Global Repeat Hydrographic/CO_2/Tracer surveys in Support of CLIVAR and Global Cycle objectives: Carbon Inventories and Fluxes

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Table of Contents

1. Abstract 2
2. Project Summary 2
3. Scientific Accomplishments 6
   3.1 CTD/O_2 and Bottle Salinity (Baringer and Johnson) 6
   3.2 Total Dissolved Inorganic Carbon (DIC) (Feely, Sabine and Wanninkhof) 7
      3.2.1 I6S final DIC data reduction 7
      3.2.2 I5 Cruise Results 9
      3.2.3 Preparations for A13.5 – discrete pCO_2 10
      3.2.4 Data use 11
   3.3 CFC Tracers (Bullister) 11
   3.4 Nutrients (Mordy and Zhang) 13
   3.5 Discrete Oxygen (Baringer and Langdon) 16
4. Education and Outreach 17
5. Publications and Reports 17
   5.1. Publications by Principal Investigators 17
   5.2. Other Relevant Publications/References 19

Figure 1. Global map of U.S (Top) and international (Bottom) Repeat Hydrography CO2/tracer Program hydrographic sections with carbon system measurements 3

Figure 2. Cross-section of DIC values for the I6S cruise 8

Figure 3. Cross-section of difference in measured DIC values and calculated DIC values for the I6S cruise. 9

Figure 4. Cross-section of DIC values for the I5 cruise. 10

Figure 5. Cross-section of discrete pCO_2 from the AJAX cruise track (1984) that will be re-occupied during A13.5. 11

Figure 6. A section of CFC-12 concentrations along I05 in 2009. 13

Figure 7. Sections of nitrate, phosphate and silicic acid along the I5 cruise track. 15

Table 1. Sequence of Repeat Hydrography CO_2/Tracer completed and planned cruises in the oceans from 2003 to 2014. 4
Table 2. Summary of number of CFC-11 samples taken and the estimated precision for the CLIVAR A13.5 cruise 12
Table 3. Summary of number of CFC-12 samples taken and the estimated precision for the CLIVAR A13.5 cruise 12
Table 4. Summary of number of SF_6 samples taken and the estimated precision for the CLIVAR A13.5 cruise 12

1. Abstract

The Repeat Hydrography CO_2/Tracer Program is a systematic and global re-occupation of select hydrographic sections to quantify changes in storage and transport of heat, fresh water, carbon dioxide (CO_2), chlorofluorocarbon (CFC) tracers and related parameters. It builds upon earlier programs (e.g., World Ocean Circulation Experiment (WOCE)/Joint Global Ocean Flux Study (JGOFS) during the 1990s) that have provided full depth data sets against which to measure future changes, and have shown where atmospheric constituents are getting into the oceans. The Repeat Hydrography CO_2/tracer Program reveals much about internal pathways and changing patterns that will impact the carbon sinks on decadal time scales.

2. Project Summary

The program is designed to assess changes in the ocean's biogeochemical cycle in response to natural and/or man-induced activity. Global warming-induced changes in the ocean's transport of heat and freshwater, which could affect the circulation by decreasing or shutting down the thermohaline overturning, can also be followed through long-term measurements. Below the 2000-m depth of Argo, Repeat Hydrography provides the only global measurements for observing long-term trends in the ocean (Figure 1, Table 1). The program also provides data for the Argo sensor calibration (e.g., www.argo.ucsd.edu), and support for continuing model development that will lead to improved forecasting skill for oceans and global climate. By integrating the scientific needs of the carbon and hydrography/tracer communities, major synergies and cost savings have been achieved. The philosophy is that in addition to efficiency, a coordinated approach will produce scientific advances that exceed those of having individual carbon and hydrographic/tracer programs. These advances will contribute to the following overlapping scientific objectives: 1) data for model calibration and validation; 2) carbon inventory and transport estimates; 3) heat and freshwater storage and flux studies; 4) deep and shallow water mass and ventilation studies; and 5) calibration of autonomous sensors.

