Intergovernmental Oceanographic Commission

Workshop Report No. 115

IOC/GLOSS-IAPSO Workshop on Sea Level Variability and Southern Ocean Dynamics

Bordeaux, France
31 January 1995

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36 Suppl.	Papers submitted to the IOC/FAO Workshop on the Improved Uses of Research Vessels; Lisbon, 28 May-2 June 1984.	E
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40	IOC Workshop on the Technical Aspects of Tsunami Analysis, Prediction and Communications; Sidney, B.C., Canada, 29-31 July 1985.	E
40 Suppl.	First International Tsunami Workshop on Tsunami Analysis, Prediction and Communications, *Submitted Papers;* Sidney, B.C., Canada, 29 July - 1 August 1985.	E
41	First Workshop of Participants in the Joint FAO/IOC/WHO/IAEA/UNEP Project on Monitoring of Pollution in the Marine Environment of the West and Central African Region (WACAF/2); Dakar, Senegal, 28 October-1 November 1985.	E
43	IOC Workshop on the Results of MEDALPEX and Future Oceanographic Programmes in the Western Mediterranean; Venice, Italy, 23-25 October 1985.	E
44	IOC-FAO Workshop on Recruitment in Tropical Coastal Demersal Communities; Ciudad del Carmen, Campeche, Mexico, 21-25 April 1986.	E (out of stock) S
44 Suppl.	IOC-FAO Workshop on Recruitment in Tropical Coastal Demersal Communities, *Submitted Papers;* Ciudad del Carmen, Campeche, Mexico, 21-25 April 1986.	E
45	IOCARIBE Workshop on Physical Oceanography and Climate; Cartagena, Colombia, 19-22 August 1986.	E
46	Reunión de Trabajo para Desarrollo del Programa "Ciencia Oceánica en Relación a los Recursos No Vivos en la Región del Atlántico Sud-occidental"; Porto Alegre, Brazil, 7-11 de abril de 1986.	S
47	IOC Symposium on Marine Science in the Western Pacific: The Indo-Pacific Convergence; Townsville, 1-6 December 1966.	E
48	IOCARIBE Mini-Symposium for the Regional Development of the IOC-UN (OETB) Programme on 'Ocean Science in Relation to Non-Living Resources (OSNLR)'; Havana, Cuba, 4-7 December 1986.	E, S
49	AGU-IOC-WMO-CPPS Chapman Conference: An International Symposium on 'El Niño'; Guayaquil, Ecuador, 27-31 October 1986.	E
50	CCALR-IOC Scientific Seminar on Antarctic Ocean Variability and its Influence on Marine Living Resources, particularly Krill (organized in collaboration with SCAR and SCOR); Paris, France, 2-6 June 1987.	E
51	CCOP/SOPAC-IOC Workshop on Coastal Processes in the South Pacific Island Nations; Lae, Papua-New Guinea, 1-8 October 1987.	E

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SUMMARY
by Dr. Christian Le Provost, Chairman of the Workshop

The importance of the Southern Ocean, and in particular the Antarctic Circumpolar current. in global climate variability is well recognized. However, his ocean is a very remote area of the world whew few data have been collected in the past, and are still difficult to get. Its importance and lack of knowledge have led to the development of a dedicated CORE within the World Ocean Circulation Experiment (WOCE), and a convergence of efforts has been focused on this ocean over the last years. Sea level variations are among the observed parameters, through satellite altimetry and *in situ* bottom pressure and coastal sea level gauges. The workshop on “Sea Level Variability and Southern Ocean Dynamics” was aimed to put together scientists involved in this field. It was held in Bordeaux, France, on 31 January 1995, under the auspices of the IOC Group of Experts on the Global Sea Level Observing System (GLOSS) and *the* Commission on Mean Sea Level and Tides of the International Association for the Physical Sciences of the Ocean (IAPSO). The workshop was organized in two parts: the first part was dedicated to presentations of scientific analysis of collected data sets, and related outputs of numerical experiments carried over this ocean. The second part offered the opportunity to report on the status of the sea level observatory sub-networks implemented over the Southern Ocean, and to share experience, a necessity for progressing in the hostile environment of the ACC and the Antarctic continent.

Five presentations have been given in the first session.

The two first are related to the Drake passage, and the preliminary analyses of the sets of data collected by the Proudman Oceanographic Laboratory (POL) across this passage, which is one of the “choke point” of monitoring of the ACC transport, during the WOCE period. Woodworth *et al* emphasize the importance of the coastal and pressure gauge measurements through this area. They analyse the agreement of these data with Topex/Poseidon (T-P) satellite measurements showing good results for the north side data sets, but not for the southern edge, which may be due to baroclinicity in the ACC. Considering that the south side is a better location for monitoring the ACC, they conclude that further investigations are needed, to understand the processes at work in the area, and be able to define a good strategy for future monitoring.

Meredith *et al* investigate the ACC transport through Drake Passage from geostrophic calculations based on the data already introduced by Woodworth *et al,* and their consistency with previous estimates. *They also* suggest that the zonally-average wind stress for the latitude band 37.5° to 67.5°S is causing the observed transport variability, on the basis of the data collected in the Drake Passage but also those previously recorded between New Amsterdam and Kerguelen islands.

Park summarizes the mail features of the large scale mean sea surface topography in the South Indian Ocean, as obtained from the analysis of the first 18 months of T-P data. This T-P derived topography compares well with the FRAM derived sea surface topography, by contrast with the hydrography derived surface dynamic topography relative to 2000 dbars. The first two solutions tend to reveal the existence of two subpolar gyres west and east of Kerguelen Plateau, while the third one does not: the difference must be in the barotropic part of the circulation.

Florenchie et al present the results of an assimilation of altimeter T/P data in a high resolution dynamical model of the South Atlantic ocean. A nudging technique is used to assimilate these data in a QG model of this ocean. The results are shown to be very reliable, at least for the upper layers of the model. A special focus is given of the position of the different fronts of the ACC, and the vertical distribution of the associated density surfaces along 30°W, showing a good agreement with a recent hydrographic section. One interest of this application is its very limited computer time cost, due to the simplicity of both the assimilation technique and the ocean model formulation.

Lyard *et al* remind the main characteristics of the numerical hydrodynamic model of the world ocean tides developed by the Grenoble Ocean modelling group. They focus their presentation on the analysis of the M2 and K1 solutions over the Weddel Sea and the Ross Sea, in term of sea surface variations, velocities and energy fluxes. Interesting new information are given on these parameters specially over the ice covered areas of these domains .

Four presentations have been given in the second session, allowing, together with part of the information given in Woodworth *et al*, to get the status of the field sea level programmes carried by Australia (Summerson, Murty), France (Le Provost *et al)*, Japan (Odomaki and Oka) and UK (the US contribution is missing, as US contributors were not able to attend the meeting). Continuous efforts to measure sea level variations in the Southern Ocean have been undertaken since many years. The aims of these complementary programmes, as reminded in the different papers of this part 2, are mainly m study the interannual variability of the ACC, to supply sea truth for satellite altimetry, and to contribute to the monitoring of the global sea level changes. The strategy relies on the use of bottom pressure recorders -bprs- (combined if possible with inverted echo sounders) deployed on the two sides of the ACC, together with repeat hydrographic sections, for the WOCE Choke point like Drake passage (Woodworth *et d'). These* bprs are complemented by coastal tide gauges with the aim to study the feasibility of monitoring the cross section sea level variabilities from these coastal stations (Woodworth *et al*, Le Provost *et al).* These programmes suffer from hostile environment, especially the Antarctic sites: the papers by Odamaki and Oka, and, most of all, by Summerson relate some of these difficulties and the technical solutions that are tried to overcome them. Some of these data are collected by satellite, like those of the coastal French sites, which allows to make them available to the international community on a month delay basis. It is also proposed by Australia to develop an archiving facility dedicated to the collection of the sea level data over the Southern Ocean (Murty).

The different talks presented during this workshop illustrated the complementarily of altimetry and *in situ* sea level measurements, particularly necessary over the high latitudes of the Southern Ocean, where it is impossible to get all year round a complete coverage of the areas of interest. It has been shown that the efforts to deploy and maintain *in situ* bottom pressure and sea level recording stations need to be maintain in order to get a clear understanding of how to monitor the ACC transport variability at the choke point, and to complement the satellite altimeter measurements. This meeting demonstrates also, once more, the need for this community to meet regularly to share experience and improvements of the technology.

MONITORING THE VARIABILITY OF THE ACC AT DRAKE PASSAGE WITH TOPEX/POSEIDON, AND COASTAL AND DEEP SEA GAUGES, AND COMPARISONS TO THE FRAM MODEL

P.L.Woodworth, C.W.Hughes and J. M. Vassie
Proudman Oceanographic Laboratory, Bidston Observatory,
Birkenhead, Merseyside L43 7RA, UK

M.P.Meredith
School of Environmental Sciences, University of East Anglia,
Norwich NR4 7TJ, UK

Since November 1988, the Proudman Oceanographic Laboratory (POL) has deployed bottom pressure recorders (BPR's), or BPR's in combination with inverted echo sounders (BPR/IES's), across the Drake Passage (DP), first at three sites at approximately 3000, 3000 and 2000m depth north to south between Port Stanley and Signy (Spencer et al., 1993), then at each side of the western-central part of the Passage (at 4000m), and most recently (since November 1992) at three sites between Port Stanley and the Antarctic Peninsula, mid-way between the previous two sections (Figure 1). These have been deployed in order to provide a monitor of Antarctic Circumpolar Current (ACC) transport through the DP 'choke point' during the World Ocean Circulation Experiment (WOCE).

The present, middle section defines the 'official (WOCE) Drake Passage', and repeat hydrography and *in-situ* recording will be made along its length throughout the WOCE period. The northernmost and southernmost sites of the present deployments are at 1000m and contain IES's in addition to BPR's, while the third site, 60 nautical miles north of the southernmost, is a deep station in 4000m, data from which will be compared to those of the nearby, shallower southernmost. The deep station consists of a long term BPR rig called 'MYRTLE' (Spencer et al., 1994). Figure 1 shows the earlier recording positions by means of crosses, while the most recent three sites ('DN93', 'DS93' and 'MYRTLE' respectively) are shown by stars. Each of the deep records is one year long, with the last (1992-93 and 1993-94) records from the 'official section' being available for comparison to the TOPEX/POSEIDON (T/P) altimetry discussed below. A description of the BPR/IES DP dataset since 1988, and its interpretation in terms of transport fluctuations and their relation to the wind field, are presented in Meredith (1995) and Meredith et al. (1995).

The BPR/IES's are complemented by coastal tide gauges (Figure 1). Port Stanley and Signy are maintained by POL, while Diego Ramirez and Esperanza in the west-central part of the Passage are operated by the National Oceanic and Atmospheric Administration (NOAA) in collaboration with Chilean and Argentine authorities. Records from the latter two sites contain numerous gaps.

Although the coastal and bottom gauges will together provide a comprehensive dataset during WOCE, there is interest in being able to monitor the cross-DP sea level, or Sub-surface pressure (SSP), gradients over the longer term. Such a commitment requires the development of advanced *in-situ* technology (Spencer et al., 1994), and the use of precise sea surface height measurements such as provided by the T/P altimeter.

From Mitchum (1994) and others, we know that *T/P* is capable of providing time series of sea surface height at most points in the ocean with a root-mean-square (rms) accuracy of the order of 5 cm. However, Whitworth and Peterson (1985) determined the rms variability in the transport through the Passage to be of order 10 Sv, which converts to 5 mbar (or 5 cm) pressure difference if barotropic flow variability is assumed (Vassie et al., 1994a). Consequently, the anticipated ocean signal of interest is comparable to the measurement system accuracy, and T/P's performance in this area therefore requires careful validation by means of the available *in-situ* systems. We shall show two examples of this altimetric validation: one using a coastal tide gauge, and one using a deep sea BPR/IES.

Figure 2 shows the time series of SSP obtained from the coastal gauge at Diego Ramirez island and from T/P, the data analysis of which is described in AVISO (1994). An advantage of SSP over sea level is that the daily SSP records at these latitudes are considerably less energetic than the sea level records, as any approximate inverse barometer sea level response to air pressure change is automatically cancelled by the air pressure load itself in the total SSP signal. However, a disadvantage in this case is that air pressure from a meteorological model must now be added to the pressure equivalent of the altimetric sea surface height in order to compare to measured SSP, and the pressure fields of the models may themselves be imprecise in the DP area.

Nevertheless, Figure 2 shows good agreement between the two techniques after the application of a 20 day low pass filter. The rms difference between the two series is 4.3 mbar. From inspection of our own *in-situ* time series and those of Whitworth and Peterson (1985) and Peterson (1988, Figure 4), a filter length of this order seems consistent with previously observed power spectra of ACC variability, with the need to suppress daily sea level variability at gauge sites, and with the need to smooth out errors in modelled air pressure fields. Such a filter also reduces errors in modelling the fortnightly tides which are observed clearly in data from the region.

Figure 3 shows the corresponding time series for the deep sea station ‘DN93’. In this case, we are comparing SSP from T/P to bottom pressure (BP) which has been corrected to first order for baroclinic changes of the water column by means of an IES. Such a correction will not be perfect, but the close agreement (2.5 mbar rms) between the very small signals in the time series with a 20 day filter is very encouraging.

Although the datasets from the north side of the DP show good agreement to T/P, those of the south side are more complex and present differences between techniques and between BPR datasets even a short distance apart (Vassie et al., 1994b). This may be due to baroclinicity in the variability of the southern circulation. Winter ice is also a serious problem on the south side of the DP, causing damage to the Signy gauge and major data drop-outs in the altimetry. This will require further study.

The south side of the DP has been shown by Peterson (1988), who used BPR data, and by Hughes et al. (1993), who studied Fine Resolution Antarctic Model (FRAM) numerical model information, to be a better location than the north side at which to monitor ACC flows. In brief, variability in southern SSP (or BP) is anti-correlated with transport variability. Indeed, models show SSP from most of the Southern Ocean south of the ACC to be anti-correlated with flow through the DP. The need to study the spatial scales of such correlations, coupled with the difficulty of obtaining year-round altimetry south of approximately 61° S for most of the Atlantic part of the Southern Ocean, points to the need for further advanced *in-situ* instrumentation.

In conclusion, T/P-quality altimetry appears to be capable of providing the sort of accuracy required for long term monitoring of the DP for timescales of interest, although there are particular problems at present in understanding the datasets from the south side. However, we are confident that when all available DP datasets (CTD etc. as well as sea level, SSP and BP) from an extended period have been compared, especially in the context of advanced ocean models, then we shall have further insight into the processes at work in the area.

Acknowledgements

We are grateful to Bob Spencer and colleagues of the POL Technology Group for maintaining the POL coastal tide gauges and deploying the BPR/IES systems in the DP area, sometimes in difficult conditions. Collaboration with the British Antarctic Survey is much appreciated. This work was funded partly by the UK Defence Research Agency and by the Natural Environment Research Council.

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Figure Captions

1. Map of the Drake Passage area showing coastal tide gauges and bottom stations referred to in the text.

2. Time series of SSP at Diego Ramirez after application of a 20 day filter (dots) compared to similarly filtered SSP data from T/P (connected triangles).

3. Time series of BP at ‘DN93’, corrected by means of IES information, after a 20 day filter (dots) compared to similarly filtered SSP data from T/P (connected triangles).

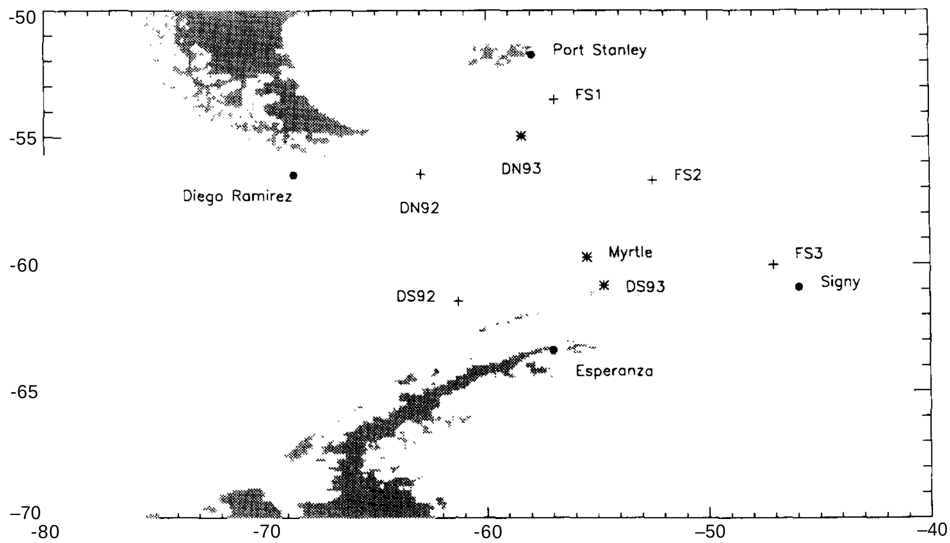

Figure 1

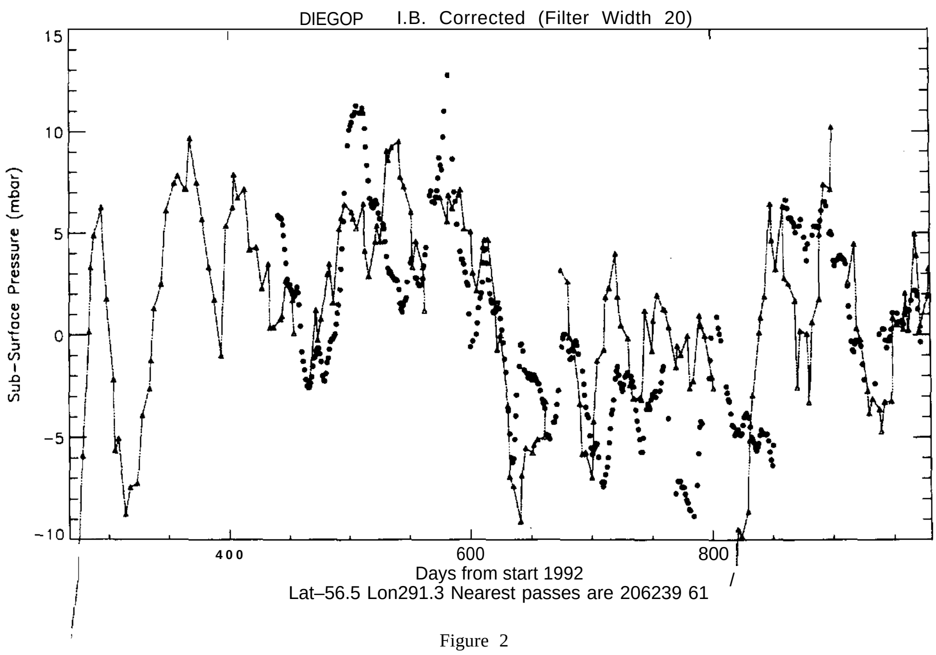

Figure 2

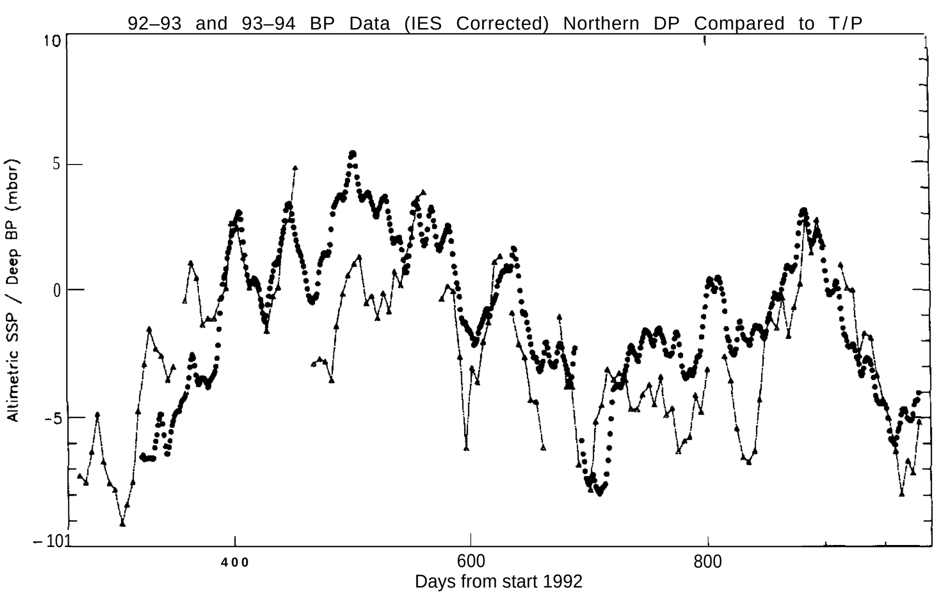

Figure 3

THE MONITORING AND FORCING OF THE ACC AT DRAKE PASSAGE

M.P.Meredith[2], J. M. Vassie[1], P.L.Woodworth[1], C.W.Hughes[1] and K.J.Heywood[2]

[1] Proudman Oceanographic Laboratory, Bidston Observatory,
Birkenhead, Merseyside L43 7RA, U.K.

