will discuss iAnZone membership and rotation schedules with SCOR executive.

**The Antarctic Zone Flux Experiment — iAnZone Field Project #2**  
**(Presenters: McPhee, Guest, Muench, Morison, Lytle)**

The cold, abyssal waters of the world ocean interact directly with the rest of the climate system in limited areas confined to high latitudes, where density structure of the upper ocean permits deep convection. Compared with most of the world ocean, static stability of the water column in the central and eastern Weddell Sea is very weak. It appears that the air-sea-ice system there exists in a precarious balance between two quasi-stable modes which display substantially different sea ice distributions and deep water formation rates. The currently active state supports a seasonal sea ice cover of ~8 million square kilometers and coastal deep/bottom water formation. The alternative mode (probably exemplified regionally by the Weddell Polynya) is characterized by winter-long deep convection driving strong vertical fluxes of heat, salt and atmospherically active gases. The convection feeds significant open ocean deep water formation and the associated vertical heat flux prevents the formation of an insulating sea ice cover. If the convective mode were to encompass the whole Weddell Gyre, lack of winter sea ice would almost certainly affect the global climate, contributing significantly to global atmospheric warming, with intense cooling and ventilation of the abyssal ocean.

Previous work in the Weddell Sea indicated that oceanic heat flux plays a pivotal role in maintaining the tenuous seasonal ice cover of the Weddell, thus understanding the small scale mechanisms governing vertical flux in the mixed layer and pycnocline is an important first step in developing capability for predicting what environmental changes could again trigger widespread deep convection. The Antarctic Zone Flux Experiment (ANZFLUX), was designed primarily to measure the response of the upper ocean and sea ice to storm events by driving a research icebreaker deep into the winter ice pack, mooring it to drift with typical floes, and deploying modern instrumentation on the adjacent ice capable of measuring fluxes through the upper ocean, ice, and into the atmosphere.

The program is described by McPhee et al., 1996. Its main thrust comprised two short-term drift stations, supported by the R/V Nathaniel B. Palmer. The first, referred to as the Warm Regime Station, was deployed about 400 km SW of Maud Rise in a region of relatively high maximum temperature in the water column. In a week it drifted more than 150 km in response to two intense cyclones, each with peak sustained surface winds approaching 20 m s<sup>-1</sup>. During the drift, warm core eddies were encountered, with large excursions in the depth of the pycnocline, and episodes of large heat flux in the mixed layer (McPhee et al. 1996). Ice deformation during the second storm forced evacuation earlier than planned, however, an unmanned buoy cluster was deployed at the site before the ship departed for the second drift site over Maud Rise. During the Maud Rise Station, storms were less energetic, and T<sub>max</sub> was about 0.5 K lower than to the west. Nevertheless, there were comparable excursions in the depth of the pycnocline, along with large variation in mixed layer heat flux.

In addition to fundamental and unprecedented measurements in the upper ocean during extreme surface stress events, ANZFLUX provided remarkable new insight into how the thin ice cover of the central Weddell is maintained. Widespread surface flooding in response to snow loading and occasional warming of the entire ice column during storm events often results in freezing from the surface rather than the base of the ice. Flooding events also produce large changes in the radiometric characteristics of the ice surface pertinent to many remote-sensing techniques.

During the icebreaker transits in and out of the region, and between drift stations, an intensive program of physical oceanography and ice physics sampling was also accomplished. This was complemented by continuous measurements of upper ocean temperature and salinity, and ice temperature gradients, made with a sophisticated ocean buoy cluster left at the site of the first (Warm Regime) drift station.

A specific ANZFLUX goal was to measure oceanic heat flux and Reynolds stress near the ice/ocean interface to confirm that large oceanic heat flux does occur during winter, and then to parameterize the process in terms of more easily measured variables. Fig. M1 illustrates results from the Maud Rise station, showing reasonably close correspondence between actual flux measurements and a parameterization based only on ice drift velocity and elevation of mixed layer temperature above freezing. A direct application of the parameterization is shown in Fig. M2, where data from the buoy cluster left at the site of the Warm Regime drift station are used to estimate the ocean-to-ice turbulent sensible heat flux for the following 76 days. Mean heat flux during the buoy drift was about  $27 \text{ W m}^{-2}$ , with several events where heat flux exceeded  $100 \text{ W m}^{-2}$ . This has a large impact on the ice mass balance. In fact, concurrent measurements of ice temperature gradient showed that the mean conduction of heat through the ice cover nearly matched the mean oceanic heat flux, so that there was essentially no net ice growth from late July on.

Reference:

McPhee M. G., S. F. Ackley, P. Guest, B. A. Huber, D. G. Martinson, J. H. Morison, R. D. Muench, L. Padman, and T. P. Stanton, The Antarctic Zone Flux Experiment, *Bull. Am. Met. Soc.*, 77, 1221-1232, 1996.

Figure M1. A. Mixed-layer temperature elevation above freezing (shaded curve) and interfacial friction velocity estimated from Rossby-similarity (dashed curve, with envelope showing uncertainty range) for the Maud Rise drift. Asterisks show estimated from turbulence measurements, extrapolated to the surface as described in the text. B. Ocean-to-ice heat flux based on the bulk exchange model (dashed curve (with uncertainty envelope), compared with turbulent heat flux measured with the topmost TIC. Error bars on the measurements represent +/- one std. deviation of the 15-min flow realizations in each 2.4-h average.

Figure M2. A. Friction velocity estimated from buoy drift speed (solid curve) and temperature elevation above freezing from the topmost T/C pair (shaded curve). B. Ocean-to-ice heat flux from the bulk model (shaded curve). The heavy dashed line is the mean heat flux value:  $27.4 \text{ W m}^{-2}$ .

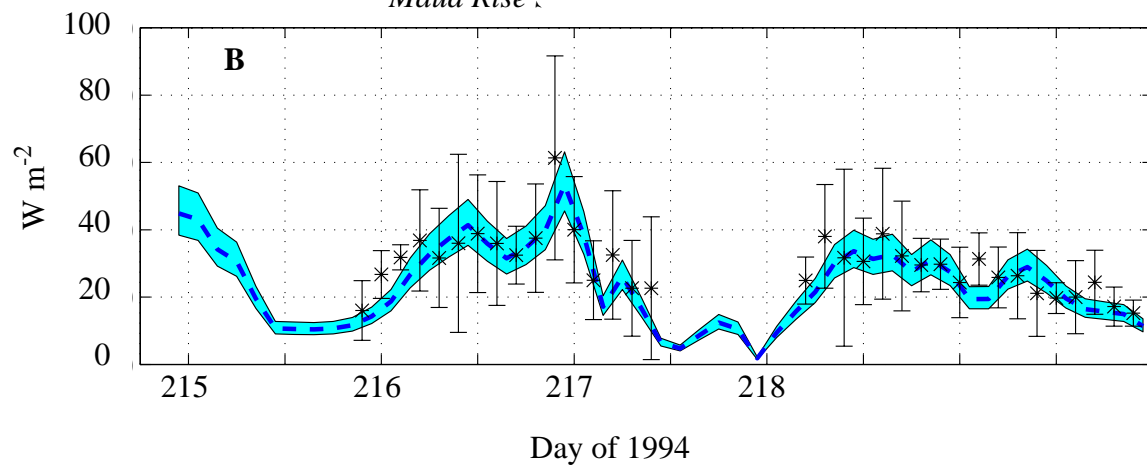
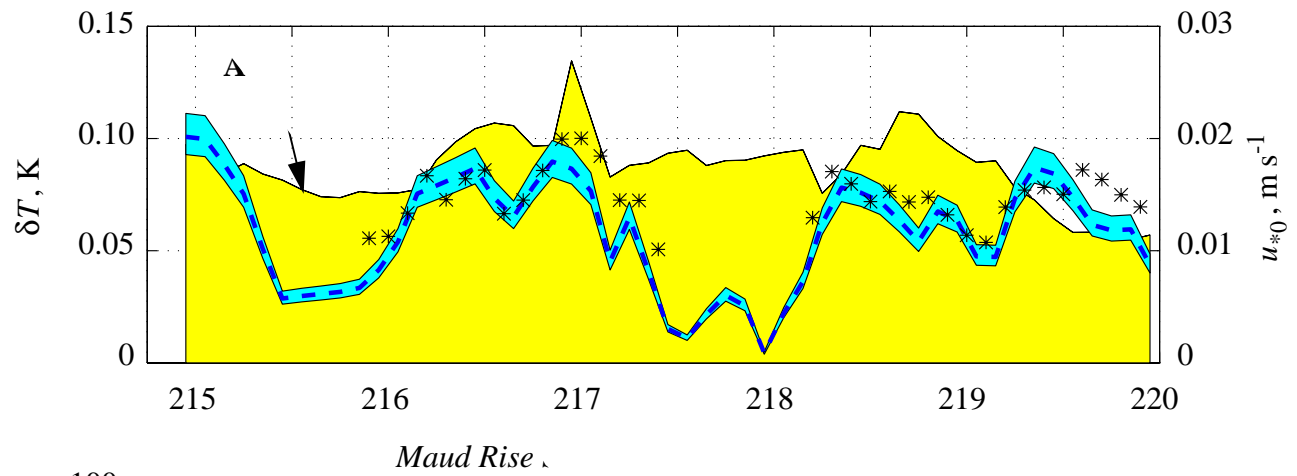
#### RECENT ANZFLUX RELATED PUBLICATIONS:

McPhee, M. G., Scales of Turbulence and Parameterization of Mixing in the Ocean Boundary Layer, submitted, *J. Mar. Syst.*, 1997 (Liege Colloquium: Marine Turbulence Revisited)

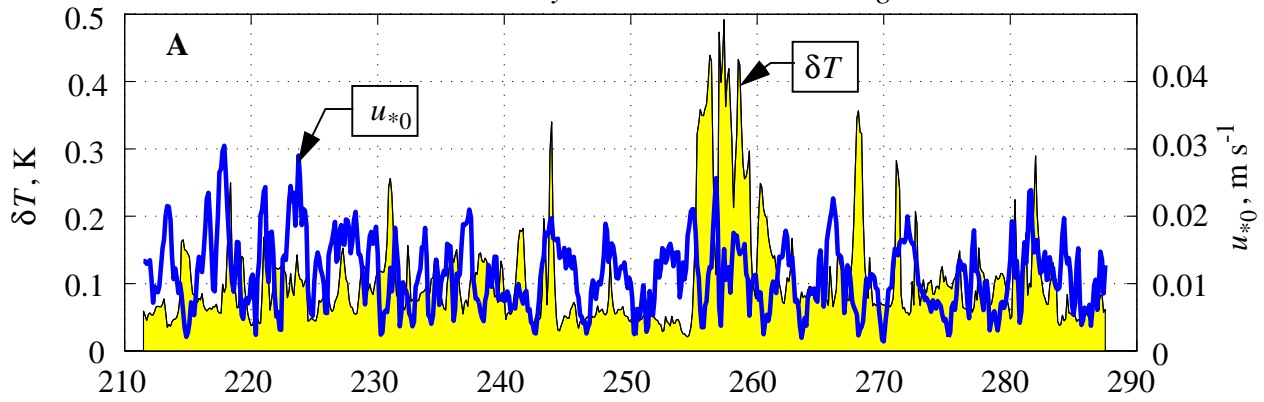
#### ABSTRACT

A method for estimating eddy viscosity and diffusivity based on a similarity theory for the vertical

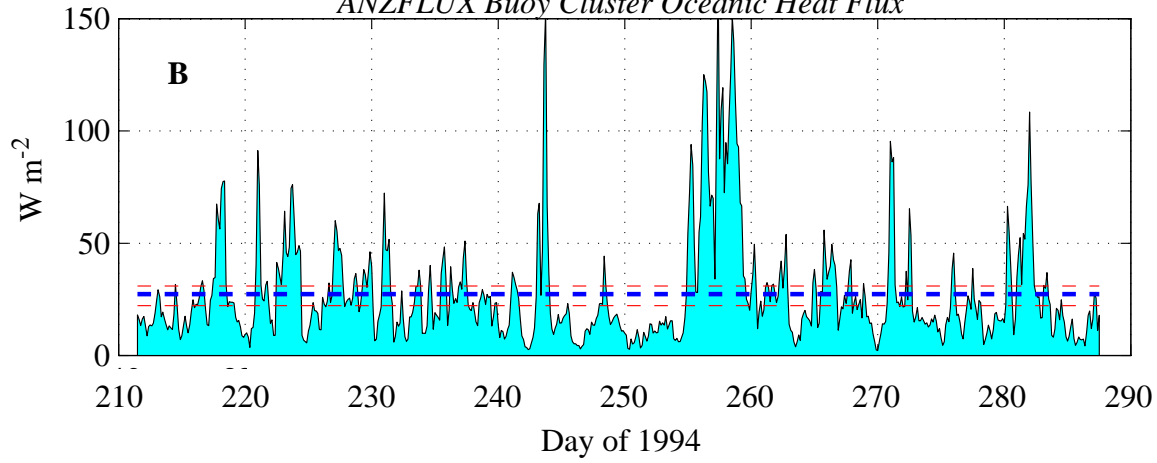




*ANZFLUX Buoy Cluster Thermal Driving*



*ANZFLUX Buoy Cluster Oceanic Heat Flux*



exchange scale of dominant turbulent eddies in a surface forced flow is used to predict profiles of momentum, heat, and salt flux in the ocean boundary layer. The technique requires specification of surface friction velocity, surface buoyancy flux, and mean temperature and salinity profiles, and solves for profiles of friction velocity, turbulent heat flux, and turbulent salinity flux through the entire boundary layer by an iterative procedure. The method is illustrated in two ways. In the first, turbulent stress and heat flux data from an intense storm during the 1994 Antarctic Zone Flux Experiment is simulated with reasonable accuracy. The model is forced by friction velocity at the ice/ocean interface (estimated from Reynolds stress measured near the surface), and buoyancy flux estimated from the thermodynamic mass balance at the ice undersurface. In the second demonstration, a prognostic model for the evolution of upper ocean temperature and salinity structure is formulated for an idealized storm scenario in which freezing or melting at the surface alternately induces destabilizing and stabilizing surface buoyancy flux. Since closure is local, prognostic equations for temperature and salinity only are carried. The model simulations are compared with a second-moment closure model (Mellor-Yamada level 21/2) forced in the same way. For surface heat flux (the main diagnostic), the two approaches agree quite well. In other respects, significant differences are noted, and it is suggested how data may be used to evaluate (and discriminate among) ocean turbulence models.

McPhee, M.G., C. Kottmeier, and J.H. Morison, Ocean Heat Flux in the Central Weddell Sea During Winter, submitted, *J. Phys. Oceanogr.*, 1997.

#### ABSTRACT

Seasonal sea ice, which plays a pivotal role for air-sea interaction in the Weddell Sea (a region of large deep water formation with potential impact on climate), depends critically on heat flux from the deep ocean. During the austral winter of 1994, an intensive process-oriented field program named the Antarctic Zone Flux Experiment (ANZFLUX) measured upper ocean turbulent fluxes during two short manned ice-drift station experiments near the Maud Rise seamount region of the Weddell Sea. Unmanned data buoys left at the site of the first manned drift provided a season-long time series of ice motion, mixed layer temperature and salinity, plus a (truncated) high resolution record of temperature within the ice column. Direct turbulence flux measurements made in the ocean boundary layer during the manned drift stations were extended to the ice/ocean interface with a mixing-length model, and used to evaluate parameters in bulk expressions for interfacial stress (a Rossby-similarity drag law) and ocean-to-ice heat flux (proportional to the product of friction velocity and mixed layer temperature elevation above freezing). The Rossby parameters and dimensionless heat transfer coefficient agree closely with previous studies from perennial pack ice in the Arctic, despite a large disparity in undersurface roughness. For the manned drifts, ocean heat flux averaged  $52 \text{ W m}^{-2}$  west of Maud Rise, and  $23 \text{ W m}^{-2}$  over Maud Rise. Unmanned buoy heat flux averaged  $27 \text{ W m}^{-2}$  over a 76-day drift. Although short term differences were large, average conductive heat flux in the ice was nearly identical to ocean heat flux over the 44-day ice thermistor record.

Padman, L., R. Muench, and E. Fahrbach, Cabbelling catastrophes, submitted *J. Geophys. Res.*, 1998.

#### ABSTRACT

The structure and dynamics of an active diapycnal cabbelling instability in the Weddell Sea is de-

scribed. The estimated rate of heat transfer from the relatively warm pycnocline to the near-freezing surface mixed layer during the event was about  $300 \text{ W m}^{-2}$ . The observed event was initiated by differential advection of a relatively saline and dense mixed layer over a filament of anomalously warm Weddell Deep Water. Other frontal regions such as near the shelf/slope front may also provide the necessary conditions for advectively-initiated diapycnal cabbeling, as well as isopycnal cabbeling. We hypothesize that diapycnal cabbeling can also occur during periods of rapid ice growth in the central Weddell Gyre, specifically under conditions of large ice divergence. Variability in step properties in the central Gyre may also be correlated with interannual variations in seasonal ice extent.

Diapycnal cabbeling can be treated as a limiting case of diffusive convection in which external forcing, such as ice formation or differential advection, initiates the instability. After the density contrast between the surface and subsurface layers is increased, either by the process itself or by summer restratification, the layers can be maintained in a less active state by diffusive convection.

Stanton, T. P., L. Padman, and R. A. Robertson, Heat Fluxes through the Permanent Pycnocline in the Eastern Weddell Sea. Submitted to *J. Geophys. Res.*, 1998.

Stanton, T. P. Shear Production and Dissipation in an Energetic Oceanic Boundary Layer. To be submitted to *J. Geophys. Res.*, Feb, 1998.

Surface Longwave Radiation Conditions in the Eastern Weddell Sea during Winter  
Peter S. Guest  
Re-submitted to *Journal of Geophysical Research (Oceans)*  
November, 1997

## ABSTRACT

This is a study of the surface longwave radiation characteristics over the Weddell Sea during winter, based on measurements performed from a ship and ice floe camps during the Antarctic Zone Flux Experiment (ANZFLUX). Net longwave radiation is the dominant term in the regional surface energy balance. The net longwave radiational cooling of the surface is  $62 \text{ Wm}^{-2}$  greater during clear skies than during overcast skies. The downwelling longwave radiation during clear skies is 17% less, during overcast skies 3% less, than that for reported Arctic cases with the same surface temperature. Previously-published formulas based on surface variables predict the ANZFLUX longwave radiation to an accuracy of  $10 - 43 \text{ Wm}^{-2}$  for the clear-sky cases and  $10 - 20 \text{ Wm}^{-2}$  for overcast cases. There is no correlation of downward longwave radiation with any standard surface meteorological parameters except air temperature, with the possible exception of wind speed which has a slight negative correlation during clear skies. Predictions from newly-derived formulas using air temperature as the sole predictor are accurate to  $5.8 \text{ Wm}^{-2}$  for overcast skies and  $7.2 \text{ Wm}^{-2}$  for clear skies. When information on cloud bottom temperature and cloud thickness are available, downwelling radiation is predicted to within  $3.9 \text{ Wm}^{-2}$ . These accuracies are based on parameterizations that are tuned to the ANZFLUX data set and are better than what would be expected when applying the parameterizations to other situations.

# **DEEP OCEAN VENTILATION THROUGH ANTARCTIC INTERMEDIATE LAYERS: THE DOVETAIL PROGRAM**

*R.D. Muench*

*Earth & Space Research, 1910 Fairview E., Suite 102, Seattle, WA 98102-3620*

A major portion of the southern hemisphere water conditioning that leads to formation of bottom water in the World Ocean occurs in the Weddell Sea. The goal of the international program for study of Deep Ocean Ventilation Through Antarctic Intermediate Layers (DOVETAIL) is to understand physical processes in the Weddell-Scotia Confluence (WSC) region sufficiently to quantify the ventilation of the World Ocean achieved by Weddell Sea water masses. The WSC is a site of energetic interactions among water masses flowing from the Weddell Sea, the Pacific Ocean and Bellingshausen Sea, Bransfield Strait, and shelf-conditioned waters from the regions surrounding the Antarctic Peninsula. It overlies a region of steep, complex bathymetry dominated by the South Scotia Ridge, which limits north-south exchange to a few deep, narrow channels, and is thought to represent a gateway for the most direct and largest of these flows of Antarctic water (Figure 1). It is imperative that we understand the associated physical processes in order that we be able to assess their sensitivity to changes in regional forcing, hence, the impact of such changes on World Ocean ventilation.

Four objectives contribute to the overarching DOVETAIL goal. The first is to assess the quantity as well as the physical and chemical characteristics of Weddell Sea source waters for the WSC region. This assessment will tell us the maximum volume of Weddell Sea water which is available for deep ocean ventilation as Antarctic Bottom Water. Additionally, it will provide initial values for chemical parameters and tracers that can then be compared with downstream conditions in the WSC region and used to estimate ages and sources of waters and to determine mixing relationships during passage through the WSC region. Information about the mechanisms of source water formation is particularly important to understanding the possible influences of climate change on bottom water production.

The second objective is to describe the dominant physical processes associated with spreading and sinking of dense Antarctic waters within the WSC region. Available information based on both field and modelling efforts suggests that these waters exit the Weddell Sea either as boundary currents in deep channels or as flow along isopycnal surfaces (surfaces of equal water density). Water as shallow as about 400 m in the Weddell Sea, following isopycnal surfaces northward, attains depths exceeding 3000 m during its northward passage through the WSC. The latter mechanism likely includes water mass modification by turbulent mixing and transport by mesoscale processes such as eddies.

The third objective is to estimate the role of the Weddell Sea in ventilation of the World Ocean. The northward volume transport of water, along with its physical and chemical properties, will help to quantify the mixing history of water available for deep ocean ventilation north of the WSC.

The final objective is to estimate seasonal fluctuations in regional ocean transport and hydrographic structure and to assess the likely influence of interannual variability on rates of ventilation by Weddell Sea waters. Past field and modeling results indicate significant seasonal and interannual variability in both the Weddell gyre and in the Antarctic Circumpolar Current (ACC). The WSC forms part of the northwestern limb of the Weddell Gyre and is bounded on the north by the ACC, hence, must be influenced by variability in both regimes. New field measurements coupled with modeling efforts and synthesis with older results will help us to understand the physical interactions which link the seasonal and interannual

changes and which might link climate change with ventilation rates.

DOVETAIL pursues its goal and objectives using a closely integrated field and modelling program. The field component measures critical hydrographic, tracer and chemical parameters and currents in the northwestern Weddell Sea, a source region for the WSC, through the WSC itself, and in the southern Scotia Sea, which is the sink for water which has passed through the WSC. The hydrographic, tracer and chemical observations take place during cruises in the austral summer, autumn and winter seasons. Currents are being measured in the same region using moored current meters deployed for periods as long as 26 months. These observations will be used to describe the mean hydrographic and current fields, to estimate seasonal differences, and to assess the roles of mesoscale processes. Numerical models will use these field data, in conjunction with historical data, to specify boundary conditions, for parameterizations, and for verification. The models will serve to interpolate and extrapolate the data, and will aid in identification and quantification of regional processes.