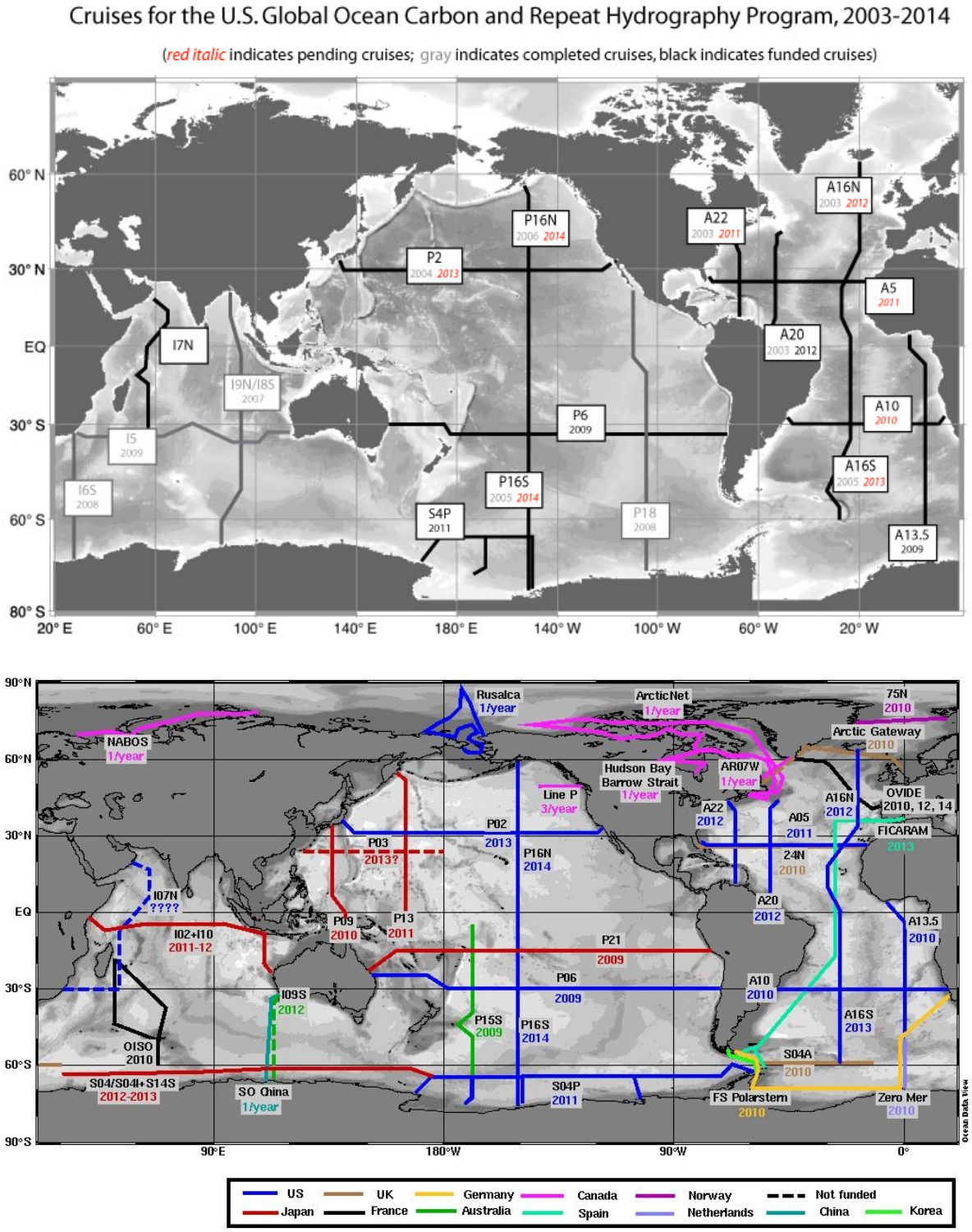

Figure 1. Global map of U.S (Top) and international (Bottom) Repeat Hydrography CO_2/Tracer Program hydrographic sections with carbon system measurements. In the bottom plan solid lines indicate funded lines. Dashed lines indicate planned lines that are not fully funded at this time. The U.S. cruises are designated with blue lines.

Table 1. Sequence of Repeat Hydrography CO_2/Tracer completed and planned cruises in the oceans from 2003 to 2014.

Schedule of US CO2/CLIVAR Hydrography Lines (as of 10/27/09)

Dates	Cruise (for documentation and results see the Data Links page)	Days	Ports	Contact/Chief Scientist (overall coordinator: Jim Swift, SIO)	Ship
06/19/03-07/10/03	A16N, leg 1	22	Reykjavik-Madeira	Bullister, PMEL	Ron Brown
07/15/03-08/11/03	A16N, leg 2	28	Madeira - Natal, Brazil	Bullister, PMEL	Ron Brown
09/15/03-10/13/03	A20	29	WHOI - Port Of Spain	Toole, WHOI	Knorr
10/16/03-11/07/03	A22	21	Port Of Spain - WHOI	Joyce, WHOI	Knorr
06/15/04-07/25/04	P2, leg 1	41	Yokohama-Honolulu	Robbins, SIO	Melville
07/28/04-08/27/04	P2, leg 2	32	Honolulu - San Diego	Swift, SIO	Melville
01/09/05-02/22/05	P16S	45	Wellington-Tahiti	Sloyan/Swift, WHOI/SIO	Revelle
01/11/05-02/26/05	A16S	48	Punta Arenas - Fortaleza	Wanninkhof,Doney; NOAA/AOML,WHOI	Ron Brown
02/13/06-03/03/06	P16N, leg 1	18	Tahiti-Honolulu	Sabine; NOAA/PMEL	Thompson Thompson Schedule
03/10/06-03/30/06	P16N, leg 2	21	Honolulu-Kodiak	Feely; NOAA/PMEL	Thompson Thompson Schedule
02/04/07-03/17/07	I8S	38	Dunedin, NZ-Fremantle	Swift, SIO	Revelle
03/22/07-05/02/07	I9N	38	Perth-Colombo, Sri Lanka	Sprintall, SIO	Revelle
12/15/07-01/16/08	P18	32	San Diego-Easter Island	Johnson, Bullister, PMEL	Ron Brown
01/19/08-02/23/08	P18	35	Easter Island- Punta Arenas	Johnson, Bullister, PMEL	Ron Brown
02/04/08-03/17/08	I6S	43	Durban-Cape Town	Speer, FSU	Revelle
03/19/09-05/14/09	I5	57	Cape Town-Fremantle	Swift, Johnson, SIO, PMEL	Revelle
11/21/09-2/11/10	P6	82	Brisbane - Valparaiso	Macdonald, Curry, WHOI	Melville
2010	A13.5	42	Cape Town-Takoradi	John Bullister, PMEL	Ron Brown
2010	A10	30	Rio de Janeiro-Cape Town	in NOAA program	NOAA
2011	S4P	60	Lyttelton-Punta Arenas	pending	NSF
2011	A5	30	Tenerife-Miami	in NOAA program	NOAA
2012	A20/A22	59	Woods Hole-Port of Spain-Woods Hole	pending	UNOLS
2012	A16N			in NOAA program	NOAA
2013	A16S			in NOAA program	NOAA
2013	P02	68		pending	NOAA
2014	P16N			in NOAA program	NOAA