[2] School of Environmental Sciences, University of East Anglia,
Norwich NR47TJ. U.K.

The bottom pressure recorder (BPR) data described by Woodworth *et al.* (1995) previously in this publication have been used for the monitoring of the temporal variability of the Antarctic Circumpolar Current (ACC) transport at Drake Passage (DP). Figure 1 of Woodworth *et al.* (1995) shows the locations of the BPR deployments. The FS1, FS2 and FS3 positions were first instrumented in November 1988, with the BPRs being moved to the DN93 and DS93 positions in November 1992, where monitoring continues. Additional bottom pressure data from the DN92 and DS92 positions were obtained for December 1991 to November 1992. Figure 1 shows the currently available time series of bottom pressure from the north and south DP positions, and north-minus-south pressure difference, with the dashed line being the data smoothed with a 1 cycle/day cut-off low pass filter, and the solid line being the same data smoothed with a 31 day low-pass filter. Geostrophic calculations on these data yield values for the standard deviation in transport of approximately 8 Sv, subject to the assumption that the variability is predominantly barotropic (e.g. Vassie *et al.,* 1994). This is slightly less than the 10 Sv obtained during the International Southern Ocean Studies ISOS) programme in the mid-1970s to early 1980s (Whitworth and Peterson, 1985).

Pressure data from the FS2 position were found to be unsuitable for direct inclusion in geostrophic calculations, due to the proximity of the FS2 instrument to the Polar Front (PF). A strong correlation between bottom pressure and bottom temperature indicates that meanders/eddies and lateral shifts of the PF (e.g. Legeckis, 1977) have a significant effect on the pressure record. The fact that this was a positive correlation indicates that the change in sea level across the PF has a greater influence on bottom pressure than the change in density across the front. Historical monthly-mean sea-surface temperature (SST) maps were obtained from the Jet Propulsion Laboratory (JPL) for the period 1982-1986, and used to investigate the low-frequency movements of the PF. The maps were filtered with a 2 pixel square gradients filter, and the mean latitude of the PF for each month extracted. A very regular semiannual signal was found in the latitude of the PF, peaking each year in May/November or June/December, agreeing well with the observed semiannual signals in the FS2 bottom pressure and temperature data. The annual signal from the SST maps was less regular, peaking between April and July each year.

Since 1992, the DP BPR deployments have also featured Inverted Echo Sounders (IESs) on the instrument rigs. Data from these have been used to empirically obtain parameters such as dynamic height and vertically-averaged density at the north side of the passage, from which sea level can be obtained (Woodworth *et al.*, 1995). No such derivation is possible for the south-side IES data, due to non-linearities in the relationships between measured acoustic travel time and the desired parameters. The IES data indicate that there is, significant steric contamination in the BPR data from the north side of DP due to activity of the Subantarctic Front (SAF), and consequently the north-minus-south pressure difference will overestimate the true transport variability. However, the fact that bottom pressure and acoustic travel time from north DP were observed to be negatively correlated implies that bottom pressure will provide a better measure of transport variability than sea level, since the change in density across the SAF partially compensates for the change in sea level.

To investigate the causes of the observed transport variability, gridded surface wind stress data were obtained from the National Center for Atmospheric Research (NCAR). These were derived from the output of the European Centre for Medium-Range Weather Forecasts (ECMWF) global analyses. Following Wearn and Baker (1980), the zonally-averaged eastward wind stress was calculated for the latitude band 37.5 to 67.5°S. Figure 2 shows this compared to the bottom pressure data from the south side of DP (here plotted inverted for comparison). It is clear that there is a strong negative correlation between the series. No such agreement was found with bottom pressure from the north side of DP, due at least partially to the steric contamination outlined earlier. Wind stress curl was also calculated for the latitude bands 40-45°S and 60-65°S, after Peterson's (1988) suggestion that changes in the wind stress curl adjacent to the ACC will influence the Sverdrup transport into the ACC band, and hence the ACC mass balance and geostrophic transport. Some agreement was found between these parameters and south DP pressure, but it is believed that this is due to the fact that these manifestations of the wind field strongly resemble the zonally-averaged wind stress, rather than being the cause of the variability in the pressure. This is suggested by the fact that south DP pressure more closely resembles wind stress curl at the north side of the ACC than wind stress curl at the south side.

BPR data previously collected (1986-1988) at Amsterdam and Kerguelen Islands in the southern Indian Ocean were also compared to the different measures of wind forcing. These data are described by Vassie et *al.* (1994). Figure 3 shows the series of bottom pressure at Kerguelen Island compared to the zonally - averaged wind stress, and again it is clear that there is significant variability common to both series. It is interesting to note that here there is a direct correlation between wind and bottom pressure, whereas there was a negative correlation between wind and south DP pressure. From the geostrophic relationship, this implies that the forcing for the pressure variability at Kerguelen actually occurs south of the islands, and hence the Amsterdam-minus-Kerguelen pressure difference will not be truly representative of the ACC transport variability. The wind stress curl time series were found to agree less well with Amsterdam and Kerguelen bottom pressure, except at very long (i.e. greater than annual) periods. This again suggests that the zonally-averaged wind stress is causing the observed variability, though it is clear that an analysis of the BPR data from the three World Ocean Circulation Experiment (WOCE) choke points is needed to resolve this matter.

Acknowledgements

We are very grateful to Tony Craig at NCAR for supplying the wind data, to the JPL PODAAC for the AVHRR data, and to Bob Spencer and the POL Technology Group for maintaining and operating the BPR/IES instruments.

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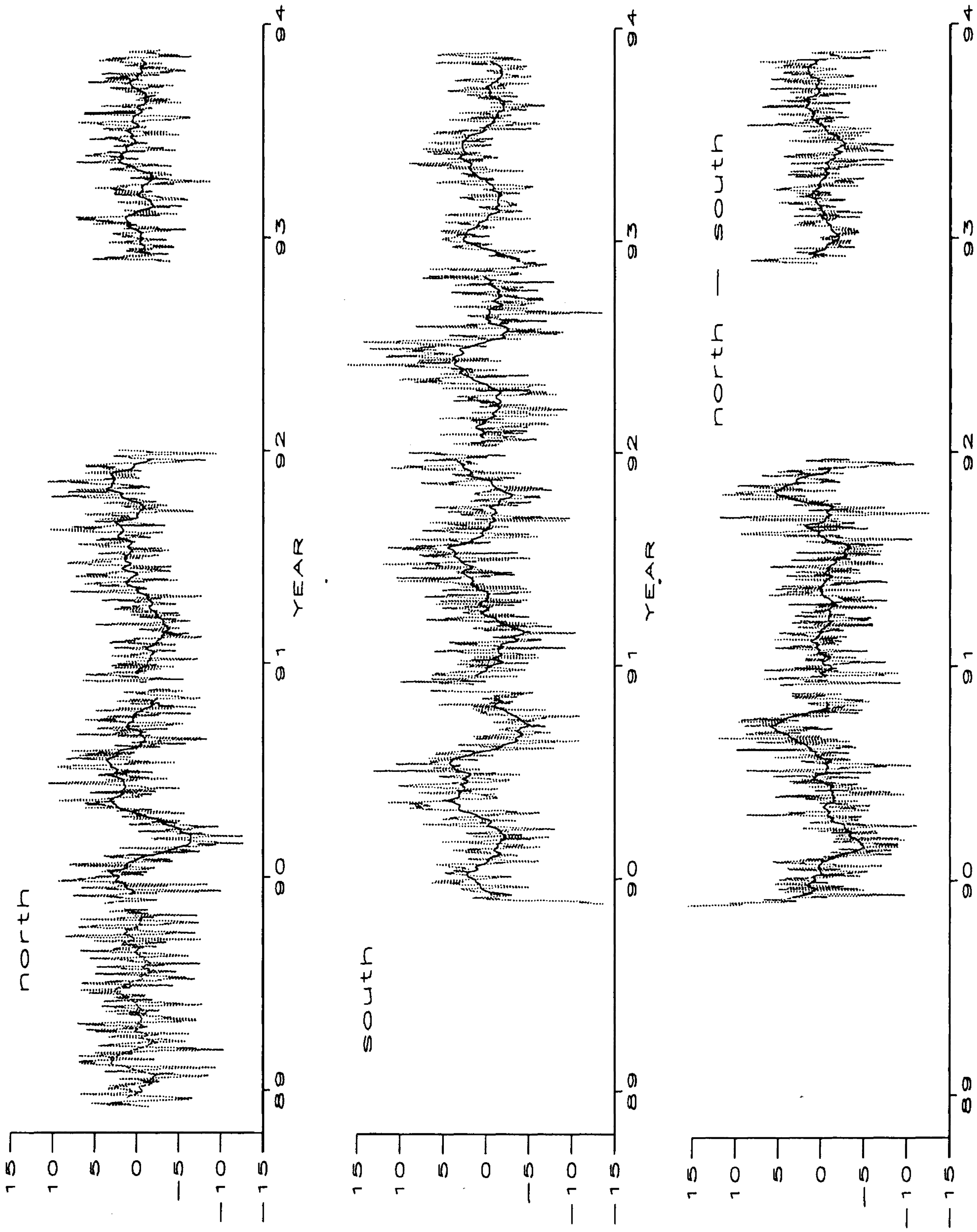

Figure 1 Drake Passage bottom pressure time series (a) from the north side (b) from the south side and (c) north-minus-south pressure difference. Dashed line is data smoothed with 1 cycle/day cut-off filter, solid line is same data smoothed with 31-day moving average filter.

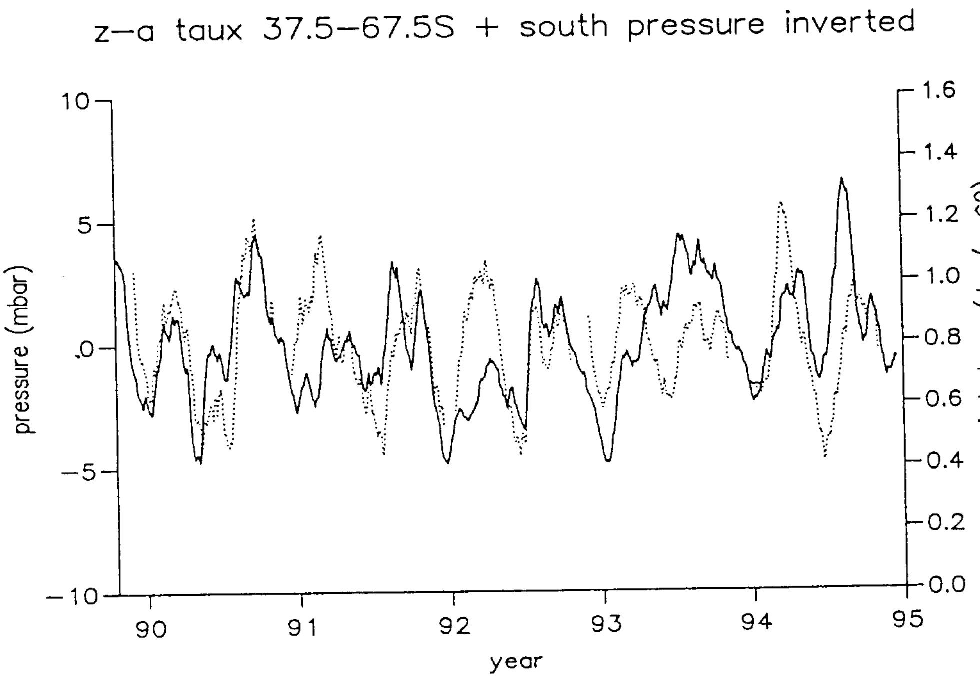

Figure 2 Zonally-averaged eastward wind stress between 37.5 and 67.5° (solid) and south Drake Passage bottom pressure (dotted; plotted inverted for comparison). Both series smoothed with 31-day moving average filter.

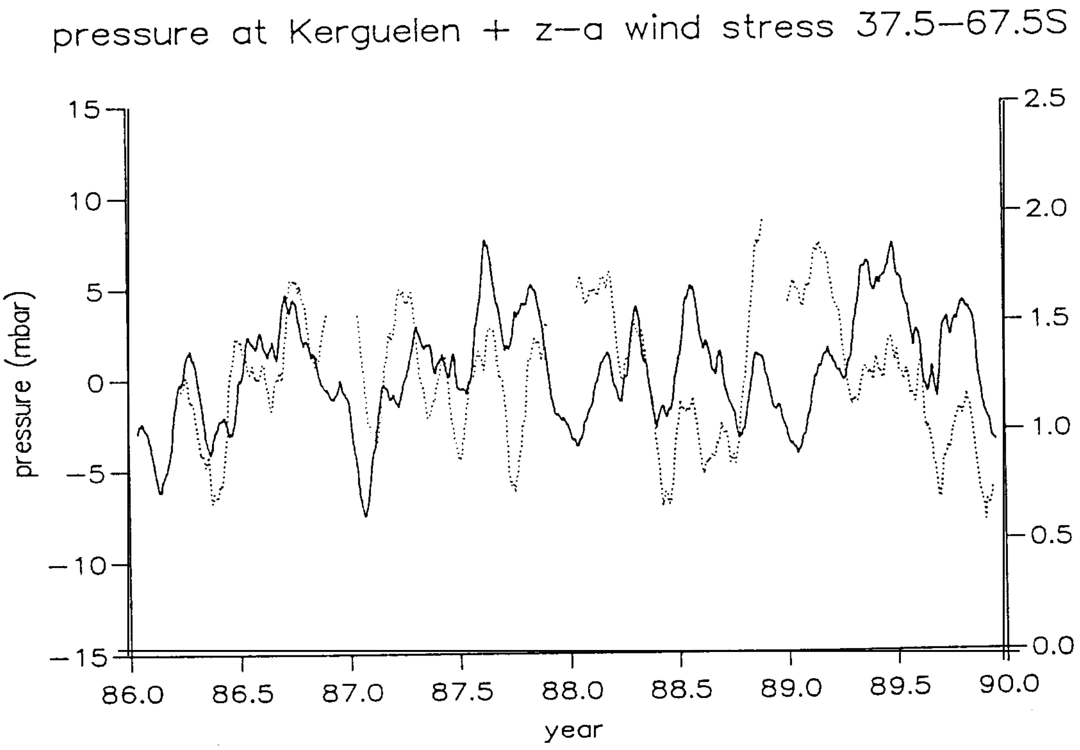

Figure 3 Zonally-averaged eastward wind stress between 37.5 and 67.5°S (solid), and bottom pressure measured at Kerguelen Island (dotted). Both series smoothed with 31-day moving average filter.

Large-Scale Circulation in the South Indian Ocean from TOPEX/POSEIDON

Y. H. Park

Laboratoire d'0céanographie Physique
Muséum National d'Histoire Naturelle
43, rue Cuvier, 75005 Paris, France

1. INTRODUCTION

TOPEX/POSEIDON (T/P) satellite altimeter, launched on 10 August 1992 into a 10 days repeating orbit of radius 1300 km with a spatial resolution of about 300 km at the equator, is providing quasi-synoptic, global sea level data with an unprecedented accuracy. When adequately corrected for a variety of inherent geophysical phenomena and then referenced to the geoid (or equigeopotential surface), the altimetric data yield the dynamic topography associated with the surface ocean circulation. In fact, the altimeter-derived dynamic height refers to the distance of the sea surface above the geoid, which can be obtained by the following equation:

Dynamic Height = Orbit - (Range + Corrections) - Geoid - Errors

where errors comprise all uncertainties in the computed altimeter orbit, measured altimeter range (or distance between the altimeter and the sea surface), geophysical corrections (tides, sea state bias, and ionospheric, tropospheric, and barometric corrections), and model geoid. Among these error sources the geoid uncertainty is the main limit to the absolute determination of the dynamic height. With the present knowledge of the marine geoid (e.g., Rapp et al., 1991), only large-scale circulation signals of wavelengths greater than some 2000 km can be separated from the geoid error, with a 10 cm level of uncertainty (Nerem et al., 1994). Another important source of error comes from the inaccuracy of tide models. A 5 cm level of the contemporary tidal error alone is equivalent to the total uncertainty of T/P measurements. Errors in short period tides (e.g., M2 and S2) appear in T/P sea level time series as aliased low-frequency signals (i.e., 60 days aliasing), which constitute the main source of error for the time-variant sea levels. Apart from the as yet unresolved geoid problem, however, the low-passed T/P sea level time series, corrected for ocean tides using the T/P-derived tide models, are found to be accurate at a 2 cm level against open ocean ground truth data, on a monthly basis (Cheney et al., 1994; Park and Gambéroni, 1994; Verstraete and Park, 1994).

We summarise here the large-scale, mean surface circulation in the South Indian Ocean as determined from the first 18 months of T/P data, together with comparisons to the two independent solutions, each from the numerical model FRAM (Fine Resolution Antarctic Model) (Webb et al., 1991) and the best available historical hydrographic data. Details on the altimeter data processing, data validation against in situ sea level measurements and interpretation of the intercomparisons are given in Park and Gambéroni (1994). It suffices to note that the OSU91A geoid (Rapp et al., 1991) and the Texas model, a T/P-derived tide model developed by the University of Texas / Center for Space Research (Eanes, 1994), have been used.

2. SEA LEVEL AND CURRENT COMPONENTS WITHIN THE WATER COLUMN

As the altimetric sea level reflects the net surface effect of water movements within the whole water column, we begin with a brief review of some theoretical relationships between the sea level and the two basic components of geostrophic currents, barotropic and baroclinic.

With the hydrostatic pressure approximation, the pressure at a given depth z within the water column is given by:

$$p = \rho_0 g \eta + \int_z^0 \rho g \, dz \qquad (1)$$

where $\eta = \zeta + p_a/\rho_0 g$ is the surface elevation ζ adjusted to the atmospheric pressure p_a, the so-called adjusted sea level (which can be determined from altimetric data); p is density whereas ρ_0 is average density (Fig. la).

