Background Document:
Strategy for Ocean Carbon in the Southern Ocean Observing System
September 2007

I. Introduction

The ocean takes up approximately 30% of the global anthropogenic CO2 emissions. Understanding and quantifying this oceanic sink for CO2 and how it will behave in the future is critical in any attempt to stabilize atmospheric CO_2 concentrations.

Research in the last few years has revealed that the Southern Ocean is responsible for more than 30% of the global uptake, and hence constitutes the most important anthropogenic CO2 sink region of the world's ocean. By substantially mitigating the effect of the human emissions of CO_2, the ocean has performed a significant earth system service, yet this comes at a steep cost – the acidification of the oceans. The uptake of anthropogenic CO_2 has caused a decrease in pH and the saturation state of calcium carbonate in near surface waters. The downward transport of this anthropogenic CO_2 has caused in many regions a 50-200 meter shoaling of the saturation horizons compared with their positions before the industrial revolution. By 2050, the saturated surface zone is projected to completely disappear in the high-latitude regions of the ocean, potentially leading to serious disruption of marine ecosystems.

Changes in climate may significantly affect the ocean's ability to continue to take up CO_2 from the atmosphere. Recent research has suggested that change in Southern hemisphere climate over the last few decades has already led to a substantial decrease in the Southern Ocean carbon sink. Whether this is a transient phenomenon, or whether this sink will continue to weaken is currently not known.

Climate impacts in this region include changes in heat- and freshwater fluxes and varying sea-ice cover, and shifts in winds, all of which may significantly affect the ocean carbon cycle and the net air-sea balance of carbon. The ocean's solubility pump for carbon is sensitive to deep convection, and anticipated increases in stratification may reduce the uptake and storage of CO2. The ocean's biological pump for carbon in the Southern Ocean is only operating at approximately at a fraction of its potential, owing to the limited availability of light and micronutrients, such as iron. Changes in light and nutrient supply resulting, e.g. from changes in stratification or from transport from continents by changing winds could either augment or diminish its strength. The ways that these different processes will interact with each other and define the overall air-sea balance of CO_2 are currently only partially understood. Observations in this globally critical area are urgently needed in order to close the gap in our understanding as well as in order to be able to quantitatively observe the changes as they are taking place.

Despite significant advances in our observational capability in recent years, we are still some distance from establishing an observing system for ocean carbon in the Southern Ocean that is optimal, i.e. that is capable of observing the carbon cycle in this region in such a manner that the major goals can be achieved (see below) and this at a minimal overall cost. Nevertheless, it is possible at this stage to identify the foundations of such an observing system, and to outline an incremental approach to developing a system that builds on enhanced data coverage and data analyses along with developments in both technology and modelling.

In our planning, we are greatly helped by the fact that ocean carbon research is a priority in major research programmes, and numerous process studies and field programmes are being carried out and planned for the coming years (see tables in Section II.B. of this report). Underway systems on research vessels operating in the Southern Ocean now provide continuous data streams, even in winter conditions, greatly increasing the available data. Several hydrographic repeat sections are being carried out or are planned / funded for the coming years, and moorings are under development. Drifting buoys measuring pCO2 have been successfully deployed in the Southern Ocean and have provided multi-year data sets in regions not covered by hydrographic sections or commercial vessels.

II. Strategy and Recommendations

The goals and objectives for carbon research in the Southern Ocean have been well-defined (see, for example, the US Ocean Carbon and Climate Change report (2004), Chapter 7, Southern Ocean Pilot Studies; EU CarboOcean Marine Carbon Sources and Sinks Assessment (2001); Integrated Marine Biogeochemistry and Ecosystem Research (IMBER) Science Plan and Implementation Strategy (2005); the Surface Ocean – Lower Atmosphere Study (SOLAS) Science Plan and Implementation Strategy (2004)). The design and implementation of an observing system to meet the objectives is in the early stages of development. Although it is not possible at present to detail an optimal number and combination of observation platforms, we can identify several cornerstones of an observing system based on recent research results, and articulate the science goals for a Southern Ocean Carbon Observing System.