Two major field programs have been carried out, to date, under the DOVETAIL umbrella. The first of these took place during March 1996 when the German icebreaking research vessel *Polarstern* carried out a sampling program for water column physical, chemical and tracer parameters and deployed six long-term current meter moorings as part of a joint German/Spanish study (Figure 2). The moorings are planned to be recovered by *Polarstern* in late autumn 1998. The second took place during August 1997 when the U.S. icebreaking research vessel *N.B. Palmer* occupied a series of transects in the WSC along which physical, chemical and tracer parameters were measured (Figure 1). On this latter cruise, 11 long-term current moorings were deployed and will commence returning data as early as April 1998 (Figure 2).

The DOVETAIL program is the third in a sequence of integrated field and modelling programs which were initiated in 1992 and carried out in the Weddell Sea, which have been coordinated by the international Antarctic Zone (iAnZone) group, now a Commission of the Scientific Council on Ocean Research (SCOR). The first two programs have focussed on processes associated with ocean ventilation in the polar waters. DOVETAIL proposes to build upon the results from these two preceding programs by focussing on the escape of recently ventilated deep water from the Weddell Sea into the World Ocean. In this way, it hopes to better define and understand the role of Antarctic waters and processes in the ocean and climate systems.

DOVETAIL priorities parallel, and the results will contribute to, ongoing global change research. The processes responsible for vertical and horizontal fluxes within the ocean and associated interaction with the sea ice and atmosphere in polar regions must be properly represented. The DOVETAIL study region, off the tip of the Antarctic Peninsula, serves as the primary gateway between the southern polar waters and the World Ocean. Results from the DOVETAIL experiment will aid in establishing a basis for long-range monitoring of this critical region, inasmuch as both the Global Ocean Observing System (GOOS) and the ocean component of the Global Climate Observation System (GCOS) have been established by a number of international bodies to provide such monitoring data.

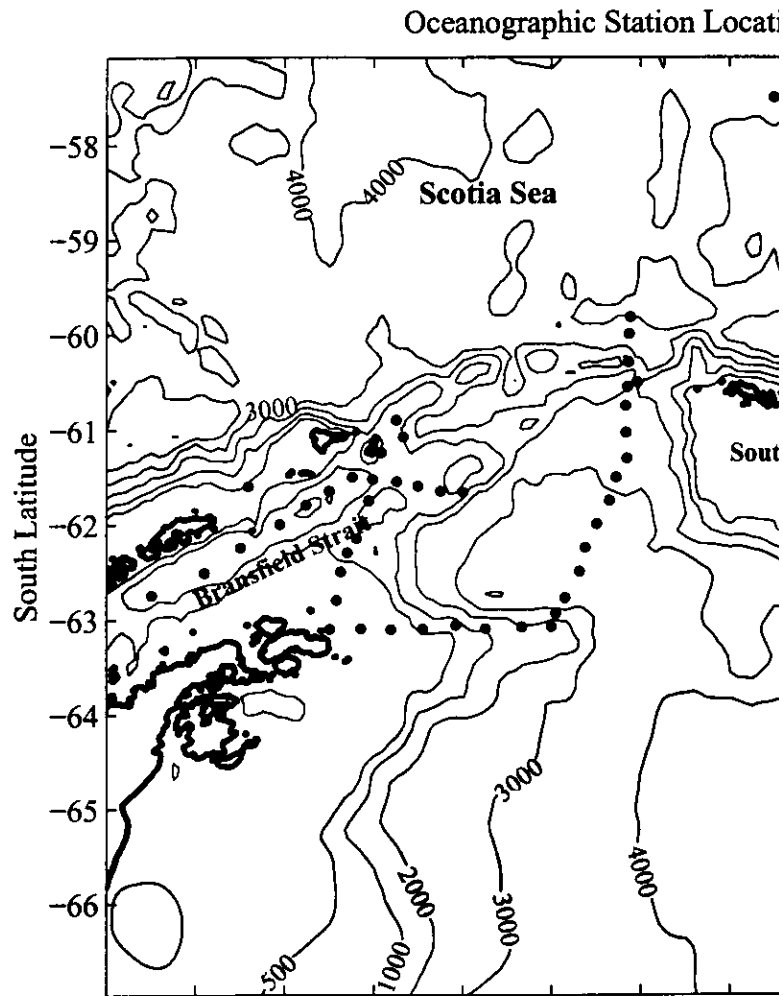
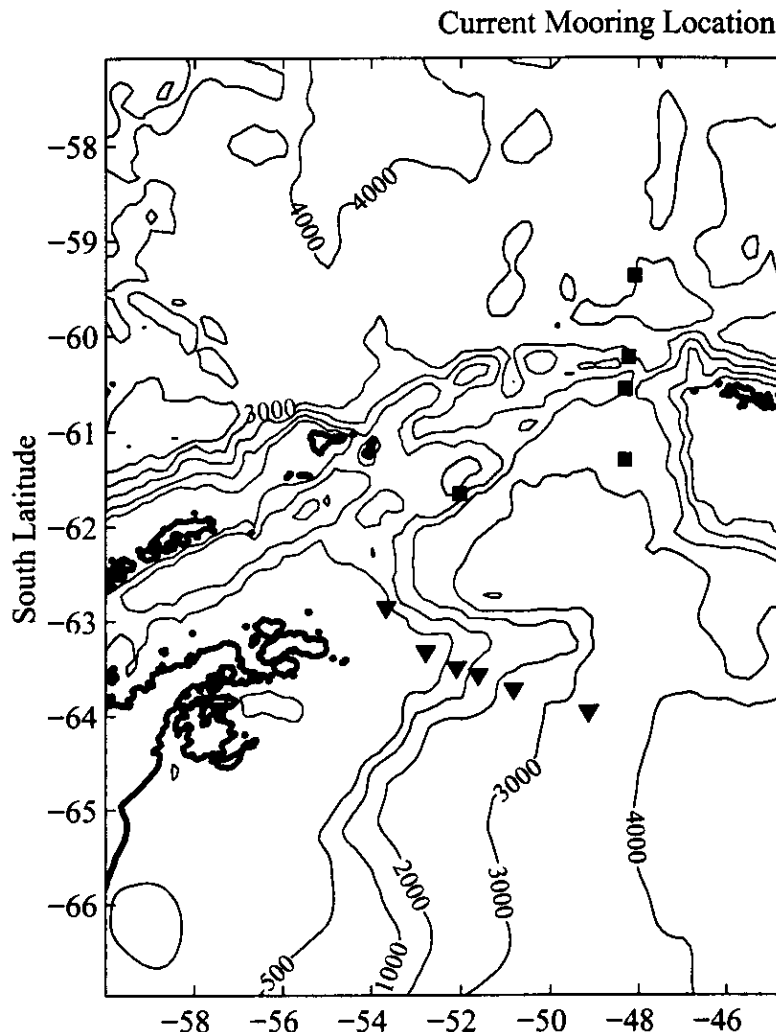


Figure 1. Location of the DOVETAIL study region. Isobaths are labeled in meters. Circles show locations of oceanographic stations occupied by the *Palmer* in August 1997. The transects are located in such a way as to sample the primary boundary currents, which tend to parallel steep bottom slopes in the WSC region.



*Figure 2.* Locations of the DOVETAIL current moorings. Isobaths are labeled in meters. Triangles show locations of the German/Spanish current moorings deployed by *Polarstern* during March 1996 and scheduled to be recovered in late autumn 1998. Squares show locations of the current moorings deployed during August 1997 by the *N.B. Palmer*. Current meters deployed by the *Palmer* are designed to self-release and return data via the Service Argos satellite link, so will not need to be recovered.

#### *Acknowledgements*

The U.S. DOVETAIL program is supported by the U.S. National Science Foundation.





**Proposed iAnZone #4 Program: Convection**  
(This summary report prepared by A.L. Gordon)

The goal of **iAnZone** is: through development and coordination of observational and modeling programs, to advance our quantitative knowledge and modeling capability of climate relevant processes, their seasonal cycle, their inter-annual and decadal variability, within the Southern Ocean's Antarctic Zone (region poleward of the Antarctic Circumpolar Current), with emphasis ocean and atmosphere coupling in regions influenced by sea ice, and to the link between the Antarctic Zone and the global ocean and climate system.

There have been a number of national programs that address these goals, and the **iAnZone** banner is associated with several national expeditions into the Weddell Gyre during the 1980s & 1990s. However, there have been three coordinated, multi-investigator, international **iAnZone** Weddell Gyre programs which were explicitly developed at the previous **iAnZone** meetings.

**Ice Station Weddell (ISW):** The first **iAnZone** program was ISW in 1992, involving US, Russian and Finland contributions. The ISW project explored the western rim of the Weddell Sea, investigating its contributions to newly formed deep and bottom layers. A description of the program was presented in an AGU EOS article (ISW Group, 1993). The German Alfred Wegener Institution (AWI) Antarctic program obtained a Polarstern section in the western rim of the Weddell in 1993 (Fahrbach et al. 1995) is considered a valuable extension of 1992 ISW observations. The German WOCE current meter monitoring program (Fahrbach et al, 1994) coupled with the ISW observations have greatly increased our understanding of the forms and vigor of the Weddell Sea ventilation processes.

**AnzFlux :** The second **iAnZone** program was AnzFlux in 1994. AnzFlux, involving US and Germany contributions, obtained a more quantitative understanding of the surface and deep water interactions in the region of Maud Rise. AnzFlux gave a new appreciation of the complex and highly variable thermohaline fluxes within the upper ocean, and its coupling to the sea ice cover and atmosphere. This program is described by McPhee et al. 1996 and in the **iAnZone** Biosphere Report.

**Dovetail:** The third **iAnZone** program is underway, called Dovetail, in 1997-1998, which includes US, Spain and Germany contributions. Dovetail's objective is to measure the integrated outflow of ventilated water masses from the Weddell Sea. Description of Dovetail is given in two Antarctic Journal 'in press' articles, copies of which may be obtained from the authors: Muench, 1997 and Gordon et al. 1997, and is further described in the **iAnZone** Biosphere Report.

The first three **iAnZone** programs involved just a few nations and occurred in the Weddell Gyre. With the enlarged scope of **iAnZone** resulting from the SCOR affiliation, it was agreed **that an iAnZone program requires broader involvement, and must consider the full circumpolar Antarctic Zone.** A theme for **iAnZone** experiment #4 that fully addresses the **iAnZone** goals, that can be met at a variety of sites around Antarctica, and for which there is wide interest deals with the **convection**, a thrust which is fully endorsed within the southern ocean component (D5) of the CLIVAR draft Implementation Plan. A preliminary name for **iAnZone** Exp. #4 is **Convection**.

While much research has been directed at the formation and spreading of Antarctic Bottom Water (AABW) in all of its varied forms, we still do not have a firm assessment of the total, circumpolar production of AABW, and even less of an understanding of varied processes that sustain production.

The Objective of **Convection** are: *To obtain a quantitative estimate of the effect of Antarctic zone water mass modification on the global thermohaline circulation and to establish the basis of an observational system which allows to improve and validate the representation of Southern Ocean convection in large scale models.*

It is anticipated that there will be a series of **Convection** field programs during the period 2000 to 2004 that address these components. Field operations may occur at the same time, but

difference sectors of the Antarctic Zone. To qualify as an **iAnZone** program the field program must involve more than one national program and be subject to discussion at **iAnZone** meetings. Three components of **Convection** are considered (Fig. 1), which involve furthering aspects of the previous three **iAnZone** experiments:

1. Continental Margin Convection: This component is directed at the formation of the 'parent' shelf water masses contributing to deep reaching convection, mixing within the continental margin frontal structures, and the plume convection feeding the deep and bottom water ventilation. This component includes:

a- shelf waters coupling to atmospheric and sea ice (and coastal polynya) forcing as well as shelf water interaction with the ice shelves, ice bergs and ice tongues;

b- the variety mixing processes, including coastal waves and tidal action, and equation of state subtleties and their associations with bottom topography and slope circulation and fronts that enable deep reaching convection; and

c- the dynamics and entertainment characteristics of the convective plumes characteristic of many continental slopes of Antarctica.

Regions of potential field measurements are Weddell Sea, Ross Sea, Prydz Bay, Adelie coast. What are the common threads of these regions that make them sites of slope convection?

2. Open Ocean Convection: Of interest in this component are the vertical transfer processes within the Antarctic Zone thermohaline stratification and their response to wind, buoyancy forcing and polynyas. The perturbation of the regional stratification and vertical fluxes by the processes imposed by topography, such as Maud Rise.

The objectives of the project are:

a - to determine the time scales and intensity of the variability in characteristics and amount of the inflowing Circumpolar Deep Water - to determine the time scales and intensity of the variations of the atmospheric forcing in seasonal to interannual time scales - to determine the time scales and intensity of the variation in water mass properties

b- to determine the potential correlation of the variations of water mass properties and ice or atmospheric forcing - to estimate the effect of topographic features like Maud Rise to intensify vertical transports

c- to determine the potential of remote and local effects to induce variability in the atmosphere-ice-ocean interaction - to determine the contribution of open convection the modify the source waters of shelf processes

d- to estimate the contribution of open ocean convection in the Antarctic zone to the ventilation of the global ocean

e- to estimate the potential of abrupt changes

A component of this component of Convection is the Weddell Polynya Quick Response Program described elsewhere in the **iAnZone** Biosphere Report.

3. Monitoring the convective products: Coupled to the two process oriented components of **Convection** is the establishment of a time series measurement program of the outflow of deep and bottom water masses formed within the Antarctic Zone which ventilate the global ocean.

This component includes:

a- Defining the primary pathways and processes that drain the products of cold Antarctic zone water masses;

b- Measurement of the thermohaline and volume flux variations of the outflow of Antarctic Deep and Bottom Water at key sites around Antarctica;

Inspection of bottom water characteristics can be used to identify a few key regions to establish a time series. In consideration of the Rossby deformation scales at high latitude and of the small residence time of newly formed water masses in the western Weddell Sea and elsewhere, the time series array must have appropriate spatial and temporal resolution. The **iAnZone** and previous research has shown that the northwest Weddell Sea topographic features make it a key site for monitoring of the outflow of Weddell Sea convective products. Other sites have similar topographic features that confine the outflow thus enabling monitoring strategies.

### What Next?

During the course of 1998 various working groups set up at the meeting will develop more details (via e/mail). They should provide: a description of the key research issues and detail their importance to the larger scale climate role of the Antarctic Zone; and prepare concise objectives and activities that would contribute to each of the Convection components. The development of **iAnZone** Experiment #4 will be the primary topic of discussion at the next (April or May 1999) **iAnZone** meeting.

The lead persons for each of the three components are as follows, others will be asked for input. The reports will be made available to the full **iAnZone** group

WG1: Continental Margin Convection. A. Gordon and S. Rintoul (co-chairs), J. Klinck, J. Morison, L. Padman, H. Hellmer, S. Jacobs, more...

WG2: Open Ocean Convection: E. Fahrbach and M. McPhee (co-chairs), J. Launiainen, M. Drinkwater, D. Martinson, Norway rep, more...

WG3: Monitoring the convective products: M. Visbeck and N. Bindoff (co-chairs), R. Muench, W. Smethie, more...

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McPhee, M. S. Ackley, P. Guest, B. Huber, D. Martinson, J. Morison, R. Muench, L. Padman, and T. Stanton, The Antarctic zone flux experiment, *Bull Amer. Met. Soc.* 77, 1221-1232, 1996.

Muench, R.D. Deep ocean ventilation through Antarctic intermediate layers: the DOVETAIL program. *Ant Jour of the US*, in press

## **iAnZone Weddell Polynya Quick Response Program (WQRP)**

(This summary report prepared by A.L. Gordon)

The Weddell Polynya event of the mid-1970s stands out as a major perturbation of ocean - atmosphere coupling and presumably of the climate system. Might it represent another mode of operation for the Southern Ocean? Might it become the norm, or perhaps was, now is being suppressed by Anthropogenic climate response? Clearly the Weddell Polynya represents a different way of ventilating the deep ocean, perhaps more akin to NADW (Labrador) convection. The Weddell Polynya must be properly simulated in global climate models if they are to be useful in predicting climate change.

At the 4-th iAnZone (SCOR affiliated international Antarctic Zone Committee) meeting in March 1996 in Barcelona, a Weddell Polynya quick response program (WQRP) was recommended. WQRP involves the deployment of a research vessel into the Weddell Polynya, should a large persistent polynya similar to that of the mid-1970s again occur. As the polynya hasn't occurred since 1976, though there is some evidence from R/V San Martin data of a 1961 cooling of Weddell Deep water (Gordon, 1982), perhaps we are 'due'; the rapid warming of WDW since the Weddell Polynya (Fig. 1) suggests cycling phenomena.

**The Suggested Procedure:** We are interested in detecting a persistent large polynya in the vicinity of Maud Rise. 'Persistent' means it must be present for more than two weeks before we tag it as something unusual. By 'large' an ice free area must be larger than 100 km horizontal scale. The ice concentration within the Polynya must be less than 30%.

**Phase I:** The first part of the plan must involve study of near real time satellite sensing of sea ice cover. In the US the National (Navy/NOAA) Ice Center (NIC) in Suitland Maryland has enthusiastically agreed to help us. They will carefully inspect the microwave, IR, and Visible light sensors data in the area of interest. Should they find a strong polynya feature they will inform A.L. Gordon who will alert the iAnZone group for an international coordinated response.

**Phase II, ship deployment:** Within the US a group of investigators has been set up to inspect the data and if a major polynya event seems evident appropriate action is taken to arrange for a research ship to enter the polynya. iAnZone will play a similar role to encourage an international response. The objective is to have a ship within the Weddell Polynya anytime from 15 July to 15 October. After 15 October the ocean/atmosphere heat flux may be into the ocean and convection could be shut-down even though the polynya continues.

1. Surveillance Period: Start **1 June** (when ice covers the Maud Rise area), extend to **1 October** (first detection around 1 September is required to deploy the ship in that year).

2. Area: We are interested in a persistent large polynya in the vicinity of Maud Rise, however the area which will be scrutinized will be much larger, **from 30W to 30E**.

**Ship Program:** The observational plan was a topic of discussion at the iAnZone Biosphere meet-

ing. The plan would be flexible enough to be adjusted to the particular form of the polynya. The observations would include XBT, CTD, hull and lowered ADCP sections and meteorological observations across the polynya and the surrounding ice edge. A strawman plan would be based on a polynya similar in form to that of 1970s, about 1000 km major axis (approximately east-west) and 400 km minor axis, near the Greenwich Meridian. A rapid XBT and hull mounted ADCP (Acoustical Doppler Current Profiler) grid will be run first, along the major axis and then three lines perpendicular to the major axis. XBT probes will be spaced at 10 km spacing, so as to capture a convective chimney (about 30 km in diameter, Gordon 1978). Meteorological sensors on the ship for air temperature and humidity, wind and air pressure would be run continuously. Radio-sondes will be taken daily. Addition of net radiation sensors will be sought. Upon inspection of the XBT data three lines for a CTD/LADCP (the CTD measures temperature, salinity and oxygen versus pressure; the LADCP is a Lowered Acoustical Doppler Current Profiler attached to the CTD package) with a star pattern over a convective chimney and over Maud Rise.

Summary of a report on “Current plans for organization  
of WCRP research into cryosphere and climate”  
delivered by V. Savtchenko (JPS for WCRP)

Achieving the objectives of the WMO/IOC/ICSU World Climate Research Programme (WCRP) requires quantitative understanding of the physical climate system, constituted by four major components:

- the global atmosphere
- the world ocean
- the land surface of the continents, and
- the cryosphere.

None of the international research programmes undertaken so far, including the WCRP, addresses specifically the role of the cryosphere in the global climate system. Following an advice of the Joint Scientific Committee (JSC) for the WCRP, the WCRP Arctic Climate System Study (ACSYS) Scientific Steering Group (SSG) discussed in 1996, at its fifth session, the need for an international co-ordination of cryospheric research relevant to climate. The SSG agreed to support an exploratory meeting of experts on cryosphere and climate and underlined that WCRP was particularly well suited in forging links between research projects dealing with the cryospheric, hydrological, oceanic and atmospheric components of the physical climate system.

A meeting of experts on cryosphere and climate was convened by WCRP in Cambridge, UK in February 1997. The meeting reviewed current and planned WCRP activities addressing polar climate, as well as related international polar research projects, and concluded that:

- (i) There are critical observational gaps in cryospheric parameters significant for climate (see WCRP-102 (WMO/TD No.867), i.e. proceedings of the Cambridge meeting, for details).
- (ii) In GCMs several cold climate processes and phenomena are either not presented or are non-interactive. These are: frozen ground, freshwater ice, glaciers, ice sheets and ice shelves.

The International Conference on the World Climate Research Programme: Achievements, Benefits and Challenges (Geneva, 26-28 August 1997) identified weaknesses and gaps in studies of cold climate processes and the role of the cryosphere in climate variability and advised that WCRP would:

- (i) investigate the role in climate of the global cryosphere (sea ice, snow cover, ice sheets and shelves, glaciers, lake and river ice, frozen ground and permafrost), and
- (ii) examine factors determining the extent and variability of the cryosphere, feedbacks to the global climate system, and role in global climate variability and change and in sea-level rise.

The second ACSYS scientific conference on “Polar Processes and Global Climate” (Seattle, WA, USA, November 1997) provided input from the broader polar/cryospheric community on the

subject. It underlined, in particular, that the need for global climate investigations to account realistically for cryospheric and high-latitude processes was well established and confirmed by the wide range of scientific inputs to the conference.

The sixth session of the ACSYS SSG (held immediately after the second ACSYS conference) assembled weaknesses and gaps in studies of cold climate processes and the role of cryosphere in climate. The need for an overall internationally co-ordinated WCRP research activity into the cryosphere and climate, which would encompass both northern and southern polar regions, was discussed in detail. The group developed a comprehensive statement on the overall status of studies of cold climate processes and the role of the cryosphere in climate. The group also prepared a proposal on the overall organization/integration within WCRP framework of studies of climatically important cryospheric components. The group was convinced that the WCRP should organize a "Cryosphere and Climate" (C&C) element to address the role of the cryosphere in and its interactions with components of the climate system, its contribution to climate system variability and change, and its impacts on sea level and atmospheric composition.

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**A footnote added in April 1998 by the editor of the iAnZone-4 report:**

The JSC-XIX (Capetown, South Africa, 16-21 March 1998) considered the proposal on the establishment of a WCRP cryosphere and climate component (made by the ACSYS SSG-VI) and formally endorsed the establishment of an ad hoc WCRP (JSC/ACSYS) task group on climate and cryosphere to formulate a scientific concept and co-ordinate plan for a WCRP Climate and Cryosphere (CLIC) project. The appointment of the membership of the group was entrusted to the ACSYS SSG. The group should report progress (through ACSYS) to JSC-XX in March 1999 and deliver a final proposal for review at JSC-XXI in March 2000 (again through ACSYS).