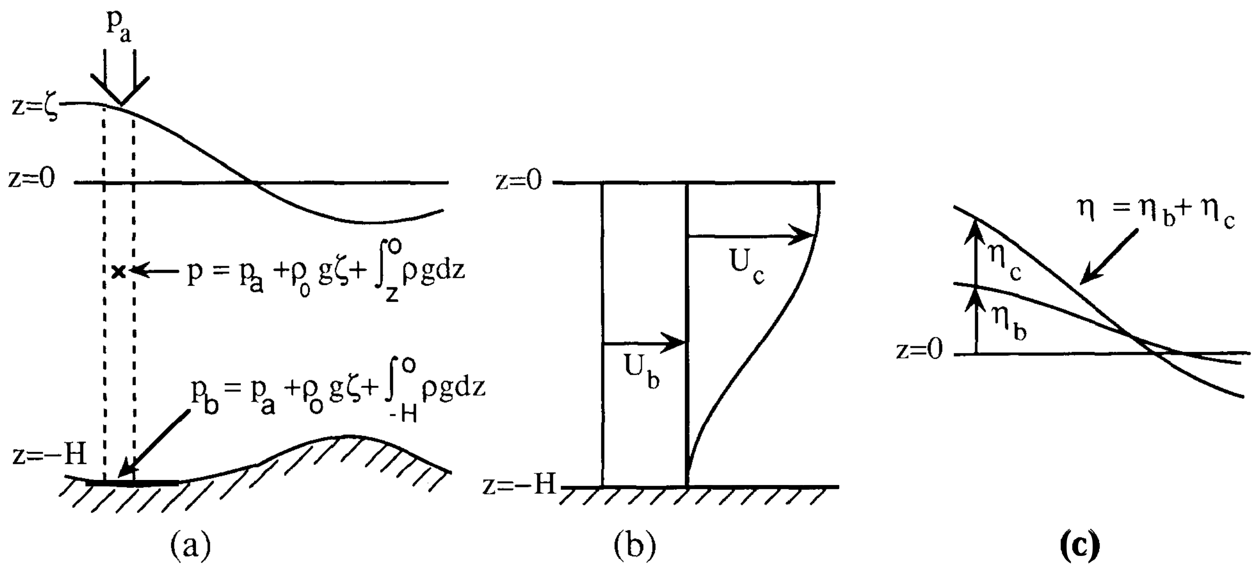

Figure 1. Schematics of the (a) hydrostatic pressure, (b) barotropic and baroclinic velocity components within the water column, and (c) corresponding adjusted sea level components. See text for details.

In their numerical study of the general circulation of the Atlantic Ocean, Mellor et al. (1982) decomposed the total current (and transport) into Ekman, baroclinic, and barotropic components. (The latter two components were actually called thermohaline and bottom velocity components by Mellor et al.) As we are interested here in the theoretical relationships between the sea level and the current components, and because the Ekman current is independent of the sea level, we restrict our discussion to the baroclinic and barotropic velocity components. Also, we use much simpler and more familiar Cartesian co-ordinates (+ x eastward; + y northward; + z upward), instead of the spherical co-ordinates used in Mellor et al., because the co-ordinate system does not affect at all the following discussion. In this simple case, the geostrophic momentum balance is classic, and the eastward geostrophic velocity u at a depth z can be written in a similar manner as in Mellor et al.:

$$fu = -\left[g\frac{\partial \eta}{\partial y} + \int_{-H}^{0} \frac{\partial b}{\partial y} dz \right] + \int_{-H}^{z} \frac{\partial b}{\partial y} dz \qquad (2)$$

where f is the Coriolis parameter; H (x, y) is the bottom depth; $b = g(\rho - \rho_r)/\rho_0$ and ρ_r (z) is a depth-dependent reference density. The northward geostrophic velocity can be written in a similar manner, but it is not considered further for the sake of brevity, without the loss of generality. The first two terms on the r.h.s, of (2) are independent of z, so they form the barotropic component fu_b, while the third term, which being a function of z with zero velocity at the bottom, is the baroclinic component fu_c, i.e. $u = u_b + u_c$ (Fig. lb).

At the surface (z= O), and putting $\int_{-H}^{0} \frac{\partial b}{\partial y} dz = -g \frac{\partial \eta_c}{\partial y}$ and $\eta_b = \eta - \eta_c$, (2) becomes:

$$fu = -g\frac{\partial \eta}{\partial y} = -g\frac{\partial(\eta_b + \eta_c)}{\partial y} \qquad (3)$$

where η_b and η_c can be interpreted as the corresponding sea level component associated with the barotropic current, u_b, and the baroclinic current, u_c, respectively. In other words, the adjusted sea level η is the sum of the above two sea level components (Fig. lc). From hydrography, η_c can be easily obtained using the classical dynamic method, but η_b is undetermined.

However, some insight into the generation of barotropic current (or current at the bottom) can be gained. From (1) and (2) we obtain at z = - H, after some manipulation,:

$$\rho_0 f u_b = \frac{\partial p_b}{\partial y} + b_H \frac{\partial H}{\partial y} \qquad (4)$$

where b_H is the buoyancy term b at the bottom. As stressed by Mellor et al., (4) shows that the barotropic current can be arisen not only from the horizontal gradient of bottom pressure but also from the joint effect of baroclinicity and bottom topography changes. On the other hand, the change in bottom pressure represents the barotropic response to changes in the wind field (Gill and Niller, 1973). It is clear that the wind field, baroclinicity, and bottom topography are all of importance for the barotropic current. In summary, hydrography yields only the baroclinic sea level component, while the total sea level (baroclinic + barotropic) can be observed both from satellite altimetry and numerical models.

3. LARGE-SCALE CIRCULATION FROM T/P AND COMPARISONS

Figure 2a shows the mean dynamic topography based on the first 18 months of T/P data and referenced to the OSU91A geoid. The data were previously filtered of along-track fluctuations much shorter than 2000-km and then averaged on a 4° longitude x 2° latitude grid before mapping. In the Southern Hemisphere, the geostrophic current flows counterclockwise around the highs of the dynamic topography and clockwise around the lows, with its speed being proportional to the local gradient of the topography. This map shows clearly the major large-scale circulation systems in the South Indian Ocean: the eastward flowing Antarctic Circumpolar Current (ACC); the anticyclonic subtropical gyre north of the ACC; and two cyclonic subpolar gyres south of the ACC.

This T/P-derived dynamic topography can be compared to the FRAM-derived sea surface topography (Fig. 2b). The FRAM solution shows an excellent agreement with the T/P solution, in particular, in the reproduction of the two subpolar gyres west and east of the Kerguelen Plateau. The western subpolar gyre, corresponding to the eastern boundary of the Weddell Gyre, appears to extend as far east as 60°E in the Weddell-Enderby Basin, contrary to the previous belief of its western limit at 30°E. Also, the Kerguelen Plateau appears as an effective topographic barrier to the zonal circulation, pushing the main vein of the ACC to the north of Kerguelen Island and separating the two subpolar gyres into either side of the plateau. The existence of these subpolar gyres is strongly supported by historical satellite-tracking iceberg trajectories around Antarctica (Tchernia and Jeannin, 1983).

However, hydrography-derived surface dynamic topography relative to 2000 dbar (Fig. 2c) does not indicate any evidence of the subpolar gyres neither east nor west of the Kerguelen Plateau, which is in great contrast with the altimetric and model solutions. As mentioned previously, this is due to the fact that hydrography yields only the sea level component associated with the baroclinic current but it is blind to that associated with the barotropic current. On the other hand, the

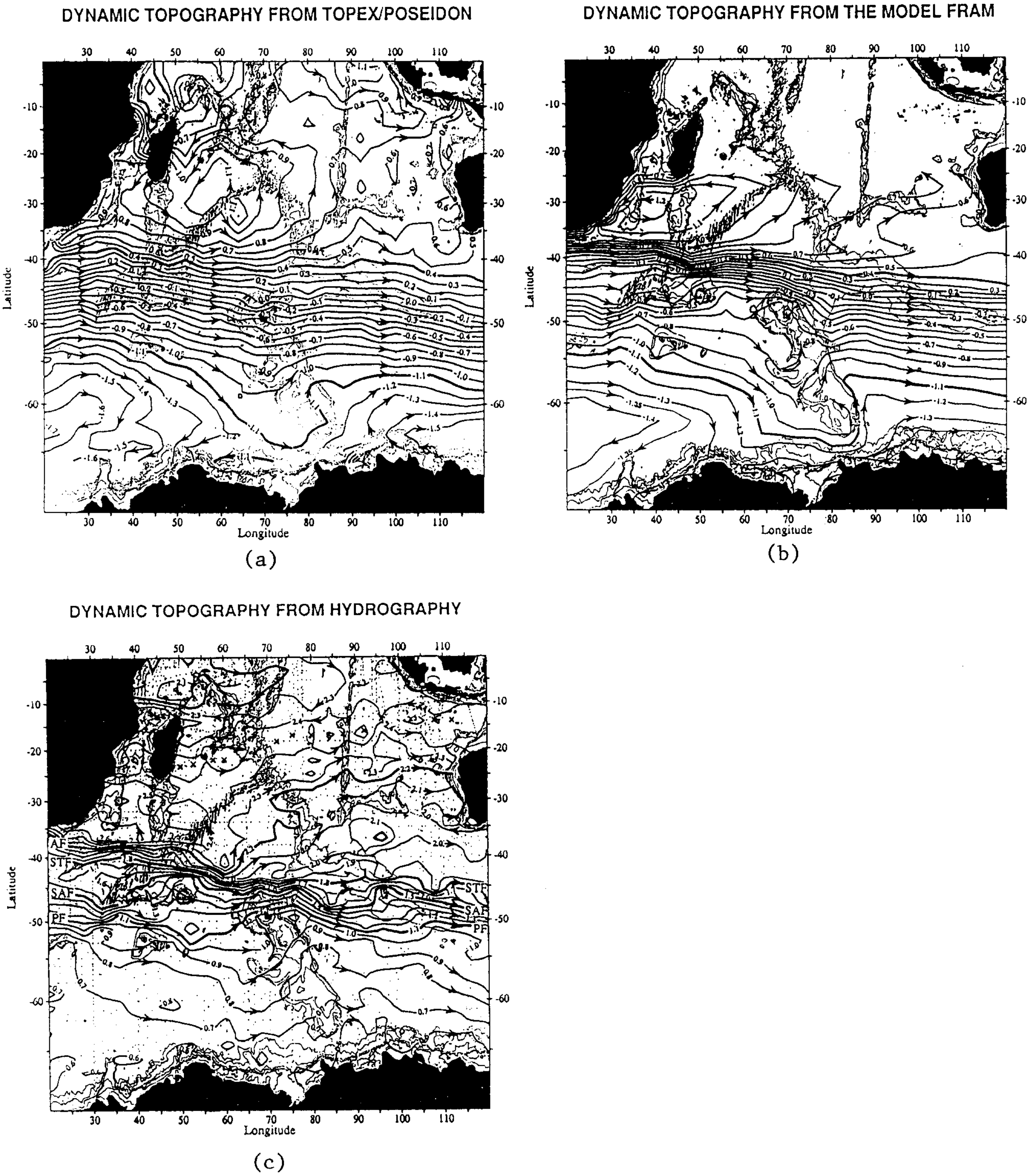

Figure 2. Large-scale, mean surface dynamic topography in the South Indian Ocean from (a) 18 months of T/P data, (b) 6 years of FRAM prognostic output, and (c) 70 years of historical hydrographic data (0/2000 dbar). Units are in meters and contours are every 0.1 m. From Park and Gambéroni (1994).

barotropic sea level component is expected to be predominant especially in the Southern Ocean, which can be captured both from the altimetry and the numerical model.

4. CONCLUSION

The T/P altimetry provides for the first time a powerful tool for oceanographers to identify an important barotropic circulation in the Southern Ocean, which has hitherto been invisible from the classical hydrography. It is important to revise the hydrography-based general belief that the eastern boundary of the Weddell Gyre lies to the west of 30°E. Also, previous estimations of the ACC transport in the Indian sector of the Southern Ocean based on meridional hydrographic sections connected to Antarctica should have been seriously misleading. The precision of the large-scale surface circulation from altimetry is at present limited by the geoid uncertainty, which will be improved with increasing knowledge of the geoid.

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A NUMERICAL MODEL OF THE SOUTH ATLANTIC OCEAN WITH ASSIMILATION OF TOPEX-POSEIDON DATA : PREDICTIONS OF THE ACC FRONTAL STRUCTURES

P. Florenchie, C.Le Provost, E. Blayo and J. Verron

LEGI, University de Grenoble, URA 1509-CNRS
BP 53X, Grenoble cedex, France

l-INTRODUCTION

The aims of the study are both technical and scientific. First, with a robust and CPU economic method, we realize a 4D extrapolation of the altimetric dataset from satellite measurements, horizontally, between satellite tracks, vertically, under the surface of the ocean, and in time, between successive paths of the satellites. Secondly, we use altimeter measurements to improve our understanding of the dynamics of the ACC, and its space variability from mesoscales eddy instabilities to large scale circulations. This study allows to illustrate the possibilities and the limitations of the approach.

2-THE MODEL

The model used is an adaptation and an extension of the two-layer quasigeostrophic model with beta-plane presented by Holland (1978). The domain extends between 16°S and 65°S in latitude, and between 68°W and 32°E in longitude. The model is eddy resolving, with a horizontal resolution of 1/6° in both horizontal direction (ie in latitude: 18.5 km, and in longitude : 17.5km at 20°S, 9.2 km at 60°S). The stratification of the ocean is schematized by a four-layer representation: layer depths are 300 m, 300 m (thermocline waters), 600 m (AAIW) and 3800 m (deep waters). Realistic topography is built into the model using the Synbaps II bathymetric data base. Coastlines are also realistic. The ocean circulation is forced by a constant annual climatological wind stress curl from Hellerman and Rosenstein. Open boundaries conditions using radiative boundary conditions (for the fluctuations) and relaxation towards a local mean climatology for the steady state are introduced at the northern, the eastern and the western model boundaries. Mass fluxes are based on in situ data and on results from global models.

In Drake Passage, at 68°W, the total mass transport of the Antarctic Circumpolar Current (ACC) is 138.5 Sv : 30 Sv in each of the two upper layers, 37.5 Sv in layer 3, and 41 Sv in the bottom layer. The horizontal distribution of the transport in Drake Passage is concentrated in major fronts : the Subantarctic front at 58.5°S, the Polar front at 60.3°S, and Continental Water Boundary at 64°S.

At the northern boundary, along 16°S, the total transport is zero :
-4.5 Sv (of outflow) in the first layer, -4.5 Sv in the second, -8 Sv in the third layer and 17 Sv (of inflow) in the bottom layer.

At the eastern boundary, inflow and outflow have to be considered. The total transport along 32°E is -138.5 Sv of outflow. In the different layers, the transport is : -25.5 Sv in layer 1, -25.5 Sv in layer 2, -29.5 Sv in layer 3 and -58 Sv in layer 4. The profile of the transport along the boundary reproduce different fronts : the Agulhas Current is 100 km width and its transport is 65 Sv flowing into the domain. The Agulhas front is located at 39°S and its transport is -81 Sv. The Subtropical front flows eastward at 42°S. The Polar and Subantarctic fronts are supposed to have merged into a single front which leaves the domain at 50°S.

3-THE ASSIMILATION OF ALTIMETRIC DATA

The assimilation procedure is an along-track, sequential, nudging technique. The satellite altimeter measurement is the sea-surface height (SSH) which can be divided into a time mean MSSH and a fluctuating part. Due to some inaccuracies in the geoid correction, we prefer to use a composite dynamic height : Topex-Poseidon altimeter residuals with a mean sea surface given by the model, itself run in a free-mode. The assimilation procedure is reinitialized on a daily basis. This paper reports on an experiment assimilating the first twelve months of T/P dataset allowing us to study the behaviour of the South Atlantic Ocean during the year October 92-September 93. For more details about the model and the assimilation technique, see Verron et al. (1992), or Blayo et al. (1994).

4 - RESULTS

4.1 - MEAN CIRCULATION

The mean surface circulation obtained during this experiment is displayed in figure 1.

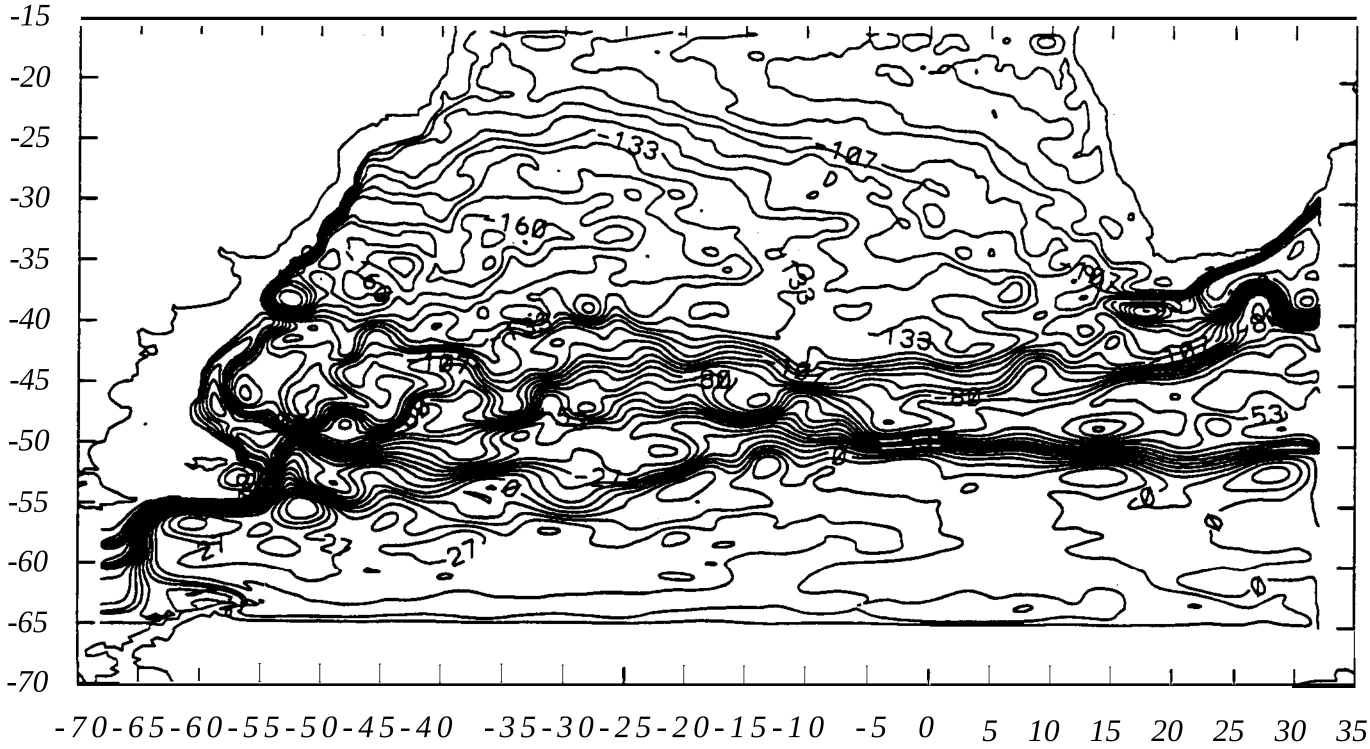

Fig I.: Mean surface transport in the first layer from the one year assimilation experiment. The mean paths of the currents are correctly reproduced (1 ci = 2 Sv).

