Southern Ocean Basin report to GSOP-1
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with input from M. Sparrow, E. Zambianchi, M. Meredith, and the International CLIVAR/CliC/SCAR Southern Ocean Panel

1. Introduction

The GSOP requests the following information from each major ocean basin CLIVAR panel:

(1) Describe regional enhancements to sustained global observations planned or implemented in this basin. What sustained measurements of boundary currents are planned or implemented in this basin?
(2) Are the sustained ocean observations adequate for describing climate-relevant variability on basin-scale?
(3) Are the sustained ocean observations adequate to provide the context for regional process studies planned during CLIVAR?
(4) Are there sustained observations relevant to CLIVAR that are outside of CLIVAR's influence?
(5) Is data tracking, data availability, and data quality sufficient for CLIVAR research?

The Southern Ocean climate system includes ocean and ice-covered regions, with both free and fast sea-ice as well as ice shelves extending into the ocean. Important processes overlap with the interests of other scientific organizations and for this reason the CLIVAR Southern Ocean panel is joint with CliC and SCAR, and advises all three SSGs. Therefore the sustained observations reported here may be carried out under three separate umbrellas. A further consideration is the approaching International Polar Year. Numerous parties are preparing plans to supplement the observing system or install new elements. At this point it is difficult to separate the wishful thinking from likely proposals; some information about the overall structure is nevertheless provided here.

Key climate research questions that will be investigated by sustained observations in the Southern Ocean include:

- ACC transport variation, relation to the AAO/SAM and other patterns, and the transmission of anomalies between oceans
- Vertical structure of heat and fresh-water anomalies and transport processes in the ocean
- Dense water formation and the transmission of climate signals by boundary currents
- Ice shelf stability and the heat and fresh-water balance of the ocean-ice system
- The role of the Southern Ocean and ice system in setting the ocean's background state and mean ocean-atmosphere-ice seasonal cycle
- Intrinsic variability and teleconnections of the Antarctic Oscillation, Pacific-South-American Anomaly (PSA 1&2), the AA Dipole, and Antarctic Circumpolar Wave
- Coupled response of atmosphere, ocean, and ice to low-latitude ENSO and other variability
- Carbon uptake, biogeochemistry, and the CO2 feedback
- Support of process studies and model development

Sustained measurements (except for satellite measurements, mostly beyond the scope of this report, and ARGO, discussed separately) have been extracted from the full set of ongoing and planned observational components (Fig. 1). These demonstrate commitments for sampling on time scales from nearly continuous (moorings, tide gauges, bottom pressure) to seasonal (XBT, XCTD), to decadal (repeat hydrography). Table 1 summarizes the combination of platforms and techniques required to achieve a sustained ocean observing system.

No new fields have appeared since Table 1 was first constructed for the 1999 Ocean Observations discussion, but biochemical fields should be added in the future. Oxygen will likely become a routine long-term measurement, for instance. The ARGO program has grown dramatically, and great progress has been achieved with XBT lines, repeat hydrography, and satellite-based wind estimates. The satellite data on some fields is in danger of degrading or has already decreased, and efforts are needed to promote the role they play in climate research for all branches of the Earth system.