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**Report on the 1997 WOCE Southern Ocean Workshop**

E. Fahrbach, Alfred-Wegener-Institute for Polar and Marine Research  
Columbusstrasse, D-27515 Bremerhaven, Germany

1997 WOCE Southern Ocean Workshop July 8-12, 1997, Antarctic Cooperative Research Centre,  
Hobart, Tasmania, Australia

**Introduction**

The Southern Ocean workshop was the third in a series of regional workshops convened by the World Ocean Circulation Experiment with the aim of focusing the joint analysis of WOCE data and modelling results. A draft report was compiled by Steve Rintoul and Nathan Bindoff. The attendees, the program, the computing resources and the invited speakers are also listed on the web site <http://>



During the workshop invited talks were given on the following topics:

1. On the formation of Anatarctic Bottom Water and its circulation - Eberhard Fahrbach
2. On the application of altimeters and scatterometers in Southern Ocean - Lee-Leung Fu
3. The dynamics of the ACC: what models teach about the balances of momentum, potential vorticity and enstrophy - Dirk Olbers
4. On the large-scale circulation of the Southern Ocean - Alex Orsi
5. A review of Drake ISOS measurments, the Antarctic Circumpolar Wave and the new chokepoint pressure records - Ray Peterson
6. Tracer studies of deep water formation and circulation in the Southern Ocean derived from WOCE and other tracer data - P. Schlosser, J. Bullister, M. Mensch, W.M. Smethie, M. Warner and R. Weiss
7. Global Antarctic Intermediate Water distribution and exchanges in intermediate and deep layers across the ACC - Lynne D. Talley
8. On the the thermohaline circulation in models - David Webb

Working Groups were established on the following subjects:

1. Dynamics of the ACC - David Webb
2. Eddy fluxes and mesoscale studies - Randy Watts
3. Large-scale variability of the ACC - Brian King
4. AAIW/SAMW formation and circulation - Kevin Speer
5. AABW formation and circulation - Eberhard Fahrbach
6. Meridional circulation - Alex Orsi
7. Data assimilation and inverse models - Jens Schroeter
8. Decadal variability - John Church

The Working Groups proosed the following action items:

- \* Dynamics of ACC
    - Establishment of modelling centre for distribution model output
    - Ecouragement of more inverse modelling and data assimilation studies
    - Quantitative model and ocean observations comparisons
  - \* Decadal Variability
    - Fingerprinting climate change signals in models and data
    - Further comparisons between historical and WOCE data
    - Repeat SCORPIO 43 South Section
  - \* AABW Formation
    - Quantitative assessment of volume of water-mass formation is required
    - Large scale synthesis of pathways of AABW is required
    - Experiments aimed at understanding time variability of bottom water formation
  - \* Eddy Parameterization
    - Spatially varying GM scheme is required
    - Relationship of eddy parameter schemes to grid resolution
- Mesoscale Dynamics

- need for more process studies of mesoscale eddies
- need to bridge observations and models on fine scales
- \* Sub-Antarctic Mode Water and Intermediate Water
  - What role does E-P or Ekman play in freshening SAMW in S.E. Pacific

What processes are important in the evolution of Intermediate Water

To the IANzone goals the discussions in the working group on bottom Water formation and circulation were the most relevant. Therefore the presentation during the IANzone meeting is restricted to this working group's report.

During two working group meetings the issues presented in the previous review talk were taken up and discussed in detail, and presentations of additional work occurred. The discussion was aimed at improving the understanding of the estimates of the bottom water formation to the thermohaline circulation. It covered the following topics:

### 1. Water mass formation

The aim is to obtain formation rates and to understand by which processes they are controlled. Both, rates and processes, are subject to significant spatial variability occurring in local, regional and circumpolar scales. There exist local estimates which can not be easily combined to circumpolar ones, when they refer to different definitions. There is a conflict between simplifying definitions, such as the change of the volume in a given density range, which can be clearly defined over a large spatial range, and more process oriented definitions such as ventilation rate which are fuzzy and not easy to combine. Understanding of the processes is rather advanced, however the quantitative assessment is still missing.

### 2. Circulation

The circulation of the water masses in the Antarctic Zone can be split into three phases: the inflow into the formation areas, the flow along the Antarctic continental margin which collects the newly formed water masses and guides them to the gaps where they leave the Antarctic Zone through gaps of different size into the adjacent basins. A large scale synthesis of the present locally defined pathways is still missing.

### 3. Time variability

Time variability occurs on different levels: formation processes can vary in their intensity, e.g. the amount of formation of high salinity shelf water can vary due to changes in the atmosphere/ice forcing. Processes can be switched on and off, e.g. reduced formation of ice shelf water, or large scale conditions can vary, e.g. transition from slope processes to open ocean convection. Observed changes in the near and far field hint that all three types of variability occur and affect the formation rates. This complicates the interpretation of relatively short time measurements. Observations on time variability are scarce and cover only relatively short time scales. Seasonal variations in the bottom water outflow have been observed in the Weddell Sea and off the Adelie coast. Longer term trends are known from the Weddell Sea. The missing knowledge of the regional distribution and the relevant time scales contributes greatly to the uncertainty of estimated rates.

#### 4. Interaction of models and observations

Large scale models have problems to include water mass formation processes as they occur on small scales. Consequently observed rates can be used to constrain and to control models as well as being used as boundary conditions. Integrating quantities such as rates or fluxes are more useful to be compared with models than local structures or characteristics as they are less affected by the grid size. Appropriate measurements of surface fluxes are essential for model forcing.

#### 5. Future perspectives

Given the missing knowledge about the time variability in particular on longer time scales, the working group emphasises the need for the maintenance of the time series measurements started under WOCE. The draft implementation plan worked out in early 1997 under the umbrella of WCRP for CLIVAR already contains the relevant measurements.

Process studies such as planned in the framework of the SCOR-affiliated programme IAnzone are still needed to obtain spatially high resolution data to evaluate process oriented models which will enable us to explain the spatial and time variability from variations in ice/ocean/atmosphere interaction and the topographical setting.

#### 6. Suggestions

Apparently a large number of local studies are underway, published, submitted or in preparation and no further action is needed to keep this effort going. The next step to combine to regional studies implies the need to combine the data and knowledge of a larger number of PIs. The major step towards this aim is the combination of data sets under the maintenance of the rights of the individual PI. In consequence two subworking groups were established with the aim to proceed in due time to a synthesis. A proposal for a procedure for further progress is included in the report.

#### Publications

To assess the viability of a special issue (or special section) of a journal devoted to presenting results of Southern Ocean WOCE, individuals were asked to provide a list of publications they plan to write. To provide a more complete picture of what was planned, we also asked people to list publications that were already submitted elsewhere or which were promised to some other publication. The results of this survey showed 24 papers were submitted or in press (showing that WOCE Southern Ocean results are being written up), 12 papers expected to be submitted by 1/98, and 17 papers expected to be submitted by 7/98.

On this basis we feel a special section of an issue of Journal of Geophysical Research is feasible, with a submission deadline of July 1998.

**Scripps-Lamont Consortium on the Oceans Role in the Climate system (CORC)**  
**Martin Visbeck**

THE SOUTHERN OCEAN AND GLOBAL CLIMATE

Scientific working team: Bob Anderson (LDEO), Wally Broecker (LDEO), Lloyd Burckle (LDEO), Chris Charles (SIO), George Denton (UM), Dale Haidvogel (RU), Sidney Hemming (LDEO), Doug Martinson (LDEO), Arnold Gordon (LDEO), Bill Large (NCAR), Sonya Legg (WHOI), Jim Price (WHOI), David Rind (GISS), Peter Schlosser (LDEO), Bill Smethie (LDEO), Robbie Toggweiler (NOAA-GFDL), John Toole (WHOI), Martin Visbeck (LDEO), Ray Weiss (SIO)

MOTIVATION

The motivation for the Southern Ocean component of CORC is to document and improve our understanding of:

- (1) The role of polar and sub-polar processes in regional and global scale climate variability; and,
- (2) The effect of global climate on regional and local scales within the polar and sub-polar region.

SCIENTIFIC OBJECTIVES

The overall scientific objective is to describe, understand, and simulate climate variability and abrupt climate change in the Southern Ocean and its global influences and response. Specifically, we will focus on the following questions:

- (i) What is the present mean state and the nature of the variability in the Southern Ocean?
- (ii) What are the local and regional processes and characteristics of the Southern Ocean that are most sensitive to climate change and/or most influential on global climate, and how can they be effectively represented in models addressing the different scales?
- (iii) What is the (tele)connection between climate change in the Southern Ocean and other regions on the globe?
- (iv) How have the fundamental characteristics of the Southern Ocean changed in the past, and what are the global, regional and local implications regarding the ocean property distributions, circulation and atmospheric forcing?

GENERAL APPROACH

These objectives can only be realized through a comprehensive, integrated program involving modern observations, paleoclimate reconstructions and modeling. We established a group of

scientists with expertise in at least one of these fields. The individual members of this group will closely cooperate to achieve the goal of an integrated approach to the scientific questions outlined above. The foci of the three subgroups are as follows:

- The modern observation studies will focus on: (i) the design and initial implementation of a long-term strategy to monitor hydrographic and tracer properties within the Weddell gyre and the production of Weddell Sea Bottom Water. (ii) Analysis of ice- ocean-atmosphere interactions and their variability within the instrumental record. (iii) Investigation of different deep and bottom water formation processes around the Antarctic continent and their importance for the larger scale circulation. Much of the proposed effort will provide data sets useful for model calibration, diagnostics and modification (e.g., through distributions of hydrographic parameters and tracers for observed forcings).

- Paleo observations will be used to reconstruct past changes in ice distributions, ocean circulation, and atmospheric circulation from records recovered both on land and in the ocean. Particular attention will be paid to temporal relationships between events identified in land and ocean records (establishing spatial extent and phasing), as well as between events in the Southern Ocean and their counterparts in the northern hemisphere. This will establish a baseline against which to gauge the extent of past changes and the mechanisms or conditions driving them.

- The modeling component will explicitly address the role of individual processes influencing the Southern Ocean characteristics over local and regional scales, and the nature of, and mechanisms governing, their global connectivity. The models will also be used to test (or generate) hypotheses emerging from both the modern observations and paleo reconstructions, and develop parameterizations of the critical local processes in the models of different scales.

Ultimately, the efforts of the three components will converge to isolate the critical components of the high latitude system, monitor their evolution, interpret their past and potential future variations, and predict their global implications.

## SPECIFIC PROBLEMS TO BE ADDRESSED

Here we only elaborate on the modern observation part of the project.

Scientific problems:

From an observational perspective the Southern Ocean and Antarctic region pose a major challenge to instrumental ocean observations. Parts of the basins are permanently ice covered making them difficult to access. Moreover, an enormous fraction of the Antarctic Sector is seasonally ice covered which significantly restricts the utility of standard measurement tools. It is currently not possible to make use of autonomous Lagrangian floats as a platform to obtain ocean observations because they are not able to detect the presence of sea-ice cover when surfacing. Moorings can not have surface expressions during the winter and large icebergs limit the depth of the uppermost sensors to 150-200m. The absence of commercial shipping activity (that can provide a platform for atmospheric and oceanographic sampling programs) have limited the data base for quantifying the air-sea-ice interaction processes and documenting their

change with time. We are currently sampling the Southern Ocean (with research ships) at a frequency that is inadequate to resolve oceanic changes in the face of intense monthly and seasonal variability.

Large regions of the Southern Ocean have not been sampled at all or just recently for the first time. Therefore, a significant fraction of the scientific research proposed here must be of explorative nature in order to develop testable hypotheses of the Southern Ocean's role in local, regional, and global climate.

The sparse historical data set makes it hard to define a climatology or mean annual cycle which then could be used as a baseline to detect climate variability as done successfully in other regions of the world's ocean. We have only rough estimates of the current water mass transformation rates for the Southern Ocean and only a poor knowledge of their variability. The poleward heat and freshwater transports in the Southern Ocean are quite uncertain because direct observations are not adequate and the indirect methods (by using the integral air-ice-sea interaction over the basin) are uncertain because of the presence of sea ice. Heat and freshwater fluxes from numerical weather forecast models have large uncertainties since they typically perform poorly in the Southern Ocean. Only at a few stations real time data are obtained to initialize those models. Improvement of this situation can be expected during the next decade with the availability of increasing amounts of space-borne remote sensing data.

## WORK PLAN

We will explore the Southern Ocean's role in the climate system by collecting new data as well as by analyzing historical data and data sets collected in the framework of recent cruises (e.g., WOCE cruises). We will focus our observational efforts on the Weddell Sea. The Weddell Gyre is one of the better studied regions in the Southern Ocean and seems the logical choice to establish a long-term observational effort. Given the limited amount of resources we have to maximize the efficiency of the new measurements. Therefore, close collaboration with scientists from other countries and with other US agencies is required to facilitate meaningful observational efforts. The existing connection between CORC and the iAnZone program and the possibility to work under the CLIVAR umbrella will provide a useful framework for such collaborations. In recent years we have been able to use such collaborative efforts to get access to research ships operating in the area of interest. We expect similar arrangements for the proposed field work and have received offers from US, German, Norwegian, Spanish, and Brazilian scientists to participate in their research programs. This will enable us to perform the proposed observations without direct costs for ship operation to this program.

We will combine the existing data sets with the regional modeling efforts of CORC to better understand the nature and variability of climate-relevant processes in the Southern Ocean. Ultimately, we would like to use information from both the paleo reconstructions and modeling efforts, together with knowledge based on modern observations to design an optimized and cost-effective observing system for key elements of the Southern Ocean climate system.

Initially, we will focus long-term observations on one basin to assess the current technology for detection and monitoring the variability of Weddell Sea deep and bottom water. A modest amount of moored observations of the outflow properties combined with biannual hydro-

graphic/tracer surveys across most of the Weddell gyre will be used as a starting point. We hope to advance and explore new technologies such as profiling moorings, floats and gliders that ultimately will be able to operate in such difficult environments.

These studies will be augmented by measurement and interpretation of circum- Antarctic tracer data sets to study the sites, processes and rates of deep and bottom water formation (CFCs, tritium). The tracer data will also be used to gain information on the interaction between shelf waters and the glacial ice sheets (helium and oxygen isotopes). Additionally, we will improve the description of the nutrient distributions around the Antarctic continent to better constrain the total rate of bottom water formation in the Southern Ocean derived from global C-14 and nutrient balances.

### Specific tasks

Our efforts can be divided into four parts:

#### (i) Biannual hydrographic section across the Weddell gyre

We are planning to revisit the Weddell Gyre at least during the summer of every other year to establish a hydrographic and tracer section time series (Gordon, Schlosser, and Smethie). This effort will be carried out in collaboration with other scientists from the US and the international community in order to be cost efficient. We envision a transect from the South Scotian Ridge towards either Cap Norvegia or the Maud Rise region. We seek support to obtain the hydrographic and tracer measurements on a ship of opportunity and analyze them in the context of other historical and modern data sets.

#### (ii) Transport and property moorings in the north-western Weddell

We will carefully design a mooring array to monitor the volume flux and property changes of Weddell Sea deep and bottom water (Toole and Visbeck). We envision to instrument a small section of 50-100 km length south of the South Orkney Islands. Ideally, this mooring array should be redeployed every year, but depending on the availability of research vessels we might have to consider two-year deployments. We propose to deploy the moored array eastward of the section that was instrumented by Fahrback (AWI, Germany) for the last few years because the expected ice cover is significantly less and should be accessible during the summer month by ice strengthened vessels (no ice breaker required). This will provide us with more opportunities to recover and redeploy the moorings.

#### (iii) Application of tracer data

Many of the Southern Ocean tracer sample sets collected during CORC phase I have not been fully analyzed due to substantial reduction in the originally proposed funding level. We plan to finish the analysis of these sample sets during phase II and to interpret the data in the context of other oceanographic data sets collected and analyzed by the physical oceanography group (Schlosser and Smethie). The CORC tracer data will be combined with the tracer data collected during several cruises in the 1980s, as well as with the WOCE data collected during the 1990s.

They will help to constrain the circulation pathways, residence times and rates of water mass transformation. The tracer data will be compared to simulated tracer distributions obtained from the regional models (cooperation with Martinson) with the aim of calibrating and eventually improving these models. This activity will be started early in the model development to ensure extensive communication between the tracer and modeling groups during the development of the regional models and to provide feedbacks from the modeling efforts to the tracer community with respect to optimization of future sampling schemes.

#### (iv) Analysis of historical data

We will jointly collect and inspect all historical hydrographic data from the regions of interest and make them available to the wider community. This data set will be the basis to develop testable hypotheses of mechanisms for climate variability in the Southern Ocean. Additionally, we will utilize inverse models to establish an advanced description of the mean circulation and mixing in the Southern Ocean. A more complete data set might also provide new insights into the variability of different water mass transformation processes. We envision close collaboration with the process and regional modeling efforts to establish the role that individual processes play in the coupled system and their susceptibility to climate change. We have already detected interesting variability in the temperature maximum of the intermediate layer and were able to get a first look at the change in bottom water temperatures in the central Weddell Sea. Ultimately we hope to correlate the instrumental records with climate proxies from ice cores and other high resolution paleoclimate data sets and link the local climate variability to global climate change.

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## **11. Next Meeting:**

The 6th iAnZone Meeting will be hosted by Alberto Piola, Servicio de Hidrografia Naval, Argentina. The Meeting will be held in Mar del Plata, Argentina in May 1999.



# AGENDA

**iAnZone**  
**INTERNATIONAL ANTARCTIC ZONE Program**  
**SCOR Affiliated Program**  
**5-th Coordination Meeting**  
**Meeting**

**ASPeCt**  
**SCAR/GLOCHANT**  
**International**  
**Coordination**

*December 1-5, 1997*  
*Biosphere-2*  
*Oracle, Arizona*

*While iAnZone and ASPeCt have some organizational issues unique to their programs, we aim to coordinate the two programs as much as possible (at least as much as the ocean and sea ice are coupled). This Draft Agenda is an attempt, though still less than perfect, to do so.*

## **Monday 1 December [ASPeCt Program]**

### 1. ASPeCt STRUCTURE and INTERACTIONS with GLOCHANT and WCRP

S.F. Ackley—Review of the ASPeCt Science Plan, formation of the Science Steering Group, and contributions to SCAR's Global Change in Antarctica Program

J. Priddle—Review of other GLOCHANT Activities in Polar Marine Science, primarily SO-JGOFS, SO GloBec and CZ-EASIZ. Potential Collaborations of these with ASPeCt.

V. Savtchenko—WCRP Antarctic Drifting Buoy and Ice Thickness Program: (E. Fahrback and V. Lytle—Results from ULS moorings on ice thickness)

### 2. DISCUSSION of Current Milestones in the ASPeCt Science Plan

A. Worby—Development of observational protocols and an observer's handbook

Compilation of existing data—Reports by:

A. Worby—Australian data sources from E. Antarctica

V. Smirnov/A. Klepikov (or A. Worby)—Russian Ice Chart translation program

M. Jeffries—Ross, Amundsen and Bellingshausen Sea cruises

S.F. Ackley, H. Eicken, P. Wadhams, R. Massom—Weddell Sea Ice Observations

Establish an inventory of potential contributors and forthcoming cruises—Reports by all SSG members of national programs and possible sea ice observation opportunities, including logistics cruises and process studies:

E. Zambianchi—Italian Program in Terra Nova Bay

A. Jenkins, J.L. Tison—Ice Shelf-Ocean Interactions

J.L. Tison—Ice Edge programs in the Belgian National program  
M. Jeffries— U.S. Ross Sea ice studies  
V. Lytle—Australian sea ice studies  
H.Eicken— German Weddell Sea ice studies  
S. Ushio—Sea ice and polynya studies in E. Antarctica  
J. Launiainen—Antarctic sea ice studies in the Finnarp and Scandinavian programs  
S.F. Ackley—U.S. Western Ant. Peninsula and Weddell Sea studies  
Others (as available)

3. Planning for US/Australia Coastal Polynya Study  
(Brief summary, Full report later during joint session with iAnZone)

4. Discuss implementation and location of an ice climatology data base—All Participants;

5. Plans for training Workshop for ice observers for future transects—S.F. Ackley and A. Worby

6. Ships and Programs of Opportunity

Report on upcoming APIS collaborations—S.F. Ackley  
Collaborations with iAnZone (to be discussed throughout the week).

Discussion of potential use of national program logistics and tourist cruises—All Participants  
Establish Protocol for Fast Ice Observations from Stations—All Participants

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**Tuesday, 2 December: Sea-ice and modeling science (joint ASPeCt and iAnZone session) [30 minutes for each lectures including question/discussion]**

1. J. Sarmiento—Impacts on Southern Ocean Carbon Cycle, sea ice and thermohaline circulation from the GFDL coupled model

2. P. Schlosser—Tracer Based Ventilation Research

3. D. Martinson/David Rind—Results from the GISS coupled model; southern ocean sea ice and thermohaline circulation

4. Zhang “Antarctic sea ice in a high resolution coupled ice-ocean model”

5. Howard Cattle “Hadley Center coupled model results for the Southern Ocean sea ice and thermohaline circulation”

6. Bill Hibler—The impact of high frequency effects (tides and inertial oscillations) on sea ice dynamics in coupled models.

7. D. Holland—Interactions of ice sheets and ocean circulation via floating ice shelves, modeling formulation and results.

8. Drinkwater “Antarctic sea-ice dynamics from satellite microwave data”
9. Comiso “Variability & trends of SST and sea ice in southern Ocean”
10. Padman “Weddell Tides”
11. Wakatsuchi “Bottom Water off Adelie Land”
12. Launiainen “Sea-air coupling in models”
13. Heywood “Antarctic coastal Current

Reception (Dinner)

-----**Wednesday, 3 December:**

**(iAnZone)**

1- (15 minutes) Introductions; objective of the meeting and Discussion and Approval of Terms of Reference for iAnZone

2- Review of Science results and achievements since our last meeting (Barcelona, Spain, March 1996):

- (1.5 hour) AnzFlux (AnZone experiment #2) lead by Miles McPhee (others: Guest)
- (1.5 hours) Dovetail (AnZone experiment #3) Fahrbach, Garcia, Muench, Gordon; Visbeck.
  
- (20 minutes each) Other National and Cooperative Projects- these talks should be primarily science results dealing with the ocean.

Russian- Klepikov  
Finland- Launiainen  
German- Fahrbach  
Indonesia- Syamsudin  
Japan- Ushio, Wakatsuchi  
China- Dong  
UK- Heywood  
USA-  
Italy- Zambianchi  
Other

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**Thursday, 4 December: iAnZone**

Review of international planning:

(30 minutes) Review of CLIVAR Southern Ocean Implementation Plan [Gordon and Martinson];

(30 minutes) Results of Cancun meeting [D.Martinson];  
(30 minutes) WOCE Southern Ocean Workshop [Fahrbach];  
(30 minutes) ACSYS and other WCRP programs [Savtchenko]  
Other

National and Cooperative Research & Monitoring Projects:

Weddell Quick Response Plans [Gordon];  
CORC [Visbeck]  
ACoPS  
ROPEX  
other

(4 hours) Develop plans for iAnZone #4 Experiment(s) [Report of ad hoc committee; group discussion];

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**Friday: 5 December: iAnZone and ASPeCt**

Coordination with ASPeCt, WCRP and other Programs;

iAnZone Steering Committee members: consideration of terms of appointment and identification of specific gaps and next meeting time/place.

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## **iAnzone National Reports**

Australia  
China  
Germany  
Spain  
United Kingdom  
Finland  
Korea  
France  
United States

### **Australian Southern Ocean Oceanography Program**

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13/April/1998

The Australian oceanographic field programme in the Southern Ocean has been largely driven by the goals of the World Ocean Circulation Experiment. This work has been also supported by ocean modelling activities within Australia. Most of the field work has been undertaken by the Antarctic Co-operative Research Centre, Australian Antarctic Division and CSIRO Division of Marine Research. Some work has also been undertaken by the Flinders University and the University of New South Wales.