The main features of the general circulation are represented : the Brazil-Malvinas confluence, the Agulhas retroflection, the subtropical gyre, and the different fronts of the ACC. The mean path of the currents are correctly reproduced. The surface circulation is similar to the description of upper-level circulation given by Peterson and Stramma (1991- figure 1):

- the southern edge of the Subtropical gyre consists of the ACC with its different fronts, among which the subantarctic front and the polar front are the most important ones. The subtropical front separates the subtropical gyre from the ACC. The northern limb of the gyre is a broad current flowing towards the northwest (the Benguela current).
- we can see clearly the western boundary Brazil current with its jet-like structure, flowing south to a point near 38°S where it separates from the coast. The intensification of the current, as it flows southward, is also well represented.
- after the Drake passage, a part of the ACC (the subantarctic front) turns northward and follows the western side of the Argentin basin, where it becomes the Malvinas current. This current meets the Brazil current in the Brazil-Malvinas confluence. After its retroflection, the Malvinas current enters the South Atlantic and becomes the subantarctic front again. The polar front remains oriented mainly toward the east.
- on the eastern side of the domain, the most characteristic feature is the Agulhas retroflection : the Agulhas current flows down the east coast of south Africa, then it flows southwestward into the South Atlantic, but before entering the South Atlantic Ocean, the current turns back and returns into the Indian Ocean.

By contrast to the good results in the upper layers, the circulation in the bottom layer (not shown) does not reproduce correctly the overall circulation of deep waters, probably because of the limited number of layers on the vertical used in this experiment.

4.2- INSTANTANEOUS CIRCULATION FIELD

The fine horizontal resolution of the model (1/6° x 1/6°) allows the explicit resolution of the mesoscale eddy activity. Other processes such as variable wind forcing are not explicitly included in the model.

However, they are indirectly introduced during the simulation thanks to the variability contained in the altimeter data. A snap-shot of the surface circulation as predicted by the model on the 4 October 1992 is displayed in figure 2.

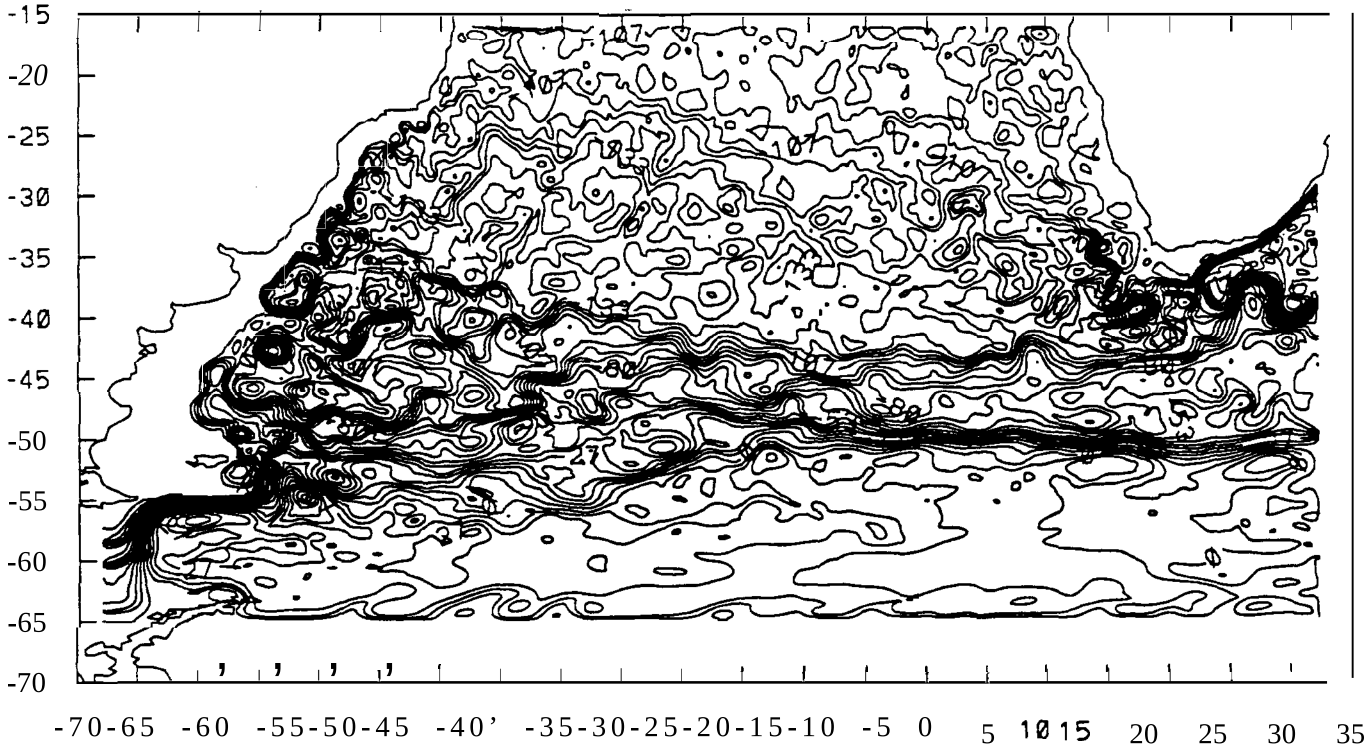

Fig. 2 : snap shot of the surface circulation on the 4 October 1992 as predicted by the model (1 ci = 2 Sv for the first layer). An anticyclonic ring is featured near 43°S/55°W. Fronts in the ACC and main currents appear clearly

In the western part of the domain, the Brazil-Malvinas confluence is well reproduced and is similar to descriptions given in other studies (Matano et al. 1992, Gordon 1988). The Brazil Current separates from the coast at 38°S, despite variations of its mass transport during the simulation. The latitude of the retroflection of the Malvinas Current varies from 43°S to 40°S, but it remains difficult to link these variations to the variability of the mass transport, because the presence of recirculation cells can affect considerably the mass transport from one place to the other. The meanderings of these currents and their instabilities lead to the formation of a certain number of cyclonic and anticyclonic features.
In the eastern part of the basin, the Agulhas Retroflection is well known for its shedding of eddies. The eddies generated by the model are spawn irregular and follow different trajectories. Eight rings have been shed during the one year period of the experiment, many were reabsorbed by the loop of the Retroflection. One part of the Agulhas Current does not participate in the Retroflection and penetrates into the South Atlantic, making meanders and generating eddies along the southwest coast of South Africa. The loop of the Retroflection makes zonal oscillations between 12°E and 21°E. Generally, one eddy or two are shed during the westward stretching of the loop. The behaviour of the Agulhas Retroflection is in good agreement with other studies based on in-situ data, or on the analysis of Geosat data (Quartly et al. 1992, van Ballegooyen et al. 1994, ...).
The Agulhas retroflection is one of the most energetic areas in the world. In our simulation, the maximum values are obtained in the area of the retroflection, where the oscillations of the loop take place. At the mesoscales, the values of eddy kinetic energy (eke) range from 200 to 1200 cm2/s2, with highly localised areas from 1200 to 1700 cm2/s2. The Brazil-Malvinas confluence is also caracterised by a high variability level. In the western side of our domain, it provides the most intense mesoscale activity. With the assimilation, the spatial extension of the high-level variability is larger than in the model run in a free mode.

4.3- ZONAL SECTION OF THE MEAN VERTICAL STRUCTURE ALONG 30°W

A long CTD/hydrographic section was made in February-April 1989 in the western Atlantic between 0°40 N and South Georgia (54°S) along a nominal longitude of 25°W (see Tsushiya et al. 1994) which, among other results, clearly allowed to identify at that longitude the different fronts of the ACC. Five major fronts were identified, among which the Polar front at 49.5°S, the Subantarctic front at 45°S and the Subtropical front at 41-42°S. If we draw a comparison between these results and the positions of the fronts in our simulation along 30°W, we note that there is a good correlation between observations and our simulation. Figure 3 displays a vertical section of the interface between layers 1 and 2, i.e. the topography of the isopycnal surface at the mean depth of 300m.

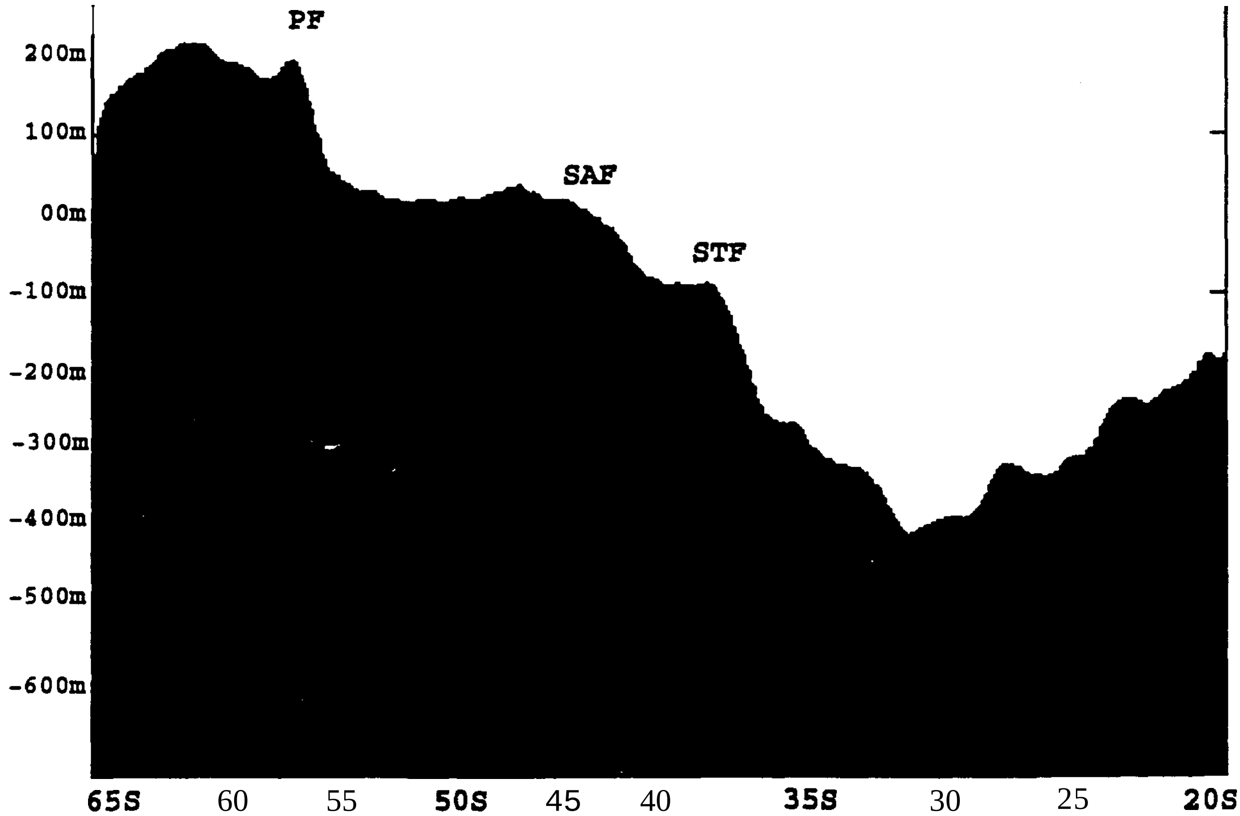

Fig3. : Vertical section of the interface between the layers 1 and 2 along 30°W

Except for the Polar Front located at 57°S in our model, the Subantarctic Front (47°S) and the Subtropical front (41°S) are consistent with observations. The study of interfaces or isopycnals depths on both sides of the fronts reveal other similarities between the model and observations (Tsushiya et al. 1994, fig.4b) (Table 1):

Table 1: **Interfaces and isopycnals depths**

<u>Model</u>							
Interface 1-2 :	100m	PF	260m	SAF	380m	STF	600m
<u>Observations</u>							
potential density (kg/m3)	100m	PF	200m	SAF	400m	STF	700m
<u>Model</u>							
Interface 2-3 :	400m	PF	800m	SAF	1300m	STF	1500m
<u>Observations</u>							
36.7 °/oo	250m	PF	750/1000m	SAF	1300m	STF	1600m
<u>Model</u>							
Interface 3-4 :	1100m	PF	1400/1600m	SAF	2200m	STF	2300m
<u>Observations</u>							
36.96 °/oo :	800m	PF	1500/2000m	SAF	2200m	STF	2500m

5- CONCLUSION

We have demonstrated that the model and the assimilation procedure described here work properly. Even the simple nudging technique allows the assimilation procedure to be efficient. Altimeter data can complement the insufficient physics of the model (such as variable wind forcing).
The usefulness of assimilating T/lP data is clearly demonstrated. And moreover, this application shows that the model predictions are more realistic than simulations realized without assimilation. The mean circulation in the upper layers reproduces correctly the path of the main currents of the South Atlantic Ocean. The topography of upper layer isopycnals given by the model is consistent with observations.
Interesting instantaneous pictures of the circulation of the South Atlantic ocean have been produced. Meanderings of the major currents, eddies generation, and westward advections clearly show up. The surface distribution of eddy kinetic energy is realistic.
We have here a tool allowing to make from the non synoptic altimeter data a 4D picture of the ocean circulation, at relatively little cost (1 hour of CRAY-C90 per year of simulation). For the future, a new experiment will be designed with, among other modifications, an increase of the number of layers vertically, so as to separate deep water masses, a new distribution of the climatological flux forcing at the open boundaries and an eastward extension of the domain to the Indian ACC sector. We intend also to make new assimilation experiments with the complete dataset (2.5 years), and with the initial Topex-Poseidon dataset: mean topography plus time variability.

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The Tides in the Weddell Sea and Ross Sea

from a Numerical Hydrodynamic Model

F. Lyard, C. Le Provost, M.L. Genco

Equipe de Modélisation des Ecoulements Océaniques et des Marées
Laboratoire des Ecoulements Géophysiques et Industrials-Institut de Mécanique de Grenoble,
BP 53X, 38041 Grenoble, France
URA 1503- CNRS

Introduction

The finite element tidal model of Grenoble has been developed frost to provide a new set of tidal charts which could meet the need of an accurate tidal correction in the GDR of the altimetric missions, especially the Topex/Poseidon mission. It is based on the classical shallow water equations, and is forced by the gradient of the astronomical and loading/self-attraction potential gradients. Its finite element spatial discretisation allows to prescribe locally higher spatial resolution to solve the shorter tidal wave lengths observed on the continental shelves and in the coastal areas. It covers now the whole world ocean, and it includes in **particular** the ice-covered seas, providing then the first hydrodynamic charts of the tides on these areas. The original results obtained for the major constituents in the diurnal and semi-diurnal bands, i.e. K1 and M2, are presented here, focusing on the Weddell sea and the ROSS Sea, which are covered by a permanent ice-shelf. Despite the main output of the Grenoble model is the tidal elevation, the tidal velocities can be derived from the model, and thus allow to estimate the different terms of the energy balance, like dissipation, astronomical input and energy fluxes. It will be seen that, although a very similar configuration, the tides are very different in the Weddell and Ross Seas.

The Model and Energy Equations

For astronomical waves *(i.e.* waves which are generated directly by astronomical forcing), the following spectral quasi-linearised system is obtained from the classical shallow water equations:

$$j\omega_k\alpha_k + \frac{1}{a\cos\varphi}\left[\frac{\partial H\mu_k}{\partial\lambda} + \frac{\partial H v_k\cos\varphi}{\partial\varphi}\right] = F_k^\alpha \quad (1) \qquad F_k^\alpha = 0$$

$$(j\omega_k + r)\mu_k + (r' - f)v_k + \frac{g}{a\cos\varphi}\frac{\partial\alpha_k}{\partial\lambda} = F_k^\mu \quad (2) \quad \text{with} \quad F_k^\mu = \frac{g}{a\cos\varphi}\frac{\partial}{\partial\lambda}\left\{(1+k_2-h_2)\frac{\Pi_{2,k}}{g} + \iint \alpha_k G\cos\varphi d\lambda d\varphi\right\}$$

$$(r'' + f)\mu_k + (j\omega_k + r''')v_k + \frac{g}{a}\frac{\partial\alpha_k}{\partial\varphi} = F_k^v \quad (3) \qquad F_k^v = \frac{g}{a}\frac{\partial}{\partial\varphi}\left\{(1+k_2-h_2)\frac{\Pi_{2,k}}{g} + \iint \alpha_k G\cos\varphi d\lambda d\varphi\right\}$$

g is the gravitational constant. The loading and self-attraction potential is assumed to be *a priori* known in order to maintain the explicit aspect of the equations, The boundary conditions associated with the system (l), (2) and (3) over a domain are :

$\vec{u}_k \cdot \vec{n}_\Gamma = 0$ along coastal boundaries Γ_1 $\alpha_k = \alpha_k^0$ prescribed along open ocean limits Γ_2

The existence of a dominant wave (α_1, μ_1, v_1) *in* terms of velocity (such as the mean lunar tide M_2 in the North Atlantic) allows the bottom friction term to be linearised (Kabbaj and Le Provost[1]) for any waves in the tidal spectrum. But it may be the case that K1 is dominant in some particular areas. To take this possibility into account, and assuming that the areas where the velocities of K1 and M2 are of the same order are negligible, both waves have been computed simultaneously in a way that the interaction between the two waves through the dissipation terms is fully assumed. Elimination of the velocity in Eq. (1) leads to the so-called 'wave equation' in the form of:

$$j\omega\cos\varphi\alpha + \frac{\partial}{\partial\lambda}\left\{\frac{B}{\cos\varphi}\frac{\partial\alpha}{\partial\lambda} - D\frac{\partial\alpha}{\partial\varphi}\right\} + \frac{\partial}{\partial\varphi}\left\{A\cos\varphi\frac{\partial\alpha}{\partial\varphi} - C\frac{\partial\alpha}{\partial\lambda}\right\} = F_\alpha\cos\varphi + \frac{a}{g}\left[\frac{\partial}{\partial\lambda}\left\{BF_\mu - DF_v\right\} + \frac{\partial}{\partial\varphi}\left(AF_v - CF_\mu\right)\cos\varphi\right]$$

This equation is written under its variational formulation and is discretised with the Finite Elements technique. After the solution of the tidal elevation unknowns, the velocity fields is given by :

$$\mu = \frac{a}{H}\left[B\left(\frac{1}{\cos\varphi}\frac{\partial\alpha}{\partial\lambda} - \frac{a}{g}F_\mu\right) - D\left(\frac{\partial\alpha}{\partial\varphi} - \frac{a}{g}F_v\right)\right] \qquad v = \frac{a}{H}\left[A\left(\frac{\partial\alpha}{\partial\varphi} - \frac{a}{g}F_v\right) - C\left(\frac{1}{\cos\varphi}\frac{\partial\alpha}{\partial\lambda} - \frac{a}{g}F_\mu\right)\right]$$

Energy budget

The tidal energy budget equation is obtained from the shallow water equations

$$\frac{\partial\varepsilon}{\partial t} + \vec{\nabla}\cdot\left[\rho(H+\alpha)\left(g\alpha + \frac{1}{2}u^2\right)\right]\vec{u} = \rho(H+\alpha)\vec{u}\cdot g\vec{\nabla}\Pi - \rho(H+\alpha)\vec{u}\cdot\vec{D}$$

Integrating in space, averaging in time yields and discarding odd terms yields

$$\underbrace{\frac{1}{T}\int_0^T\left\{\oint_{\partial\Omega}\left[\rho\alpha\left(gH + \frac{1}{2}u^2\right)\right]\vec{u}\cdot\vec{n}dl\right\}}_{(1)} = \underbrace{\frac{1}{T}\int_0^T\left\{\iint_\Omega \rho H\vec{u}\cdot g\vec{\nabla}\Pi ds\right\}dt}_{(2)} - \underbrace{\frac{1}{T}\int_0^T\left\{\iint_\Omega \rho H\vec{u}\cdot\vec{D}ds\right\}dt}_{(3)}$$

(1) quantifies the energy fluxes, (2) the work of the potential forcing (including the loading/self-attraction forcing) and (3) the dissipation.