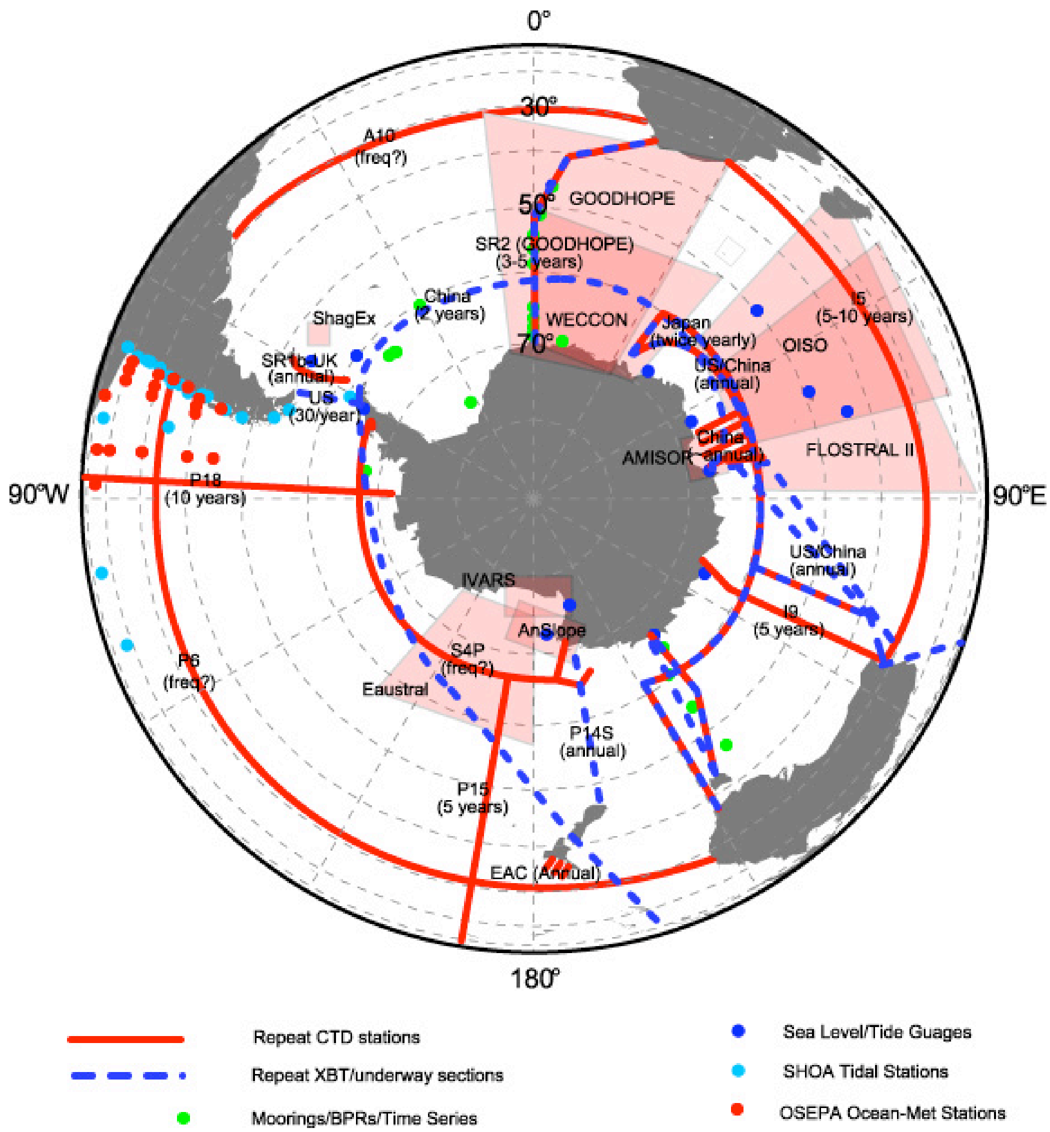

Figure 1. Sustained observational components of the Southern Ocean observing system; note that ARGO is discussed separately.

Table 1: The combination of platforms and techniques required to provide sustained observations of each of the key fields. Specific recommendations are given in the text. (OT = overturning circulation, BW = Antarctic Bottom Water, SO = Southern Ocean, DWBC = deep western boundary current, ACC = Antarctic Circumpolar Current, SSH = sea surface height, SST = sea surface temperature, SSS = sea surface salinity.)