Schedule of US CO2/CLIVAR Hydrography Lines (as of 10/27/09)

Dates	Cruise (for documentation and results see the Data Links page)	Days	Ports	Contact/Chief Scientist (overall coordinator: Jim Swift, SIO)	Ship
2014	P16S	42		pending	UNOLS
	I7N	51	Port Louis/Muscat		UNOLS

The Repeat Hydrography CO_2/Tracer Program is being implemented to maintain decadal time-scale sampling of ocean transports and inventories of climatically significant parameters in support of the Ocean Carbon Monitoring Network (Objective 7) of the Program Plan for Building a Sustained Observing Network for Climate. The sequence and timing for the sections (Figure 1; Table 1) takes into consideration the program objectives, providing global coverage, and anticipated resources. Also considered is the timing of national and international programs, including the focus of CLIVAR in the Pacific in the 2005-2008 timeframe; the Ocean Carbon and Climate Change Program (OCCC) that emphasizes constraining the carbon uptake in the Northern Hemisphere oceans, in part, in support of the North American Carbon Program (NACP); and the international Integrated Marine Biogeochemistry and Ecosystem Research (IMBER) program. Emphasis during 2010 is on the Southern Hemisphere. In addition, the proposed sections are selected so that there is roughly a decade between them and the WOCE/JGOFS occupations.

The scientific objectives are important both for the CLIVAR and the OCCC programs, and for operational activities such as Global Ocean Observing System (GOOS) and Global Climate Observing System (GCOS). In mid-2001 the US scientific steering committees of CLIVAR (www.clivar.org) and the Carbon Cycle Science Program, (CCSP; www.carboncyclescience.gov) proposed the creation of a joint working group to make recommendations on a national program of observations to be integrated with international plans. Several community outreach efforts have been implemented to provide information about the program, such as a web site with interactive forum (http://ushydro.ucsd.edu/index.html), articles in EOS (Sabine and Hood, 2003) and the JGOFS newsletter, as well as AGU and Ocean Science meeting forums. The Repeat HydrographyCO_2/Tracer Program addresses the need, as discussed by the First International Conference on Global Observations for Climate (St. Raphael, France; October 1999), that one component of a global observing system for the physical climate/CO_2 system should include periodic observations of hydrographic variables, CO_2 system parameters and other tracers throughout the water column (Smith and Koblinsky, 2000; Fine et al., 2001). The large-scale observation component of the OCCC has also defined a need for systematic observations of the invasion of anthropogenic carbon in the ocean superimposed on a variable natural background (Doney et al., 2004). The CCSP has identified the critical need for the federal government to begin delivering regular reports documenting the present state of the climate system components. Through this plan NOAA has developed the infrastructure necessary to build, with national and international partners, the ocean component of a global climate observing system and to deliver regular reports on the ocean's contribution to the state of the climate and on the state of the observing system.

Recognizing the need to develop an international framework for carbon research, various working groups of programs like the International Geosphere-Biosphere Programme (IGBP), the World Climate Research Programme (WCRP), the International Human Dimensions Programme

(IHDP), the Intergovernmental Oceanographic Commission (IOC), and the Scientific Committee on Oceanic Research (SCOR) have worked together to develop research strategies for global carbon cycle studies. Based on the recommendations coming from these programs, NOAA and NSF have co-sponsored the Repeat Hydrography CO_2/Tracers Program, with program direction coming from the Repeat Hydrography Oversight Committee (Richard Feely and Lynne Talley, co-chairs; http://ushydro.ucsd.edu/index.html). Many other nations are also sponsoring similar carbon studies that are comparable in focus and have been designed to be complementary to our program (http://www.clivar.org/carbon_hydro/index.htm). Consequently, there is an immediate need for global-scale coordination of these carbon observations and research efforts to achieve the goal of a global synthesis. There is also an urgent need to critically assess the overall network of planned observations to ensure that the results, when combined, will meet the requirements of the research community. Because of these issues, the Global Carbon Project (GCP; http://www.globalcarbonproject.org/) has initiated the International Ocean Carbon Coordination Project (IOCCP; http://www.ioc.unesco.org/ioccp/) to: (1) gather information about on-going and planned ocean carbon research and observation activities, (2) identify gaps and duplications in ocean carbon observations, (3) produce recommendations that optimize resources for international ocean carbon research and the potential scientific benefits of a coordinated observation strategy, and (4) promote the integration of ocean carbon research with appropriate atmospheric and terrestrial carbon activities. It is through the workings of the IOCCP and international CLIVAR that international coordination of data management, data synthesis and scientific interpretation of the global repeat sections results will be implemented. In addition, the Repeat Hydrography CO_2/Tracer Program is being managed in accordance with the COSP Ten Climate Monitoring Principals.