The Weddell Sea

The bottom topography of the Weddell Sea shows a large continental shelf at its end, and extending along the Antarctic Peninsula. The limit of the permanent ice-shelf is located between the latitudes 75° to 78° south. The consequence of the permanent ice-shelf is double : first, the water column thickness is reduced by the underwater part of the ice shelf. The bathymetry and the ice shelf thickness, necessary to compute the water column thickness, has been provided by H. Hinze (1993). Second, as the ice-shelf is horizontally fasten to the coast line, friction occurs at the bottom of the ice shelf and participate to the tidal energy dissipation. This additional friction has been taken into account in the Grenoble model by doubling the Chezy-like friction coefficient on the ice-covered area. The M2 solution shows an amphidromic point, around which the phases are turning

[1] : A. Kabbaj and C. Le Provost, *Tellus 32,* pp. 143-163 (1980).

clockwise, located in the northern west part of the Weddell Sea. The amplitude increases from a few tens of centimetres in the open ocean to more than 2 metres along the south coastline. The M2 velocity is in the range of a few centimetres per second in the deep ocean and of ten centimetres per second on the continental shelf. A remarkable amplification can be noticed at the permanent ice front, showing values of 40 cm/s and more. This amplification coincide with a locally very shallow water area (about 100 metres). Nevertheless, and although the remarkable quality of the data used to compute the water column thickness, the existence of these very shallow water area may be subject to doubt, and therefore, the existence of the velocity amplification. The energy fluxes show a large energy propagation, from the eastern part to the western part of the Weddell Sea, transiting along the south coastline. Although the high dissipation, a significant part of this energy is going out of the continental shelf area along the south Antarctic peninsula. The K1 tidal wave distribution shows a smooth increase from about 20 centimetres in the deep ocean to 40 centimetres in the south end of the Weddell Sea, when the phases propagate quite uniformly westward. The most remarkable feature is the signature of topographic trapping effects along the shelf edge and, partly, along the ice front, characterised by a sting of local minimum and maximum. The velocity shows similar signatures, with local maximum up to 40 cm/s, when the range mainly doesn't exceed 5 cm/s on the rest of the continental shelf. The K1 energy fluxes shows also a westward energy propagation, but of a much smaller amplitude and with-no significant outward fluxes. Along the shelf edge, the energy fluxes are turning anticlockwise around the trapping sites.

The Ross Sea

The Ross Sea is entirely located on the continental shelf, which is about twice larger than the Weddell shelf. The permanent ice front follows approximately the 77° 30' latitude line. The water thickness in the ice-covered area has been deduced from the Greischar and Bentley maps. A similar treatment to the Weddell Sea model has been performed for the friction coefficient. The M2 tide is very weak in the whole basin, despite a smooth amplification in the south-east end up to 20 centimetres. The phase distribution is very uniform in northern and western part of the Ross Sea, with values bounded between 15° and 30°. The distribution in the southern and eastern part is driven the existence of two amphidromic points, the first close to the southern coastline, on longitude 180°, the second beyond the continental shelf edge. The velocities are also weak, less than 1 cm/s in most of the basin. The result then is in a negligible energy propagation and dissipation. The K1 tide is much larger in terms of amplitude than the M2 tide, with a remarkable amplification up to 60 cm in the south-east end of the basin. But the most interesting feature is the huge local maximum located at the western part of the continental shelf edge, which rises up to an equivalent amplitude. It is the most energetic of several topographic trapped sites observed all along the shelf edge. A complicated arnphidromic structure is located between this trapping site and the north-west coastline. The K1 velocities increases from a few cm/s in the deep ocean to a maximum of more than 20 cm/s along the shelf, and are in the range of about 7 to 10 cm/s in the basin itself. The consequence is a large dissipation of energy in that area, and, as observed in the Weddell Sea, strong energy fluxes turning anticlockwise around trapping site.

Conclusions

The Grenoble model allows us to access an original information on permanently ice-covered seas like the Weddell and Ross Seas. Despite apparently similar configuration, the tidal waves M2 and K1 show very different behaviors from a basin to another. In particular, the Weddell Sea is remarkable first by the strong westward energy transit along its coastline, and second by the large energy dissipation taking place on the continental shelf, enhanced by the presence of the ice shelf. The Ross Sea is also much remarkable because of the presence of intense trapping sites along the continental shelf.

MONITORING SEA LEVEL IN ANTARCTICA AND THE SOUTHERN OCEAN - THE AUSTRALIAN EXPERIENCE

Rupert Summerson.
Australian Antarctic Division, Channel Highway, Kingston, Tasmania 7050,
AUSTRALIA

1. ABSTRACT

A brief description of the objectives of the Australian sea level monitoring network is followed by a brief description of its configuration and of the instrumentation deployed at each monitoring site. The experiences of operating tide gauges in these environments are discussed including gaining access [o data, making corrections for atmospheric pressure, where necessary, and establishing high precision geodetic connections between the tide gauges and the fiducial points where permanent GPS receivers are operated. The paper is concluded with the observations that despite the hostile environment the instrumentation has to a large degree survived and yielded good quality data.

2. INTRODUCTION

This paper is based on a presentation given at the IAPSO/IOC-GLOSS Workshop on Sea Level Variability and Southern Ocean Dynamics, 31 January 1995, Bordeaux. The presentation given was necessarily brief and comprised a condensed description of the work being carried out by the Australian Antarctic Division in tidal and sea level monitoring and a description of a number of key difficulties experienced. The airing of problems was done in the hope of tapping into the vast pool of knowledge present at the meeting. During the discussions that followed a number of potential solutions emerged.

3. BACKGROUND

The Australian Antarctic and Southern Ocean Sea Level Network was initiated in 1990 in order to meet a number of scientific and operational objectives:

* Determination of datums for mapping and hydrographic charting;
* Tidal predictions for shipping;
* Supporting satellite altimetry missions (such as the TOPEX/POSEIDON mission);
* The study of shelf waves and cross-shelf transport;
* The study of inter-annual variability of the Antarctic Circumpolar Current;
* Monitoring global sea-level change; and
* Participation in international oceanographic programs such as GLOSS and WOCE.

4. CONFIGURATION OF THE ANTARCTIC AND SOUTHERN OCEAN SEA LEVEL NETWORK

The Network currently comprises the following instruments at the following locations (see figure 1):

4.1 MACQUARIE ISLAND

Aquatrak acoustic transducer and Druck pressure transducer, each deployed in an inclined hole drilled through bedrock. Data is logged from each transducer and a total of six thermistors onto two Vitel VX 1004 data loggers, one for each hole. Both the Aquatrak (in its inclined position) and Druck transducers, have a resolution of about +/- 2 mm. Five thermistors have been installed in the Aquatrak hole and one with the Druck to assist with the characterisation of the values recorded and as a valuable source of ocean temperature data. Data are currently down loaded every 28 days with a laptop computer on site, the data then being transferred to the Antarctic Division by Wide Area Network. A system to automate the downloading of data using radio modems is being designed and it is hoped to have it installed during 1995.

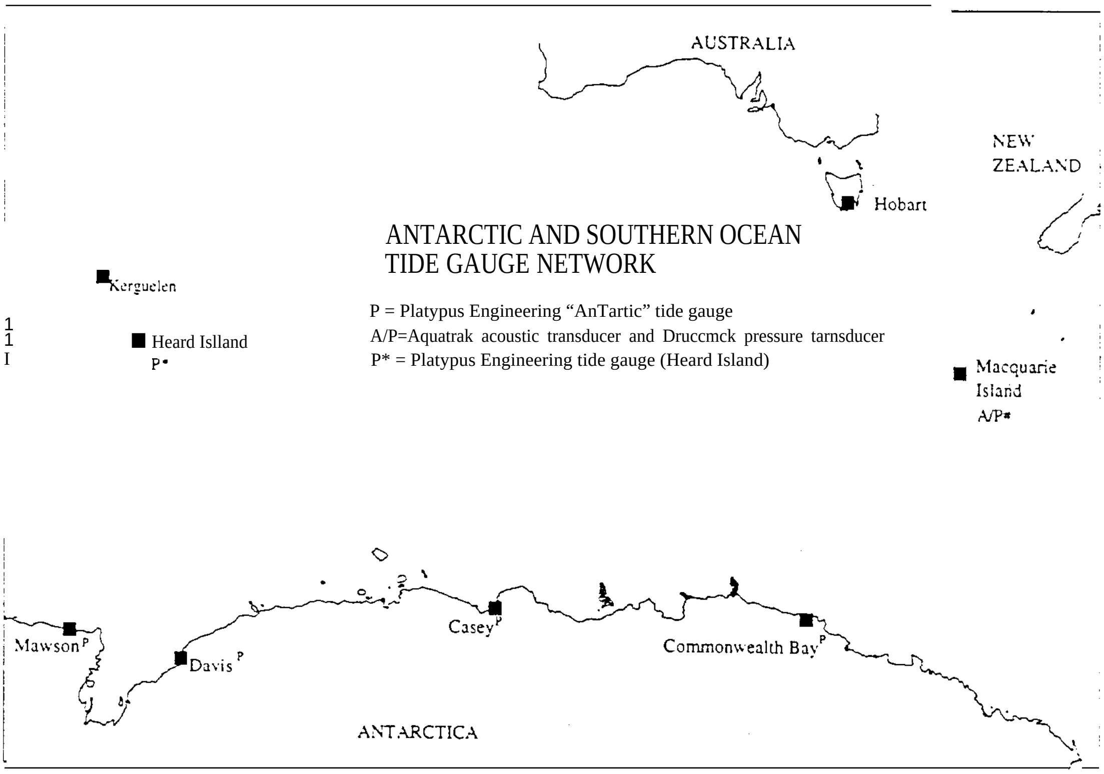

Figure 1. The distribution and types of tide gauges in the Australian Antarctic and Southern Ocean Sea Level Network. Mawson, Davis, Casy and Macquarie Island are permanently occupied Australian National Antarctic Research Expeditions (ANARE) stations

4.2 HEARD ISLAND

Platypus Engineering bottom-mounted tide gauge in a 750 kg steel mooring, deployed in 26 metres of water and marked with surface and submerged buoys (see figure 2). The Paroscientific pressure transducer has a resolution of about +/- 6 mm. The recorder has a five year battery life and four years data storage. No data telemetry system is included.

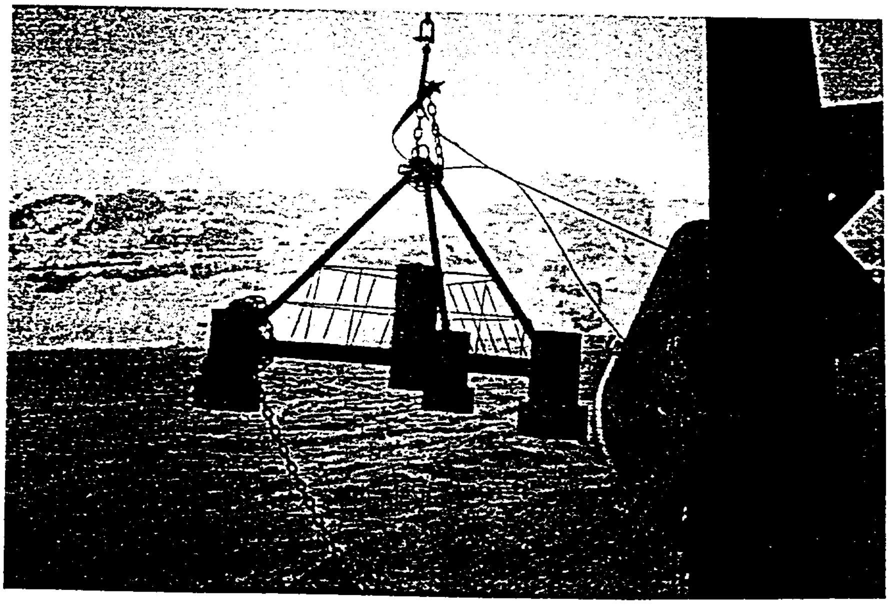

Figure 2. The tide gauge mooring being deployed at Heard Island from RSV *Aurora Australis* in August 1993.

4.3 ANTARCTICA

4.3.1 Mawson, Davis and Casey

Platypus Engineering bottom-mounted tide gauges in water depth of 7-8 metres. The Paroscientific pressure transducers in these tide gauges have a resolution of 1.4 mm. The recorders have a five year battery life and IWO years data storage. Data are logged on board the tide gauge. Data can be stored for up to two years before the rotating buffer overwrites the oldest data. Data are downloaded from the tide gauge by means of an induction coil lowered from the surface over the top of the tide gauge (Summerson and Handsworth 1995), see figure 3.

Figure 3. The author demonstrating the lowering of an induction coil onto a Platypus Engineering tide gauge

4.3.2 Cape Denisen

Platypus Engineering bottom-mounted tide gauge deployed in a 25 kg steel mooring in a water depth of about 5 metres. The specifications for the recorder are the same as the other Antarctic tide gauges. This tide gauge has been deployed for a 1-2 year period in order to compare present mean sea level with that measured by the Australasian Antarctic Expedition in 1912.

5. OPERATING EXPERIENCES

5.1 MACQUARIE ISLAND

5.1.1 Data storage and access

The tide gauge installation at Macquarie Island has been operating for over a year and has survived at least one complete submersion during an easterly gale (figure 4). Problems have, however, been experienced with the low data storage capacity of the data loggers used which has meant that data have been lost when it was not possible to visit the site to down load data, for example during such a storm. A system to automate the downloading of data is being designed and it is hoped to have it installed during 1995.

5.1.2 Atmospheric pressure correction

It is not necessary to correct either the Aquatrak or the Druck for atmospheric pressure, though the data from Macquarie Island exhibits a marked inverse barometer effect. Atmospheric pressure, corrected to mean sea level, from the ANARE station, which is close to the tide gauge, is therefore only used here to understand the nature of the residuals.

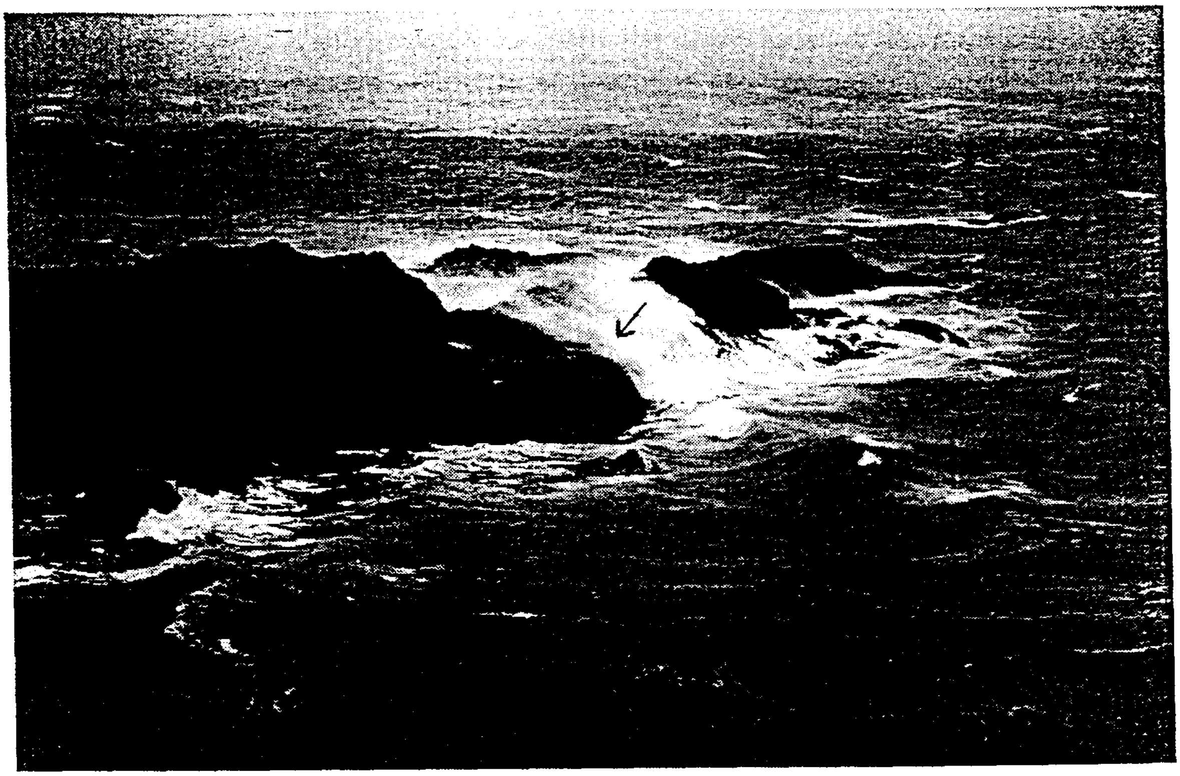

Figure 4. Waves breaking over the site of the Macquarie Island tide gauge during an easterly gale.

5.1.3 Geodetic connection

A permanent (TurboRogue) GPS tracker has been installed at Macquarie Island and is operated by the Australian Surveying and Land Information Group (AUSLIG), principally for long-term geodetic studies. A geodetic connection has been made from [he tide gauge to the GPS pillar by two-way optical levelling and by GPS baseline. Close agreement was reached between the value achieved by optical levelling and GPS baseline. Included in the levelling run was a benchmark established by the Australasian Antarctic Expedition (AAE) in 1912. Following the determination of mean sea level at the new site, a comparison will be made with the value determined for mean sea level by AAE. It is likely that the difference between the two values will be more a function of the uplift of the island than long term change in global sea level.

5.2 HEARD ISLAND

5.2.1 Data storage and access

The Heard Island tide gauge has not been revisited since its deployment. While it is hoped to visit it during the summer of 1995-96, the next scheduled visit is in 1997. The installation and maintenance of a tide gauge at Heard Island is fraught with difficulties because of its remote and stormy location. Nevertheless, it may be an important site for monitoring inter-annual variation in the Antarctic Circumpolar Current (Park 1995, Meredith, M.P. , Woodworth, P. L., Le Provost, C. *personal communications).* Should this be the case it will be necessary to design a new installation which is capable of acquiring high resolution data, is connected to a geodetic reference framework and allows data telemetry, none of which are possible with the present design. Such a design is currently under consideration which will allow the use of an Aquatrak acoustic transducer and vented pressure transducer.

5.2.2 Atmsopheric pressure correction

The pressure transducer used in the Heard Island tide gauge records the total pressure exerted by both the water column and the atmosphere. In order to correct for the latter the nearest source of atmospheric pressure is 530 km away at the French station on Isles Kerguelen. It is planned to install an Aquatrak acoustic transducer and vented pressure transducer which will overcome these limitations. A barometer will also be included in the installation to calculate the reverse barometer effect on sea level.

5.2.3 Geodetic connection

No geodetic connection has been possible to date at Heard Island, and even if it is possible when the instrument is scheduled for replacement, it is considered to be of marginal value [o the present installation. It may, however, be possible to include a GPS in the proposed new installation.