Fields	Platforms
Stratification $T(\mathbf{x},z)$, $S(\mathbf{x},z)$	
- $z < 2000$ m	Argo; repeat hydrography; repeat XBT
- $z > 2000$ m	Repeat hydrography
SO-subtropical exchange	Argo; repeat hydrography/tracers; repeat XBT; boundary current moorings; satellite altimetry
Air-sea flux	Flux observatories; improved VOS measurements (e.g. IMET); SLP from drifters for assimilation in NWP models; SST from drifters, satellite, and VOS thermosalinograph
Wind	Satellite scatterometer; improved re-analysis products obtained by assimilating additional SST and SLP data; regional models
Tracers/CO_2	Repeat hydrography; VOS for pCO_2
ACC transport	Repeat hydrography; high density XBT; moored arrays; end-point monitoring; satellite altimetry
SSH	Satellite altimetry and gravity missions, sea level gauges
SST	Satellite (IR + MW); surface drifters; VOS thermosalinograph; Argo
SSS	Argo; VOS thermosalinograph; repeat hydrography; drifters?; satellite (?)
DWBC-overflow transport	Repeat hydrography; current meter moorings across AABW outflow
Sea ice extent, volume, motion	Satellite (various); upward looking echo sounders for ice thickness; ice drifters

2. Regional enhancements to sustained measurements

2.1 ARGO

As of November 2004 there are 306 ARGO floats south of 30 S. Figure 2 shows the latest distribution of floats, and Fig. 3 shows this distribution in relation to the AAO. Compared to the situation just a year ago the coverage has improved substantially. Large areas of the South Pacific sector are now covered, and gaps are starting to arise in previously well-sampled areas simply because floats are drifting away from their deployment region. A total of 306 floats are active (4 Nov. 2004), while 88 floats have died, for a net production of 13,526 profiles.

Major new deployments are expected south of Australia (Australia, 46 floats), in the Weddell Sea (Germany, 30 floats), and in the South Pacific (US, ~60 floats).

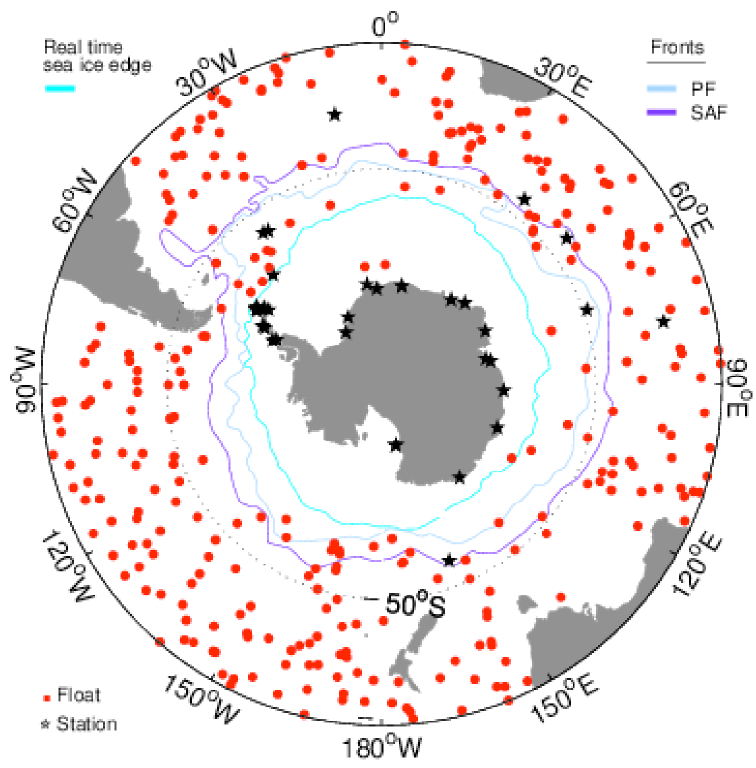

Figure 2. Distribution of ARGO floats in the Southern Ocean.