The design of the observing system depends critically on the understanding of the time and space scales of variability, from seasonal to decadal and longer, which in this region also include natural variations such as the Antarctic Circumpolar Wave, the Antarctic Dipole, and the Southern Hemisphere Annular Mode. The results from recent large-scale field programmes such as WOCE, JGOFS have not been fully synthesized, and the observing system design is expected to undergo refinements as these results become available. Several major field programmes (CarboOcean, CLIVAR) are scheduled to end in the next 2-4 years, also offering new data for synthesis and input to the development of the observing system. Owing to the distance and harsh environment of the Southern Ocean, advances in technology and the development of new autonomous sensors are needed for a comprehensive sustained observations. Because many of the research questions for carbon in the Southern Ocean address processes and their potential alterations by changing conditions, the improvement of models is crucial.

We next outline the major scientific goals for a carbon observing network in the Southern Ocean, followed by our specific recommendations . They include

1. Synthesis activities;
2. Technological development; and
3. Model development.

II.A. Major scientific goals and their implications for a regional observing system

A sustained carbon observing system for the Southern Ocean should permit both the determination of the long-term behavior of the system on time-scales of years to decades, as well as the short-term observations required to improve understanding of seasonal and sub-seasonal variability.

The ocean carbon community has achieved consensus on the basic observation goals for global and regional systems:

- To resolve air-sea fluxes of CO_2 to +/- 0.2 PgC/yr for constraining global carbon budgets.
- To constrain basin-scale decadal changes of anthropogenic carbon inventory to +/- 20%.

For the Southern Ocean we have specific concerns that require large-scale and sustained observations to understand the response of the carbon cycle to climate change and the future storage of CO2 in the ocean :

- The importance of the southward shift of the westerly winds and their intensification that the system has experienced in the last couple of decades (shift toward positive phase of the SAM). The ocean carbon system seems to have responded to this with shift quite sensitively as illustrated in the work of Le Quéré et al. (2007) and Lovenduski et al. (2007). This trend toward more positive phases of the SAM is predicted (at least in some models) to continue into the future. This may lead to a reduced uptake of CO2 by the Southern Ocean.
- The impact of the predicted changes in stratification.
- Aragonite and carbonate saturation levels, pH, and ecosystem indicators of impacts of ocean acidification.

These responses have signatures through the water column and over the entire latitude band of the Southern Ocean, which we take to mean from the subtropical front to the Antarctic coast. Thus, two essential cornerstones of a possible future observing system for the Southern Ocean region are:

Measurements of full water-column changes carbon and related parameters

Ideally, core program lines should measure temperature, salinity, pressure, nitrate, phosphate, silicate, oxygen, chloroflurocarbon tracers (CFC-11, -12, -113), shipboard and lowered ADCP and at least 2 carbon parameters (e.g., Dissolved inorganic carbon (DIC), Alkalinity (ALK), pCO_2, pH). The type of carbon measurements and their quality need to be sufficient to determine DIC and Alkalinity to approach the accuracy goals of the program (2µmol kg^{-1} for DIC; 4 µmol kg^{-1} for ALK). Also recommended is a third carbon parameter for internal consistency purposes, separate measurements of NO_2 and NO_3, as well as organics (POC, DOC) and ^{13}C. The frequency of repeat sections in the Southern Ocean may need to be repeated faster than the current 10 year surveys. For the future, we will need to continue to rely on repeat hydrographic surveys from ships; however, it is hoped that float-based systems will be available in the coming years to permit improved spatial and temporal coverage. Oxygen equipped floats are already available and will complement the carbon observations leading to better spatial and temporal coverage.