3. Scientific Accomplishments

3.1 CTD/O_2 and Bottle Salinity (Baringer and Johnson)

In FY 2009 the AOML CTD group helped to support the I5 and P6 carbon cruise on the R/V Roger Revelle and the R/V Melville. We were to provide one salinity analyst to the I7 Indian Ocean cruise; however piracy issues resulted in the cancellation of that cruise. The hydrographic section P6 across 30°S in the Pacific Ocean will be occupied in 2010 instead. For this cruise, the ODF/Scripps group requested that we send instead an oxygen analyst (A. Stafanick). In addition preparation for FY2010 fieldwork including general instrumentation maintenance and upgrades continued. This year, one paper by Baringer *et al* (2009) was published using repeated CTD sections to show potential changes in the strength of the meridional overturning circulation through the evaluation of the changes in deep temperature and salinity measurements.

In FY 2009 the PMEL CTD group supported the 2009 reoccupation of the trans-Indian Ocean WOCE Section I5 along about 32°S from Cape Town, South Africa to Fremantle, Australia. We helped our NSF-funded colleagues to collect 194 full-depth CTD/O_2 stations and associated water property samples during this 55-day cruise. Dr. G. Johnson served as co-chief scientist. Our lead CTD/O_2 data processor, K. McTaggart, stood a CTD watch, as did S. Purkey. D. Wisegarver and E. Wisegarver measured CFCs and SF_6. D. Greeley and R. Castle measured DIC and underway pCO_2. C. Featherstone measured dissolved O_2, and P. Proctor nutrients. The cruise data and report are publically available online at

http://cchdo.ucsd.edu/data_access/show_cruise?ExpoCode=33RR20090320.
These data are our primary deliverable for the year, and contribute to the decadal repeat of a global hydrographic survey. They comprise instrumental records of ocean heat content and transport, sea level, and ocean carbon uptake and will contribute to global analyses of these topics. When finalized, these data will be archived at NODC.

In FY 2009 we also started preparations for the upcoming reoccupation of WOCE Section A13.5, a meridional section through the deep basins of the eastern S. Atlantic along 0°E that will extend from the Antarctic Circumpolar Current at 54°S to the continental shelf of Ghana, Africa at 5°N. We built new CTD frames and a trolley to move the CTD from the rail to the sampling bay on the ship. We are calibrating the CTD/O_2 sensors prior to the cruise, assembling the instruments, computers, and supplies necessary for the cruise, and shipping the equipment to Charleston, SC where they will be loaded on the NOAA Ship Ronald H. Brown and await departure of the vessel.

While analyses of repeat hydrographic data are not funded through this proposal, they are vital to the success of the program, so our efforts in this regard in FY2009 are summarized here. This year we worked on analyses of repeat hydrographic section data demonstrating significant Antarctic Bottom Water (AABW) warming and freshening the southeast Indian Ocean (Johnson et al., 2008a) as well as warming and reductions in northward transport the western North Atlantic (Johnson et al., 2008b). Together, the results in the S. Indian, Pacific, S. Atlantic, and even the N. Atlantic Oceans suggest the possibility of a global pattern of AABW warming (and freshening near the source) in the past decade, which could constitute an important mode of climate variability, and a significant contribution to the global heat and sea level budgets. University of Washington graduate student S. Purkey is working with G. Johnson on a synthesis of these deep changes and their contributions to global budgets, which are important in reducing uncertainties of global warming. We have also used repeat hydrographic data in a detailed study of the Pacific Ocean circulation (Macdonald et al., 2009), an analysis of continued long-term warming in the deep Caribbean Sea (Johnson and Purkey, 2009), a discussion of the role of climate-change amplified ocean mixing in attenuating ocean climate change signatures (Johnson and Kearney, 2009), and a comprehensive study of increasing low-oxygen zones in the tropical oceans (Stramma et al., 2009). All of these works pertain to diagnosing the role of the ocean in the climate system. Aspects of the abyssal warming analyses were reported at an the international scientific lead-up to COP-15 (Johnson, 2009), and are discussed in two sections of the annual "State of the Climate" report (Baringer et al., 2009; Johnson et al., 2009). The increase of low-oxygen zones could have important implications for changes in ocean ecosystems, both pelagic and coastal.

3.2 Total Dissolved Inorganic Carbon (DIC) (Feely, Sabine and Wanninkhof)

3.2.1 I6S final DIC data reduction

DIC and underway PCO_2 measurements were performed on the I6S cruise that was run under the auspices of NSF. Cruise I6S on UNOLS vessel *Roger Revelle* departed Durban, South Africa on February 4, 2008 entered the southward-flowing Agulhas Current and traveled due south along a transect coinciding with Longitude 30 ˚E into the Antarctic Circumpolar Current down to the ice edge at 70 ˚S, and returned to Cape Town, South Africa on March 16, 2008.

The initial results were presented in the FY2008 report with the cross section reproduced below in Figure 2. Very high DIC values are observed in the Southern Ocean with a shallow thermocline south of 55˚S. The penetration of North Atlantic Deep Water from the north at a depth of 2000-3500 m is manifested by lower DIC values. This is attributed to better ventilation of this water mass compared to the older waters of Antarctic origin.

During this performance period the DIC data underwent rigorous quality control including comparisons with other inorganic carbon parameters. The final data was submitted to the CDIAC and CCHDO data centers. Figure 3 shows the cross section of difference between measured DIC and calculated DIC – DIC(calc) using TAlk and $pH(25)_T$ measured by the group of Prof. A. Dickson of SIO. Of the 1349 co-located sample points for DIC, TAlk, and pH the average offset in DIC - DIC(calc) = 5.1 ± 3.9 µmol kg^{-1}. Figure 3 shows no systemic trend in the difference within the uncertainty of measurements and calculation, even thought there are significant differences in concentration of the parameters compared with depth and location (see Figure 3).