Two funded efforts are underway to enhance ARGO coverage in the subantarctic mode waters of the southern Indian Ocean (FLOSTRAL, France) and southeast Pacific Ocean (during SAMFLOC, US). The French FLOSTRAL program has provided regular re-seeding of the Crozet-Kerguelen-Amsterdam area, but future resources are unclear. The SAMFLOC process experiment in the southeast Pacific will have extra floats for enhanced coverage during the period of the experiment.

The ARGO program did not originally plan for the region of seasonal sea-ice coverage, and this has become the largest gap in the ARGO observing system in the Southern Ocean. A German project is underway in the Weddell Sea to develop floats that survive the winter sea-ice cover, and to extend the positioning capabilities via acoustic networks. A similar program is pending on the US side (EAUSTRAL), focusing on the Ross Gyre region. Year-round profiling and positioning in the sea-ice zone is the objective.

A number of ARGO floats enter the sea-ice zone by chance, and some of these survive the winter and re-appear the following summer. There have been examples of data return from, e.g. a float that survived, for 2 years, such an encounter. These observations are few but quite valuable for the new information they provide on the upper ocean heat and fresh-water balance within the sea-ice zone.

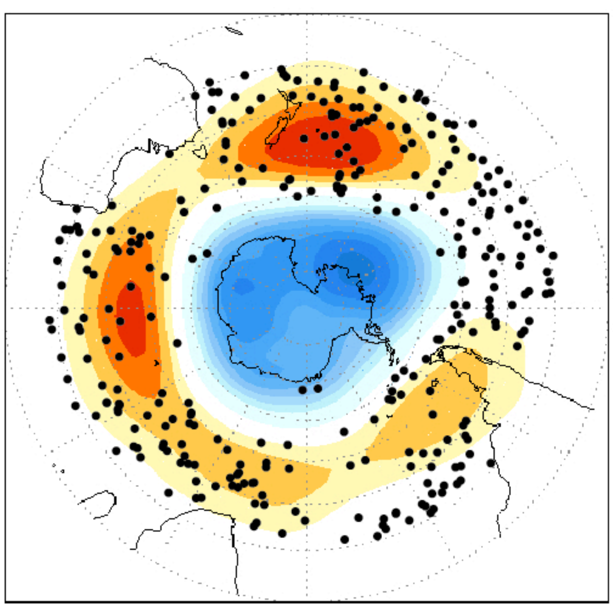

Fig. 3 ARGO floats distribution overlaid on the AAO (first EOF) pattern.

2.2 Current meter moorings

A component of the observational system long thought to be important is a set of transport measurements at the three main “chokepoints”: Drake Passage, a line south of Africa, and a line south of Australia. More recently, outflow arrays on the continental boundary: the Weddell Sea, the Ross Sea, the Princess Elizabeth Trough, and Adelie are being planned as components of the system, and have the advantage of being more practical. Only the Drake Passage is approaching adequate sampling to resolve the seasonal cycle of total transport, and perhaps higher frequencies, depending on the presence of additional moorings during a process study.

Measurements from fixed points are required to monitor ocean transport. Repeat sections are necessary, but not sufficient: the sampling in time is too coarse to avoid aliasing. In the future these transport measurements should incorporate altimetry data as well to improve sampling.

Fixed-point time series have a key role in:

- boundary current signals
- absolute velocity and transport

2.2.1 ACC and Agulhas transport

Boundary current/ACC moorings are showing some progress, but not for full ACC transport. Some monitoring of Agulhas (under ASTEX) has occurred, but this is not likely to be sustained. A French plan for Drake Passage is underway, but current meters are not likely to be coherent, and therefore full transport estimates are unlikely. German moorings are being maintained over a long time frame (c. 10 yrs) at southern end of the Africa-Antarctica line, but these are really designed to measure the Weddell gyre, not the ACC, with a wide spacing between moorings.