Measurements of near surface properties

Expanding the current network of continuous underway VOS measurements, and the development of surface drifters and time series stations will help characterize both the scales of variability in the Southern Ocean and the biogeochemical response to changes in environmental forcing. Future developments of profiling floats and gliders with CO2 system sensors are many years away, but will enhance the observing system. The standard parameters measured on all platforms should include continuous measurements of temperature, salinity and pCO2, and dissolved oxygen. The surface underway measurements should be enhanced where possible to include either continuous or discrete measurements of DIC, Alk, pH, nutrients, dissolved oxygen, chlorophyll-*a*, particulate organic carbon, particulate inorganic carbon, and bioptical properties (fluorometry, transmissometer). The same set of parameters should be determined on time series, where sensors are available. Some consideration needs to be given to developing the capacity to sample ecosystem indicators (e.g., pteropods, calcareous phytoplankton, etc.)

The tables below provide information about on-going and planned hydrographic sections, underway measurements, and time series measuring carbon variables in the Southern Ocean (last updated in April 2007). The International Ocean Carbon Coordination Project (IOCCP) works with national, regional, and global research programmes to promote the development of a global network of ocean carbon observations for research through technical coordination and maintaining compilations of observation programmes, international agreements on standards and methods, and advocacy and links to the global observing systems. Information about ocean carbon observations and programmes in other regions can be found at: www.ioccp.org.

Carbon research in the region will also benefit from integration of the observing system across disciplines, for example:

- Companion efforts should be developed to build on the atmospheric observations of CO2, O2/N2 and aerosol iron that are relevant to understanding the variability in the ocean carbon cycle.
- The CO2 should be more closely integrated with the work of the physical oceanography component of the obs system(Argo, XBT and hydrographic section work). This is underway.
- The CO2 work should be more closely integrated with biological monitoring of phytoplankton, and zooplankton for acidification and biological pump.
- The CO2 work should be more closely integrated with micronutrient observations (Geotracers), particularly on sections.

Hydrography

Name of the line	Area	Description (ship track)	Year planned	PI (carbon)	Country
Southern Ocean					
S04P	Pacific	60°S	2009	R. Feely	USA
Antarctic Zero Meridian and Weddell section	Antarctic-Atlantic sector, Weddell Sea	A) Repeat section along zero meridian from Polar Front (ca. 50 S) to Antarctica; once every 2-3 years, B) Weddell Sea section Kapp Norvegia-Joinville Island	A) since 1984 AJAX cruise onwards; next Feb-Apr 2008 B) 2008, 2010/11	M. Hoppema, H de Baar	Germany, Netherlands
Fremantle-Prydz Bay	Southern Ocean	Leaving from Fremantle of Australia, pass southern Indian Ocean, transactions investigation between 60°S and 69°S.	Yearly	Z. Dong	China
P12/SR3	Southern Ocean	Hobart – Antarctica (140E)	2007	B. Tilbrook	Australia
I9S	Southern Ocean	Fremantle – Antarctica	2012	B. Tilbrook	Australia

56°S,63°W - 62°S,58°W	Southern	Drake Passage (Punta Arenas, Chile <-> King George Island, West Antarctica)	2007, 2008 (yearly continuous)	Y.C. Kang	Korea
A13.5	Atlantic Sector / Southern Ocean	meridional section following 0° from equator to continent	2009	R. Wanninkhof	USA
IS6	Indian	55 °E	2008	C.Sabine	USA

Underway

Track/Ship name	Dates of operation	Area	Brief description (ship track)	Frequency	PI	Country
Southern Ocean						
Palmer	2000-	Pacific / Southern Ocean	Various	Random	T. Takahashi	USA
l'Astrolabe	2002-	Southern	Hobart – Terre Adelie (Antarctica.)	3/austral summer	B. Tilbrook C. Goyet	Australia France
Aurora Australis	2006-	Southern	Hobart -Mawson Base/ Hobart - Casey Base	4/year	B. Tilbrook	Australia
JARE by Icebreaker Shirase	On going	Southern	Fremantle – Syowa Stn. (Lützow-Holm Bay, Antarctica) Syowa Stn. – Sydney	Annual Dec. *Feb-Mar	G. Hashida S. Nakaoka	Japan
Xuelong	Nov-Mar	Southern	Leaving from Shanghai, pass northern and southern Pacific, investigate in Prydz Bay and tracks between Zhongshan St (East Antarctica) and Changcheng St (Antarctic Peninsular).	1/year	L. Chen,	China
RRS James Clark Ross	2006-2009	Southern	Variable but mainly Falklands-South Georgia-Signy-Rothera	Variable	N. Hardman-Mountford	UK
RV Umitaka Maru	Dec 2007-Feb 2008	Southern	Cape Town – Fremantle - Hobart (Off of Lützow-Holm Bay, 110ºE, 140ºE)	1/year	G. Hashida S. Nakaoka	Japan
RV Hakuho Maru	Feb 2008	Southern	Port Elizabeth – Fremantle (near Kerguelene, Off of Lützow-Holm Bay)	Variable	H. Y. Inoue	Japan