5.3 ANTARCTIC TIDE GAUGES

5.3.1 Data storage and access

The Antarctic tide gauges had mixed success initially but the most severe problems encountered have now been overcome. Both the tide gauges deployed in 1992 (Mawson and Casey) encountered difficulties. The Casey tide gauge disappeared during the first winter of deployment, probably due to the ice gripping a small diameter rope which had been attached to the mooring with which to float a buoy to mark the mooring's location during the establishment of transit poles. It was not possible to remove the buoy and rope once the marking had been completed because of the onset of a severe blizzard following which the ship made an immediate departure. It was considered inconceivable that the mooring, which weighed about 800 kg, could be moved with the rope that was attached. Comprehensive searches made over two consecutive summers failed to locate it so the inevitable conclusion was that the sea ice, by gripping the rope, had dragged the mooring when the ice was blown out at [he end of the winter.

At Mawson, communication with the tide gauge could not be established and after three months it was decided to withdraw the tide gauge from its mooring. The problem was later diagnosed to be temperature sensitivity in the induction loop set-up parameters. The communications system was designed to exploit two characteristics of Antarctic sea water namely the clarity of the water and the fact that it forms a stable surface of sea ice to walk on for most of the year (Summerson and Handsworth 1995). This system also overcomes a very substantial difficulty in that the use of a diver is not necessary. Australian legislation requires substantial logistical and medical support for a diving operation which makes routine or frequent dives impracticable. This does not appear to be confined to Australia (Tait 1986). If a diver was available it would be possible to lay cabling along the sea floor ashore. This would, however, be a substantial undertaking especially through the littoral zone where the vertical movement of sea ice with the tide would soon destroy any cabling laid on the sea floor and only complete burial would ensure its security. In most cases this would entail the excavation of a channel through bedrock.

Since the problem with the Mawson tide gauge has been resolved, the induction loop method of communication for down loading data from the Antarctic tide gauges is now considered to be working reliably. The procedure for establishing communication has, however, remained somewhat problematical. The original concept was to make contact afresh each month and remove the coil after data had been down loaded in order to prevent loss should the sea ice blow out. It soon became clear that a more efficient method was to establish the connection early in the winter once the sea ice had formed sufficiently to be secure from being blown out by gales. This system has worked well at Mawson but an accident occurred at Davis while attempting to retrieve the communications coil at the end of the winter in 1993 and the wire to the coil was severed by the ice drill. For a while it appeared that the coil was still in position on top of the tide gauge preventing access by another coil but this has recently been proven not to be the case and the tide gauge has been accessed and data down loaded.

This sort of difficulty could have been easily resolved by a diver and it took a considerable amount of time and effort in low temperatures by the staff of Davis Station to rectify this problem. It is hoped to avoid this particular problem in the future by lining the hole with a length of steel pipe the same diameter as the coil. If this can be broken free of the ice and withdrawn it would allow the speedy retrieval of the coil at the end of the winter without the need to drill it out.

The other components of the tide gauge system have been proven to be successful. The moorings,at Mawson and Davis at least, are still in position and damage by ice berg or rafting sea ice has been avoided. The method of inserting and withdrawing the tide gauge recorders in the moorings with the purpose-built grab has proved to be successful. Most importantly, however, the tide gauges have been demonstrated to be recording high quality data which can be used with confidence.

Clearly any thing that can be done to automate data retrieval would be appreciated by the station personnel, who have to establish and remove the communications coil, and would speed up access to the data.

The most promising technique to date seems to be very low frequency (VLF) data transmission from the tide gauge to a receiver on the shore connected to the station's local area network. The Platypus Engineering tide gauges log data in a very efficient format using only 600 bytes per day. Even at a frequency of 9 kHz it would only take 1 minute to transmit one day's data. A battery-powered VLF data transmission system could be lowered onto the tide gauge to utilise the existing induction loop communications system with the tide gauge recorder without disturbing the tide gauge and hence the datum of its data. All the tide gauges are sufficiently close to the shore to allow a receiving antenna to mounted on the shore within range. It is considered possible to build such a system with sufficient battery power to last one year (Handsworth, R.J. personal communication).

It is planned to install an Aquatrak acoustic transducer at Mawson during the summer of 1995-96 but it is unlikely that it will be possible to install such an instrument at Davis or Casey because the profile of the shoreline is unsuitable at these places. While there may be suitables sites for the installation of Aquatrak transducers remote from the stations, it is considered impractical to do so because of the difficulties of providing adequate power, especially to maintain a free water surface, and the logistics of installation and maintenance. The installation of an Aquatrak at Mawson will, of course, introduce a new set of problems but it is hoped that these will be largely solved at the design stage.

5.3.2 Atmospheric pressure correction

The pressure transducer used in all the Antarctic tide gauges records the total pressure exerted by both the water column and the atmosphere. In order to correct for the latter atmospheric pressure, corrected to mean sea level, is acquired from the Australian Bureau of Meteorology which operates a weather station at each of the ANARE stations. Until recently atmospheric pressure was only acquired three-hourly which required a spline fit to interpolate to the 10 minute averages recorded by the tide gauges. Automatic weather stations (AWS) have now been established which make pressure readings every 10 minutes. To date it has only been possible to log these data at Mawson but it is planned to log the data from all AWSs when physical connections have been made between the AWSs and the VAX computers on the stations.

5.3.3 Geodetic connection

A permanent (TurboRogue) GPS receiver has been installed at each of the ANARE Antarctic stations and are operated by the Australian Surveying and Land Information Group, principally for long-term geodetic studies. Geodetic connections have been established with each of the Antarctic tide gauges by the indirect method of a timed water level measurement made with spirit level and levelling staff with respect to a local bench mark. This is not very satisfactory as the depth of the instrument is measured by 10 minute averages of pressure, the density of the water column is imperfectly understood and correction for atmospheric pressure is also subject to imperfections. A better system would be to measure the height/depth of the water column directly using a rigid calibrated pole placed over the top of the tide gauge from the surface and then to make a connection from the pole to a bench mark using conventional levelling, or by GPS base line. The distances the tide gauges are from the shore varies from less than 50 m at Casey to over 200 m at Davis.

It is considered that while optical levelling would yield greater precision over the shorter distances involved at Casey and Mawson, if a sight had to be made from the shore at Davis there would be a significant loss of precision due to the optical resolution of the telescope. Ideally the level should be setup on the shore rather than on the sea ice to avoid errors being induced by the tidal motion of the sea ice. While these could be minimised by attempting this operation during slack water at high or low tide, this may not be practically possible due to other constraints, particularly weather, and there may still be residual movement in the sea ice.

GPS base lining would achieve a precision over the distances involved of about +/-5 mm (N. Ward personal communication). Thus, while achieving at best a similar precision as optical levelling, the technique has the advantage that the value obtained is automatically with respect to the GPS pillar - the fiducial point. This obviates the need to carry out high precision levelling between the benchmarks and the GPS pillar which is a time consuming exercise and if carrid out in adverse weather may result in a loss of precision. At Casey, for example, the GPS pillar is over one kilometre from the coast and is at an elevation of 35 metres.

The GPS base lining technique is not without its difficulties, however. The GPS antenna should be established on the pole and at least one 24 hour period observed. Three or five 24 hour observing periods would be preferable. It is vital that the pole to the tide gauge be maintained in the vertical as the sea ice movres up and down with the tide. If the antenna moves at all, it may not prove possible to process the GPS data as a static observing session in which case a kinematic solution may have to be sought. The type of GPS unit used should be a dual frequency, P-code geodetic receiver with antenna type matched to that of the base station.

6. CONCLUSIONS

In the hostile environments of the Southern Ocean and Antarctica, the mere survival of an oceanographic instrument is a success. Following the early experiences with the Mawson and Casey tide gauges, the tide gauge systems seem to be working satisfactorily and acquiring high quality data. Establishing automated communication using VLF built into the stations' local area networks will be the next stage to reduce the burden on station personnel. It is hoped that geodetic connections can be established to the Antarctic tide gauges with a high degree of precision using either optical levelling or GPS base line.

7. ACKNOWLEDGMENTS

Thanks to Dr Christian Le Provost. Dr Tad Murty, Professor Pat Quilty, Dr Martin Riddle and Mr Martin Betts, without whom I would not have been able to attend the Workshop. Noel Ward and Martin Hendy for useful discussions on the use of GPS for high precision levelling. Roger Handsworth for many useful discussions, advice and support. Finally, I would like to acknowledge the assistance rendered by the staff at Mawson, Davis, Casey and Macquarie Island stations over the years and the staff on RSV *Aurora Australis* in August 1993; without their dedication little or none of the above would have been achieved.

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LONG TERM SEA LEVEL OBSERVATION PROGRAMME IN THE SOUTH INDIAN OCEAN A FRENCH CONTRIBUTION TO WOCE, GLOSS AND GOOS

C. Le Provost *, J.M. Molines*,
F. Lyard ** and G. Wöppelman***

*** Laboratoire des Ecoulements Géophysiques et Industrials**
CNRS - Université de Grenoble, France
**** Proudman Oceanographic Laboratory, Biston, UK**
*** **Institut Géographique National, Saint Mandé, France**

1- INTRODUCTION

A multi-year programme is conducted in the South Indian Ocean, with the support of CNRS (Centre National de la Recherche Scientifique) and IFRTP (Institut Français pour la Recherche et les Technologies Polaires). The scientific objective is to study the variability of the sea level over the Crozet-Kerguelen-Amsterdam sector, with the aim to identify and understand its interannual, decadal and secular variabilities and trends, in relation with the Antarctic Circupolar Current (cf figure 1). The data supplied by this programme are also used to validate satellite altimetric measurements in this remote area of the world ocean where weather and sea conditions are particularly difficult. This programme is part of the WOCE sea level research programme, with the objective to study what could be the contribution of long term sea level observations to the monitoring of the Antarctic Circumpolar Current. It could be considered, in a near future, as part of GLOSS/GOOS as a contribution-to its climate component.

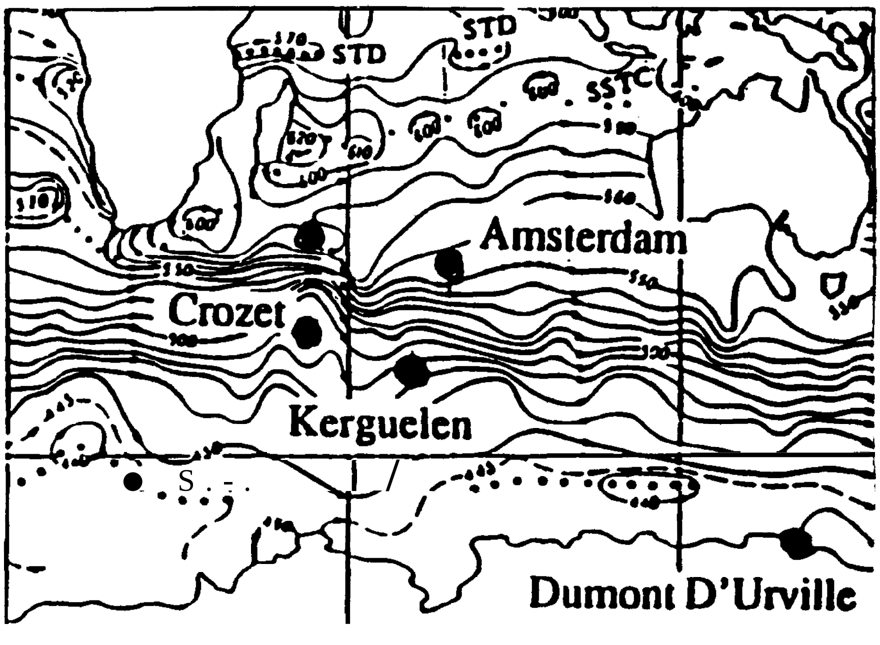

Figure 1: Location of the French sea level stations, along with dynamic topography of the Antarctic Circumpolar Current refered to 1500 decibars.

2- THE STRATEGY

To meet the above objectives, three complementary sub-programmes have been considered and implemented:
1) The frost one is to maintain over a long period of at least ten years a network of coastal sea level stations on the French subantarctic and Antarctic bases, linked to an absolute geodetic reference system (i.e. IERS- the International Earth Reference System), for observing real sea level variations, free of local land motions, if any.
2) The second component of the programme is to maintain in parallel, for the WOCE period (and further if needed) bottom pressure gauge stations on the edge of the continental shelves, near the

coastal gauge stations, for understanding the relations between the coastal and plateau gauge measurements, and validate the adequacy of the coastal gauge stations to the global objectives of the programme.

3) The third component is to relate these local, but continuous, sea level variation measurements to satellite altimeter measurements which are quasi-global in space, but with a several day sampling, in order to help understanding the space and time distributions of the variability of the sea level heights over the whole area of concern. As said before, the in situ measurements contribute also to the checking of the accuracy of the altimeter measurements.

3- THE TECHNIQUES USED

For the coastal stations, because of the very severe environmental conditions, the technical solution developed is based on a pressure sensor placed in a well fixed on a peer (in Kerguelen) or on a steep rock (in Crozet and Saint Paul - Amsterdam), This pressure sensor is linked through a cable to an automatic data acquisition device, located in land. This station includes an atmospheric pressure barometer. The data are stored in solid memory, but also transmitted through satellite to Grenoble, via ARGOS, cf figure la. These coastal stations will be calibrated on a multi-year basis, in order to insure a real measure of the sea level at the site, with benchmarks linked in a local geodetic network, itself linked to the IERS system through GPS technique (Carter et al, 1989).

The sea bed plateau stations are based on the use of pressure gauges with paroscientific probes, cf figure lb. They have an autonomy of 1 to 4 years, depending on the data sampling of 15 minutes to one hour. These stations are deployed from the supply and research vessel Marion Dufresne from TAAF (Terres Australes et Antarctiques Françaises) and IFRTP. Practically, these stations are deployed and recovered on a one-year basis.

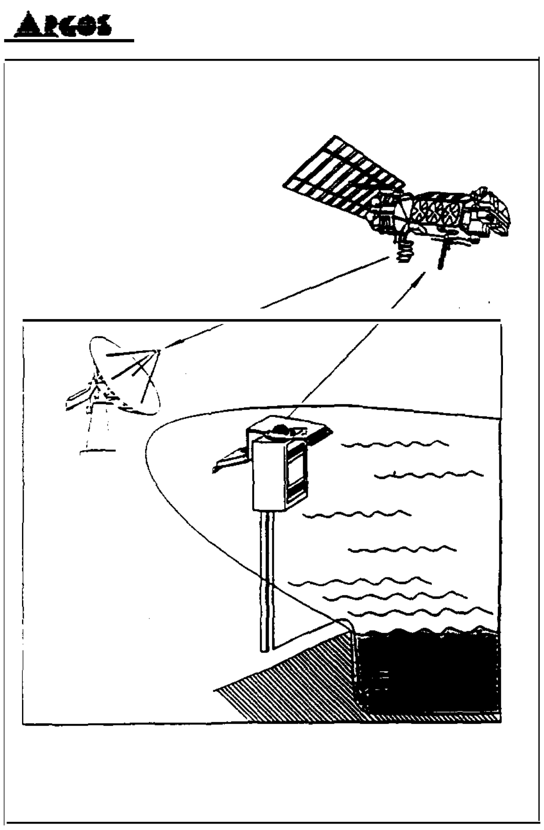

Figure la: diagramme of the coastal stations with the pressure gauge, and the onland ARGOS transmitting device.

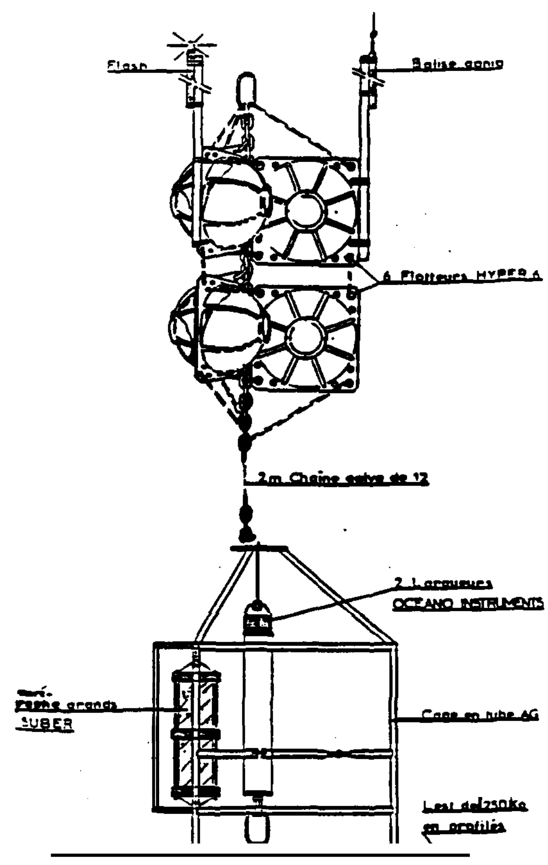

Figure lb: diagramme of the plateau station with its SUBER pressure gauge and its Oceano-Instruments release device.

4- THE STATUS OF THE FIELD PROGRAMME

The plateau gauge subprogramme was initiated by B. Saint Guily in 1986, in cooperation with the Proudman Oceanographic Laboratory, with two stations deployed on the two sides of the fraction of the ACC flowing between Kerguelen plateau and Amsterdam island, with the aim to deduce by geostrophy the ACC transport variability (Park and Saint Guily, 1992; Vassie et al, 1994). This programme was interrupted due to logistic problems from 1989 to 1991 for the site of Amsterdam, and during only one year (1990) for the Kerguelen site. It started again in 1991. However the Kerguelen station deployed in early 1992 has been lost, leading to a second gap in this time series of about one year and a half. This programme is on going: the last available data are up to October 1994, and new stations have been deployed which will be recovered next november. In addition, since mid 1993, another site has been instrumented on the Crozet plateau which is planned to be continued untill end of 1996, at least (see figure 2).

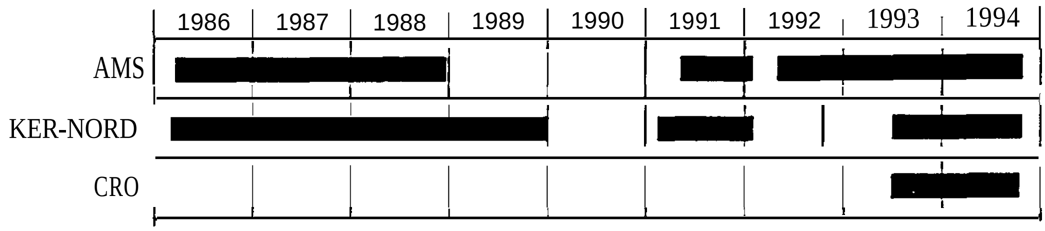

Figure 2: Status of the sea level records available at the sea bed stations: South of Amsterdam Island (AMS), North of Kerguelen Plateau (KER) on the Crozet Plateau (CRO).

The coastal stations have been implemented in Apri 1993 for Kerguelen Island, and October 1994 for Crozet and St Paul (a small island near Amsterdam Island). The three stations were operational at the end of 1994. The data are received on a daily basis in Grenoble through ARGOS satellite transmitting system. The data are validated on a half-month basis and transmitted via email to the WOCE fast delivery center of Hawaï.

Only Kerguelen station has been levelled through a local network of benchmarks, linked through GPS to a geodetic site located a few kilometers inland, surveyed through a permanent GPS station, and a permanent DORIS beacon, used for TOPEX / POSEIDON satellite tracking. The two other sites will be levelled in a near future, and linked through GPS to the Kerguelen reference site.

5- CONCLUSION

This programme is supported by the French WOCE committee until the end of 1996. At least the coastal stations are supposed to be maintained as part of the GLOSS network. But this maintenance sets us the problem of moving the responsibility from a research approach to a long term observing system agreement. This must be done under the responsibility of a permanent agency, typically as part of the climate component of GOOS. However, the scientists involved in this programme (dynamic oceanographers from LEGI-Grenoble and LOPMNHN-Paris, altimetrists from CLS and GRGS-Toulouse, and geodetists from IGN-Paris) will hopefully continue their joint venture for analysing these observations on the long term, and for assimilating these in-situ data, combined with others, especially from altimetry, in global/regional models of the ACC.