### **Recent Programmes**

Figure 1 shows the major oceanographic programmes that have been undertaken in the last 8 years. The emphasis of the field program for this period has been the WOCE one time and repeat hydrographic sections defining the large scale circulation and water masses of the sub-Antarctic and Antarctic Zones (SR3, P11, S4, PET, and MARGINEX). In addition this field work has been supported by an XBT program of repeat measurements between Tasmania and the Antarctic continent aimed at determining the variability of the seasonal transport of the Antarctic Circumpolar Current. An extensive array of current meters were also deployed in collaboration with American scientists to determine the full depth profile of ocean currents and fluxes of heat and momentum across the ACC along the SR3 hydrographic section (Figure 1). The WOCE hydrographic sections (eg SR3 and one time sections P11, S4, PET, and MARGINEX) have also included biological and surface partial pressure of measurements, but two voyages were specifically dedicated to examining the carbon cycle in the sub-Antarctic Zone, and also across the SAF (SS9511 and SS9501).

### **Future Programmes**

Plans have been established for future oceanographic projects for the period 1998 to 2003 (Figure 2). These plans are guided largely by the national strategic plan. The high frequency sampling of the upper ocean thermal temperatures between Tasmania and Antarctica will continue (XBT programme). It is planned that Australia will participate in the CLImate VARiability programme through the sustained mea-

surements of the whole water column along the SR3 repeat hydrography section, and also along the WOCE I9 hydrographic section. These two sections will be occupied once every 5 years.

The Sub-Antarctic Zone field program has just been completed and has examined in greater detail the mechanisms of the carbon cycle in the surface waters of the two earlier cruises (SS9511,SS9501).

The POLYNIA experiment is a multi-disciplinary project, involving both sea-ice and oceanography, and is located in the Mertz Polynya, the largest polynya in this sector of Antarctica. Locally formed bottom water is found offshore in the deep waters here, and the aim of this experiment is to determine the role of brine rejection from the growth of sea-ice, and the onshore transport of saline Circumpolar Deep Water on the formation of these bottom waters.

ICE-T (Ice Time Series) is also a multi-disciplinary experiment, designed to examine the role of the retreat of the marginal sea ice zone on the biological communities on the carbon cycle in this region. The experiment involves sea-ice, biological and bio-geochemical scientists.

The oceanographic component of the AMISOR (Amery Ice Shelf- Ocean Response) experiment is designed to examine and monitor the thermohaline circulation beneath the Amery Ice Shelf. This experiments involves the deployment of current meters at the edge of the ice-shelf combined with fine resolution CTD/ADCP surveys across the front of the ice-shelf to estimate the ocean currents at the ice-shelf. Three holes drilled through the ice sheet extending from the ice-edge to the grounding zone will be used deploy current meters and temperature-conductivity sensors below the ice sheet to provide validation of the ocean flow beneath the shelf from numerical models.

KERGUELEN-WBC: is an experiment designed to determine the transport of the boundary current on the eastern side of the Kerguelen Plateau.

MARGINEX-WEST: a follow on to the MARGINEX experiment (January-February 1996) in the region 30E to 80E designed to define the rate of formation of bottom water and the large scale circulation of this region.

Figure 1. The Australian Southern Ocean oceanographic field programme for the period 1991-1996.

Figure 2. The Australian Southern Ocean oceanographic field programme planned for the period 1998-2003. Note that the field work for the SAZ experiment has already occurred.

**Chinese Oceanographic Research in the Southern Ocean, Antarctica**  
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**Abstract**

Since 1984, ten cruises have been made for oceanography to the Southern Ocean, typically in the regions of the Prydz Bay, the Southern Indian Ocean (62°S—69°S, 63°E—98°E), by the Chinese National Antarctic Research Expeditions (CHINARE). Scientific contributions in physical and chemical oceanography in the Southern Ocean, typically in/around the Prydz Bay and to the north-west of the Antarctic Peninsula including Bransfield Strait, in the scientific fields of water mass, circulation and ice-ocean-atmosphere interactions have been made. And the current five-year program mainly in the region of the Prydz Bay has been implimenting well on the way.

**1. Scientific Contributions**

Attentions in the Chinese marine science of the Southern Ocean from 1984 to 1989 was paid to the enhancement of interactions between physical, chemical and biological oceanography. From 1990 to 1995, the Eighth-Five-Year National Antarctic Research Program including marine science in the Southern Ocean was carried out with great progress in oceanography.

China has made contributions to physical and chemical oceanography in the Southern Ocean, typically in/around thePrydz Bay (62°S—69°S, 63°E—98°E) and to the northwest of the Antarctic Peninsula including Bransfield Strait, by success of CHINARE ten cruises to the Southern Ocean. And a series of data in physical and chemical oceanography have been obtained and a series of reports, monographs and scientific papers in oceanography of the study regions have been published.

Scientific contributions have mainly been made in the regions of the Prydz Bay, the Southern Indian Ocean, on water masses and circulation, fronts and its seasonal variability; chemical characteristics, distribution and nutrient cycle, sea-air exchange of sulfur, phosphorus and nitrogen in marine aerosols, mercury and fluoride in sea water, as well as carbon dioxide flux in the upper ocean, the study of the role of Antarctic sea ice and glacier ice in formation and modification of the Antarctic water masses.

**2. Future Plan**

China has started the Ninth-Five-Year Antarctic Research Programme including marine science of the Southern Ocean (1996/2000). One cruise of 1996/97 has been completed and the 1997/98 one is underway in the field. There will be two cruises to the Prydz Bay region during the austral summers of 1998/99 and 1999/2000.

And to deepen our understanding of oceanographic conditions in the region of Prydz Bay, we will make more research efforts on the topic of “Physical and chemical processes of interactions between ocean, ice and atmosphere and geochemical processes of biogenic elements (C, N, S, P)”.

- Physical and chemical oceanography and variability in/around the Prydz Bay region.
  - (1) AABW formation and spreading in the region of the Prydz Bay;
  - (2) Modification of water masses in the region of the Prydz Bay;
  - (3) ACC, fronts and their variability in the region of the Prydz Bay;
  - (4) Process of formation and dynamic variability of sea ice in the region of the Prydz Bay;
  - (5) Interactions among ice shelf, sea ice and water masses in the region of the Prydz Bay.
  
- Biogeochemical processes and variability in/around the Prydz Bay region.
  - (1) Mass flux of interface between ocean and atmosphere in the region of the Prydz Bay;
  - (2) Ecological process of the sea ice zone and its role in biogeochemical cycle in the region of the Prydz Bay.
  - (3) Primary productivity and new productivity in the region of the Prydz Bay;
  - (4) Biogeochemical processes of biogenic elements (C, N, S, P);
  - (5) Production of particles in the upper-ocean and its dynamic process;
  - (6) Geochemistry of selected isotopes;
  - (7) Dynamic variability of phytoplankton.

### 3. Attachment

- (1) Table: Chinese marine science cruises to the Southern Ocean
- (2) Reference 1 Publications
- (3) Reference 2 A Part of Scientific Papers

## Table Chinese marine science cruises to the Southern Ocean

Cruise No.	Cruise Date	Ship Name	Working Area
<b>Oceanographical Measurements</b>			
CHINARE No.1 Antarctic Pen.	Jan-Feb 1985	R/V <i>Xiangyang Hong No.10</i>	northwest of CTD, XBT, current, wave, nutrients <i>etc.</i>
CHINARE No.3 Islands as cruise No.1	Jan-Feb 1987	R/V <i>Jidi</i>	around South Shetland
CHINARE No.5 as cruise No.1	Jan-Mar 1989	R/V <i>Jidi</i>	Prydz Bay and its North
CHINARE No.6 around Elephant Island along sea ice edge	Jan-Feb 1990	R/V <i>Jidi</i>	Prydz Bay Region and deep-ocean CTD,XBT, current,nutrients;surface measurements
CHINARE No.7 above	Jan-Feb 1991	R/V <i>Jidi</i>	Prydz Bay and its North as
CHINARE No.8 above	Jan-Feb 1992	R/V <i>Jidi</i>	Prydz Bay and its North as

CHINARE No.9 Elephant Island	Jan-Feb 1993 R/V <i>Jidi</i> as above	Prydz Bay and around
CHINARE No.11 Bay and its North	Dec.1994- Feb 1995 as above	R/V. <i>Xue Long</i> Prydz
CHINARE No.12 CTD,ADCP,nutrients,surface measurements	Dec.1995 R/V. <i>Xue Long</i> on cruise track, <i>etc.</i>	Drake Passage
CHINARE NO.13 Bay and its North on cruise track, <i>etc.</i>	Dec. 1996— Feb. 1997 deep-ocean CTD, ADCP, XBT, nutrients, surface measurements	R/V <i>Xue Long</i> Prydz

### Reference 1 Publications

- (1) Report on 1984/1985 Southern Ocean Research, China Ocean Press, PP482, 1987 (in Chinese with English abstract).
- (2) Report on 1986/1987 Southern Ocean Research, China Ocean Press, 1989. (in Chinese with English abstract)
- (3) Proceedings of China First Symposium on Southern Ocean Research, Shanghai Press of Science and Technology, PP444, 1989. (in Chinese with English abstracts)
- (4) Proceedings of the International Symposium on Antarctic Research, China Ocean Press, PP540, 1989. (in English)
- (5) Biogeochemistry of Elements F, Se and I in the Southern Ocean, China Ocean Press, PP100, 1993. (in Chinese with English abstracts)
- (6) Antarctic Research A, Vol.1-10, No.1-38, China Science Press, 1988-1997 . (in Chinese with detailed English abstracts)
- (7) Antarctic Research B, Vo.1-8, No.1-16, China Science Press, 1990-1997. (in English)
- (8) Collecting Papers on Antarctic and Southern Ocean Research, Vol.1-6, China Ocean Press,1985-1997. (in Chinese with English abstracts)
- (9) Chinese Achievements in Scientific Research of Antarctica and the Southern Ocean, Modern China Press, PP548, figure 196, 1994. (in Chinese with English abstracts)

### Reference 2 A Part of Scientific Papers

- Chen Liqi, Yang Xulin and Huang Jianhuai (1989):** Sea-air exchange of sulfur, phosphorus, and nitrogen in marine aerosols over the Antarctic Peninsula waters. Proceedings of China 1st Symposium on Southern Ocean Research, held at Hangzhou from 5-10 May 1988, 126-132.
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## Report on German Projects

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The German work in the Weddell Sea was focussed on three topics:

1. Variations of the depth and bottom water properties in the Weddell Sea
2. Inflow of Circumpolar Deep Water in the Eastern Weddell Sea
3. Variations of the circulation and water mass properties off the Filchner/Ronne Ice Shelf

1. Variations of the depth and bottom water properties in the Weddell Sea

Manuscript in prep: Gradual Warming of the Weddell Sea Deep and Bottom Water by E. Fahrbach, R. Meyer, G. Rohardt, M. Schroeder and R. Woodgate, Alfred-Wegener-Institute for Polar and Marine Research, Columbusstrasse, D-27515 Bremerhaven, Germany

Between October 1989 and May 1996 five cruises with “Polarstern” were carried out to measure the water mass properties in the Weddell Sea by means of CTD and tracer surveys as well as by an extensive mooring programme.

The repeated CTD surveys in the southern and the central Weddell Sea (Fig. 1) and the temperature time series of moored instruments show a consistent increase of the temperature of the Warm Deep Water and Weddell Sea Bottom Water layers of large parts of the Weddell Sea. The warming is most pronounced in the Warm Deep Water layer which results from the inflow of Circumpolar Deep Water into the Weddell Gyre and can be traced back to the AJAX-section carried out in 1984. We conclude that the inflow from the Antarctic Circumpolar Current into the Weddell Gyre is either enhanced or has changed its characteristics since at least 1984. From 1992 to 1996 the warming propagated from the Warm Deep Water level into larger areas and deeper levels in particular north of Maud Rise. It is related to the change of the shape of the Weddell Gyre which was split into two distinct domes in 1992. The southern one centered at 62°30'S vanished between 1992 and 1996.

The variation of the major source water mass can be followed from the central to the western Weddell Sea. It leads either to a reduction of the bottom water formation or to a change of the characteristics of the recently formed bottom water. The temperature increase spreads from the west to the east and vertically. It is most pronounced in the Warm Deep Water and the Weddell Sea Bottom Water layers and barely noticeable in the Weddell Sea Deep Water. The warming in the bottom water continues over a period of 6 years with somewhat less than 0.01 K per year.

As the deep and bottom waters of the Weddell Sea spread into the global ocean, the observed changes must affect larger ocean areas and can most likely be used as an indicator to future developments.

2. Inflow of Circumpolar Deep Water in the Eastern Weddell Sea

Manuscript in press: Water Mass Transformation in the Eastern Weddell Gyre by Michael Schröder and Eberhard Fahrbach Alfred-Wegener-Institut für Polar- und Meeresforschung, Postfach 12 01 61, 27515 Bremerhaven, F. R. Germany

In the northeastern rim of the Weddell Gyre eastward flowing water masses from the Antarctic Circumpolar Current and the Weddell Sea converge due to the topographic constraint of the Southwest Indian Ridge. The convergence of the Weddell and Southern ACC fronts at 25°E enhances the meridional gradient and generates downwelling. The vorticity gain at the eastern edge of the ridge induces the formation of eddies which contain Circumpolar Deep and Weddell Sea water masses. Downwelling depresses the maximum of the cold regime Warm Deep Water below the maximum of the adjacent Circumpolar Deep Water to its appropriate density level. The Winter Water from the Weddell cold regime is depressed to the upper part of the Circumpolar Deep Water. The convergence of these two water masses allows the intensive frontal mixing. In the intense mesoscale eddy field between 15° and 30° E, eddies with water from the Weddell cold regime and the Antarctic Circumpolar Current waters mix and form the water masses of the Weddell warm regime. Southward flow entrains the eddies towards the southern rim current which flows westward and forms the Weddell warm regime.

In the vicinity of the Greenwich Meridian the westward flow is strongly affected by the topography of Maud Rise. The circulation pattern, transports and the transformation rate in the eastern Weddell Gyre are estimated on the basis of hydrographic data collected by RV "Polarstern" between 1989 and 1996.

The circulation and transformation of Warm Deep Water is schematically represented in Fig. 4. During the 1989 to 1994 period a flow of 26 to 29 Sv characterized by Warm Deep Water of the cold regime arrives at the northern rim of the Weddell Gyre at the eastern boundary. About 6 to 8 Sv recirculate within the cold regime to the west without being significantly modified. The remaining 18 to 23 Sv are injected into the mixing area with warm intrusions from the Antarctic Circumpolar Current leading to an increase of the temperature maximum from 0.5° to 1.2°C. As 25 Sv leave the area bounded by 15°E, 30°E, 55°S and 65°S, 2 to 5 Sv have to be injected from the circumpolar water belt. The increase in the volume transport of the gyre is not sufficient to explain the heat gain so that an additional heat input through intensive turbulent mixing has to be assumed. A flow of 5 Sv transits the warm pool along the eastern boundary and leaves the gyre to the east. The coastal current gains 5 Sv between 10° and 20°E and loses 3 Sv further to the east. In the warm regime 18 Sv recirculate to the west. During the 1996 survey, the transports are smaller. From 25 Sv circulating in the Weddell cold regime to the east, only 1 Sv recirculates in the cold regime across the Greenwich Meridian to the west. The warm regime flow north of Maud Rise amounts to 16 Sv. The coastal current lies with 8 Sv in the previously measured range. In this transport scheme no net transport from the Circumpolar Current is required.

We estimate the flow of Warm Deep Water from the cold to the warm regime as about 8 Sv for both time periods. This water mass is warmed from 0.5° to 1.2°C by 0.7 K, which requires a heat transport of  $2.3 \times 10^{13}$  W. According to Gouretski and Danilov (1993) a warm core ring has a heat excess in reference to the cold regime of  $0.2 \times 10^{20}$  J. After a life time of about 1 year, this heat is transferred to the cold regime. Consequently about 35 rings per year are required to supply enough heat to transform the cold regime into warm regime water.

Whereas the major inflow of Circumpolar Deep Water occurs at the eastern boundary of the Weddell Gyre, topographically-induced southward intrusions of warm water can be observed in the central Weddell Sea at about 20°W. Those intrusions lead to a relative warming in the level of the Warm Deep Water which contributes to heat flux from circumpolar regime into the Weddell Gyre.

### 3. Variations of the circulation and water mass properties off the Filchner/Ronne Ice Shelf

Manuscript in prep.: Water Mass Modification off and under the Filchner Ice Shelf in the Weddell Sea by Klaus Grosfeld, Michael Schröder, Eberhard Fahrbach and Rüdiger Gerdes, Alfred-Wegener-Institut für Polar-und Meeresforschung, Postfach 12 01 61, 27515 Bremerhaven, F. R. Germany

A combination of numerical model results and CTD-measurements during a cruise in the southern Weddell Sea in January and February 1995 is used to study the circulation and the water mass formation under the Filchner Ice Shelf, in the Filchner Depression in front of the ice shelf and over the shelf around the depression. The circulation in that area feeds into an overflow of water at the shelf edge which is observed as a distinct current vein at the continental slope. The circulation in the depression under the ice shelf has to be studied by model results only due to missing measurements, whereas the overflow on the slope is only investigated by field data only due to the limits of the model domain. The combination of both allows to diagnose the effect of the shelf-ice ocean interaction for the water mass formation in the southern Weddell Sea. Significant changes result in comparison to earlier studies. These changes are partly due to the changes of the shape of ice shelf from which three giant icebergs broke loose in 1986 and stranded north of Berkner Island. However, changes in source water masses advected from the north might be of relevance as well. Both affect the flow of High Salinity Shelf Water into depression. In consequence a water mass is formed which feeds directly from the shelf into the overflow. The deviated less saline flow permits enhanced mixing of High Salinity Shelf Water and Ice Shelf Water, which leads to weaker stratification the water masses in the depression and to a decrease of salinity in the deep layers. The overflow of Ice Shelf Water on the continental slope results from a shallow branch emanating from the sub-ice cavity which mixes with High Salinity Shelf Water. It is most likely that the formation of large icebergs occurs repeatedly in a decadal to centennial time scale as a similar event was observed by the second German Polar Expedition in 1912. We conclude that the formation of source water to Weddell Sea Bottom Water formation is subject to significant variations due to changes in the intensity of the involved processes.

### **Future Plans**

### **Report on German projects**

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“Polarstern”-cruise leg ANT XV/4 Punta Arenas - Cape Town (28. March to 21. May 1998)

The “Polarstern”-cruise ANT XV/4 will start on 28. March 1998 in Punta Arenas and will lead to the Weddell Sea (Fig. 1). The major scientific aim of the cruise is the investigation of the role of the Weddell Sea in global climate variations. The cruise will consist of two parts - the first will take place in the western Weddell Sea and the Weddell-Scotia Confluence, whereas the second will concentrate on investigations along the Greenwich Meridian between the coast of Antarctica and the Southwest Indian Ridge.

A major part of the deep and bottom waters of the global ocean are ventilated by water mass formation in the Weddell Sea. Its intensity controls the global thermohaline circulation and consequently the effect of the ocean on large scale climate change. Water mass formation in the Weddell Sea is driven by cooling in winter and consequent sea ice formation as well as by the interaction between the ocean and the ice shelves. On the shelf, water masses can be generated which are dense enough to sink to the bottom of the Weddell basin. During their descent, they mix with ambient water masses and are carried with the cyclonic Weddell Gyre circulation to the north where they partly leave the Weddell Sea towards the Antarctic Circumpolar Current and partly recirculate.

To investigate the water mass formation processes and their role in the thermohaline circulation, the programme consists of two components: to measure the outflow of newly formed waters from the Weddell Sea into the Antarctic Circumpolar Current in the Weddell-Scotia Confluence and to measure the characteristics of the water masses in the central Weddell Sea and their exchanges between the eastern and western Weddell Sea across the Greenwich Meridian. For this purpose, the water mass properties and the transport will be measured on sections across the Weddell-Scotia Confluence (Fig. 2) and along the Greenwich Meridian with a CTD-probe (Conductivity/Temperature/Depth) combined with a rosette water sampler and an ADCP (Acoustic Doppler Current Profiler). From the water samples, measurements of the following tracers will be carried out: CFCs (Freon-11 and Freon-12, Freon-113, CCl<sub>4</sub>), tritium, <sup>3</sup>He, He, and Ne. The CFC measurements will be done onboard by gas chromatography. For the other tracers, samples will be collected for subsequent analysis on shore. Salinity will be measured from the water bottles to control the CTD and the water samples. Current meter moorings will be recovered and redeployed along the Greenwich Meridian (Fig. 3, top) and in the western Weddell Sea off the Joinville Island (Fig. 3, bottom).

The physical oceanography programme onboard is part of the international DOVETAIL project (Deep Ocean VEntilation Through Antarctic Intermediate Layers), a contribution to the SCOR affiliated iAnzone programme (Scientific Committee on Oceanic Research). In this context, the instruments in the moorings in the western Weddell Sea will be provided by the Universitat Politecnica de Catalunya in Barcelona, Spain.

A project of sea ice investigations with remote sensing techniques aims to develop a new algorithm for cloud masking with infrared images. For this purpose in-situ data, e. g. observations of clouds and surface conditions, weather charts and radiosonde measurements, will be collected to validate the analyses.

Measurements of the CO<sub>2</sub>-system and nutrients will be performed to investigate the processes which determine the potential of Weddell Sea to take up atmospheric CO<sub>2</sub>. For this purpose, the total inorganic carbon content, TCO<sub>2</sub>, the total alkalinity, the partial pressure of CO<sub>2</sub> (pCO<sub>2</sub>) and pH will

be measured.

The cruise will end on 21. May 1998 in Cape Town.

# SPANISH RESEARCH ACTIVITIES IN THE ANTARCTIC ZONE FROM JANUARY '96

A report to iAnZone

Biosphere, Oracle, December 1997

## 1. FRUELA

The FRUELA multidisciplinary project aimed at assessing the carbon cycle in an area of high primary productivity. The selected study sites were the western basin of the Bransfield Strait, the Gerlache Strait and the southern part of the Drake Passage, so FRUELA can be envisaged as a Spanish follow-up of the 1986-87 RACER project carried out in the same area by the US. One of the most remarkable differences between FRUELA and RACER was the extent of the physical oceanography measurements, which were limited in RACER to the shallowmost 200 m layer only.

The FRUELA project was led by the University of Oviedo and involved about 60 researchers from different disciplines and institutes. The project was funded by the Spanish National Programme on Antarctic research. As for the experimental aspects, two successive cruises were conducted on board R/V Hesperides in December '95 and in January '96. In both of which, a basic "mesoscale" set of transects with 15 nautic miles between adjacent sampling stations was occupied (see figure 1) and additional stations were sampled in the Gerlache Strait (figure 2). A "microscale" sampling grid was also covered during the FRUELA '95 cruise to assess the lower mesoscale features of the local hydrographic structure and circulation.