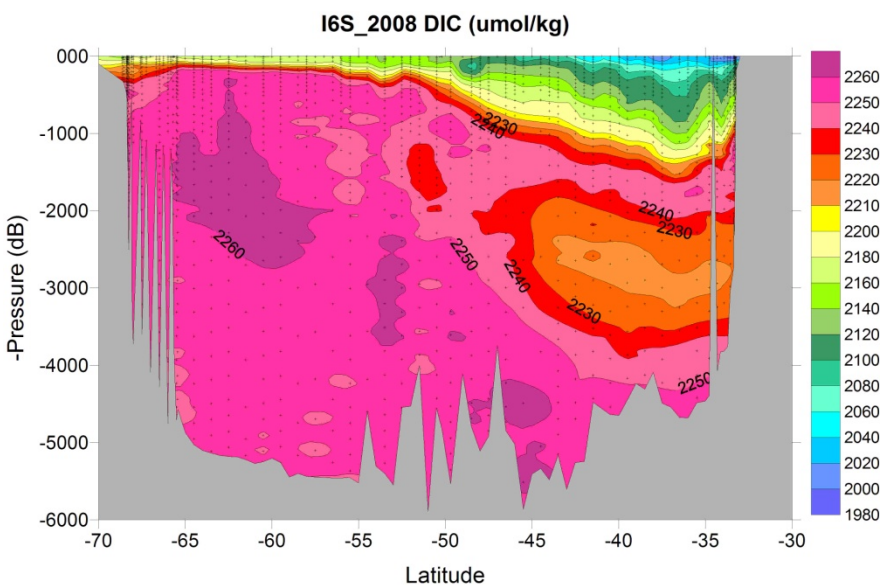

Figure 2. Cross-section of DIC values for the I6S cruise. Note the higher resolution scale for values greater than 2200 µmol/kg to accentuate small changes in deep water values

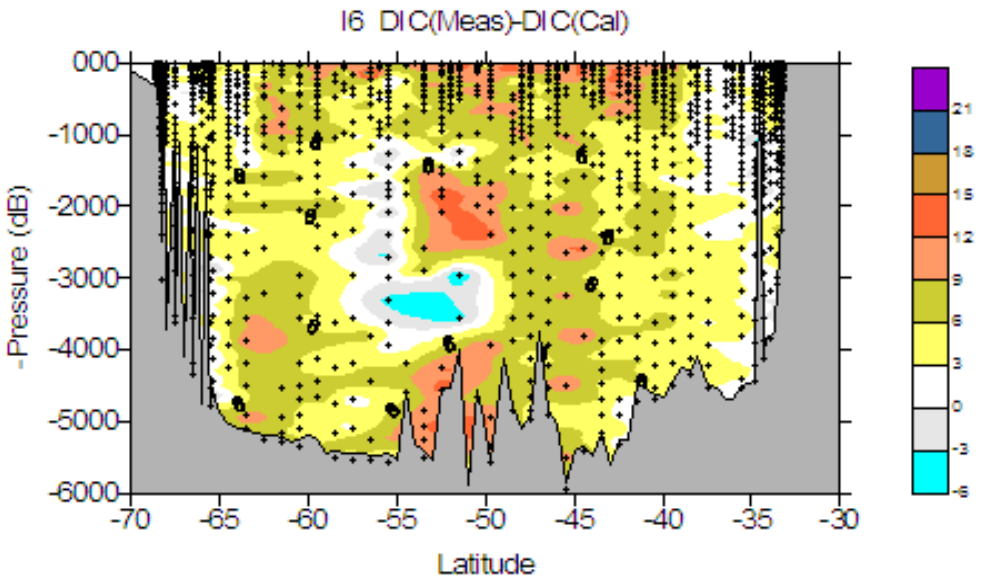

Figure 3. Cross-section of difference in measured DIC values and calculated DIC values (from TAlk and pH, A. Dickson, SIO) for the I6S cruise.

3.2.2 I5 Cruise Results

A total of over 500 pure (99.995%) CO_2 gas calibrations were run on both SOMMA systems during I5. The precision and accuracy obtained from these calibrations can be described as follows:

1. The precision is displayed by the greater than 450 replicate samples drawn. The absolute average difference from the mean of these replicates are less than 0.85 µmol/kg. No significant systematic differences were noted.

2. The accuracy can be described by the greater than 250 Certified Reference Materials (batch 94) that were analyzed. The average difference from the certified value for these is 0.65 µmol/kg with a standard deviation of 1.5 µmol/kg.

Full profiles were completed on half the total stations, with replicate samples taken from the surface, oxygen minimum, and bottom bottles. On the other half of the stations, partial profiles were drawn throughout the water column with focus on the upper 1000m. The replicate samples (N=465) were interspersed throughout the station analysis for quality assurance and integrity of the coulometer cell solutions. No systematic differences between the replicates were observed. Over 5000 samples were analyzed for discrete DIC.

The stability of each coulometer cell solution was confirmed three different ways: the Certified Reference Material (CRM), Batch 94 supplied by Dr. Andrew Dickson of SIO, was measured at the beginning, gas loops were run at the beginning and at the end, and the replicate samples interspersed – but typically run at the beginning, middle, and end of each cell solution. The

coulometer cell solution was replaced after no more than 27 mg of carbon was titrated, typically after 9–11 hours of continuous use.