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PROGRESS OF THE SEA-LEVEL OBSERVATION AT SYOWA STATION, ANTARCTICA

Minoru Odamaki* and Katsuziro Oka**
(•Maritirne safety Academy, **Hydrographic Department., MSA, Japan)

1. Progress of the observation

Japan Antarctic Research Expedition Project (JARE) started the sea level observation in 1960's at near site of the Syowa station shown in Figure 1, but its continuous record length was only a few months because its mechanical pressure tide gauge was frequently troubled by sea ice rush. Beyond these early trials, JARE succeeded in getting the record over 1 year in 1981 using a pressure tide gauge of strain gauge which data was outputed through a electric cable. However, this tide gauge was aged in recent years. Then JARE started a project renewing the system and installed a new pressure tide gauges of quartz oscillate in Jan. 1987 and in Jan. 1988, but both troubled down in Nov. 1989 and in Nov. 1988, respectively. In Jan. 1989, sea ice at Syowa Stn. was too thick to install T.G. Finally, in 1990 Jan., JARE suceeded in the installation of the third pressure T.G. of quartz oscillator.
In 1991, the old T.G. tended to show a large fluctuation of sensitivity and reference level and stopped down in July. Therefore new T.G. was in time to keep the tidal record continuous. These T.G. systems were described in the papers [1, 2].

The new T.G. measures the relative hydraulic pressure compensated the atmospheric pressure in situ. This is remarkably different from the old T.G. mesuring the total pressure of hydraulic and atmospheric pressures.

The old T.G., which drift was only 16.4cm in the zero point of record for 10 years from 1981 to 1990, was working fairly well for a long time. The new T.G. installed in 1990 had been working well from 1990 to 1991. But in the checking of T.G. in Jan. 1993, it was found that its compensating tube for the atmospheric pressure was choked in 1992 and its record was suspected to become wrong on the way. Now we are trying to check the data of 1992 in detail one more time.

Recently, the vertical displacement of sea ice accompanied by the ocean tide were measured at the Syowa tide station and compared with our tide gauge records by Sato T. et al [3]. According to the measurements of 6 times made in the 8 months from May to December 1993, it was concluded that the difference in amplitude between them were 5% at most. Thus their experiment has given another proof for the reliability of our tide gauge system.

2. Recent Monthly and Annual Mean Sea-Level

Zero point heights of old and new T.G.s were measured 3.952m and 3.381m under the Bench Mark 1040, respectively, on 23rd - 26th Jan. 1990. Therefore, the sea-level value by the new T.G. are systematically 57.lcm lower than those of the old T.G. Then we can connect the new data to the old data by adding the value 57.lcm. Figure 2 shows the recent fluctuation of the connecting monthly Mean Sea-Levels (MSL) from 1985 to 1989 by the old T.G. and from 1990 to 1991 by the new T.G. Zero point heights of the new T.G. has been measured 3.511m in Jan. 1991 and 3.589m in Jan. 1992, respectively. These drifts are not corrected in Figure 2. The seasonal changes of 1990 and 1991 are recognized small compared to those of the former years. This difference may be due to the difference of the tide gauges measuring the absolute and the relative pressures.

The tendency of long term decending of annual MSL at Syowa Stn. appears from 1985 to 1989 in Figure 2, which is almost same as the former report [2] from 1981 to 1987. However the annual MSL in 1990 and 1991 by the new T.G. does not show such tendency of decending. Regrettably the present observation system is not completed even now so that we cannot make sure of the tendency by the new T.G. sufficiently. Then we shall continue to improve the system and to raise up its reliability furthermore.

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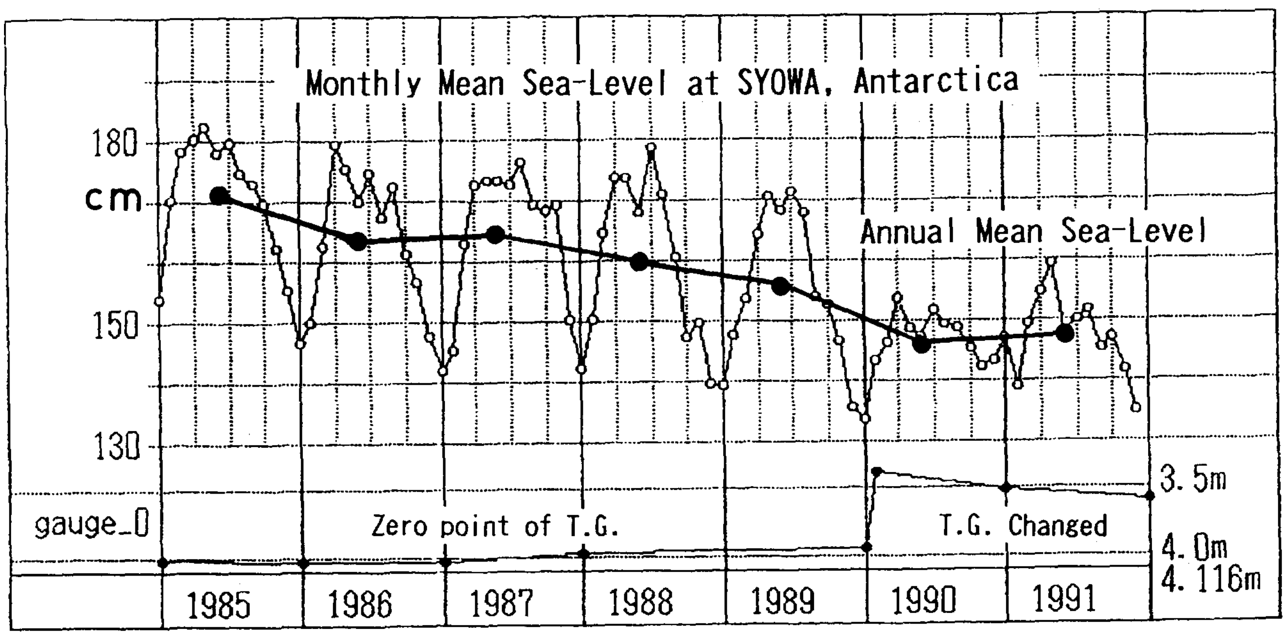

Figure 1- Recent monthly Mean Sea-Level at Syowa Station, East Antarctica.

The observing tide-gauge is changed in Jan. 1990. **The data are connected by correcting the difference of the zero point of T.G.s. Thick line means annual MSL.**

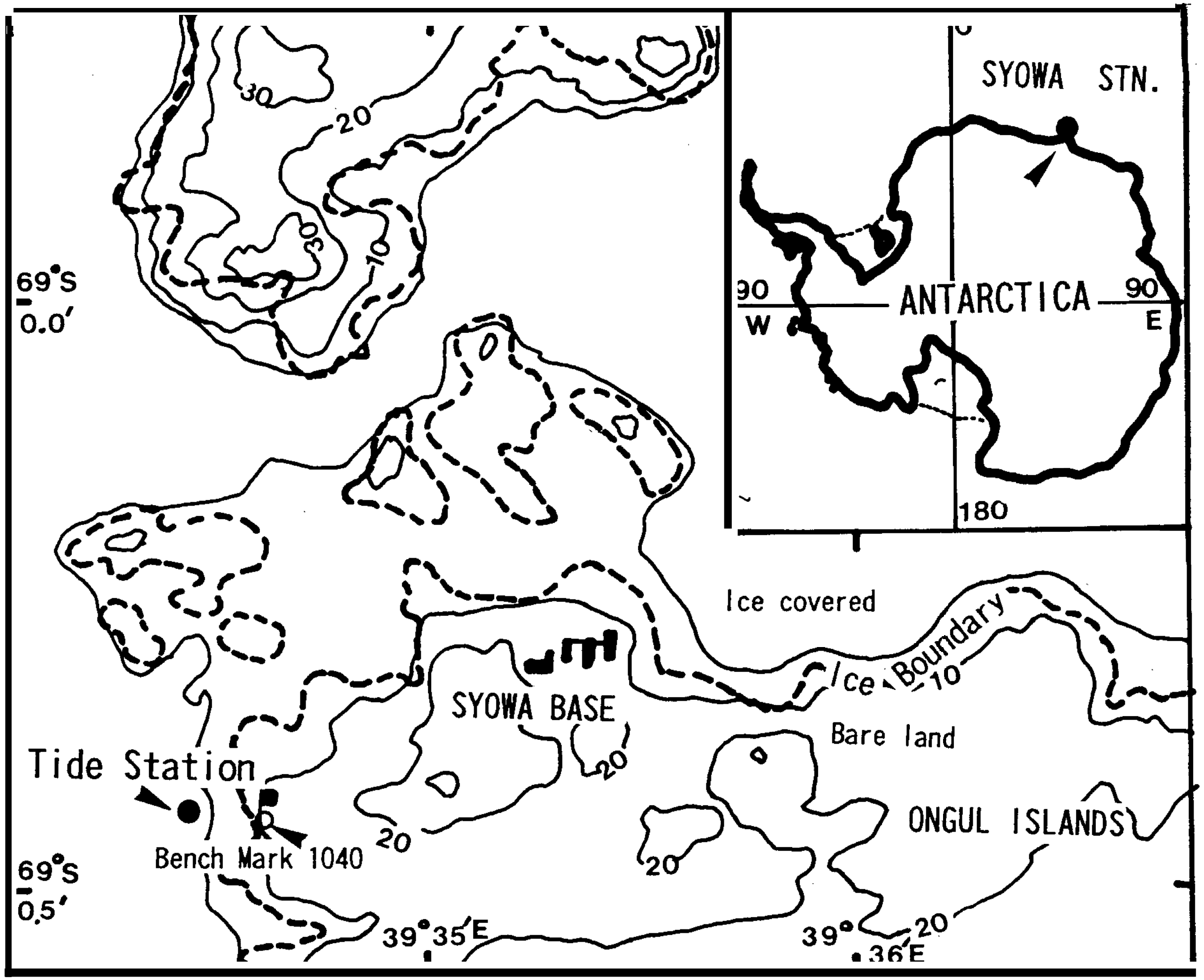

Figure 2 - Location of Syowa and its tide station.

CENTER FOR SEA LEVEL IN THE SOUTHERN OCEAN

T.S. Murty
National Tidal Facility
The Flinders University of South Australia
GPO Box 2100, Adelaide SA 5001
AUSTRALIA

1. ABSTRACT

The objectives of the project are to improve knowledge of sea levels in the Southern Ocean, and to foster increased international co-operation into Southern Ocean sea level research. In addition the investigators plan to use sea level results for research into the role of the Southern Ocean and the circumpolar current in global climate studies.

To achieve this objective it is intended to institute a Sea Level Pilot Project following a request from the I.O.C. of UNESCO for the Southern Ocean (SLPP-SO), by setting up a centre for Southern Ocean Sea Levels at the National Tidal Facility, which will start soon with funding made available by the Australian Government.

2. INTRODUCTION

The importance of the Southern Ocean, and in particular, the circumpolar current in global climate is well recognized. It is a deep, relatively well-mixed current driven by the seasonal or climatic variations in the wind stress and water mass distribution. The angular momentum stored in this current is comparable to the whole observed semiannual discrepancy in the angular momentum budget of the solid Earth plus atmosphere. The largest zonal mean wind stresses occur at latitudes 30-60° south and reach a maximum in the austral winter. It is fluctuations in this wind stress and subsequently the angular momentum of the circumpolar current that feed back into interannual time scales and transfer angular momentum from south to north. Large perturbations of the equatorial wind system in this process lead to a breakdown of the tropical circulation and trigger El Niño Southern Oscillation (ENSO) events. These events are one of the principal causes of climate variability on a time scale of 3 to 6 years.

It is anticipated that much can be learned about the El Niño cycle from studies of the variability of the currents in the Southern Ocean, and sea level information forms an integral part of this research. There is a comparative paucity of sea level information from southern high latitudes, and in particular from latitudes greater than 45 degrees south. The work of the National Tidal Facility has already identified a link between sea level, as observed along the southern coastline of Australia, and climate. Work is in progress to utilize these sea level measurements as an effective predictor for climate variations, and in particular, ENSO events. It is to be expected that data from locations further south in the Southern Ocean, where data is generally scanty, will enhance this procedure. Such predictions will have significant impact on drought and flood forecasts in certain parts of Australia, and other locations.

Sea level observations from other Southern Ocean locations would become more readily accessible as a result of the Pilot Project, and would also be undertaken by the investigators as a part of the project. In addition to the climate predictions already mentioned, an improved knowledge of sea level and tidal regimes in Antarctic waters would have other advantages for many other users and the Pilot Project would hope to serve all those with a valid interest in the results. Studies on the behaviour of the circumpolar current and global circulation models would all benefit from increased Southern Ocean sea level data and improved access to these data. Another example is the expanding field of satellite altimetry. Currently the NTF is supporting the TOPEX/POSEIDON satellite altimetry project, with ground-truthing information being provided from a high precision gauge at Burnie in Tasmania.

3. MEMORANDUM OF UNDERSTANDING

This Memorandum of Understanding sets out the collaboration agreed between the Antarctic Division of the Department of Environment, Sport and Territories, the National Tidal Facility (NTF) of the Flinders University of South Australia and the Australian Surveying and Land Information Group of the Department of the Arts and Administrative Services on the establishment and operation of a Centre for Sea Level in the Southern Ocean.

The participants' aim, recognizing the significance of the Southern Ocean in World scale circulation and its links with issues of climate change, is to secure high quality, geodetically controlled sea level data from the Southern Ocean by establishing the Sea Level Centre for the Southern Ocean. This centre will be established at the National Tidal Facility (NTF), Flinders University of South Australia.

The objectives of the centre are measurements of sea levels in the Australian sector of the Southern Ocean (Antarctic Division), geodetic data processing (AUSLIG) and processing of the collected sea level data and development of products (NTF) for the following reasons:

(i) To support oceanographic, geodetic and geographic research requirements for national and international programs (including GLOSS, GCOS and GOOS projects and initiatives sponsored by the SCAR Working Group on Geodesy and Geographical Information).
(ii) To enable a focus upon sea level measurements as indicators of ocean dynamics in the context of climate change.
(iii) Datum control for mapping and charting.
(iv) Tidal predictions for shipping and operational needs including safety of ships, personnel and equipment.

In the first year, a data archive will be developed. An informational database will also be developed on sea level measurements being undertaken by other countries in the Southern Ocean.

The initial product will be a monthly sea level anomaly map for the Southern Ocean, using mostly Australian continental data, supplemented with data form the gauges of the Antarctic Division, when this data is available. In subsequent years it is hoped that these monthly maps would make use of data from other countries as it becomes available.

4. TIMETABLE

In this three-year project, the timetable is to set out a program for phased implementation of the IOC's Sea Level Pilot Project for the Southern Ocean.

4.1 Year 1

(i) Develop procedures for the orderly collection and archive of data from the Australian Antarctic and Southern Ocean Tide Gauge Network and the AUSLIG-Antarctic Division network of GPS installations.
(ii) Prepare an annual report, copies of which are to be forwarded to all nations known to be interested in sea level in the Southern Ocean.

4.2. Year 2

(i) Maintain and refine the procedures developed in Year 1 for data from Australian sites and extend them to the rest of the Southern Ocean where possible. This will include the preparation of an annual report. Should it be considered necessary due to frequency of data input, more frequent reports can be produced.
(ii) Development of an informational database on international work on sea levels in the Southern Ocean.

4.3. Year 3

(i) Full operation of the network of tide gauge stations geodetically controlled with permanent GPS receivers. The data to be made available on the World Wide Web. Reporting and database procedures to continue as in previous years.

5. COLLABORATION

Within the framework outlined above, the collaboration to be undertaken will take the following form:

5.1 Australian Antarctic Division

During this period the Antarctic Division will endeavour to deploy and maintain tide gauges, which are appropriately designed for the hazardous environment, at the following locations, subject to its logistic capacity to do so:

Mawson	Davis
Casey	Macquarie Island
Heard Island	Commonwealth Bay

The Antarctic Division will supply data from these stations to the NTF for processing and archiving. Where appropriate, these data will be corrected for atmospheric pressure. Owing to the difficulties in retrieving data from the Antarctic tide gauges, however, it may not be possible to collect data regularly every 30 days. It is possible, therefore. that up to two years of data may be collected and forwarded m NTF at one time.

5.2 National Tidal Facility (NTF)

The NTF will conduct quality control and tidal time series analysis, consistent with the requirements outlined above, and will prepare a regular report to the Antarctic Division, AUSLIG and the Hydrographic Service RAN on this work. The frequency of these reports will depend upon the data flow to the NTF. It is estimated that these reports will be annual, although more frequent reports will be produced if necessary. The NTF will also produce a regular monthly sea level anomaly map, which will primarily include Southern Ocean sea level data from its own stations in the region, but will also include data from gauges of the Antarctic Division when available. This map will be distributed via the monthly Climate Monitoring Bulletin of the Australian Bureau of Meteorology. If other data from international sources has been made available to the Centre, then this data will also be included in the maps.

The NTF will also make the data from the gauges of the Antarctic Division available to all other interested parties on the World Wide Web. The content of the annual reports to include the following:

(i) Data Period
(ii) Number of days of data from: tide gauge, atmospheric pressure, GPS
(iii) Analysis of tidal data to include the following:
  a) Observed - predicted - residuals
  b) Harmonic analysis
  c) Derivation of mean sea level (Zo)

and, in collaboration with AUSLIG:

(iv) Elevation of the GPS pillar above MSL (derived monthly from five days data of the first five days of each month)
(v) Value of MSL below GPS position by monthly average
(vi) Value of MSL below GPS position by continuous monthly average.

5.3 Australian Surveying and Land Infomation Group (AUSLIG)

AUSLIG will carry out the following tasks:

(i) Process data from the permanent GPS receiver at each Antarctic station and Macquarie Island over the first five days of each calendar month from which to derive a vertical position above mean sea level.
(ii) Build and maintain a database of tide gauge benchmarks at each station here a tide gauge has been deployed.
(iii) Build and maintain a database of levels from the tide gauge to the benchmarks to the GPS receiver.

These values are to be supplied to NTF for inclusion in the Centre’s databases and regular reports. Technical assistance is to be supplied to the NTF where required to assist in the interpretation of geodetic information.

The importance of the Southern Ocean, and in particular, the circumpolar current in global climate is well recognized. It is a deep, relatively well-mixed current driven by the seasonal or climatic variations in the wind stress and water mass distribution. The angular momentum stored in this current is comparable to the whole observed semiannual discrepancy in the angular momentum budget of the solid Earth plus atmosphere. The largest zonal mean wind stresses occur at latitudes 30-60° south and reach a maximum in the austral winter. It is fluctuations in this wind stress and subsequently the angular momentum of the circumpolar current that feed back into interannual time scales and transfer angular momentum from south to north. Large perturbations of the equatorial wind system in this process lead to a breakdown of the tropical circulation and trigger El-Niño Southern Oscillation (ENSO) events. These events are one of the principal causes of climate variability on a time scale of 3 to 6 years.