The results of the FRUELA cruises are now being compiled in a number of papers that should be due for submission to DSR by March 1998. Figures 4 to 8 illustrate some interesting results extracted from the physical oceanography field work. Figures 4 to 7 show the distribution of T, S,  $\sigma_t$  and the geostrophic velocity at 10 m depth in the December '95 cruise "mesoscale" leg, and figure 8 shows the distribution of CTD fluorescence data at the same depth, which displays two important relative maxima northwest of the South Shetlands. The repeated survey performed in January '96 showed that these features were transient blooms possibly favoured by the late spring local hydrography (low surface densities leading to increased water column stability) and not linked to the CWB front, which can be best traced in the geostrophic velocity fields. On the other hand, vertical motions computed with the quasi-geostrophic omega equation showed to be too weak to sustain some initial thoughts that primary production could be enhanced significantly by hydrographic fronts in the study area.

## 2. DRAKE 95 and DRAKE 96

R/V *Hesperides* occupied the WOCE SR1b repeat section across the Scotia Sea both on 15-20 February 1995 and on 15-20 February 1996. In each cruise (hereafter referred to as DRAKE '95 and DRAKE '96 respectively), the same set of 21 hydrographic stations with characteristic spacing of 20 nm was sampled. On each station, surface-to-bottom CTD casts were performed with a MkIII C probe to obtain continuous profiles of temperature, salinity, dissolved oxygen concentration, fluorescence and light transmission, and water samples were collected at 24 levels. On the other hand, velocity profiles were recorded both en-route and on stations by means of a hull-mounted 150 kHz NarrowBand ADCP. The Skyfix station located in the Falkland Islands was used for DGPS positioning.

The results of the two cruises displayed the characteristic zonation of water masses defined by the four ACC hydrographic fronts -the Subantarctic Front (SAF), the Polar Front (PF), the Southern ACC Front (SACCF) and the Continental Water Boundary (CWB)-. The net geostrophic transport computed with reference to the common deepest layer of each pair of adjacent stations was similar in both cruises (about 140 Sv in DRAKE '95 and 131 Sv in DRAKE '96). However, closer comparison of the February 1995 and February 1996 results revealed changes in the structure of the ACC which in principle could be attributed either to the interannual variability of the ACC regime or to the current mesoscale activity. AVHRR imagery screened for us and provided kindly by UCSD's AARC has further shown that the main observed differences were related to the ACC mesoscale variability.

Figures 9 and 10 show the vertical distributions of potential temperature on SR1b derived from the DRAKE '95 and DRAKE '96 data sets using the same interpolation method (kriging with Surface Mapping System v. 5.00). Adopting the criteria proposed by Deacon (1933) and by Peterson and Whitworth (1989) to locate the core of the SAF and the PF in those distributions, we conclude that the SAF was approximately at 56°08'S in DRAKE '95 and at 55°52'S during DRAKE '96. A similar northward shift was observed in the case of the PF, the front core being at 57°17'S in 1995 and at 56°56'S in 1996. In contrast to that, the hydrographic signature of the SACCF defined according to Orsi (1993) was some 40 nm further to the south in DRAKE '96 with respect to its position during DRAKE '95.

Another remarkable feature is the dome-like structure centered on 59°30'S in figure 1, which is related to the discontinuity of the 1.5°C isotherm observed south of the SACCF in DRAKE '95. A similar structure was observed by King and Alderson (1994) on board RRS *James Clark Ross* in November 1993, but no such feature was observed in DRAKE '96. The DRAKE '95 ADCP data evidence that the previous feature was linked to a cyclonic circulation pattern (see figure 3). The inspection of available cloud-free AVHRR images

contemporary to the DRAKE '95 and DRAKE '96 cruises (not shown here) made us conclude that in February 1995 we steamed across the eastward-shifting cyclonic eddy which can be traced in the image northwest of Elephant Island at 59°30'S whereas we did not cut through any similar mesoscale structure in February 1996. Bottom-reaching cyclonic eddies as the one Hesperides steamed across at the southern Scotia Sea in February 1995 can play a crucial role in the export of Antarctic Bottom Water (AABW) to lower latitudes.

### 3. Future plans

#### 3.1. E-DOVETAIL

The Spanish participation in DOVETAIL comprises a summer cruise (E-DOVETAIL) by R/V Hesperides and the contribution of instruments to the "German-Spanish moorings" deployed southeast of Joinville Island. These moorings will be next serviced by R/V Polarstern in May 1998.

E-DOVETAIL will start in Ushuaia on 10th January 1998 and will end at the same port on 20th February. The cruise plan is sketched in figure 12. Field measurements will include CTD data, water sampling for salinity, oxygen, nutrients and Chlorophyll, shipborne ADCP measurements and hauls with plankton nets.

#### 3.2. DHARMA

A multidisciplinary study aiming at gathering a data base about microbial plankton in the northwestern Weddell and Scotia seas and at testing several hypothesis about the apparent uncoupling between phyto-, bacterio- and protistoplankton in Antarctic ecosystems will be carried out on board R/V Hesperides in December 1999. See study area in figure 13.

#### List of figures

Figure 1. Basic "mesoscale" transects of the FRUELA project.

Figure 2. Additional sampling stations occupied in the Gerlache Strait during the FRUELA '95 cruise.

Figure 3. "Microscale" sampling grid of the FRUELA '95 cruise.

Figure 4. FRUELA '95 cruise. Temperature at 10 m depth (°C).

Figure 5. FRUELA '95 cruise. Salinity at 10 m depth (psu).

Figure 6. FRUELA '95 cruise. Sigma-t at 10 m depth (kg/m<sup>3</sup>).



Figure 7. FRUELA '95 cruise. Geostrophic velocity at 10 m depth.

Figure 8. FRUELA '95 cruise. Fluorescence at 10 m (arbitrary units).

Figure 9. Observed vertical distribution of potential temperature on WOCE SR1b during DRAKE '95. Units are  $^{\circ}\text{C}$ .

Figure 10. Observed vertical distribution of potential temperature on WOCE SR1b during DRAKE '96. Units are  $^{\circ}\text{C}$ .

Figure 11. DRAKE '95 cruise. ADCP current velocity distributions on SR1b at depth layers from 16 to 96 m. "Blanks" are due to lack of data.

Figure 12. Sampling plan for E-DOVETAIL. Solid lines are transects with 15 nautic miles characteristic spacing between adjacent stations. Dashed lines are navigation-only transects.

Figure 13. Study area of the DHARMA project.

**UK Activities in the Antarctic Zone**  
**Brief Report for IANZONE, Biosphere 2, December 1997**  
**Karen J. Heywood**

**UK Results**

*1. Geneflow*

BAS have led an oceanographic cruise in the Scotia Sea in November 1997, with the primary goal of investigating the genetic relationships between organisms around South Georgia, the South Shetlands and the Antarctic Peninsula. The biological work was coupled with limited physical observations of the Weddell Scotia Confluence using CTD and ADCP, although unusually heavy ice cover was encountered so surveys were not as extensive as had been hoped.

(a ship track is enclosed with the hardcopy version of this report)

*2. Drake Passage Hydrography and Bottom Pressure*

SOC in collaboration with BAS have undertaken an (almost) annual repeat in 1993, 1994 and 1996 of the WOCE hydrographic line SR1 across Drake Passage. This is located underneath an ERS satellite track. The most recent occupation was December 1997-January 1998, which was completed with closer station spacing than previously, and which included a nutrient measuring programme. The time series is now yielding interesting results concerning the location of the polar front and the temperature of the bottom water. Bottom pressure recorders have also been maintained across the ACC on this hydrographic section. Bottom temperature at the southernmost BPR indicates interannual changes in the temperature of the AABW exiting from the Weddell Sea. The BPR data have been used to debate the wind forcing and variability in transport of the ACC.

*3. BAS Annual oceanographic surveys*

BAS have been undertaking surveys each austral summer in the region of South Georgia. These include a detailed survey over the shelf, and a CTD section between South Georgia and the Maurice Ewing Bank. These cruises are funded until 2000, with 3 of the 5 annual surveys already completed. The goal of this project is to determine the interannual variability in both the biological and physical environments. Initial results suggest that there is a connection between the ecosystem variability and ENSO.

*4. Flow of AABW through the Princess Elizabeth Trough*

Hydrographic, current meter and ADCP data collected during two recent cruises in the South Indian Ocean (*RRS Discovery* cruise 200 in February 1993 and *RRS Discovery* cruise 207 in February 1994) were used to investigate the current structure within the Princess Elizabeth Trough (PET), near the Antarctic continent at 85°E, 63-66°S. This gap in topography between the Kerguelen Plateau and the Antarctic continent, with sill depth 3750 m, provides a route for the exchange of Antarctic Bottom Water between the Australian-Antarctic Basin and the Weddell-Enderby Basin. Shears derived from ADCP and hydro-

graphic data were used to deduce the barotropic component of the velocity field, and thus the volume transports of the water masses.

Both the Southern Antarctic Circumpolar Current Front (SACCF) and the Southern Boundary of the ACC (SB) pass through the northern PET (latitudes 63 to 64.5°S) associated with eastward transports. These are deep-reaching fronts with associated bottom velocities of several  $\text{cm s}^{-1}$ . Antarctic Bottom water (AABW) from the Weddell-Enderby Basin is transported eastwards in the jets associated with these fronts. The transport of water with potential temperatures less than 0°C is 3 ( $\pm 1$ ) Sv. The SB meanders in the PET, caused by the cyclonic gyre immediately west of the PET in Prydz Bay. The AABW therefore also meanders before continuing eastwards.

In the southern PET (latitudes 64.5 to 66°S) a bottom intensified flow of AABW is observed flowing west. This AABW has most likely formed not far from the PET, along the Antarctic continental shelf and slope to the east. Current meters show that speeds in this flow have an annual scalar mean of 10  $\text{cm s}^{-1}$ . The transport of water with potential temperatures less than 0°C is 20 ( $\pm 3$ ) Sv. The southern PET features westward flow throughout the water column, since the shallower depths are dominated by the flow associated with the Antarctic Slope Front. Including the westward flow of bottom water, the total westward transport of the whole water column in the southern PET is 45 ( $\pm 6$ ) Sv.

## UK Plans

### 1. ROPEX (*Ronne Polynya Experiment*)

Keith Nicholls from BAS is leading an expedition to the Ronne ice shelf in January-February 1998 on HMS Endurance. The goals are to study the formation and outflow of Ice Shelf Water and High Salinity Shelf Water in the areas of the Ronne and Filchner ice shelves. The expedition includes collaborators from AWI and POL, involving recovery and deployment of current meter moorings, bottom pressure recorders, as well as detailed hydrography.

### 2. Drake Passage Hydrography and Bottom Pressure

It is hoped that the Drake Passage repeat hydrographic section will be maintained, possibly through CLIVAR, by collaboration between SOC and BAS. However funding for this exercise is always under scrutiny. We welcome any comments with which we can impress upon the funding agencies the importance of this time series.

POL also plan, subject to funding, to maintain the bottom pressure recorder and inverted echo sounder network in Drake Passage.

### 3. ALBATROSS (*Antarctic Large-scale Box Analysis and The Role Of the Scotia Sea*)

This proposal (see map) was submitted in November 1997 and we shall learn if it has been funded in March 1998. Shiptime on the RRS James Clark Ross has been requested for February 1999. The cruise would be a box of closely spaced CTD stations to WOCE specification enclosing the Scotia Sea. The cruise would be led by UEA. It would include measurement of tracers such as CFCs, O18 and helium/tritium. The goals are to quantify the outflow of AABW from the Weddell Sea through the Scotia Sea, the influence of waters from Drake Passage, and the dynamics of the ACC.

#### *4. SOIREE (Southern Ocean Iron Enrichment Experiment)*

This has been funded to take place in 1999 on German and South African vessels in collaboration with German and New Zealand colleagues. UEA will be responsible for the tracking of the iron enriched patch using SF6. The location of the experiment is not yet finalised.

## **Finnish Sea Ice and Atmosphere-Ocean Heat Exchange Studies in the Weddell Sea**

( J. Launiainen, T.Vihma, J.Uotila and B. Cheng )

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As a part of the Finnish Antarctic Research Program (FINNARP) an ocean - atmosphere interaction project was started in the early 1990s to study

- ice dynamics and ice mass transport out of the Weddell Sea, and
- heat exchange between the atmosphere and the ocean.

A specific practical goal of the project is to define areally representative heat exchange grid estimates for general circulation (GCM) models. In addition to experimental data and diagnostic studies, the project is accompanied by relevant modelling. The project has been designed to follow the goals of iAnZone, ASPeCt and IPAB (International Program for Antarctic Buoys). The project is based mainly on data from marine meteorological satellite buoys. The buoys were deployed on drifting ice floes, in the open ocean and on a floating continental ice shelf. The total amount of buoys deployed in 1990-1996 was 12. Three meteorological buoys were deployed in 1990, two in 1992 and four in 1996. In 1996, additionally, 3 position drifters were deployed. Data from three of the 1996 buoys deployed in late January and early February were gathered up to May 1997. In addition to buoys, marine meteorological surface observations and atmospheric radiosonde soundings were made from the research vessels.

The data from the all 12 buoys have been reported in technical reports and the data can be obtained from the authors. The studies of the sea ice dynamics have been reported in Vihma and Launiainen, 1993 (J. Geophys. Res.,98:14471-14485) and in Vihma et al., 1996 (J.Geophys.Res.,101:18279-18296). The study of 1996-1997 data is still in progress. The drift trajectories of the buoys deployed in 1996 are given in Fig. 1. The results indicate the sea ice dynamics in the Weddell Sea to be primarily wind-dependent in time scales of days, except in cases of high concentration and internal ice resistance. The mean ice drift is 2 to 3% of the local wind speed and directed  $10^{\circ}$  to  $30^{\circ}$  left from the wind. The ice drift kinematics shows apparent differences between the eastern and western part of the Weddell Sea. Inertial motion was detected from the ice drift in areas east of  $35^{\circ}$  W especially in summer and in less compact ice fields, as revealed by the trajectory of a free drift movement of our research vessel anchored to a 0.7km x 0.9 km ice floe in January 1996, in Fig. 2. Less periodic movements were detected in the central area around  $40^{\circ}$  W, and in the west the data indicated periodic motions presumably dominated by the  $M_2$ - tide. Various simulations for the ice drift were made using the local wind as the forcing, and the ice drift was also analysed with respect to the geostrophic wind. For time scales longer than weeks, purely wind-based simulations resulted in a discrepancy between the observed and simulated trajectories, but the inclusion of a slow residual current (0.02 m/s to NNW) made the simulations significantly better. The geostrophic wind was found to provide almost as good a basis for the general drift estimation as the surface wind observed by the

buoys.

In early February 1996, one buoy was deployed (73.1°S, 37.6°W) in an extensive ice floe connected with a mile-long ice berg. Before mid-March 1996, the assumed time of detachment of the ice berg from the flow, the behaviour of the floe (buoy) was rather different from the experience gained from the previous observations and from the other buoys drifting in the field in that time. For example, rotation of the ice floe was less than that of the other floes, and, the speed ratio between the wind-induced drift and the wind was lower, from 1.6 to 2.2 %. In the statistics of the speed ratio in Fig. 3a, this is seen as a binodal distribution, which is distinct also for the turning angle distribution in Fig. 3b. The turning angle was higher, 25 to 40°, for the first part of the period, suggesting e.g. a vertically integrated effect of the Ekman layer on the ice floe connected with an ice berg.

Ice export out of the Weddell Sea (through section from the tip of the Antarctic Peninsula to Kapp Norwegia) has been estimated on the basis of the geostrophic winds, the drifts response to the wind and, on literature information on ice concentration and thickness. The mean annual net sea ice export in 1992-1994 varied from 11000 to 39000 m<sup>3</sup>/s and the most of the net export took place in winter and spring. The figure for 1996 was 54000 m<sup>3</sup>/s.

Heat exchange calculations were reported in Launiainen and Vihma, 1994 (Geophys. Monogr. Ser., AGU, 85:399-419). The studies with the data from the 1996 field campaign data is in progress, to report year-round calculations of air-ice-sea heat exchange. An estimate for heat exchange components over leads is given in Fig. 4. In the air-sea exchange problematics, a main question rises how to derive areally representative exchange estimates for a mixture of ice and leads, for which the surface heat exchange components differ significantly mutually, and the turbulent fluxes are frequently even different in direction. This problem has been addressed by various "mixture" parameterization methods and by using information of 2D modelling (cf. Vihma, 1995; J. Geophys. Res., 100:22625-22646). One more crucial issue of heat calculations over ice and snow is how to define the real (skin) surface temperature necessary for the bulk aerodynamic exchange calculations. The surface heat balance causes the interfacial temperature to be different from the air temperature or that of in-ice temperature, as measured by ordinary measuring equipments. For the purpose, a high resolution 1D model (Launiainen and Cheng, 1998; in press) is being used and Fig. 5 gives an example of ice-air vertical temperature profile and fluxes. Additionally, the model can simulate the thermodynamic ice growth and is connected as a module with the 2D model above, by which also e.g. the local atmospheric boundary layer can then be better studied.

This seems to be especially worthwhile realizing e.g. a high discrepancy between the ECMWF (model based analysis) surface air temperature and the buoy air temperature given in Fig. 6.

Within a couple of next years, our main efforts concentrate still with sea ice dynamics, ice transport estimates and to produce areally representative values for heat and momentum fluxes. In future, we'll plan further to contribute to the IPAB and experiments of iAnZone and ASPeCt, e.g. contributing to the planned polynya experiment or/and to the drifting ship and ice stations in the time frame round 2002 to 2005 .

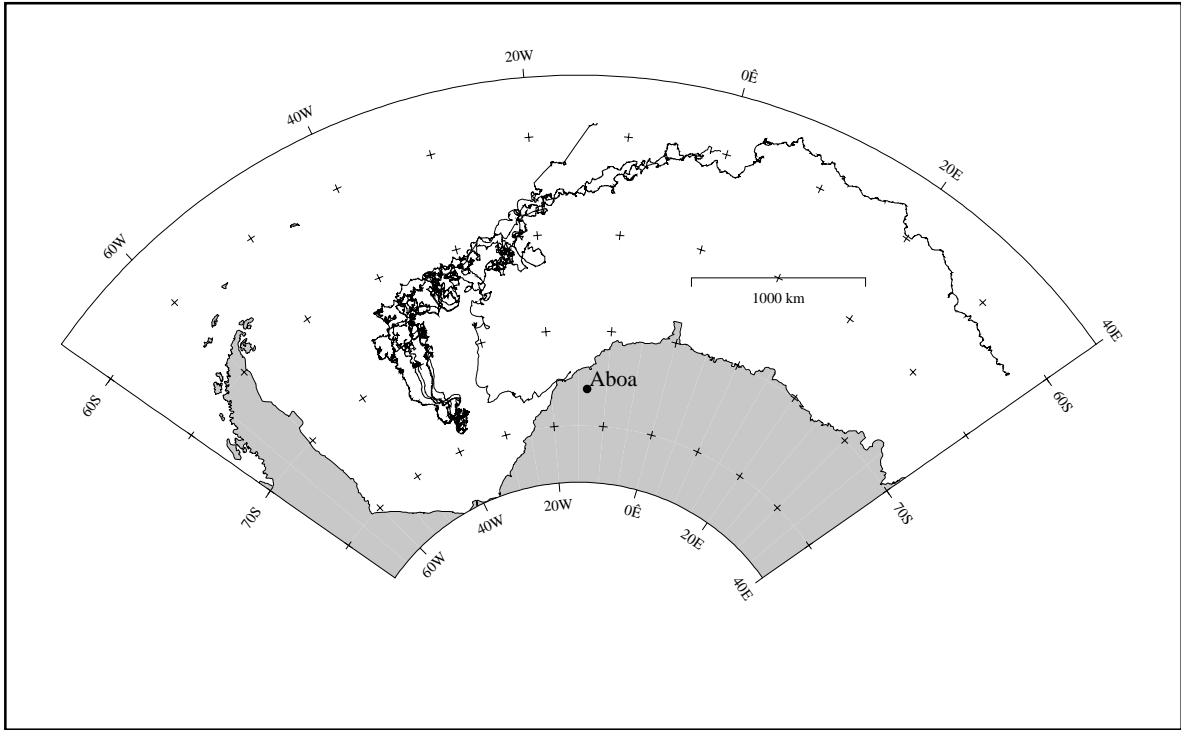


Fig. 1. Drift trajectories of the seven buoys deployed in ice floes in January- February 1996.