The instruments each have a salinity sensor, but all DIC values were recalculated to a molar weight (µmol/kg) using density obtained from the CTD's salinity sensor. The DIC values were corrected for dilution by the saturated $HgCl_2$ addition used for sample preservation. The correction factor used for dilution was 1.0004. A correction was also applied for the offset from the CRM. On this cruise, the overall accuracy and precision for the CRMs on both instruments combined was 0.65 µmol/kg (n=228). DIC data reported to the database directly from the ship are to be considered preliminary until a more thorough quality assurance can be completed shore side.

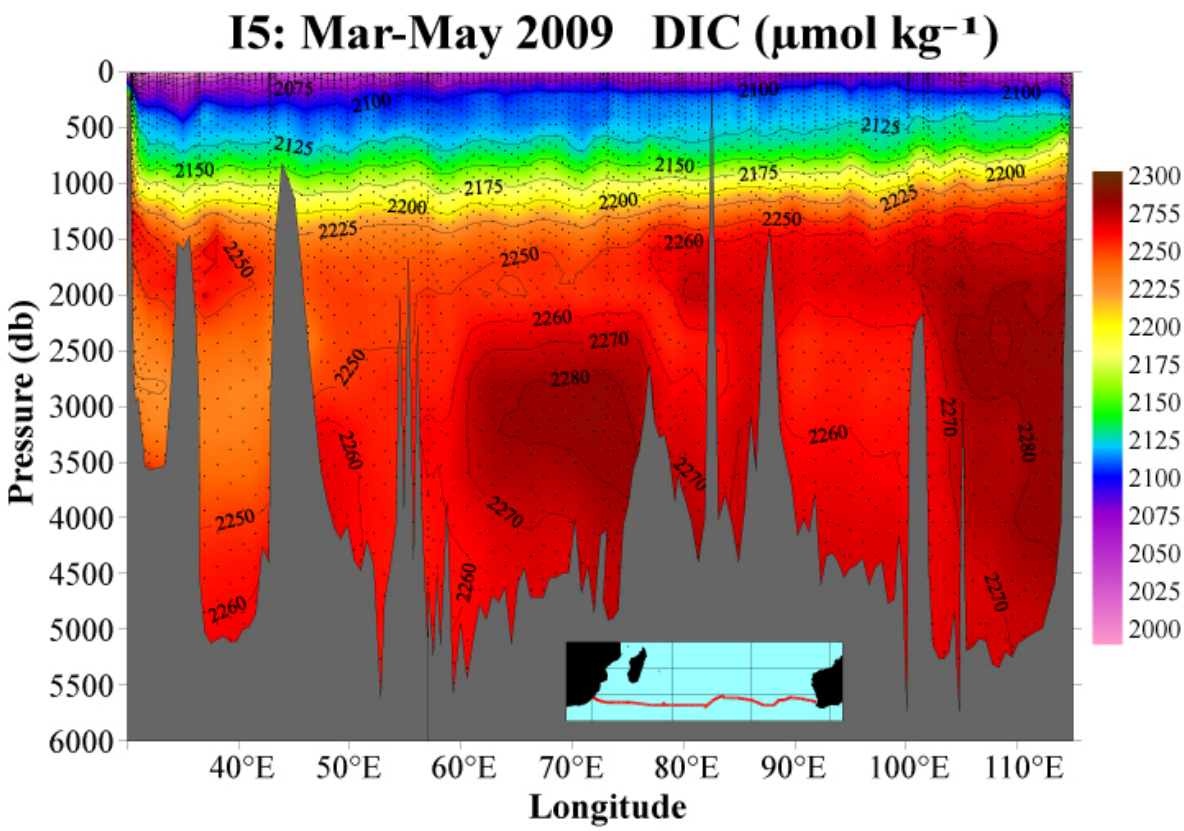

Figure 4. Cross-section of DIC values for the I5 cruise.

3.2.3 Preparations for A13.5 – discrete pCO_2

The A13.5 cruise along the prime meridian from 54° S to 5° N will be the first re-occupation of this section since the AJAX cruise of 1984. Since there were instrumental problems measuring DIC during the AJAX effort (T. Takahashi pers. com.) we decided to include discrete pCO_2 measurement on our upcoming occupation to be able to make a direct comparison with the historical measurements, and because of the high sensitivity of pCO_2 to natural and anthropogenic change. The historical data is shown in figure x. We expect changes of about 40 µatm in the near-surface due to invasion of anthropogenic CO_2 over this time period.