Marion Dufresne / OISO	1998-	Southern / Indian Ocean Sector	Reunion - Crozet - Kerguelen - Amsterdam Is	2/year; also includes low-resolution hydrographic sampling	N. Metzl	France
LM Gould / Drake Passage	2005 -	Atlantic / Southern Ocean	Ponte Arenas - Palmer	20 / year	T. Takahashi C. Sweeney	USA
Polarstern	2007 -	Atlantic / Southern Ocean	Variable, but mainly Weddell Sea and adjacent ACC	Variable	H. Zemmelink M. hoppema	Netherlands Germany

Time Series

Mooring/Station/ Ship name	Date of operation	Location	Description	Frequency (i.e. monthly, continuous)	PI	Country
Southern Ocean						
Stations monitored by moorings						
PULSE time series	2008 -	47°S,142°E	sub-Antarctic mooring	Continuous	B. Tilbrook (CO_2)	Australia
NIWA Southern Biophysical Mooring	March 2005– (for SAMI)	SW Pacific, sub-antarctic surface water	Permanent mooring, including SAMI-CO_2 instrument	Continuous	K. Currie S. Nodder	New Zealand
Marian Cove, King Sejong Station, King George Island	2003-	62°13´S, 58°47´W	Surface measurements	Continuous	Y.C. Kang	Korea
Stations monitored from ships						
Zhongshan Station	1984-	69°S, 75°W	Water column including DIC, pH, ^{234}Th, DO, Chl, nutrients, biomass	Annual	L. Chen	China
Changcheng Station	1984-	62°S, 59°W	Water column including DIC, pH, ^{234}Th, DO, Chl, nutrients, biomass	Annual	L. Chen	China

II.B. Synthesis activities

The ocean carbon community has initiated several activities to develop a global, merged, quality-controlled data set for use in synthesis activities. Groups in the Atlantic and Pacific have been formed, with coordinated Southern Ocean components, using the same global data set, protocols, and data managers. By

December 2007, the global database will be composed of more than 550 cruises from 1972 - 2007, with approximately 3 million measurements of various carbon parameters.

Atlantic Carbon Synthesis Groups (includes Southern Ocean component)

This project was initiated at the IOCCP-CarboOcean Initial Atlantic Ocean Carbon Synthesis Meeting, June 28-30 2006, Laugarvatn, Iceland. One major research objectives is the quantification of decadal-to-centennial large-scale Southern Ocean carbon inventory changes. Operationally this implies a need to quantify the Southern Ocean carbon sink, and its decadal change, through highest accuracy measurement of the changing inventories of inorganic carbon and carbon-related tracers. Southern Ocean data will then be integrated into a coherent global data base. The ability of prognostic models to represent the observed changes for a reliable now-cast will be assessed against the data-based syntheses. The science delivery associated with this objective is a large scale assessment of the ocean carbon storage.

Following the initial kick-off meeting, this group has continued under the leadership of CarboOcean, with a follow-up meeting in April to initiate the data base development.

The main goal is to deliver:

- A merged and quality controlled data set
- A table with recommended adjustments for each variable and each cruise
- A data product that is the same as the data set, but with the recommended adjustments applied.