2.2.2 Outflow arrays

A few arrays are planned or happening, mostly in the process-study mode. Attempts are being made to convert these to monitoring arrays by various means. Arrays or moorings are in place in the NW Weddell Sea, the Greenwich meridian, and the Ross Sea outflow. Planned Princess Elizabeth Trough, Kerguelen DWBC, and Adelie depression moorings also fit in this category.

A goal has been put forward to have at least three to four outflow arrays in place for long-term measurements of bottom water formation. Two of these (Weddell and Ross) are started. These would be the initial array needed to ascertain synchronous behavior and make the link to circumpolar patterns of variability.

2.3 Repeat XBT lines

Repeat XBT is reasonably good, in the sense that probably everything that could be done is being done (Table 2). The Drake Passage is in good shape. The Tasmanian line is 6x/year, but only in an October - March timeframe, so the annual sampling is biased. The GOODHOPE project is spinning up and helping to fill the gap south of Africa, but still some improvement is needed. The initiation of zonal lines in subtropics will be an important contribution.

Table 2. XBT lines in the Southern Ocean

Tasmania Line: SURVOSTRAL 6x/year but only Oct-March
S. Atlantic zonal: (AX18, 32 S) 0-2x per year
Drake Passage Line: started at 6-8x per year, now up to 2x per month.
Africa Line (GOODHOPE): AX25 1-2x per year?
Circumpolar (China): 0.5x per year
New Zealand Line (Italy): 1x per year?

A map (Fig. 4 from SOOP) of all sampled locations over the period Oct 2003 – Sept 2004 shows the coverage for this month, as an indication of net annual sampling.

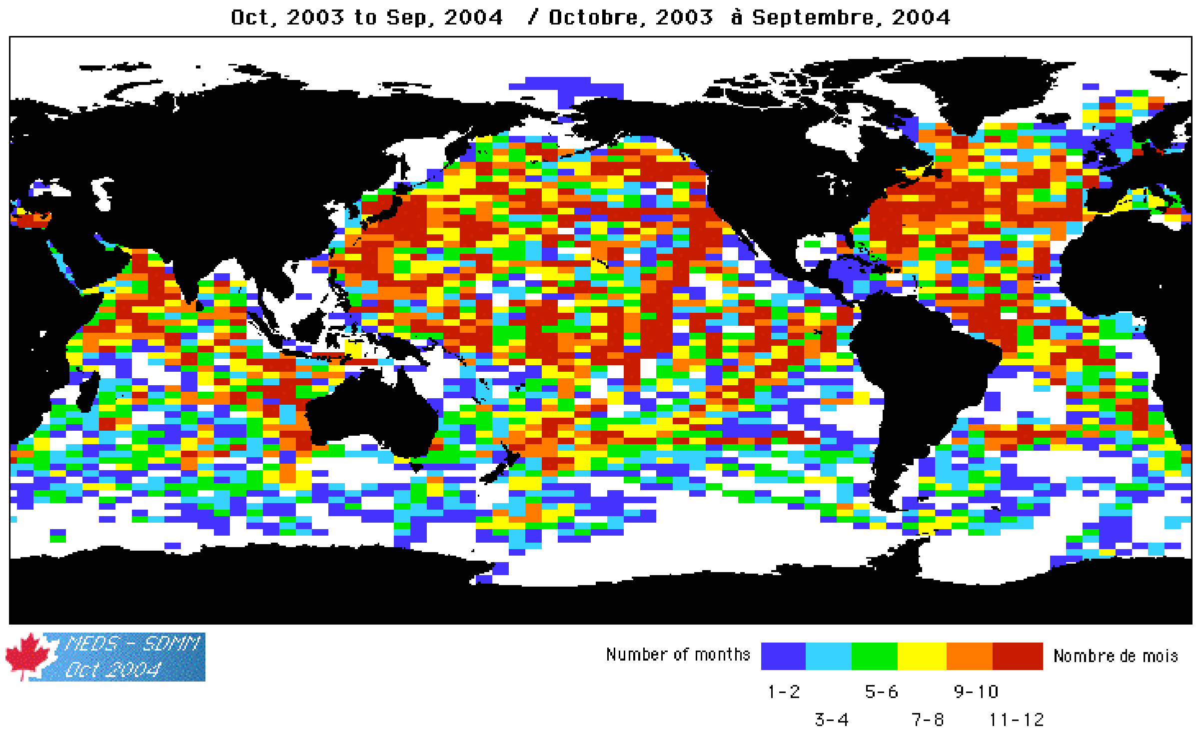

Fig. 4 One year of reported XBT observations.