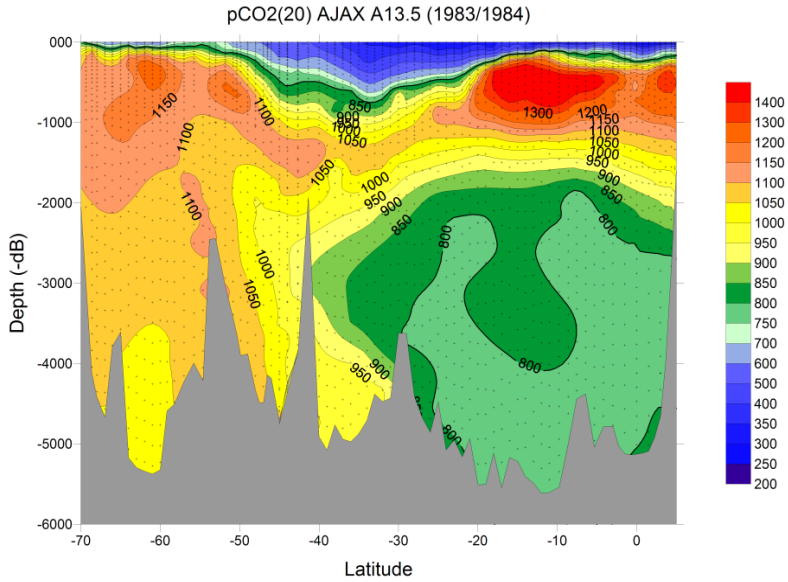

Figure 5. Cross-section of discrete pCO_2 from the AJAX cruise track (1984) that will be re-occupied during A13.5 (see color bar in µatm).

3.2.4 Data use

The full datasets from the CLIVAR/CO_2 cruises is submitted and stored at CDIAC and CCHDO for open access with no tracking of data use. The Atlantic data has been used as reference cruises for the historical re-analysis in the CARINA effort (see synthesis and data management progress report and for papers see
http://www.earth-syst-sci-data-discuss.net/special_issue2.html
in which the NOAA CLIVAR/CO_2 investigators were active participants. The data will be used in major projects organized by GCP in the RECCAP (regional carbon cycle assessment and processes). Basin and global inventories analyses are planned as a result of the ocean carbon synthesis meeting in Monte Verita Switzerland in the summer of 2009.

3.3 CFC Tracers (Bullister)

Participation on the CLIVAR I5 Indian Ocean expedition:
A primary FY 2009 goal was to perform high precision measurements of CFCs and SF_6 (CFCs/SF_6) on the I5 CLIVAR Repeat Hydrography Program expedition in the Indian Ocean. This goal was completed successfully. We designed, constructed and tested a CFC/SF_6 analytical system for use on the 2009 CLIVAR I5 expedition. Two skilled analysts from PMEL participated on the ~57 day long expedition on the research vessel Roger Revelle.

D. Wisegarver from PMEL coordinated preparing the CFC/SF_6 equipment for the cruise. He was the lead analyst for the CFCs/SF_6 measurements, processed the data sets, and calibrated and maintained the equipment. Concentrations of CFC-11, CFC-12 and SF_6 in air samples, seawater and gas standards were measured by shipboard electron capture gas chromatography (EC-GC)

using techniques modified from those described by (Bullister and Weiss, 1988) and (Bullister and Wisegarver, 2007).

Samples for the analysis of dissolved CFC-11, CFC-12 and SF_6 were drawn from ~3509 of the 6726 water samples collected during the I05 expedition. Efforts were made to sample CFCs and SF_6 from the same bottles sampled for key carbon system parameters (DIC, alkalinity, pCO_2 and pH) and other tracers. We were successful in reaching our sampling goals.

Data collected on this cruise are available and archived at:
http://whpo.ucsd.edu/data_access/show_cruise?ExpoCode=33RR20090320

The estimated precisions for the CFC-11 and CFC-12 seawater analyses are shown in the following tables. These fully meet international quality standards for these measurements.

Table 2. Summary of number of CFC-11 samples taken and the estimated precision for the CLIVAR A13.5 cruise

	CFC-11
Number of samples	3509
Number of replicates	350
Average standard deviation	0.003 pmol kg^{-1} (or 1.0%), whichever is greater

Table 3. Summary of number of CFC-12 samples taken and the estimated precision for the CLIVAR A13.5 cruise

	CFC-12
Number of samples	3509
Number of replicates	350
Average standard deviation	0.003 pmol kg^{-1} (or 1%), whichever is greater

Table 4. Summary of number of SF_6 samples taken and the estimated precision for the CLIVAR A13.5 cruise

	SF_6
Number of samples	3509
Number of replicates	350
Average standard deviation	0.02 fmol kg^{-1} (or 2.0%), whichever is greater

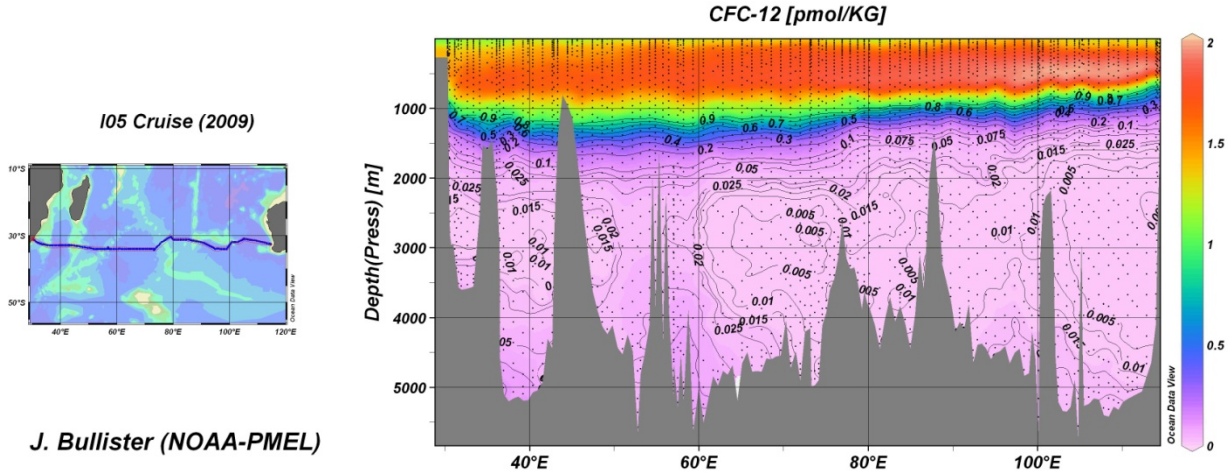

Figure 6. A section of CFC-12 concentrations along I5 in 2009. Dots indicate locations where samples were collected.