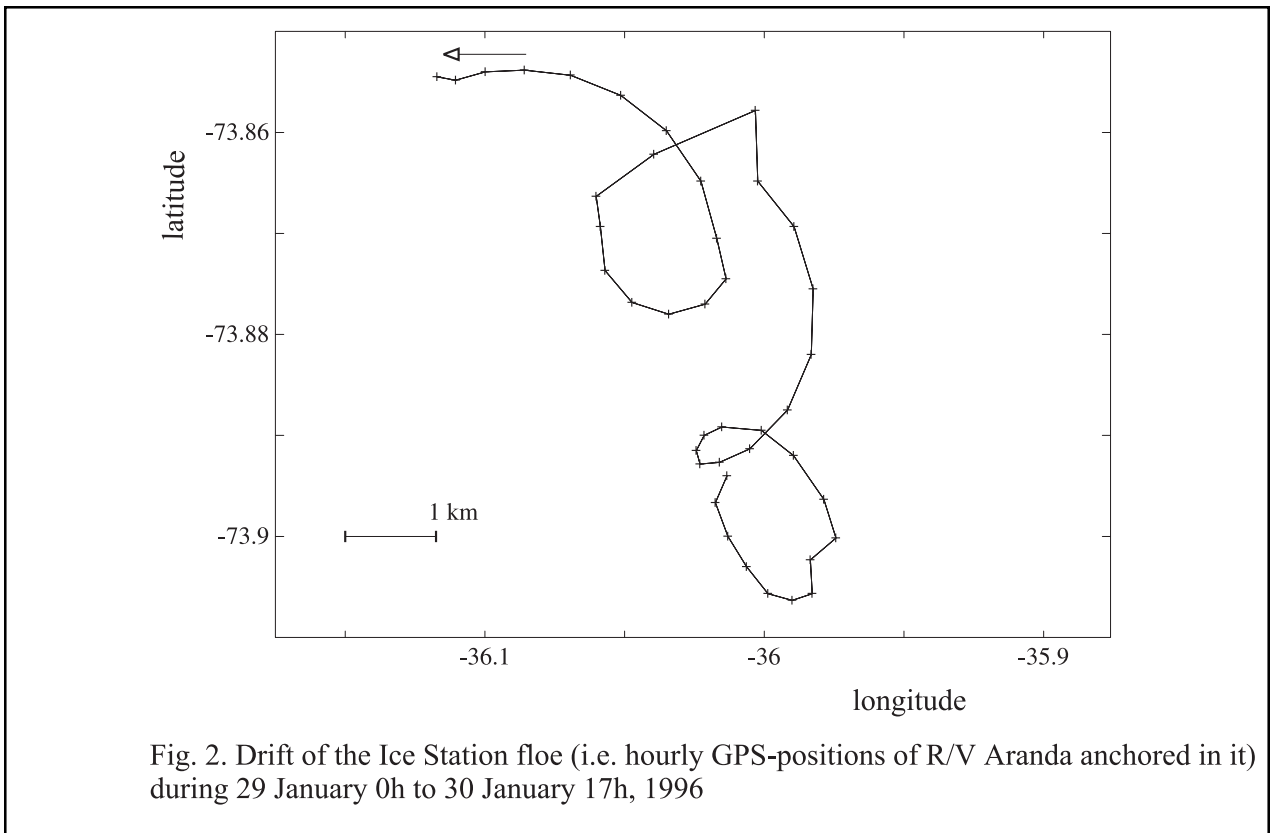


Fig. 2. Drift of the Ice Station floe (i.e. hourly GPS-positions of R/V Aranda anchored in it) during 29 January 0h to 30 January 17h, 1996

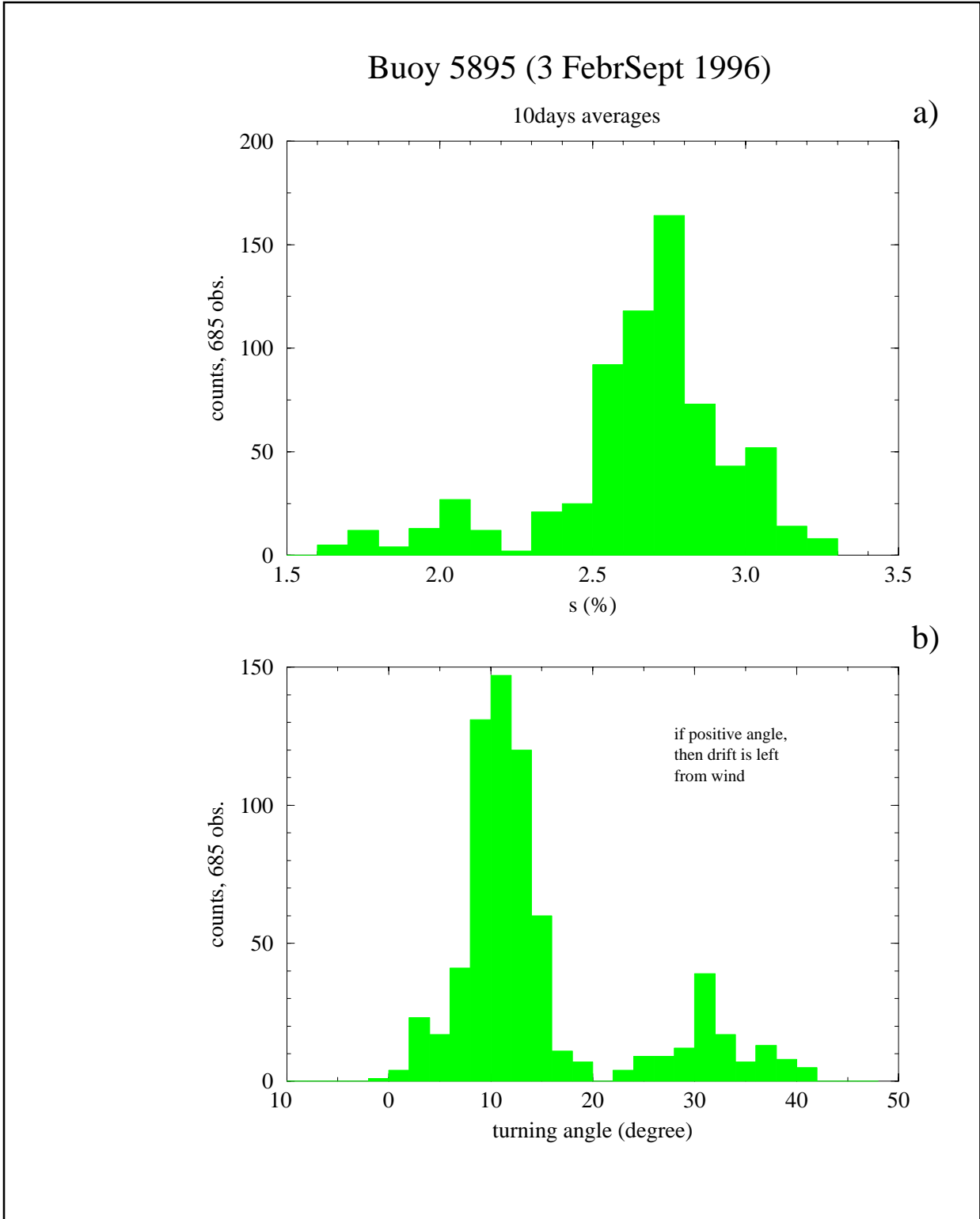


Fig. 3 a. Distribution of the speed ratio between the wind and wind induced drift.

3 b. Distribution of the turning angle between the local wind and wind induced drift. Positive angle indicates a drift left from the wind.



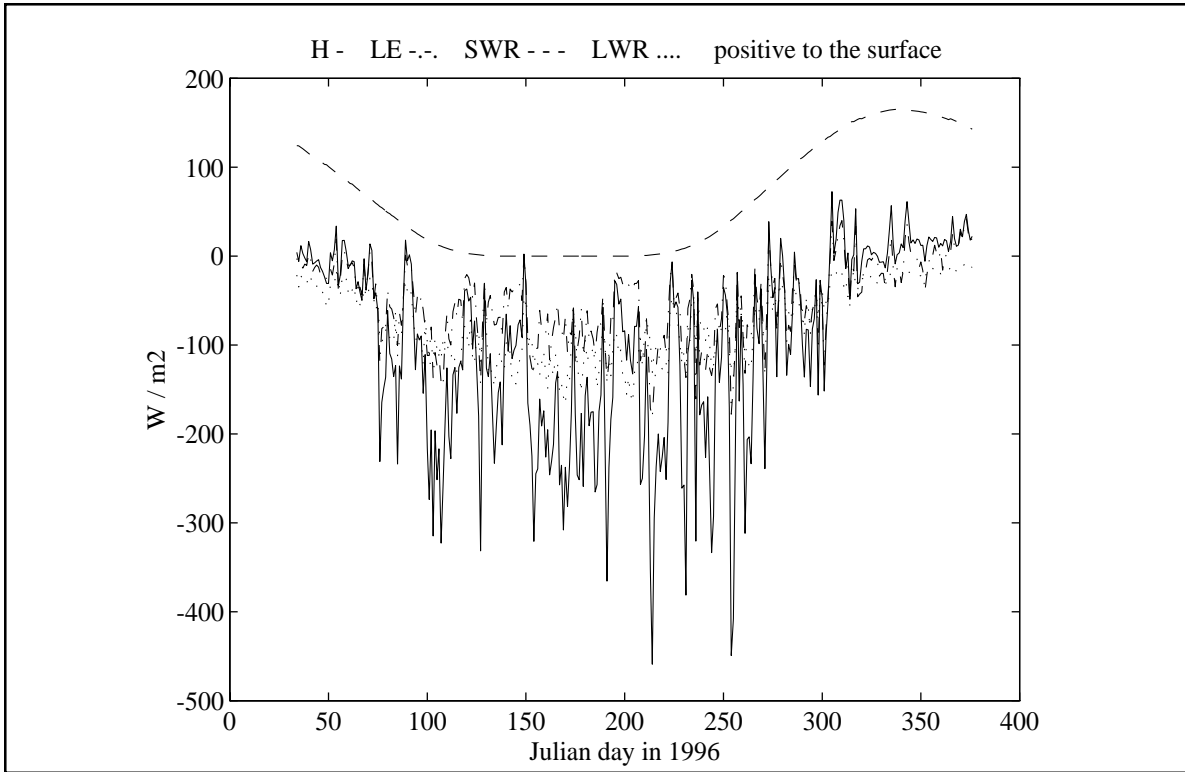


Fig. 4. Estimates of ice surface energy balance components over leads based on the buoy data. Sensible heat flux H, latent heat flux LE, net short-wave radiation SWR, net long wave radiation LWR.

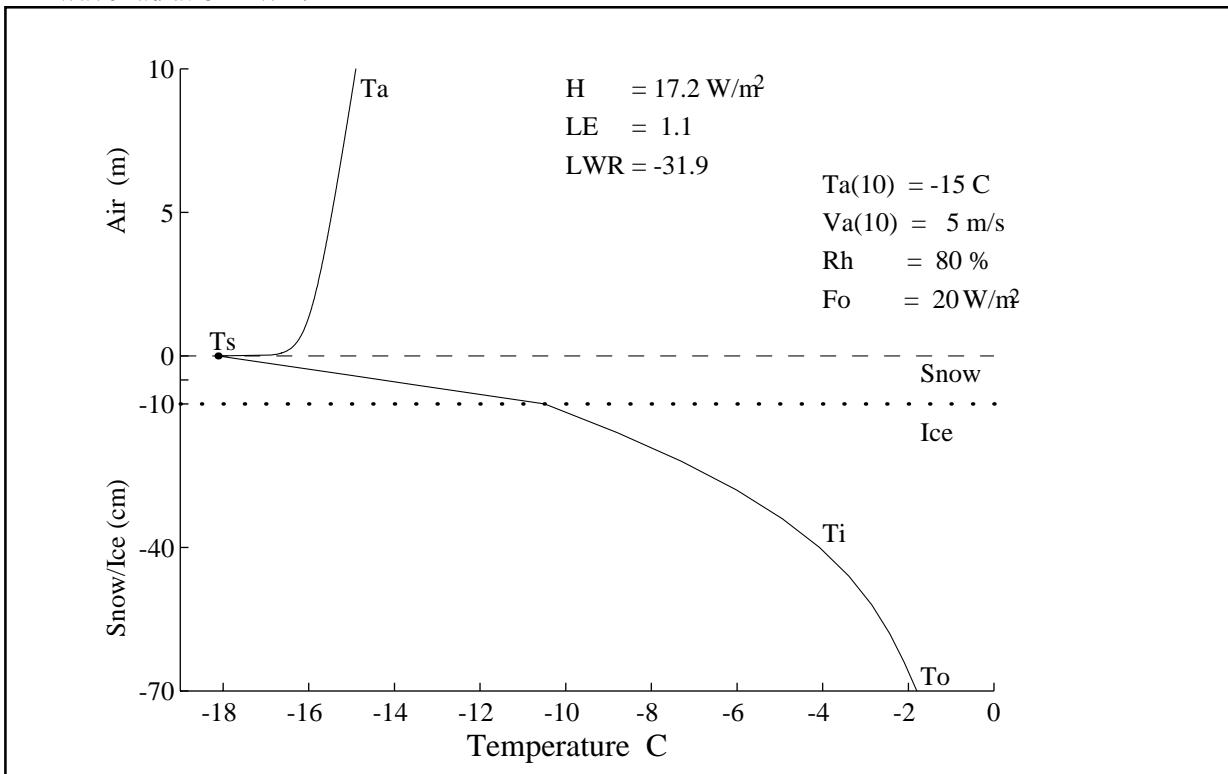


Fig. 5. Model estimated ice ( $T_i$ ) and air temperature ( $T_a$ ) profiles, and air-ice surface fluxes of sensible heat ( $H$ ), latent heat ( $LE$ ) and net long-wave radiation ( $LWR$ ). Stationary forcing of  $-15\text{ }^\circ\text{C}$  air temperature,  $5\text{ m/s}$  wind speed,  $80\%$  relative humidity and,  $20\text{ W/m}^2$  heat flux from the ocean, respectively. The sea ice is  $60\text{ cm}$  thick and covered by  $10\text{ cm}$  snow.

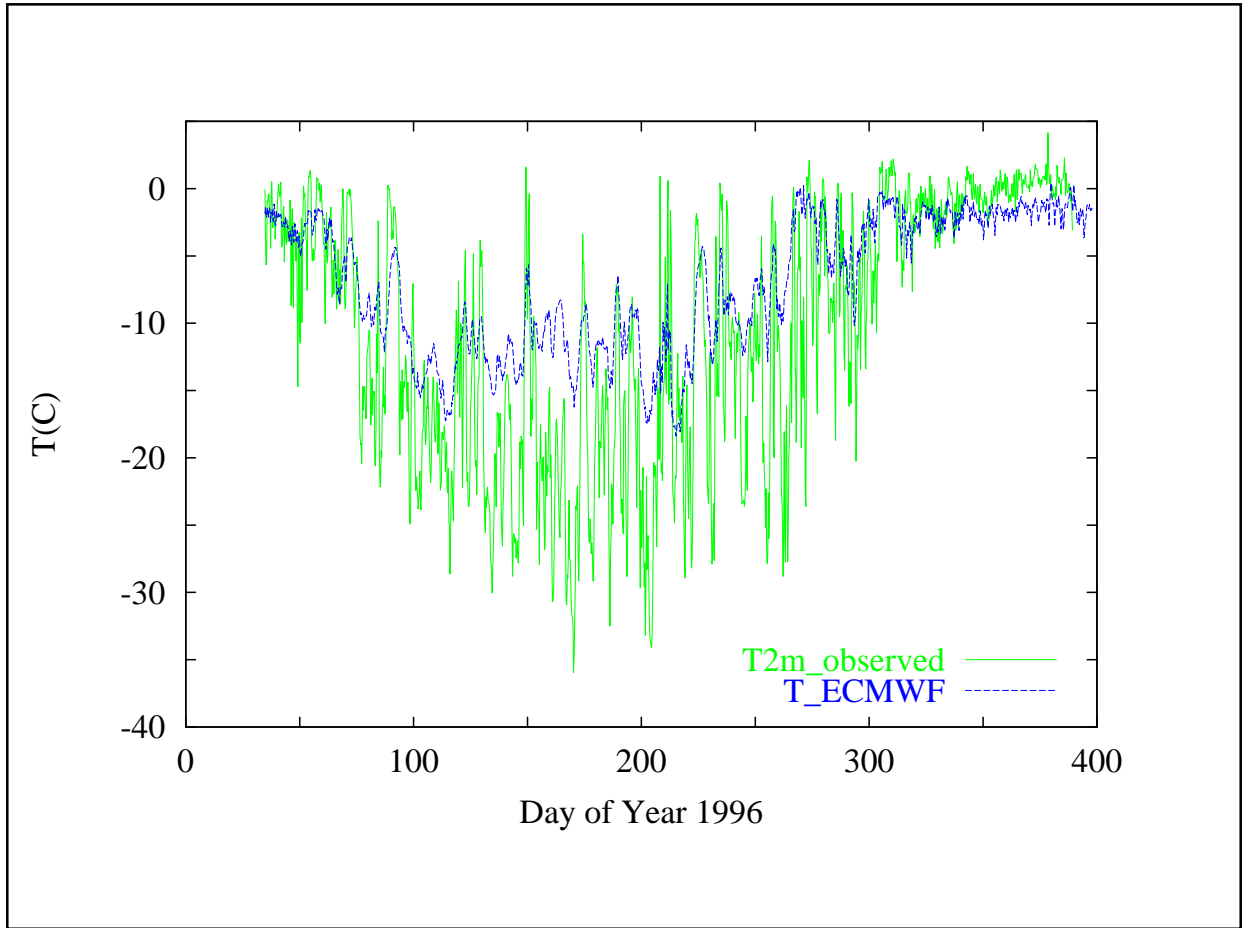


Fig. 6. Time series of the ECMWF given (broken) and buoy observed (dotted) air temperature in the Weddell Sea in 1996.

## NATIONAL REPORT FROM KOREA

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### Objective

To make advances in the quantitative knowledge of Antarctic coastal environment

The field work performed during the 1997/1998 field season

The field work is performed as a part of the eleventh Korea Antarctic Research Program.

- 1) Accomplishment  
Mapped oceanographic variables and deployed current meters off Joinville Island
- 2) The period of field observation: 17-21 January 1998
- 3) 13 stations on hydrographic Section between (54°W, 63.07°S) and (51.63°W, 62.40°S)
- 4) Observed Variables; Abundance of zooplankton and micro-algae, concentrations of suspended sediment and nutrients, temperature and salinity, DO,  $\delta^{18}\text{O}$
- 5) current-meter mooring  
location: (62° 50.154'S, 53° 12.871'W)  
water depth: 766m  
C-M depths: 500, 600, 700m  
mooring period: approximately one year

### Future Plans

- 1) Cruise for current-meter recovery and hydrographic survey in 1998/1999 field season
- 2) Study of parameterizations used in circulation models for Antarctic coastal ocean



## **USA iAnZone Program**

Prepared by A. Gordon

Much of the US research related to iAnZone is reported in the AnzFlux (iAnZone Experiment #2) by M. McPhee and in the DOVETAIL (iAnZone Experiment 3) by R. Muench sections of this report. Varied sea ice studies will be included in the ASPeCt report. The US Antarctic Journal Sept/Oct issue of each year reviews the US Ocean Sciences programs supported by NSF Office of Polar Programs. A useful source of information regarding the US Southern Ocean program can be obtained from the web site: <http://www.nsf.gov>.

As L. Padman was unable to attend the iAnZone workshop and that his 1997/98 research is of direct relevance to iAnZone, a description of his research downloaded from the US NSF Office of Polar Programs web site follows:

### **Turbulent mixing near the Filchner-Ronne Ice Shelves.**

**Laurence Padman, Oregon State University**

(present affiliation 'Earth & Space Research').

This study concerns the formation processes of Weddell Sea Bottom Water, a very cold and saline water mass found at the continental shelf edge of the southernmost Weddell Sea. The formation process is believed to involve saline but warm Circumpolar Deep Water and extremely cold but relatively fresh Ice Shelf Water, but little is known about the process itself. Weddell Sea Bottom Water is important because it is a precursor to Antarctic Bottom Water, a dense, globally distributed water mass. The outflow of Ice Shelf Water from beneath the Filchner-Ronne Ice Shelf has been the subject of a continuing international field program.

In February and March of 1998, a British Antarctic Survey (BAS) cruise on board H.M.S. Endurance will focus on the oceanic and atmospheric exchange processes within the open water at the face of the ice shelf. This study is an integral part of the scientific program of the cruise and will concern the mechanisms responsible for the mixing of Ice Shelf Water with other regional water masses as it emerges from under the ice shelf. The measurements that will form the basis for the analysis include:

1. vertical profiles of temperature, conductivity, and velocity microstructure;
2. acoustic doppler current profiles; and rapidly sampling temperature sensors mounted on BAS current meter moorings.
3. Datasets collected by other participants in the cruise will include: atmospheric measurements; a regional survey of the hydrographic structure of the upper ocean; and satellite-based remote sensing products. (S-265)

Stan Jacobs, Lamont-Doherty Earth Observatory, Palisades, New York ([sjacobs@ldeo.columbia.edu](mailto:sjacobs@ldeo.columbia.edu))

### **Circumpolar Deep Water and the West Antarctic Ice Sheet**

A primary facet of the ASPeCt/iAnZone meeting at Biosphere 2 concerned future plans. On that topic little could be said at the time, as proposals for a U.S. component in the Mertz Polynya and Antarctic

Pack Ice Seal programs had recently been scuttled. However, we have subsequently learned that NSF/OPP will support proposed oceanographic work on the continental shelf in the Amundsen Sea. The field program will most likely be carried out from the *NB Palmer* in the February-March time frame during the last year of the present millenium, and/or the first year of the next. While this project does not qualify as an official iAnZone program, not having been discussed at any meetings, a brief summary of the proposed work appears below. We would welcome synergistic collaborations, particularly with investigators who utilize remotely-sensed data and seawater chemistry.

We hypothesize that Circumpolar Deep Water is a significant factor in the attrition of the West Antarctic Ice Sheet. Field work to investigate that concept will focus on the continental shelf of the Amundsen Sea, where a 1994 survey revealed area-averaged basal melting in excess of 10 m a<sup>-1</sup> beneath the fast-moving Pine Island Glacier. This record-high melt rate results in part from 'warm' deep water that strongly intrudes onto the Antarctic continental shelf in this sector, and elsewhere in the southeast Pacific. The sea floor of the little-studied Amundsen shelf will be mapped in as much detail as allowed by a typically perennial sea ice cover. Conductivity-temperature-depth instruments and acoustic doppler current profilers will be used to define the pathways and strengths of deep water transport onto and along the continental shelf, and flow into and out of the sub-ice cavities. Short and/or long-term moorings will be set, depending upon equipment availability and odds for recovery. Basal mass balance will be calculated from salinity budgets and from velocities measured in the inflowing deep water and outflowing meltwater plumes. Particular efforts will be made to determine the basal melt rates of Thwaites Glacier Tongue and one of the long, heavily-pinned ice shelves like the Getz or Abbot. Results from this project will furnish the data to validate models of the regional sub-ice circulations, and to update estimates of the current ice sheet mass balance.

### **JGOFS Southern Ocean Program**

A major effort of the US Southern Ocean program in 1997-98 of some relevance to iAnZone is that of the JGOFS Southern Ocean Program, a 3-year effort south of the Antarctic Polar Front Zone in the southwest Pacific sector. It is aimed at:

1. understanding better the fluxes of carbon, both organic and inorganic, in the southern oceans;
2. identifying the physical, ecological, and biogeochemical factors and processes that regulate the magnitude and variability of these fluxes;
3. placing these fluxes into the context of the contemporary global carbon cycle.

The southern oceans are critical in the global carbon cycle, as indicated by the region's size and the important physical processes that occur in it (e.g., deep and intermediate water formation), but its quantitative role in the contemporary global carbon cycle is uncertain. Because the broad continental shelf of the Ross Sea is characterized by relatively high biomass with large phytoplankton blooms in the austral spring and summer, this region has been selected for intensive process studies as part of the U.S. JGOFS comprehensive investigation of carbon and biogenic fluxes in the southern oceans.

## **National Report - Italy**

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Italy participates in the activities of the international scientific community in Antarctica through the research undertaken in the framework of the PNRA (Programma Nazionale di Ricerche in Antartide = National Programme for Antarctic Research). Within the PNRA, a specific project has been designed, called CLIMA (Climatic Long-term Interaction for the Mass-balance in Antarctica), whose scientific responsible is Prof. G. Spezie, of the Istituto Universitario Navale of Naples, devoted to examining the physical and biogeochemical characteristics of the Ross Sea, the traditional focus of the Italian oceanographic investigations.

In the last four years two major oceanographic cruises have been carried out in the area of the Ross Sea, in the 1994-95 and 1997-98 austral summers. In particular, in the austral summer 1994-95 more than 150 hydrological stations were performed, clustered in three subregions: Terra Nova Bay, South East of Cape Adare and off the Ross Ice Shelf Edge. A wider and more widespread station network was covered in the 1997-98 cruise, during which more than 200 CTD casts were carried out over the whole Ross Sea, even if the massive presence of sea ice did not allow to get close to the RIS edge. The choice of the subareas was motivated by the search for the Antarctic bottom water formation sites and dispersion paths in the Ross Sea. Among the most outstanding results of the cruises we can mention a very accurate description of the formation of the High Salinity Shelf Water in the region of the Terra Nova Bay polynya and of its spreading along the shelf off Cape Adare (both cruises), as well as a very satisfactory mapping of the tongue of Shallow and Deep Ice Shelf Waters exiting from underneath the Ross Ice Shelf Edge (1994-95 cruise), and an estimate of their residence times. In addition, in the 1997-98 cruise two mesoscale experiments were performed, aimed at investigating the shelf-slope processes affecting the spreading of the Antarctic bottom waters formed in the Ross Sea. Besides temperature and conductivity/salinity, a series of other biogeochemical parameters were measured at the stations, such as oxygen, nutrients, suspended particulate matter, phytoplankton, obviously along with meteorological data and with remotely sensed sea surface temperature and ice coverage over the whole area.