2.4 Repeat hydrography

Repeat hydrography is in good shape, essentially all recommended stations have been done or have commitments. Most of this achievement is due to the work of the carbon community.

The long time scales of repeat sections requires long lead times for planning, so the frequency of sampling is not always known on a given section (Fig. 1).

2.5 Other repeat transits

The southern Indian Ocean sector is monitored by surface CO2 chemistry, meteorology, and ADCP, 2 occupations/yr under the OISO program. Other underway programs exist but are less regular.

2.6 Sea-level, bottom pressure recorders

Bottom pressure recorders (BPRs) and tide gauges have been shown to be extremely useful tools in monitoring the Antarctic circumpolar transport variability on timescales from sub-seasonal to inter-annual. BPRs have been maintained at around 1000m depth in Drake Passage by the UK since 1988, with measurements from the south side of the passage representing the key proxy for transport variability. These BPR deployments are due to continue for the foreseeable future, and will also complement the larger French-led (LODYC) project to instrument Drake Passage with current meter moorings along a JASON track. Other BPR deployments in the vicinity of Drake Passage will be made, including deployment of the UK's 4-year MYRTLE system. Previous BPR deployments outside Drake Passage include those close to SANAE (near the Greenwich meridian) and Dumont d'Urville (near 135E).

Tide gauge data are available from a range of sites around the Antarctic coast, including (clockwise from the Antarctic Peninsula) gauges at Rothera, Faraday/Vernadsky, Syowa, Mawson, Davis, Casey, Dumont d'Urville and Cape Roberts. Faraday/Vernadsky is the longest series, and has shown itself to be extremely valuable as an indicator of inter-annual changes in transport; maintaining this gauge is thus of great importance, as is protecting the other tide gauge series so that the longitudinal distribution of transport variability on inter-annual timescales can be investigated.

Various tide gauges exist at islands in the Southern Ocean, including the UK gauge at Signy, and the French gauges at Kerguelen, Amsterdam and Crozet (deployed as part of the ROSAME network, along with the Antarctic gauge at Dumont). It is, however, less clear how these island gauges relate to transport variability – recent investigations have suggested that the sea level variability they reflect can owe more to local forcing by wind stress curl than the circumpolar transport variability around Antarctica. This does not diminish the importance of monitoring sea level in these most remote of regions however.

The UK has plans to upgrade Faraday/Vernadsky within the next couple of years, and also install either Orbcomm or Iridium at its Antarctic gauge sites to enable real-time data return as part of a Southern Ocean monitoring system. Equipping other sites the same way would be most desirable, but obviously requires funding. The big weakness at present in the Antarctic tide gauge network is the gap in instrumentation between the Ross Sea area (around 170E) and the Antarctic Peninsula (around 65W). This largely reflects the absence of bases and suitable sites where gauges could be installed, and the relative infrequency of visits by ship to this area, which hinders deployments or recoveries of BPRs.

2.7 Sea-ice

There has been little or no progress to date in determining sea-ice thickness in a sustained manner. Note that while the use of ice-tethered platforms, ice thickness sonar from floats, etc., is under rapid development for the Arctic, the thin, divergent, and short-lived sea ice in the Southern Ocean makes the Antarctic region more challenging.

2.8 Meteorological buoys

Open ocean buoys.