It is anticipated that much can be learned about the El-Niño cycle from studies of the variability of the currents in the Southern Ocean, and sea level information forms an integral part of this research. There is a comparative paucity of sea level infomation from southern high latitudes, and in particular from latitudes greater than 45 degrees south. The work of the National Tidal Facility has already identified a link between sea level, as observed along the southern coastline of Australia, and climate. Work is in progress to utilize these sea level measurements as an effective predictor for climate variations, and in particular, ENSO events. It is to be expected that data from locations further south in the Southern Ocean, where data is generally scanty, will enhance this procedure. Such predictions will have significant impact on drought and flood forecasts in certain parts of Australia, and other locations.

ANNEX

LIST OF PARTICIPANTS

INVITED EXPERTS

Mr. L. AWOSIKA
Nigerian Institute for Oceanography
& Marine Research
P.M.B. 12729 Victoria Island
Lagos
NIGERIA
Tel: (234 1) 619 517
Fax.: (234 1) 619 517
Tlg: OCEANOGRAF

Mr. A. BOLDUC
MEDS, Dept. of Fisheries & Oceans
12th Floor, 200 Kent Street
Ottawa, ONTARIO K1A OE6
CANADA
Tel: (1) 613 990 02 31
Fax: (1) 613 990 55 10
[Internet]bolduc@ottmed.meds.dfo.ca

Mr. C. BOUCHER
Institut Géographique National
136bis rue de Grenelle
75700 Paris Cedex 07 SP
FRANCE
Tel: (33 1)43 98 83 27
Fax: (33 1)43 98 80 53

Mr. Bruce C. DOUGLAS
Director, NOAA National Oceanographic
Data Center
1825 Connecticut Ave. N. W., Room 406
Washington, DC 20235
UNITED STATES OF AMERICA
Tel: (1) 202 606 45 94
Fax: (1) 202 606 45 86
[Internet]bdouglas@nodc.noaa.gov

Mr. Bjørn ENGEN
Director, Geodetic Institute
Statens Kartverk
N-3500 Hønefoss
NORWAY
Tel: (47) 32 11 81 00
Fax: (47) 32 11 81 01
[Internet]bjorne@statkart.no

Dr. Christian LE PROVOST (Chairman)
Directeur de Recherche
Institut de Mécanique de Grenoble
B.P. 53X
38402 ST. MARTIN D'HERES CEDEX
FRANCE
Tel: (33) 76825065
Fax: (33) 76825001 or 76825271
[Internet]clp@img.fr

Dr. F. LYARD
Proudman Oceanographic Laboratory
Bidston Observatory
Birkenhead, MERSEYSIDE L43 7RA
UNITED KINGDOM
Tel: (51) 6538633
Fax: (51) 6536269
[Internet]fll@pol.ac.uk

Mr. M.P. MEREDITH
School of Environmental Sciences
University of East Anglia
Norwich NR4 7TJ
UNITED KINGDOM
Tel: (603) 593402
Fax:
[Internet]m.meredith@uea.ac.uk

Dr. G. MITCHUM
UH Sea Level Center
University of Hawaii
1000 Pope Road, MSB 307
Honolulu, HAWAII 96822-2336
UNITED STATES OF AMERICA
Tel: (1) 8089566161
Fax: (1) 8089562352
[Internet]mitchum@soest.hawaii.edu

Dr. Tad S. MURTY
Director
National Tidal Facility
Flinders University of South Australia
GPO Box 2100
ADELAIDE
South Australia 5001, AUSTRALIA
Tel: (618) 201 75 24 (Direct) or 7532
Fax: (618) 201 75 23
[Internet]motid@pippin.cc.flinders.edu.au

Mrs. R.E. NEILAN
Director, IGS Central Bureau
international GPS Service for Geodynamics
Jet Propulsion Laboratory
4800 Oak Grove Drive
Pasadena, CA 91109
UNITED STATES OF AMERICA
Tel: (1) 818 354 83 30
Fax: (1) 818 393 66 86
[Internet]igscb@igscb.jpl.nasa.gov.

Mr. Y.H. PARK
Laboratoire d'Océanographie Physique
Muséum National d'Histoire Naturelle
43, rue Cuvier
75005 Paris
FRANCE
Tel: (33 1) 40 79 31 70
Fax: (33 1) 40 79 31 63
[Internet]lg@mnhn.fr

Dr. A. PATWARDHAN
Department of Engineering & Public Policy
Carnegie Mellon University
Pittsburgh, Pennsylvania 15213-3890
UNITED STATES OF AMERICA
Tel: (1)412 268 30 00
Fax: (1) 412 268 37 57
[Internet]anandp@cmu.edu

Dr. David T. PUGH
Natural Environment Research Council
Institute of Oceanographic Sciences
Deacon Laboratory, Brook Road
Wormley, GODALMING. SURREY GU8 5UB
UNITED KINGDOM
Tel: 428 68 41 41
Fax: 428 68 56 37
[Internet]dtp@uk.ac.nerc-wormley.unixa

Dr. L. RICKARDS
British Oceanographic Data Centre
Proudman Oceanographic Laboratory
Bidston Observatory
Birkenhead, Merseyside L43 7RA
UNITED KINGDOM
Tel: (151) 653 86 33
Fax: (15 1) 652 39 50
[Internet]bodcmail@ua.nbi.ac.uk

Mr. Eduardo A.RODRIGUEZ
Comision Ocenografica Intergubernamental
Representacion Argentina
Cerrito 1248
1010 Buenos Aires
ARGENTINA
Tel: (54 1) 812 16 89
Fax: (54 1) 812 20 39
[Internet]fiore(tj)oceamar.mil.ar

Dr. S.R. SHETYE
National Institute of Oceanography
Dona Paula, Goa 403-004
INDIA
Tel: (832) 22 13 23/22 62 53
Fax: (832) 22 33 40/22 13 60
[Internet]shetye@bcgoa.ernet.in

Mrs. E. SPENCER
Proudman Oceanographic Laboratory
Bidston Observatory
Birkenhead. MERSEYSIDE L43 7RA
UNITED KINGDOM
Tel: (5 I) 653 86 33
Fax: (51) 653 62 69
[Internet]psmsl@ua.nbi.ac.uk

Mr. Rupert SUMMERSON
Australian Antarctic Division
Channel Highway
Kingston
Tasmania 7050. AUSTRALIA
Tel: (61 02) 32 35 28
Fax: (61 02) 32 34 15
[Internet]rupert_sum@antdiv.gtw.au

Dr. P. WOODWORTH
Director, PSMSL
Proudman Oceanographic Laboratory
Bidston Observatory
Birkenhead, MERSEYSIDE L43 7RA
UNITED KINGDOM
Tel: (51) 653 86 33
Fax: (51) 653 62 69
[Internet]plw@pol.ac.uk

Prof. S. ZERBINI
Università Degli Studi Di Bologna
Dipartimento di Fisica, Settore di Geofisica
Viale Berti Pichat, 8
I-40127 Bologna
ITALY
Tel: (39 51) 630 50 19
Fax: (39 51) 25 01 06
[Internet]zerbini@astbol.bo.cnr.it

Dr. Oleg I. ZILBERSTEIN
Head of Department
State Oceanographic Institute
Kropotkinsky per, 6
119838 Moscow
RUSSIAN FEDERATION
Tel: (7 095) 246 81 20
Fax: (7 095) 246 39 70
[Internet]aarcisea@com.sovam
postmaster@soins.msk.ru

Dr. James ZUMBERGE
IGS Central Bureau
International GPS Service for Geodynamics
Jet Propulsion Laboratory
4800 Oak Grove Drive
Pasadena, CA 91109
UNITED STATES OF AMERICA
Tel: (1) 818 354 67 34
Fax: (1) 818 393 66 86
[Internet]jfz@cobra.jpl.nasa.gov

OBSERVERS

International Hydrographic Bureau (IHB)

Mr. Hans-Peter ROHDE
Professional Assistant (Hydrography)
International Hydrographic Bureau
7, Avenue Président J.F. Kennedy
MC-98011 Monaco Cedex
PRINCIPALITY OF MONACO
Tel: (33) 93 50 65 87
Fax: (33) 93 25 20 03
[Internet]ihb@unice.fr

IOC SECRETARIAT

Intergovernmental Oceanographic Commission (IOC)

Dr. A. TOLKATCHEV
GLOSS Technical Secretary
GOOS Support Office
IOC
UNESCO
1 rue Miollis
75732 Paris Cedex 15
FRANCE
Tel: (1) 45 68 39 78
Fax: (1) 40 56 93 16
[Internet]a.tolkatchev@unesco.org

Ms. Françoise L.SCHILLER
Secretariat GOOS Support Office
Tel: (1) 45 68 39 77

No.	Title	Languages
52	SCOR-IOC-UNESCO Symposium on Vertical Motion in the Equatorial Upper Ocean and its Effects upon Living Resources and the Atmosphere; Paris, 6-10 May 1985.	E
53	IOC Workshop on the Biological Effects of Pollutants; Oslo, 11-29 August 1986.	E
54	Workshop on Sea-Level Measurements in Hostile Conditions; Bidston, UK, 28-31 March 1988	E
55	IBCCA Workshop on Data Sources and Compilation, Boulder, Colorado, 18-19 July 1988.	E
56	IOC-FAO Workshop on Recruitment of Penaeid Prawns in the Indo-West Pacific Region (PREP); Cleveland, Australia, 24-30 July 1988.	E
57	IOC Workshop on International Co-operation in the Study of Red Tides and Ocean Blooms; Takamatsu, Japan, 16-17 November 1987.	E
58	International Workshop on the Technical Aspects of the Tsunami Warning System; Novosibirsk, USSR, 4-5 August 1989.	E
58 Suppl.	Second International Workshop on the Technical Aspects of Tsunami Warning Systems, Tsunami Analysis, Preparedness, Observation and Instrumentation. *Submitted Papers*; Novosibirsk, USSR, 4-5 August 1989.	E
59	IOC-UNEP Regional Workshop to Review Priorities for Marine Pollution Monitoring Research, Control and Abatement in the Wider Caribbean; San José, Costa Rica, 24-30 August 1989.	E, F, S
60	IOC Workshop to Define IOCARIBE-TRODERP proposals; Caracas, Venezuela, 12-16 September 1989.	E
61	Second IOC Workshop on the Biological Effects of Pollutants; Bermuda, 10 September-2 October 1988.	E
62	Second Workshop of Participants in the Joint FAO-IOC-WHO-IAEA-UNEP Project on Monitoring of Pollution in the Marine Environment of the West and Central African Region; Accra, Ghana, 13-17 June 1988.	E
63	IOC/WESTPAC Workshop on Co-operative Study of the Continental Shelf Circulation in the Western Pacific; Bangkok, Thailand, 31 October-3 November 1989.	E
64	Second IOC-FAO Workshop on Recruitment of Penaeid Prawns in the Indo-West Pacific Region (PREP); Phuket, Thailand, 25-31 September 1989.	E
65	Second IOC Workshop on Sardine/Anchovy Recruitment Project (SARP) int he Southwest Atlantic; Montevideo, Uruguay, 21-23 August 1989.	E
66	IOC *ad hoc* Expert Consultation on Sardine/Anchovy Recruitment Programme; La Jolla, California, USA, 1989.	E
67	Interdisciplinary Seminar on Research Problems in the IOCARIBE Region; Caracas, Venezuela, 28 November-1 December 1989.	E (out of stock)
68	International Workshop on Marine Acoustics; Beijing, China, 26-30 March 1990.	E
69	IOC-SCAR Workshop on Sea-Level Measurements in the Antarctica; Leningrad, USSR, 28-31 May 1990.	E
69 Suppl.	IOC-SCAR Workshop on Sea-Level Measurements in the Antarctica; *Submitted Papers*; Leningrad, USSR, 28-31 May 1990.	E
70	IOC-SAREC-UNEP-FAO-IAEA-WHO Workshop on Regional Aspects of Marine Pollution; Mauritius, 29 October - 9 November 1990.	E
71	IOC-FAO Workshop on the Identification of Penaeid Prawn Larvae and Postlarvae; Cleveland, Australia, 23-28 September 1990.	E
72	IOC/WESTPAC Scientific Steering Group Meeting on Co-Operative Study of the Continental Shelf Circulation in the Western Pacific; Kuala Lumpur; Malaysia, 9-11 October 1990.	E
73	Expert Consultation for the IOC Programme on Coastal Ocean Advanced Science and Technology Study; Liège, Belgium, 11-13 May 1991.	E
74	IOC-UNEP Review Meeting on Oceanographic Processes of Transport and Distribution of Pollutants in the Sea; Zagreb, Yugoslavia, 15-18 May 1989.	E
75	IOC-SCOR Workshop on Global Ocean Ecosystem Dynamics; Solomons, Maryland, USA, 29 April-2 May 1991.	E
76	IOC/WESTPAC Scientific Symposium on Marine Science and Management of Marine Areas of the Western Pacific; Penang, Malaysia, 2-6 December 1991.	E
77	IOC-SAREC-KMFRI Regional Workshop on Causes and Consequences of Sea-Level Changes on the Western Indian Ocean Coasts and Islands; Mombasa, Kenya, 24-28 June 1991.	E
78	IOC-CEC-ICES-WMO-ICSU Ocean Climate Data Workshop Goddard Space Flight Center; Greenbelt, Maryland, USA, 18-21 February 1992.	E
79	IOC/WESTPAC Workshop on River Inputs of Nutrients to the Marine Environment in the WESTPAC Region; Penang, Malaysia, 26-29 November 1991.	E
80	IOC-SCOR Workshop on Programme Development for Harmful Algae Blooms; Newport, USA, 2-3 November 1991.	E
81	Joint IAPSO-IOC Workshop on Sea Level Measurements and Quality Control; Paris, 12-13 October 1992.	E
82	BORDOMER 92: International Convention on Rational Use of Coastal Zones. A Preparatory Meeting for the Organization of an International Conference on Coastal Change; Bordeaux, France, 30 September-2 October 1992.	E
83	IOC Workshop on Donor Collaboration in the Development of Marine Scientific Research Capabilities in the Western Indian Ocean Region; Brussels, Belgium, 12-13 October 1992.	E
84	Workshop on Atlantic Ocean Climate Variability; Moscow, Russian Federation, 13-17 July 1992.	E
85	IOC Workshop on Coastal Oceanography in Relation to Integrated Coastal Zone Management; Kona, Hawaii, 1-5 June 1992.	E
86	International Workshop on the Black Sea; Varna, Bulgaria 30 September - 4 October 1991.	E
87	Taller de trabajo sobre efectos biológicos del fenómeno «El Niño» en ecosistemas costeros del Pacífico Sudeste; Santa Cruz, Galápagos, Ecuador, 5-14 de octubre de 1989.	S only (Summary in E, F, S)
88	IOC-CEC-ICSU-ICES Regional Workshop for Member States of Eastern and Northern Europe (GODAR Project); Obninsk, Russia, 17-20 May 1993.	E
89	IOC-ICSEM Workshop on Ocean Sciences in Non-Living Resources; Perpignan, France, 15-20 October 1990.	E
90	IOC Seminar on Integrated Coastal Management; New Orleans, USA. 17-18 July 1993.	E
91	Hydroblack'91 CTD Intercalibration Workshop; Woods Hole, USA. 1-10 December 1991.	E
92	Réunion de travail IOCEA-OSNLR sur le Projet « Budgets sédimentaires le long de la côte occidentale d'Afrique » Abidjan, Côte d'Ivoire, 26-28 juin 1991.	F
93	IOC-UNEP Workshop on Impacts of Sea-Level Rise due to Global Warming. Dhaka, Bangladesh, 16-19 November 1992.	E
94	BMTC-IOC-POLARMAR International Workshop on Training Requirements in the Field of Eutrophication in Semi-Enclosed Seas and Harmful Algal Blooms, Bremerhaven, Germany, 29 September - 3 October 1992.	E
95	SAREC-IOC Workshop on Donor Collaboration in the Development of Marine Scientific Research Capabilities in the Western Indian Ocean Region; Brussels, Belgium, 23-25 November 1993.	E
96	IOC-UNEP-WMO-SAREC Planning Workshop on an Integrated Approach to Coastal Erosion, Sea Level Changes and their Impacts; Zanzibar, United Republic of Tanzania, 17-21 January 1994.	E
96 Suppl. 1	IOC-UNEP-WMO-SAREC Planning Workshop on an Integrated Approach to Coastal Erosion, Sea Level Changes and their Impacts; *Submitted Papers* 1. Coastal Erosion; Zanzibar, United Republic of Tanzania 17-21 January 1994.	E
96 Suppl. 2	IOC-UNEP-WMO-SAREC Planning Workshop on an Integrated Approach to Coastal Erosion, Sea Level Changes and their Impacts; *Submitted Papers* 2. Sea Level; Zanzibar, United Republic of Tanzania 17-21 January 1994.	E
97	IOC Workshop on Small Island Oceanography in Relation to Sustainable Economic Development and Coastal Area Management of Small Island Development States; Fort-de-France, Martinique, 8-10 November, 1993.	E
98	CoMSBlack '92A Physical and Chemical Intercalibration Workshop; Erdemli, Turkey, 15-29 January 1993.	E
99	IOC-SAREC Field Study Exercise on Nutrients in Tropical Marine Waters; Mombasa, Kenya, 5-15 April 1994.	E
100	IOC-SOA-NOAA Regional Workshop for Member States of the Western Pacific - GODAR-II (Global Oceanographic Data Archeology and Rescue Project); Tianjin, China, 8-11 March 1994.	E
101	IOC Regional Science Planning Workshop on Harmful Algal Blooms; Montevideo, Uruguay, 15-17 June 1994.	E
102	First IOC Workshop on Coastal Ocean Advanced Science and Technology Study (COASTS); Liège, Belgium, 5-9 May 1994.	E
103	IOC Workshop on GIS Applications in the Coastal Zone Management of Small Island Developing States; Barbados, 20-22 April 1994.	E
104	Workshop on Integrated Coastal Management; Dartmouth, Canada, 19-20 September 1994.	E
105	BORDOMER 95: Conference on Coastal Change; Bordeaux, France, 6-10 February 1995.	E
106	IOC/WESTPAC Workshop on the Paleographic Map; Bali, Indonesia, 20-21 October 1994.	E
107	IOC-ICSU-NIO-NOAA Regional Workshop for Member States of the Indian Ocean - GODAR-III; Dona Paula, Goa, India, 6-9 December 1994.	E
108	UNESCO-IHP-IOC-IAEA Workshop on Sea-Level Rise and the Multidisciplinary Studies of Environmental Processes in the Caspian Sea Region; Paris, 9-12 May 1995.	E
108 Suppl.	UNESCO-IHP-IOC-IAEA Workshop on Sea-Level Rise and the Multidisciplinary Studies of Environmental Processes in the Caspian Sea Region; *Submitted Papers*; Paris, 9-12 May 1995.	E
109	First IOC-UNEP CEPPOL Symposium; San José, Costa Rica, 14-15 April 1993.	E
110	IOC-CEC-EMC-NOAA Regional Workshop for Member States Bordering the Mediterranean Sea; Valletta, Malta, 25-28 April 1995.	E
111	Chapman Conference on the Circulation of the Intra-Americas Sea; La Parguera, Puerto Rico, 22-26 January 1995.	E
112	IOC-IAEA-UNEP Group of Experts on Standards and Reference Materials (GESREM) Workshop; Miami, USA, 7-8 December 1993.	E
113	IOC Regional Workshop on Marine Debris and Waste Management in the Gulf of Guinea; Lagos, Nigeria, 14-16 December 1994.	E

No.	Title	Languages
114	International Workshop on Integrated Coastal Zone Management (ICZM); Karachi, Pakistan, 10-14 October 1994.	E
115	IOC/GLOSS-IAPSO Workshop on Sea Level Variability and Southern Ocean Dynamics; Bordeaux, France, 31 January 1995.	E