Several moorings have been deployed, maintained and recovered over the last four years, equipped with current meters, portable CTD units and bottom traps. As of the end of the 1997-98 cruise, four moorings are still collecting data in the Ross Sea, namely in the polynya area in Terra Nova Bay, North of the Drygalsky Glacier tongue, off the Ross Ice Shelf Edge and in the center of the Ross Sea, and will be recovered next year.

XBTs have been routinely launched from the R/V *Italica* on the route from New Zealand to Terra Nova Bay, roughly corresponding to the P14S WOCE section, covered three or four times a year (including the austral summers 1995-96 and 1996-97, in which the oceanographic activity was essentially limited to mooring maintenance and to the deployment of XBTs and drifters across the Antarctic Circumpolar Current). Almost 1000 probes were deployed, providing an excellent description of the hydrological structure of the upper 700 m of that sector of the Southern Ocean, with its multiple

frontal structure, and in particular of the ACC.

The dynamics of the ACC both at the surface and at around 1000 m depth was also investigated by Lagrangian measurements: along with the XBTs, surface drifters have been deployed every year between New Zealand and Terra Nova Bay, and have been providing data concerning the structure of the ACC over the whole Pacific sector of the Southern Ocean in terms of the velocity field, of the kinetic energy of the mean and of the eddy field, of the eddy momentum flux and of the shear and vorticity fields. Subsurface drifters were deployed at the beginning of the project and are still yielding information on the flow at depth.

No final plan for future activities has been officially approved as yet; however, we expect to carry out another large scale cruise in the austral summer 1999-2000. Locally focussed investigations will be mainly concentrated on the Terra Nova Bay polynya, which Italy will be monitoring in the framework of ASPECT activities. Next year, i.e. austral summer 1998-1999, will be only devoted to recovering the four moorings left and to deploying, again, XBTs and surface drifters across the P14S section.



## Abstracts

### VARIABILITY AND TRENDS IN ANTARCTIC ICE EXTENT AND SURFACE TEMPERATURE FROM SATELLITE AND SURFACE MEASUREMENTS

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#### ABSTRACT

Long term changes in the Antarctic sea ice cover have been a subject of interest because they may provide early signals of a potential global warming induced by increasing CO<sub>2</sub> in the atmosphere. In 1997, two papers on Antarctic sea ice trend and variability using basically the same set of satellite data were published, but one shows a negative and insignificant trend in ice extent, while the other shows significantly positive trend. Inconsistencies in such studies are not unexpected because the historical data set consists of data from several satellite sensors launched during different time periods and not having exactly the same instrumental characteristics. While attempts were done in both studies to correct for sensor differences by making results compatible during overlap periods, the correction techniques used were not the same. Also, there are other factors that can affect the trend results such as the handling of weather and land contamination effects. It is, however, apparent that there are some areas, like the Bellingshausen/Amundsen Seas where the trend results are consistently negative, and have been established to be well correlated with temperature trends. To get these results in proper perspective, studies of surface air temperatures from station data around Antarctica have indicated predominantly positive trends, which are as high as 0.5K per decade along the Antarctic Peninsula. However, the temporal fluctuation of the surface temperature is large, even with the seasonal fluctuation subtracted, and the trends vary in magnitude and sign in different regions. Long term station data sets were used to study the length of record required for trend studies and the results show that about two decades of data are needed before the trend values begin to stabilize. To evaluate whether the trends inferred from station data are part of a local or large scale phenomenon, we analyzed about 19 years of infrared satellite data (1979-1997) over the entire Antarctic region during a winter and a summer month. The surface temperatures inferred from infrared data are shown to agree well with those observed from these sparsely distributed Antarctic stations with a correlation coefficient of 0.98 and a standard deviation of 3K. The satellite infrared data indicate a generally positive trend and with negative trends in parts of the continent. In the sea ice regions, the position of the ice edge in winter with respect to the northernmost position of sea ice during the 19 year period is shown to be influenced by temperature anomalies. The effect of the Antarctic Circumpolar Wave (ACW) is suggested from analysis of these anomaly data, but the wave appears to be predominantly mode 3 (instead of reported mode 2) for the Antarctic region. Thus,

although surface temperature may be highly correlated to sea ice extent in near freezing areas like the Bellingshausen Sea, the trends need to be evaluated in the context of the effect of the ACW in other areas, since the latter can cause a retreat and an advance in adjacent parts of the same sector during the same year. Furthermore, the satellite data record reveal a relatively large anomaly in 1995 in the Antarctic plateau and this may have enhanced the positive trends.

## **“Antarctic Sea-Ice Dynamics from Satellite Microwave Data”**

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Daily and three-daily ice motion vectors were recovered from ERS-1/2 Synthetic Aperture Radar, scatterometer, and SSM/I satellite microwave images using an automated ice tracking algorithm. Climatological mean motion fields were generated from the data and compared with ECMWF surface (1000 mb) pressure fields for their consistency with geostrophic wind forcing. We are currently extending these time series using NSCAT data, which has improved spatial resolution and an anticipated improvement in accuracy in ice drift tracking. Resulting gridded sea-ice motion fields indicate that large-scale mean Southern-Ocean sea-ice drift responds to the synoptic-scale climatological pressure field, following roughly along the isobars. High resolution (100m resolution) SAR-image derived motion vectors confirm this characteristic of the long-term, large-scale and lower-resolution motion field. The clockwise gyre circulation dominates the recovered climatological ice motion field in the Weddell Sea due to negative vorticity imparted by persistent cyclonic activity. Discrepancies between the ice-drift speed and direction and the direction and magnitude of the isobars indicate inaccuracies in the intensity and location of the low-pressure centers described by the ECMWF pressure fields. These inaccuracies stem from the lack of station and/or buoy data input into ECMWF analyses via the GTS network. Higher frequency motion results from tidal and short term pressure field fluctuations from passing storms. Summary charts of the sea-ice dynamics may be displayed in terms of climatological streamlines of drift or in the form of dynamical parameters such as: divergence, shear, and vorticity (curl). These products will eventually be determined in a routine fashion from all available satellite image time-series data and be distributed to interested parties wishing to validate sea ice models, or assimilate real ice dynamics into their ice model. Additionally, it is proposed to use optimal interpolation schemes to use overlapping datasets from existing and future IPAB buoys, with weightings to ensure that the satellite products accurately reproduce observed variability in the Antarctic ice pack.

# The Surface Heat Budget of the Eastern Weddell Sea in Winter

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Naval Postgraduate School

Longwave radiation dominated the total surface heat budget over the eastern Weddell Sea during the winter of 1994. Using a combination of direct measurements and bulk estimates obtained during the ANZFLUX (Antarctic Zone Flux Experiment) project, all terms in the surface heat budget were directly measured or estimated. The mean total regional heat flux,  $Q_{\text{tot}}$ , in the cruise region was  $52 \text{ Wm}^{-2}$  (all fluxes positive upward) with net longwave radiation contributing  $38 \text{ Wm}^{-2}$  toward that value. Although sensible and latent heat fluxes over leads and other ice-free areas was substantial,  $179 \text{ Wm}^{-2}$  and  $99 \text{ Wm}^{-2}$  respectively, only 5% of the region was ice-free, so the regional heat lost from these areas was only  $18 \text{ Wm}^{-2}$ . The net longwave radiation and therefore  $Q_{\text{tot}}$  were sensitive to cloud cover, with  $Q_{\text{tot}}$  averaging  $36 \text{ Wm}^{-2}$ s for overcast conditions vs.  $101 \text{ Wm}^{-2}$  for clear skies. During clear skies, net radiation cooled the surface  $20 \text{ Wm}^{-2}$  to  $36 \text{ Wm}^{-2}$  more than has been reported for Arctic situations, a result of cooler and drier upper-air conditions in the Antarctic region. Overcast longwave radiation values were similar to the Arctic, but poorly-predicted by many of the commonly-used longwave radiation algorithms. Although variations in  $Q_{\text{tot}}$  were dominated by cloud conditions, the corresponding upper-ocean fluxes (measured by colleagues) were more affected by the wind speed. The ice acted as a buffer, melting rapidly on the bottom during storms and freezing internally during the clear, cold periods between storms.

A numerical radiation model that was initialized with *in situ* rawinsonde atmospheric profiles, simulated the effects of gases, clouds and aerosols on the downwelling surface radiation. Despite cloud-top temperatures down to  $-23 \text{ }^{\circ}\text{C}$ , there was no evidence of ice-phase water affecting surface radiation. The effect of aerosol below the clouds was also small. Inferred sizes and concentrations of cloud droplets were somewhat smaller than typical oceanic stratus.

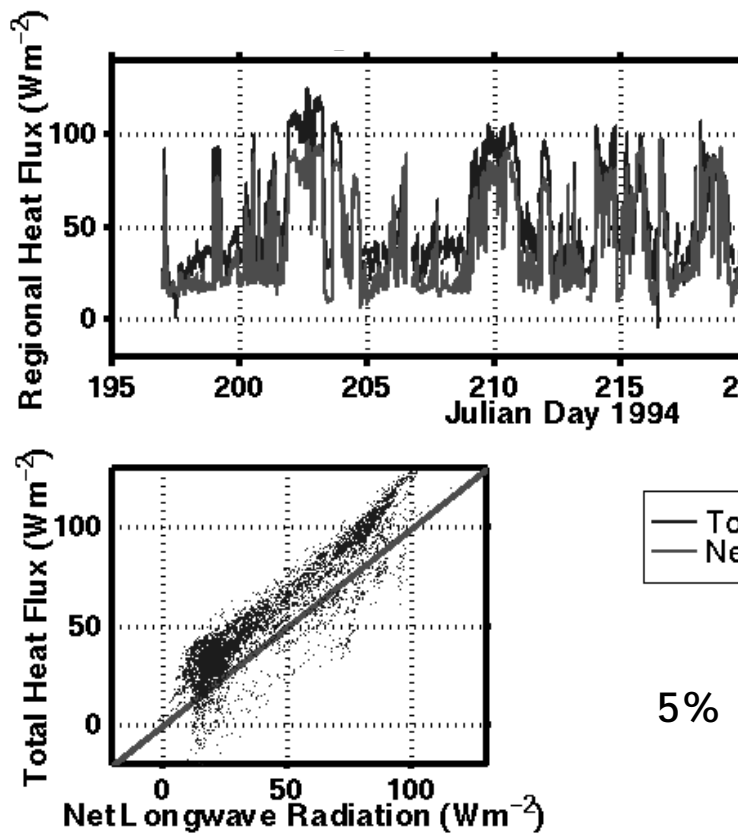


Figure. Time series of regional total heat flux,  $Q_{tot}$ , and net longwave radiation (top) and scatterplot of the two parameters (bottom). A major grouping<sup>tot</sup> of the net longwave radiation values occurs around 35  $W m^{-2}$  and a smaller grouping occurs around 100  $W m^{-2}$ , corresponding to overcast and clear conditions, respectively.

Processes that determine the large-scale thermohaline circulation in the Weddell Sea are:

- (1) the transfer of local momentum, heat and fresh water at the sea surface, modified by sea ice dynamics and thermodynamics,
- (2) the water mass modification underneath the ice shelves, and
- (3) the interaction with the Antarctic Circumpolar Current (ACC).

A long-term modelling project has been initiated at the Alfred-Wegener-Institute to investigate this complex regime, and the role of each component with regard to seasonal, interannual and decadal variability. We use a terrain-following ocean circulation model (SPEM), modified to include the major sub-ice shelf regions (Filchner/Ronne, Ross, Amery, Larsen, and Brunt/Riiser Larsen). The model configuration is circumpolar (south of 50S), with higher resolution (20-100km) in the Weddell Sea sector. The model is initialized with data from the Hydrographic Atlas of the Southern Ocean and driven by monthly mean values of surface temperature and salinity, obtained from a stand-alone sea ice model. Results of a 6-year integration show temperature and salinity distributions in agreement with the observations, sub-ice cavity circulations interacting with the open ocean, and a total Weddell Gyre transport of  $\sim 60$  Sv,  $\sim 26$  Sv across the line Kapp Norvegia - Tip of Antarctic Peninsula (Figure 1).

The importance of ice shelves for deep and bottom water formation at the Weddell Sea continental slope has been investigated by using different sub-ice cavity combinations for BRIOS' model configuration. The exclusion of Filchner/Ronne and Larsen ice shelves increases temperature and salinity of the shelf water masses, enhancing deep water formation in the western Weddell Sea. The influence of Larsen Ice Shelf on this formation process is minor, but water mass characteristics of the Weddell Scotia Confluence are affected in the same way. Similarly, the eastern Weddell ice shelves do not control deep or bottom water formation, but cause a pre-conditioning of the shelf water masses entering the southern Weddell with the coastal current. The strength of the latter, however, is controlled by the eastern ice shelves which maintain the horizontal density gradient across the continental slope front.

The spreading of the water masses has been investigated by "deploying" Lagrangian floats at different locations in the Weddell Sea. The results confirm that the ridges of the western Weddell continental slope are the dominant sites for water masses to sink to great depth (Figure 2). Further flow is controlled by the bottom contours along the South Scotia Arc. At the Endurance Ridge (43 W), the flow splits with the upper branch leaving the Weddell Sea mainly through the 40-deg Gap, east of the South Orkney Islands, and less through the gap further to the east. Both flows continue north-eastward toward the passages between South Georgia and South Sandwich Islands. The lower branch flows eastward along the Arc's southern slope participating either in the complex circulation of the South Sandwich Trench or entering the eastern Weddell Abyssal Plain.

The sea ice model, a Hibler/Lemke dynamic-thermodynamic type with viscous-plastic rheology, is

driven by wind, cloudiness and temperature fields obtained from the ECMWF 6-hour re-analysis. The coupled ocean/sea ice model reproduces the annual cycle in close agreement with SSM/I satellite observations. For the Weddell Sea, winter sea ice thickness distribution compares well with drill hole measurements (Figure 3) and data from upward looking sonars (ULS). The ocean surface currents are important for the advection of ice, but even more for the advection of heat into the southern Weddell Sea during the melting season. Next, our interest will be focused on the interaction of the Weddell Gyre with Maud Rise to study the sensitivity of the sea ice cover in this area on different forcing scenarios.

Fig. 1: Modelled transport streamfunction (in Sverdrups) for the Southern Ocean south of 50S after 6 years of integration. The black line indicates the hydrographic section sampled by the Alfred-Wegener-Institute.

Fig. 2: Representative path of a model float deployed on the southwestern Weddell continental shelf for a 6-year period (upper panel), and corresponding depth (lower panel).

Fig. 3: Modelled August sea ice thickness distribution (in meters) for the Southern Ocean south of 50S (left), and its comparison with drill hole measurements in the central Weddell Sea during Winter Weddell Gyre Study (WWGS) 92 (right).

## **SIMULATING HIGH FREQUENCY VARIABILITY IN SEA-ICE DYNAMICS MODELS**

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### **1. INTRODUCTION**

A dominant feature of sea ice deformation in both the Antarctic and Arctic regions is the presence of substantial high frequency variability, typically with considerable power at inertial frequencies (see e.g., Hibler et. al, 1974, Geiger et. al. 1998, Heil et. al., 1998). The oscillatory character of the motion has been related to ice concentrations and interaction using field observations (Hibler and others, 1974) which generally show a substantial quelling of the inertial oscillations under compact high ice interaction conditions. These high frequency motions can contribute substantially to the mass budget of the ice and in some cases modify the air-sea heat exchange by up to 50%. This high frequency content of the motion (Figure 1) is in contrast to the wind forcing which occurs at much lower frequencies.

While his type of deformation is close to tidal motion periods, since tidal forcing is relatively smooth spatially, it is not clear how such forcing can lead to variations in ice deformation; although it would certainly lead to variations in ice velocity. If a mechanism for generating fluctuating deformation from smoother forcing exists, then this deformation could be amplified by the inertial resonance; a result which is suggested by observations of pack ice deformation in the Western Weddell Sea (Geiger and others, 1997).

In this note we outline progress (see Hibler et. al., 1998 for a more complete description) on elucidating mechanisms for this phenomenon involving the coupling of inertial oscillations with an interacting ice field. The results essentially show that using a realistic formulation for the ice ocean boundary layer, coupling between propagating kinematic waves in pack ice together with inertial oscillations in the ice ocean boundary layer can lead to substantial deformation oscillations in agreement with observations.



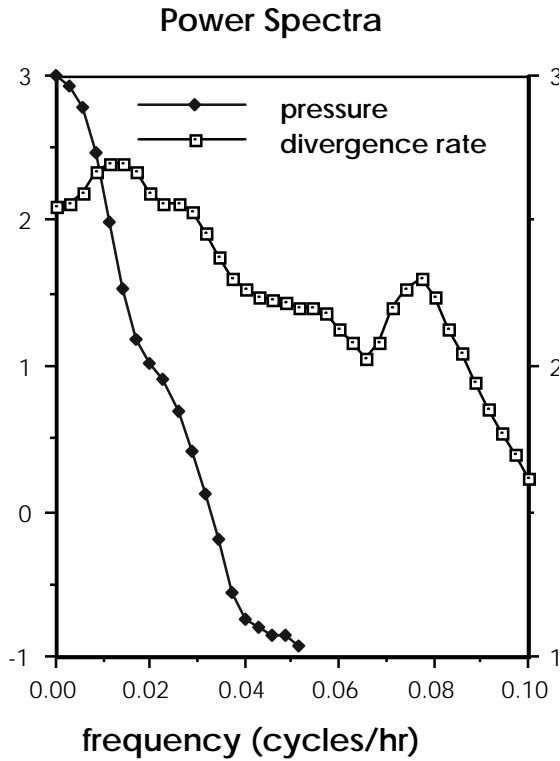


Figure 1. Power spectra of atmospheric pressure variations and mesoscale (~10 km) sea ice deformation rate during March-April, 1972 in the Beaufort Sea. The Data spanned approximately a one month long period.

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## 2. ICE OCEAN COUPLING

In almost all sea ice dynamics models used in climate investigations inertial motion is typically overdamped due to the method of coupling the ice with the oceanic boundary layer which assumes an averaging over time scales long compared to the inertial period. Under this formulation the water stress on the ice is taken to be function of the ice velocity, usually of a quadratic form. In complex form the water stress on the ice is taken to be given by

$$(1) \mathcal{I}_w = -\underline{u}e^{i\theta}$$

where  $\mathcal{I}_w = \tau_{wx} + i\tau_{wy}$  is the water stress in complex form and  $\underline{u} = u_i - u_o = u_x + iu_y$  is the complex ice velocity relative to the geostrophic ocean current. Using this water drag formulation the equation of motion for the ice is given by

$$(2) \frac{D\underline{u}}{Dt} + ifm\underline{u} = \mathcal{I}_w + \mathcal{I}_a + \nabla \cdot \sigma$$

where  $f$  is the coriolis parameter,  $\tau_a$  is the air stress usually taken to be quadratic in the geostrophic wind velocity  $v_a$ ,  $\tau_a = (\rho_a C_a / f) v_a v_a e^{i\phi}$ , and  $\sigma$  is the ice stress tensor. While this formulation is reasonable for time scales long compared to the inertial period it tends to effectively decouple the ice mass from the mass of the dynamically active ocean boundary layer which also undergoes inertial oscillations (see e.g. McPhee, 1978).

A more consistent way to carry out this coupling is (following McPhee, 1978) to relate the ice motion directly to the boundary layer motion by taking the boundary layer water mass transport  $\underline{m}_w$  (relative to the geostrophic flow) to be related to ice velocity (relative to the geostrophic ocean current)

$$(3) \underline{m}_w = (\rho_w C_w / f) \underline{v} e^{-i\beta}$$

With this formulation, the equation of motion of total mass transport  $\underline{m} = \underline{m}_w + \rho_i h \underline{v}$  of the boundary layer system consisting of ice plus water is given by

$$(4) \frac{D\underline{m}}{Dt} + i f \underline{m} = \tau_a + \nabla \cdot \sigma$$

To make this equation have one dependent variable we need to take  $\sigma$  the ice stress tensor to be expressed in terms of the total mass transport  $\underline{m}$  of the ice plus water.

This formulation could be presented in terms of the ice drag of equation 1 together with a separate ocean motion, but then one must also account for the net convergence of the ice in the mass transport equations of the ocean. What is clear from equation 4 is that the stress transported into the ocean system is the wind stress less the ice interaction. The formulation of equations of motion in terms of equation 4 also has the advantage that if the ice stress is formulated in an appropriately energy dissipative form then the  $\nabla \cdot \sigma$  term will always act as a dissipative term (albeit non linear) on the equations of motion.

### 3. SIMULATION RESULTS

To examine coupling issues an idealized 1.5 dimensional dynamic-thermodynamic sea ice model was configured to be relevant to results of a winter deformation experiment in a tide free region of the East Antarctic sea ice zone (Worby and others, 1996). During this time, a number of drifting buoys were monitored hourly for studies of sea ice drift and deformation (Heil and others, 1997) with results yielding substantial inertial signals in the deformation. The model configuration (Figure 2) consisted of a 40km lagrangian grid with wind forcing taken to be perpendicular to the coast. In this model (Hibler et. al., 1998), full two dimensional ice dynamics is assumed but all variations along the coast are assumed to be zero. For simplicity, we also neglect pressure gradient variations in the ocean due to Ekman convergence.

## **Modeling the Interaction of Ocean Circulation and Ice Shelves**

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This talk presents preliminary work in a numerical modeling effort to investigate the interactions between Antarctica's ice shelves and the adjacent shelf and deeper regions of the Southern Ocean. The overall goal is to determine the extent to which the ocean controls the attrition of the ice shelves and thereby influences the size of the continental ice sheet. In this coupled system we also evaluate how melting and freezing impact regional water properties and the larger-scale ocean circulation, and how this system might respond to climate change. A fully-coupled ocean, ice-shelf, sea ice and atmosphere model is applied to geographical distinct subdomains which include the Ross and the Filchner-Ronne ice shelves. An important aspect of this study is the validation of component fields of the coupled model simulation against available observations. The numerical experiments presented utilize domains with both idealized and realistic geometry, and sensitivity studies to assess confidence in the fidelity of the simulations. We are looking for natural internal oscillations and variability arising from external forcing. As an additional model diagnostic tool we have introduced model tracers to gain insight into system behavior.

Central to the goal of accurately modeling the interaction between ice shelves and ocean circulation is as realistic as possible determination of the melt rate that occurs at the ice shelf base. In the coupled model used in this study an additional one-dimensional (vertical) thermodynamic model is introduced with the objective of improving the description of the heat and freshwater exchanges that occur between the ice shelf base and the ocean. A distinguishing feature of this model lies in the details of the treatment of the thermal conductive flux in the base of the ice shelf. A second distinguishing feature is the use of a molecular sublayer model at the ice-ocean interface in addition to the usual bulk mixed-layer ocean model. A sensitivity study is performed with a much simpler thermodynamic model and it is shown that the basal melt rate is indeed sensitive to the nature of the parameterization of thermodynamic exchange at the ice-ocean boundary. It is argued that because of this sensitivity that a thermodynamic model such as outlined in this talk be used when modeling the interaction between the ice shelves of Antarctica and the waters of the Southern Ocean.