At OOPC-8 Reynolds presented an analysis of the impact of the number of buoys in the Southern Ocean. Work has continued on this, in the direction of adding ARGO near-surface temperature as SST observations. Tests are being conducted to verify the nature of the ARGO SST value.

An indication of the sampling presently occurring is shown by the September 2004 buoys reporting to jcommops (Fig. 5).

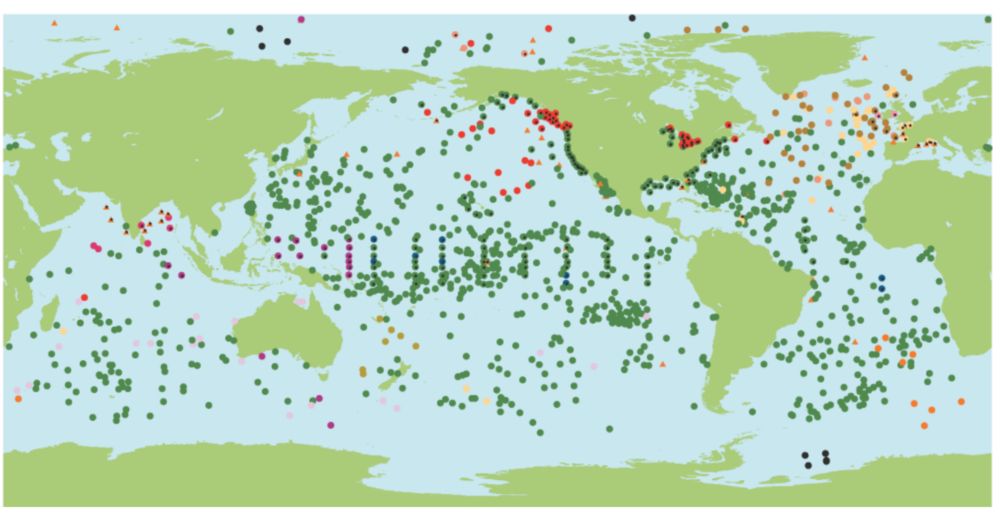

Figure 5. Drifting and moored buoys reporting Sept 2004 (jcommops).

Future enhancements to the system are needed, especially maintaining adequate coverage. Continental stations and buoys have been known to suffer from rejection in the operational system because of large, presumably real, differences between the observation and the model.

The sea-ice zone.

The International Program of Antarctic Buoys supports the deployment of something like 50 buoys per year in the marginal ice zone, with a target of 100 buoys per year. They measure ice motion, pressure, and temperature, and are meant to provide meteorological information in real-time to the numerical weather centers. Fig. 6 shows the net result of deployments over the six years 1995-2001. Resources for this program are small, but efforts are being made to augment the number of buoys deployed.

Deployments also occur along with process studies, and these could be systematically supported to maintain adequate coverage.

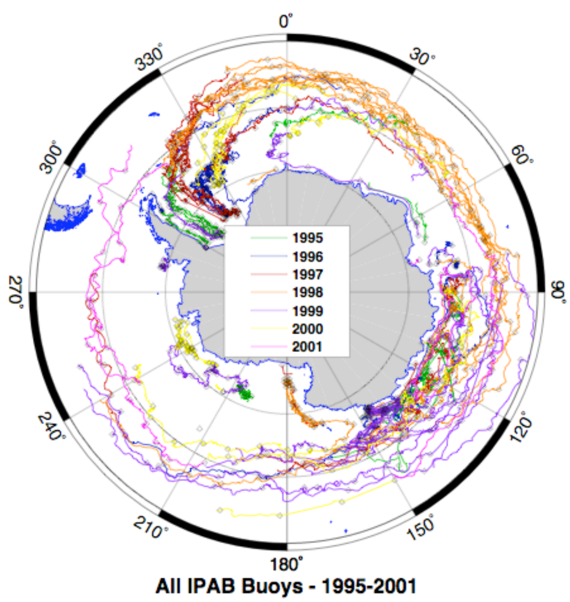

Fig. 6 International Antarctic Buoy Program buoys reporting 1995-2001.