This will be carried out through:

- Cross-over analysis. Data to be compared in the deep waters and on density surfaces (except for salinity that will be done on depth surfaces)
- Regional MLR analysis
- Deviations from regional mean profiles
- The offsets determined in the first three steps will form the basis for determining recommended offsets.

Specifically for the Southern Ocean, the following questions will be addressed:

- Which is the optimal method to determine Cant in the Southern Ocean?
- Estimate the regional or whole SO Cant inventory, using as many data as possible.
- Compare Cant with CFCs. Any agreements / disagreements?

- Compare observations with models. Sensitivity to changes in circulation / physics.
- Separating Cant from natural DIC changes.

The group has developed secondary QC protocols, MATLAB routines to streamline the cross-over analyses, and an internet portal for sharing data and results from cross-over analyses. The Southern Ocean working group will divide the work into specific regions and close cooperation with the South Pacific Working group is foreseen. All 2nd level QC should be done for the data base by mid-December 2007. A follow-up meeting is planned for November 2007. For more information, including data, working documents, and follow-up activities, please visit the synthesis home page at: http://www.carbon-synthesis.org/

North Pacific Carbon Cycle Group (includes a Southern Ocean component)
This synthesis activity was launched at the Understanding North Pacific Carbon-Cycle Changes: A Data Synthesis and Modeling Workshop, June 2-4, 2004 to bring together those researchers that have studied variability in the North Pacific to synthesize the individual experiences into a basin-scale picture of the North Pacific carbon-cycle. The synthesis, which began in early 2004, followed a 3-step approach:

1. Synthesis Preparation - Establishment of science issues and working groups; Assessment of state of knowledge and identification of relevant data sets, model results, and analysis approaches; Development of common frameworks for data and goals among all working groups; Preparation of new calculations and figures based on the agreed synthesis framework. This step is mostly accomplished through email.
2. Workshop - Presentation of assessments and new findings; outlining synthesis manuscripts; Developing collaborative follow-up activities; Identification of future research needs.
3. Collaborations, Data Synthesis Development, Publications - Finalizing synthesis papers; Synthesis data set development and publication; Continued collaborations.

The Pacific data synthesis is carried out through three working groups: North Pacific (Sabine, Murata, Ishii), Equatorial Pacific (Feely, Ishii), and South Pacific (Tilbrook), and a "data manager" (Bob Key, Princeton) that will compile the data as they are made available. This group agreed on close cooperation with the Atlantic synthesis effort, particularly for the Southern Ocean group where substantial overlap exists. The two synthesis activities are using the same data center, compiled global data set, and data manager for their activities. For more information, visit the synthesis web-site at: http://www.pmel.noaa.gov/co2/NP/

CDIAC / CarboOcean Common Format Surface CO_2 Database Project

As part of the EU ORFOIS Project, Dorothee Bakker and Benjamin Pfeil began compiling the historical, publicly-available surface CO_2 data at CDIAC into a common format database based on the IOCCP recommended formats for metadata and data reporting. This activity continues under the EU CarboOcean project, and the compilation will soon include the CARINA and CarboOcean datasets. The final database will be composed of more than 550 cruises from 1972 - 2007, with approximately 3 million measurements of various carbon parameters. It is expected that this will be a continuing effort, and all new surface CO_2 data submitted to CDIAC will be formatted and included in the compilation. CDIAC has developed several metadata search techniques and live-access server products that to search and sub-select the surface pCO2 data holdings:

- The Web-Accessible Visualization and Extraction System (WAVES)
- Live-Access Server Products
- Mercury web-based system to sear for metadata and retrieve associated data.

For more information, visit CDIAC Ocean CO2 for the latest available data and products.

Surface Ocean CO_2 Atlas (SOCAT) Project

At the recent IOCCP workshop on Surface Ocean Carbon Variability and Vulnerability, it was agreed that there is a strong scientific need for gridded ocean CO_2 products for the observational and modeling communities. The participants suggested the development of an annually-updated "Surface Ocean CO_2 Atlas" that consists of a 1° x 1° grid of monthly surface pCO_2 means (including number of data points and standard deviation), with no interpolation. In discussions with the modelers present at the workshop, it was agreed that surface pCO_2 was more useful than air-sea flux estimates. This exercise will be initiated following the release of the common-format CO2 database in December 2007. Regional groups, including a Southern Ocean group, were developed to analyze the data with respect to regional research priorities.