## **Southern ianZone - Reports from the Antarctic Continental Shelf**

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### **The Antarctic Research Series Volume 75**

At the December 1997 ASPeCt/iAnZone meeting in Oracle AZ, several speakers referred to a volume of the Antarctic Research Series (ARS) currently in production. The focus of that volume, edited by S. Jacobs and R. Weiss, is on the oceanography of the Antarctic continental shelf, but it often spills over into the abyss or takes flight in the atmosphere. Aside from its interdisciplinary aspects, the southerly region covered and the international cast of authors may make it eligible for iAnZone status. In any event, camera-ready manuscripts are at the American Geophysical Union, which anticipates publication within the next few months. [The related ARS volume 74, on Antarctic sea ice and edited by M. Jeffries, is also due for release within the next several weeks.] The following list of ARS Volume 75 co-conspirators also gives the titles of their theses.

Baines & Condie: Observations and modelling of Antarctic downslope flows: A review

Bombosch: Interactions between floating ice platelets and ocean water in the southern Weddell Sea

Bromwich, Liu, van Woert & Rogers: Winter atmospheric forcing of the Ross Sea Polynya

Goodrick, McNider & Schroeder: On the interaction of the katabatic-land-sea wind system of the Antarctic with the high latitude Southern Ocean

Gordon: Western Weddell Sea thermohaline stratification

Grosfeld, Hellmer, Jonas, Sandhager, Schulte & Vaughan: Marine ice beneath Filchner Ice Shelf: Evidence from a multi-disciplinary approach

Hellmer, Jacobs & Jenkins: Oceanic erosion of a floating Antarctic glacier in the Amundsen Sea

Heywood, Locarnini, Frew, Dennis & King: Transport and water masses of the Antarctic Slope Front system in the eastern Weddell Sea

Hoffman & Klinck: Thermohaline variability of the waters overlying the West Antarctic Peninsula continental shelf

Jacobs & Giulivi: Interannual ocean and sea ice variability in the Ross Sea

Mensch, Smethie, Schlosser, Weppernig & Bayer: Transient tracer observations from the Western Weddell Sea during the drift and recovery of Ice Station Weddell

Nicholls & Makinson: Ocean circulation beneath the western Ronne Ice Shelf, as derived from in situ measurements of water currents and properties

Nost & Osterhus: Impact of grounded icebergs on the hydrographic conditions near the Filchner Ice

## Shelf

Penrose: Acoustical techniques in Antarctic oceanography

Rintoul: On the origin and influence of Adelie Land Bottom Water

Robertson, Padman & Egbert: Tides in the Weddell Sea

Schenke, Hinze, Dijkstra, Hoppman, Niederjasper & Schone: The new bathymetric charts of the Weddell Sea: AWI BCWS

Whitworth, Orsi, Kim, Nowlin & Locarnini: Water masses and mixing near the Antarctic Slope Front

Williams, Jenkins & Determan: Physical controls on ocean circulation beneath ice shelves revealed by numerical models

Wong, Bindoff & Forbes: Ocean-ice shelf interaction and possible bottom water formation in Prydz Bay, Antarctica

## **Activities on the western side of the Antarctic Peninsula and in the Scotia Sea**

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Two projects are active which consider 1) the hydrography and circulation on the continental shelf on the western side of the Antarctic Peninsula and 2) the transport of krill larvae from the Antarctic Peninsula shelf to South Georgia Island. Each of these projects involves analysis of historical observations and dynamical modeling.

Variability on the West Antarctic Peninsula (WAP) continental shelf is analyzed from four cruises that occurred between January 1993 and February 1994 (Jan-Feb 93, Mar-May 93, Aug-Sept 93, and Jan-Feb 94) over a region 400 km alongshelf and 150 km across-shelf. From these observations we estimate typical distributions of water properties as well as seasonal changes.

This shelf is about 500 m deep with variable bathymetry ranging from 200 to 800 m deep. Most property surfaces (isotherms, isohalines, isopycnals) are horizontal on this shelf throughout the year. There is no dense water formed within the region we have sampled.

The considerable depth of this shelf allows water to exist as two layers separated by a permanent pycnocline, centered at about 150 m, which is found during all four cruises. In the upper layer, temperature and salinity are modified by surface fluxes creating cold (-1.8C) and salty (33.8 to 34.0) water in the winter. The near-surface water warms and becomes fresher in the summer; with surface waters being above 1.0C with salinity below 33.5. The coldest water in the upper layer (called Winter Water [WW], occurring at about 100m) also warms from above and below to temperatures above -1.5C). At a small number of places, for example, near Anvers Island, WW is completely eroded leaving water above 1.0C throughout the water column. This erosion seems to be related to shallow (less than 200 m) bottom depths.

Water below the permanent pycnocline is a cooled variety of a warm oceanic water mass (Upper Circumpolar Deep Water, UCDW). This oceanic water flows northeastward with the southern edge of the Antarctic Circumpolar Current (ACC) at the shelf break (about 500 m deep). Each of the four cruises reveals a plume of UCDW intruding onto the shelf. During the intrusion, UCDW loses heat vertically warming the base of WW, creating the cooler (1.2 to 1.5 C) water mass on the shelf. It appears that meandering of the ACC is the mechanism driving this exchange. The plumes also seem to appear in regions of deep across-shore bathymetric cuts (or submarine canyons) extending from the shelf break into the midshelf and sometimes almost to the coast.

The second project examines the processes responsible for krill transport from WAP shelf to South Georgia Island. Observations from the Discovery Investigations revealed early krill stages off the Antarctic Peninsula but not around South Georgia. Adult krill were found in profusion near South Georgia forcing the hypothesis that juvenile krill are brought to the

island.

Historical data (wind climatology, hydrography, and FGGE drifters) are used to analyze circulation in the Drake Passage and the Scotia Sea. The Southern ACC Front (SACCF) sits along shelf break of WAP shelf and extends to the vicinity of South Georgia. A plausible hypothesis is the current associated with this front carries krill larvae.

Results to date reveal that Ekman drift can move particles from the shelf into the southern ACC. Meanders may also pull particles from the shelf. Some krill spawning occurs offshore, eggs may also be released directly into the current. The speed of the surface flow of the jet associated with the SACCF, estimated from surface drifters, is sufficient to move particles from the WAP shelf to South Georgia in 140 to 160 days. This time is about the same as time it takes eggs to develop into feeding stages of larval krill.

Given the consistency of this estimate between advection and development times, a dynamical model of Drake Passage and the Scotia Sea is being developed to extend this analysis to more realistic and dynamically consistent flow fields. A Lagrangian model of krill development will use temperature estimated by the model to calculate the size and stage of krill larvae at each step along the path.

## **Spatial/Temporal Variations in Antarctic Sea Ice and Its Global Connectivity**

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While models have suggested numerous linkages and influences of the polar oceans on extra-polar climate, the specific global modes or climate patterns that link the high and lower latitude regions are remarkably ill-defined in all but the most fundamental climate mode - the El-Nino Southern Oscillation (ENSO). We have undertaken an exploratory study aimed at identifying the global "teleconnections" between the Antarctic polar sea ice fields and global climate (Yuan and Martinson, 1998), with the longer term goal of ultimately determining the mechanisms responsible for the connections and their sensitivities, once the connections have been established and further evaluated.

Our specific objectives were to quantify: (1) the variability documented in Antarctic sea ice fields in an effort to identify specific patterns of variability and their characteristics; and, (2) the distribution and significance of linear covariations between the Antarctic sea ice fields and regional climate elsewhere on the globe. With regard to the latter, we wished to identify: regions around Antarctica with the strongest global connectivity; extra-polar regions with strongest links to the Antarctic sea ice fields; and linkages with fundamental modes of climate variability (e.g., ENSO, PNA, NAO, etc.).

For convenience, we used 16 years of satellite microwave data to generate a sea ice edge (SIE) index reflecting monthly anomalies from climatology of the northernmost latitude of the ice edge. The index was detrended and binned into 10 degree bands around Antarctica (which approximates the spatial decorrelation length). These SIE anomaly time/space series were then compared to extra-polar climate data consisting of: (1) Jones (1994) monthly mean near-surface temperature anomaly data for the globe on a 5\_ x 5\_ grid from 1975 to 1993; (2) the time series (principal components) of the leading EOFs for the near surface temperature data; and (3) standard climate indices such as NINO3 (an ENSO proxy), a tropical land precipitation index (28\_ S - 28\_ N), a tropical Indian Ocean SST index (an Indian monsoon intensity proxy), and indices for the NAO and PNA. Particular care was given to evaluating the statistical significance of the extensive correlations using Monte Carlo and resampling statistics to account for spatial and temporal correlations inherent in the data.

Variability within the Antarctic sea ice fields is characterized as follows. Spatially, the SIE anomaly is strongest in 3 regions around the Antarctic: the eastern Pacific (Amundsen and Bellinghausen Seas; 50-90\_ W), eastern Weddell gyre/western Indian Ocean (0-50\_ E) and Weddell Sea (20-30\_ W). Temporally, the variability is concentrated roughly in cycles of 1-2 and 4-5 years. The 4-5 year cycle is associated with a coherent mode of behavior that displays a wavenumber 2 pattern that has been named the Antarctic Circumpolar Wave by White and Peterson (1996). This pattern is clearly apparent without any filtering of the data, and it shows eastward propagation of the SIE anomaly, strong covariability with ENSO and even stronger covariability (though only marginally so) with the Asian monsoon index. The spatial coherence of this pattern appears to be constrained to the three primary gyre regions around Antarctica, with little signature between them. This suggests to us that the signal is not spatially continuous in the SIE, and therefore, likely to represent the individual response of each polar gyre to a spatially-continuous atmospheric forcing. The 1-2 year cycle appears to be regional in extent and does not show any clear evidence of propagation.



The Antarctic sea ice fields display significantly more strong and significant correlations with the surface temperature elsewhere on the globe than expected by correlating to red noise. Specifically, the Weddell Gyre/western Indian Ocean region, and Eastern Pacific region of Antarctic shows the strongest global connectivity, particularly with regions linked by ENSO/Monsoon variability, while the Weddell Sea shows strong correlation with the climate mode dominated by the tropical and northern Atlantic SST variability. In general, the SIE appears to be well correlated to the first two modes of global climate variability as expressed by the EOF analysis; the first mode is dominated by ENSO. Some of the correlations show the ice leading changes in extra-polar surface temperature, while others show a lag. We are currently investigating the significance and implications of the leads and lags, and isolating those regional correlations that most likely reflect causal links.

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## Physical Oceanographic cruise to the Southern Weddell Sea

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During January and February 1998 HMS Endurance will attempt to visit the southern Weddell Sea to carry out meteorological and oceanographic measurements. Six current meter moorings will be recovered, and four others deployed, along with six bottom pressure recorders. The core of the cruise will be CTD sections, with one Yo-Yo station. Surface meteorological work will use sonic anemometers, psychrometers, and IR thermometers to determine air-sea momentum and heat fluxes.

The oceanographic conditions on the continental shelf of the southern Weddell Sea largely determine the thermal regime of the vast Filchner-Ronne system of ice shelves. High salinity water produced through sea-ice formation is thought to drain into the sub-ice shelf cavity and supply the heat to warm the ice, and to allow the net melting at the ice-shelf base. When it melts the base of the ice shelf the high salinity water (HSSW) is converted to Ice Shelf Water (ISW). It is this ISW that has been identified as flowing down the continental slope north of Filchner Ice Shelf. That flow was estimated from current meter measurements taken in 1979 and the early 1980's. During 1986 large bergs broke from Filchner Ice Shelf and grounded on the Berkner Bank. Semi-permanent fast-ice has since covered large areas of Berkner Bank, and it is thought that the presence of the bergs, together with the fast-ice, has modified the hydrographic conditions north of Filchner Ice Shelf. It is important to reassess the outflow of ISW from the Filchner Depression before the conditions revert to the pre-1986 state.

Principal among the aims of the cruise is the deployment of the four current meter moorings across the path of the ISW plume where it has been observed at about W036x. The instrument strings will include microCats and high resolution recording temperature sensors. A fine horizontal scale CTD section cutting across the slope, along the putative line of moorings, will be undertaken in order to check the precise locations. An additional aim is to perform a Yo-Yo CTD station to study the time variability of the water column in the vicinity of one of the moorings sites. Further CTD sections will attempt to determine its route west of the line of moorings.

Should sea-ice conditions permit, the ship will steam to the Ronne Depression, an area thought to be an important source of HSSW both for sub-ice shelf ventilation, and for other processes, such as shelf break mixing processes. This rather poorly sampled region will be explored by obtaining CTD sections in an attempt to determine the fate of an ISW plume thought to emerge from beneath the west end of Ronne Ice Front, and to map the distribution of HSSW. Further CTD stations will be occupied along the ice front to continue the time series of CTD sections from that region.

Four current meter moorings that were deployed near Ronne Ice Front during 1995 as part of an AWI-University of Bergen collaboration will be retrieved, together with two others in the northern Filchner Depression. Bottom pressure recorders will be deployed at three points just north of the ice front in an attempt to provide better datasets for the validation of tidal models for the region.

The science team will be 12-strong, representing seven institutions and three nations. Including collaborators supplying instruments, and those who will assist in the sample analysis, nine institutes

and four countries are involved.

## Potential Impacts of Climate Warming on Anthropogenic CO<sub>2</sub> Uptake in the Southern Ocean

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A coupled atmosphere-ocean simulation with time-dependent radiative forcing for 1765 to 2065 suggests that the largest potential impact of climate change upon the uptake of anthropogenic CO<sub>2</sub> by the ocean may be in the Southern Ocean.

The modelled global warming scenario includes the increase in both greenhouse gases and the direct effect of sulfate aerosols for 1765 to 1990, and estimated future trends of both until 2065 in accordance with the IPCC IS92a scenario. An ocean carbon cycle model including both the biological and solubility pumps, is nested within the coupled simulation.

Given the uncertainties surrounding the response of biology to environmental change, the central scenario for the biological sub-model is an assumption of minimum change whereby the production and export of organic matter and CaCO<sub>3</sub> continue undiminished unless the major nutrient phosphate is depleted to zero at the surface.

The coupled simulation predicts a global increase in stratification of the surface ocean under greenhouse warming, due to warming at low latitudes and freshening in high latitudes. The formation of North Atlantic Deep Water begins to drop as early as next decade; however the reduction in CO<sub>2</sub> uptake due to warming and circulation changes is dominated by the Southern Ocean. The primary reasons are its large area, and the slower warming of sea surface temperatures here, which cause it to be the region of maximum zonally-integrated perturbation heat flux into the ocean. The increased stratification also causes the reduction of both vertical mixing along isopycnals (now more horizontal) and convective overturning. The heating effect predominates in the early period, but by the final decade (2056-65), transport processes account for 76% of the reduction in CO<sub>2</sub> uptake in a model without biology.

Changes in the biological pump counteract this reduction: the slowing of vertical exchange reduces the upward supply of deep excess biogenic carbon, which in the “constant biota” model, leads to an accumulation of carbon in the deep ocean. The enhancement of atmospheric CO<sub>2</sub> uptake by the biological pump is again dominated by the high latitudes of the Southern Ocean, mirroring the reduction in CO<sub>2</sub> uptake by the solubility pump.

A possible lower limit to the uptake by the biological pump is suggested by a model where the surface phosphate is kept constant, perhaps resembling the case where the primary limit to phytoplankton growth might be a micronutrient that is supplied primarily from within the ocean. The 1990 to 2065 cumulative uptake of anthropogenic CO<sub>2</sub> is reduced to 219 Pg C in the constant phosphate run from 262 Pg C in the constant biota case. A maximum upper limit is provided by a run where surface phosphate is consumed entirely (similar to one of the hypotheses for the lowering

of atmospheric CO<sub>2</sub> during the last ice age), resulting in a 1990 to 2065 cumulative uptake of 400 Pg C. Although such an extreme scenario would never be realized, these experiments do suggest that changes in the biology could substantially modify the future uptake of anthropogenic CO<sub>2</sub> by the ocean.

According to our simulation, the ocean's carbon cycle might already be experiencing effects of climate change today, which could become significant over the next century. The critical importance of the Southern Ocean, and the need to represent both its physical circulation and biological sensitivity correctly, urge a scientific focus on this region.

## **Palmer Long-Term Ecological Research - a Sea Ice Dominated Marine Ecosystem**

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A central tenet of the Palmer Long-Term Ecological Research Project (PAL LTER) is that the annual advance & retreat of sea ice is a major physical determinant of spatial & temporal changes in the structure & function of the Antarctic marine ecosystem, from total annual primary production to breeding success in seabirds. We are currently evaluating a number of testable hypotheses linking sea ice to:

- the timing & magnitude of seasonal primary production,
- the dynamics of the microbial loop & particle sedimentation,
- krill abundance, distribution, & recruitment, &
- the breeding success & survival of apex predators.

The overall objectives of the PAL LTER are to:

- (1) document the interannual variability of annual sea ice & the corresponding physics, chemistry, optics, primary production & the life-history parameters of secondary producers & apex predators within the PAL LTER area,
- (2) create a legacy of critical data for understanding ecological phenomena & processes within the Antarctic marine ecosystem,
- (3) identify the processes that cause variation in physical forcing & the subsequent biological response among the representative trophic levels,
- (4) construct models that link ecosystem processes to environmental variables, which simulate spatial/temporal ecosystem relationships, & employ such models to predict & validate ice-ecosystem dynamics.

Since 1991 the PAL LTER program has included spatial sampling during annual (every January to mid-February) & seasonal (approximately 2 per 6-yr period) cruises in portions of our regional grid in the western Antarctic Peninsula region & temporal sampling from spring through fall (October to March) in the area adjacent to Palmer Station (TABLE 1). Our program was designed to sample at multiple spatial scales within one regional scale grid, permitting repeated sampling on both seasonal & annual time scales, thus addressing both short & long-term ecological phenomena, as well as providing a basis for specific mechanistic studies. Documentation & data storage are organized through an electronic hub at the Institute for Computational Earth System Science (ICESS) at the University of California at Santa Barbara which also serves as a data archive as needed. See our website for a project overview and online definitions of core data, datasets & metadata, organized to facilitate rapid information exchange & online data documentation (<http://www.icess.ucsb.edu/lter/lter.html>).

The PAL LTER program is multidisciplinary & currently involves ten Principle Investigators (Table 2). Work to date indicates that the PAL LTER is ideally sited in a climatically sensitive region where ecosystem studies have the potential for detecting, against a background of natural variability, long-term trends &/or human disturbance to the Antarctic ecosystem. It is an area where “natural” experiments can be conducted to investigate mechanisms linking physical forcing & ecosystem response under vastly different year-to-year climate conditions & where perturbations such as global warming, ozone-related UV-B increases & associated anthropogenic impacts on ecological processes can be studied in an otherwise remote & relatively pristine environment.

An overview & synthesis of various aspects & processes associated with the Antarctic marine ecosystem in the WAP & in the vicinity of Palmer Station, as well as analyses of historical data & early PAL LTER results, have been published in an AGU Antarctic Research Series book (Vol 70) entitled, Foundations for Ecological Research West of the Antarctic Peninsula (R.M. Ross, E.E. Hofmann & L.B. Quetin (eds), 1996).

TABLE 1. Annual monthly distribution of LTER cruises (indicated by month and year) and field seasons at Palmer Station (indicated by x's). Cruises extending beyond one month are indicated by '\*' and overlap with the field seasons if between October and March.

Month	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun
91/92			x	Nov91	x	x	x	x				
92/93			x	Nov92	x	Jan93	*	Mar93	*	*		
93/94			Aug93	*	x	x	x	Jan94	*	x		
94/95			x	x	x	Jan95	*	x				
95/96			x	x	x	Jan96	*	x				
96/97			x	x	x	Jan97	*	x				
97/98			x	x	x	Jan98	*	x		May98	*	
98/99			x	x	x	Jan99	*	x				
99/00			Sep99	*	x	x	Jan00	*	x			
00/01			x	x	x	Jan01	x	x				
01/02			x	x	x	Jan02	x	x				

TABLE 2. Palmer Principle Investigators

Raymond Smith      Lead-PI, Optics, Remote Sensing, Sea Ice (1991- )  
 Karen Baker      Data Management (1993- )  
 William Fraser      Seabirds (1991- )  
 Eileen Hofmann      Modeling (1991- )  
 David Karl      Microbial Processes (1992- )  
 John Klinck      Modeling/Physical Oceanography (1991- )

Barbara Prezelin      Phytoplankton (1991-1994)  
Langdon Quetin      Prey (1991- )  
Robin Ross      Prey (1991- )  
Wayne Trivelpiece      Seabirds(1991-1996)  
Maria Vernet      Phytoplankton (1994- )



## 1. Convection in coastal polynyas

(Shuki Ushio at National Institute of Polar Research, Tokyo)

Aircraft observations off East Dronning Maud Land, Antarctica, verified that a coastal polynya forms even in severe winters and that new ice production continuously occurs there. In the polynya, water temperature profiles were measured for the first time using the aircraft-launched expendable bathythermograph (AXBT). The AXBT data show that thickness of the winter mixed layer is 350 m or more, and that the layer temperatures are near the freezing point. This polynya is therefore regarded as a latent-heat polynya. According to the water mass analysis of the mixed layer, the active haline convection by the high ice production in the winter polynya contributes to the formation of more homogeneous and saline mixed layer than that under the fast-ice cover, where the ice grows slowly and the convection is calm. Furthermore, the active convection leads to the entrainment of the oxygen-poor deep water underlying the winter mixed layer. Consequently, in the polynya located over the continental shelf break, the oxygen content of the mixed layer is somewhat lower than that in the other polynya of the Breid Bay, where the haline convection reaches to the shallow sea bottom of the continental shelf. The oxygen undersaturation of the thick mixed layer in the coastal polynya suggests that the deep-water entrainment rate is more intense than that under pack ice in the Weddell Sea with a relatively thin mixed layer. It is therefore important to consider such a coastal polynya process which may contribute to water mass modification in the Antarctic coastal region.

## 2. Japanese activity of the Southern Ocean studies

(Shuki Ushio and Masaaki Wakatsuchi)

### Observations of ocean currents with subsurface floats (ALACEs)

To clarify characteristics of current fields in the Southern Ocean, three subsurface floats "ALACE" (Autonomous Lagrangian Circulation Explorer, made by the Webb Res. Co., USA) have been deployed by JARE-38 in December 1996 and in March 1997. The target of this study is the eastern area of the Kerguelen Plateau. It is suggested that this area is important to contribute to heat and salt exchange in the Indian Ocean sector. However, current fields have not been fully understood yet. Positions of the ALACE floats are being measured by the ARGOS system every three or four weeks. Trajectories of the floats have been successfully obtained. One of the floats were deployed at a location of 63.5S, 120E and has been drifting clockwise. The average speed shows about 1.6km/day (2cm/sec). It has been found that cyclonic eddies formed in this region. As shown by Wakatsuchi et al.(1994), this area of the floats drifting coincides with the location of cyclonic eddies formed around 115E, 64S. Also, temperature profile data, which are obtained in rising to the surface, will be useful to reveal thermal structures around the area of drifting floats. These data will be considered together with historical hydrographic data and sea ice variations.

This floats observation will be continued for understanding of current fields and their temporal

variations. Then, two more floats will be deployed in the eastern slope region of the Kerguelen Plateau.