2.9 Time-series stations and air-sea fluxes

The technical feasibility of air-sea flux buoys in the Southern Ocean has not yet been demonstrated. There are US plans to request a time-series platform for the region of high winds in the southern Indian Ocean sector, but the process is still at a very early stage.

3. Summary of the Adequacy and Evolution of the Observing System

Needed enhancements:

1. SEA-ICE

- Extension of profiling floats to sea-ice zone, with positioning.
- Sea-ice thickness (echo sounders) and Met buoys in the sea-ice zone for sea-ice dynamics.

2. SURFACE METEOROLOGY

- Enhance IMET coverage. In situ sampling of the diurnal cycle of SST and wind will help with interpretation of sun synchronous satellite observations.
- Meteorological buoys in the seasonal sea-ice zone (Tair, wind…).
- AWS on subantarctic islands.
- Surface Time-series stations in SE Indian (high mean wind conditions) - and Pacific-AA (synoptic variability) sectors. -*some technological buoy development required*.

3. DRIFTERS

- ARGO spatial coverage in areas opening up from initial deployment.
- Surface drifters – enhance coverage following Reynolds scheme

4. TRANSPORT ARRAYS

- Coherent circumpolar array in Weddell outflow/Ross outflow/Princess Elizabeth Trough/Adelie

5. XBT

- Retain high sampling rates or improve sampling rates

4. Special opportunities – International Polar Year 07/08

An overarching theme is freshwater fluxes between air-sea-ice components. The implementation of the following observing systems is recommended as the highest priority, and agrees with IPY guiding themes.

- Observations in the sea-ice zone: profiling floats and Met buoys.
- Air-sea flux improvements via IMET, time-series stations.
- Simultaneous transport arrays to reveal internal modes of ocean variability, synoptic sections.

5. Data management

Data management is an area in which CLIVAR is still weak. As far as ocean data goes, CLIVAR has a number of Data Assembly Centers (the old WOCE DACS plus a few new ones) to manage specific data streams. Links to these DACs and details of their responsibilities can be found at: http://www.clivar.org/data/. There are no specifically Southern Ocean data centers or archives under CLIVAR, although the CLIVAR IPO keeps track of hydrographic cruises at: http://www.clivar.org/carbon_hydro/hydro_table.php, and of other elements of the Southern Ocean observing system at: http://www.clivar.org/organization/southern/CLIVAR_CliC_Obs.html.

A number of data management items are being worked on:

- The IPY people have data as a high priority. Although the DACS are good for storing data it might well be that some sort of Data Information Centers are needed, especially for the amalgamation of contributions to the sustained system from various programs, e.g. iAnZone, and to a certain extent IPY.

- The data from the Japanese Antarctic Research Expeditions (till March 2001) were submitted to J-DOSS, and are freely available online at http://www.jodc.go.jp/service.htm. However, other countries have made similar steps to data availability.

- Contact with Raytheon is being made to encourage submission of underway data collected on US ships (e.g. thermosalinograph) to the Coriolis Data Center.

5. Final remarks

The recurring question for CLIVAR researchers is the poor quality of the reanalysis in the Southern Ocean, and the means to improve it. Additional data helps only if it is assimilated. Some steps have been made by the centers but systematic comparisons between the products and the data are still few, and their impact is unclear given the center's focus.

We recommend that a focused effort be undertaken to produce an Antarctic reanalysis, encompassing the Southern Ocean. A high-resolution regional atmospheric model might be the basis to initiate such an effort, including, for example, the ability to represent katabatic winds. High-resolution forward atmospheric and oceanic models are in use, and are starting to be coupled. Progress in assessing climate models will require close comparisons and links with observations, and these are not satisfactory in the present reanalysis programs.