II.C. Technological developments

Considerable effort has gone into developing common instrumentation, quality control procedures, reference materials, and uniform and accessible data bases for the CO2 measurements.

- Protocols and documentation for measurements of all CO2 parameters were developed for the JGOFS/WOCE "CO_2 in the Oceans" program and an updated "Guide of Best Practices for Oceanic CO2 Measurement and Data Reporting" is being released at the end of 2007. The standardized procedures have significantly improved data quality and availability.
- In the last two years, commercial systems have been developed for VOS measurements of CO2 and are being integrated into VOS systems used on many lines around the world. These new systems were designed by the research community, and are expected to increase the efficiency and data return of many VOS CO2 programs.
- A major research effort has begun to develop new autonomous sensors for carbon and related parameters (e.g., O2 on argo, additional carbon parameters from drifting buoys, etc.).
- CO2 is now routinely measured on a large number of time series moorings, and these stations have been integrated into the OceanSITES coordination effort, including data and information management. The development of time series moorings that can withstand Southern Ocean conditions is still in progress.
- Uniform databases are being developed (mentioned in Synthesis section).

At present, autonomous sensors exist for pCO2, O2, and pH, but are still in the research phase for DIC, Alk, and nutrients. While great improvements have been made in commercializing the VOS systems, they are still not fully autonomous and require attendance by an operator.

II. D. Model developments

From US OCCC: " The comparison of ocean carbon models by the Ocean Carbon Model Intercomparison Experiment (OCMIP) revealed some important features about the Southern Ocean, as well as some issues in need of attention. Ocean carbon models generally show the greatest uptake of anthropogenic CO2 south of 50S, in part due to the exposure to the atmosphere of old deep waters that have never before been exposed to anthropogenic Co2. For this reason, models also show the Southern Ocean becoming increasingly important as a sink for anthropogenic CO2 during the next century. Whereas there is agreement among ocean models that the Southern Ocean is a site of substantial uptake of anthropogenic CO_2, the Southern Ocean is also the region in which the greatest disagreement exists among models in terms of absolute uptake rates, with results varying by as much as a factor of three among models. The source of these inconsistencies is currently being investigated."

Until recently, substantial discrepancies also existed between the ocean's uptake of CO_2 at high southern latitudes inferred from ocean observations and those obtained from atmospheric models. This issue has recently been largely resolved by the recognition of a substantial summer-time bias in the oceanic observations. Nevertheless, comparison of the various flux estimates at regional resolution still reveal substantial discrepancies.

Recent modeling work pointed out that the Southern Ocean carbon cycle responds rather sensitively to changes in atmospheric forcing, particularly the mean position and the strength of the westerlies. All models investigated so far point toward an increased outgassing of CO_2 during periods of a positive index phase of the Southern Annular Mode (poleward contracted and intensified winds over the open Southern Ocean). This response on interannual time-scale appears to also have dominated the response of the Southern Ocean carbon cycle to the decadal trend in the Southern hemisphere climate toward a more positive state of the SAM. As a result, several models and atmospheric CO_2 observations suggest that the Southern Ocean carbon sink has substantially decreased relative to what is expected in a constant climate. It is conceivable that this trend toward more positive phases of the SAM will continue into the future, therefore causing a continuation of this decreasing trend.

Many of the variables that influence carbon fluxes in the Southern Ocean also play a role in the transport of heat and freshwater. Consequently, model development should be undertaken jointly between the physical oceanographic and carbon / biogeochemistry communities. Key common issues include:

- uncertain forcing;
- critical but insufficient sub-grid scale parameterizations;
- differences between eddy- and non-eddy resolving models (where eddy-resolving models tend to be better for ocean carbon, but not in all cases); and,
- Interaction with sea-ice and boundary processes.