CFC concentrations are highest in the upper 1000 meters of the water column along the entire I5 section, indicating the potential of this region to rapidly take up atmospheric gases (including CO_2) on decadal time scales. CFC concentrations in the water column general decrease in the depth range from about 1000-2000 meters, reflecting the relative isolation of deeper waters from recent exchange with the atmosphere. In 2009 there were detectible levels of CFC-12 throughout the deep and abyssal waters along the section, with near-bottom maxima at about 40°E, 60°E and 100°E. These near-bottom maxima reflect the western boundary intensified northward transport of abyssal waters and indicate where surface-derived climate signals (eg. anthropogenic CO_2 and excess heat) can be carried into the deep ocean on decadal-to-century time scales.

In 2009, the PMEL CFC Tracer Group also prepared high precision gas standards containing trace levels of CFCs, SF_6 and other important gases. These standards will be distributed to US and international groups involved in ocean tracer studies, ensuring a consistent, long term global data set of value to the research community.

3.4 Nutrients (Mordy and Zhang)

The primary tasks of the nutrient group were to assist in the collection of nutrient data on the I5 and I7 (cancelled) repeat hydrographic lines in the Indian Ocean, to make preparations for the A13.5 repeat hydrographic section in the Atlantic Ocean, and contribute to GOSHIP manual and the development of Japanese reference material.

We have participated in an international effort to develop the reference material for nutrients in seawater led by Meteorological Research Institute of Japan and its collaborators in Japanese industry. Samples for stability test of nutrient reference material have been analyzed in 2009 and the results have been reported to the project coordinator in Japan. We also worked with international nutrient community and contributed to the updating the standard operating procedure for shipboard nutrient analysis in the GOSHIP manual.

Preparations for A13.5 included re-building much of the autoanalyzer (new glass coils and tubing, new debubblers), and preparing and shipping reagents. Additional preparations and shipping of the autoanalyzer will be carried out in FY10.

On the I5 repeat hydrography cruise, Peter Proctor assisted the Ocean Data Facility at the Scripps Institution of Oceanography (SIO-ODF) in the collection and analysis of dissolved inorganic nutrients (silicic acid, phosphate, nitrate and nitrite) on board the research vessel Roger Revelle. In all, 7726 samples were analyzed for nutrients with 6710 samples drawn from hydrographic casts and 1016 drawn from trace metal casts. Analysis was completed on a Technicon AutoAnalyer II using the standard analysis protocols for the WOCE hydrographic program as set forth in the manual by Gordon et al. (1994). Duplicates from 24 stations were drawn and analyzed on a Technicon AA3 system.

The cruise started with new pump tubes and then they were changed five times during the cruise (after Stations 025, 068, 099, 141 and 180, respectively). Ten Beer's Law calibration checks were run throughout the cruise. Six sets of Primary/Secondary standards were made up over the course of the cruise. Primary and secondary standards were compared to the "old" standards before they were used to insure continuity between standards. The cadmium column efficiency was checked periodically. Initially column efficiencies were 93%, however, after replacing with a new cadmium column, efficiencies were 100% for the remainder of the cruise.

Several problems were encountered on the cruise. The pump for the silicate channel was changed out after station 028 due to mechanical problems that caused it to stop pumping periodically. The nitrite detector was changed out after station 077 which improved the stability of the baseline. The standard cal was adjusted for nitrate after station 010, and all Beer's Law checks run after this could only be used for smoothing the final nitrate data. Two of the ten Beer's Law check runs were not acceptable and thus not used in the nutrient calculations. Small phosphate variations were observed in the deep water; however, these variations were close to or at the limits of the methods for both sample collection and sample analysis. The temperature of the laboratory used for the analyses ranged from 23.0°C to 24.5°C. During nutrient analysis of Station 141 cast 1, the air-conditioning unit was switched off, and the lab temperature increased. This caused a drift in nitrate values at the end of the analysis. However, a correction was applied to the nitrate raw data, and it was reprocessed and is acceptable.

As standard ODF practice, a deep calibration check sample was run with each set of samples, and the deviations in the check samples are as follows:

Parameter	Concentration
NO3	30.5 µM ± 0.3
PO4	2.17 µM ± 0.02
SIL	71.6 µM ± 0.7
NO2	0.01 µM ± 0.01

Figure 7 shows vertical sections of nutrients. Deep water concentrations of nitrate and phosphate were relatively consistent along the zonal I5 transect, except for the strong minimum centered at

~2800 m in the southwest Indian Ocean. Deep water silicic acid concentrations generally increased to the east. Figure 8 is a comparison of 2009 I5 results with historical data in the southeastern Indian Ocean (similar results were observed to the west). There was no apparent decadal change in deep concentrations of nitrate, silicic acid or oxygen (oxygen is not shown); however, there was an offset of ~0.04 µmol/kg in phosphate. This was attributed to errors in phosphate standardization or blanks (true variability would be proportionally expressed in phosphate, nitrate and oxygen).

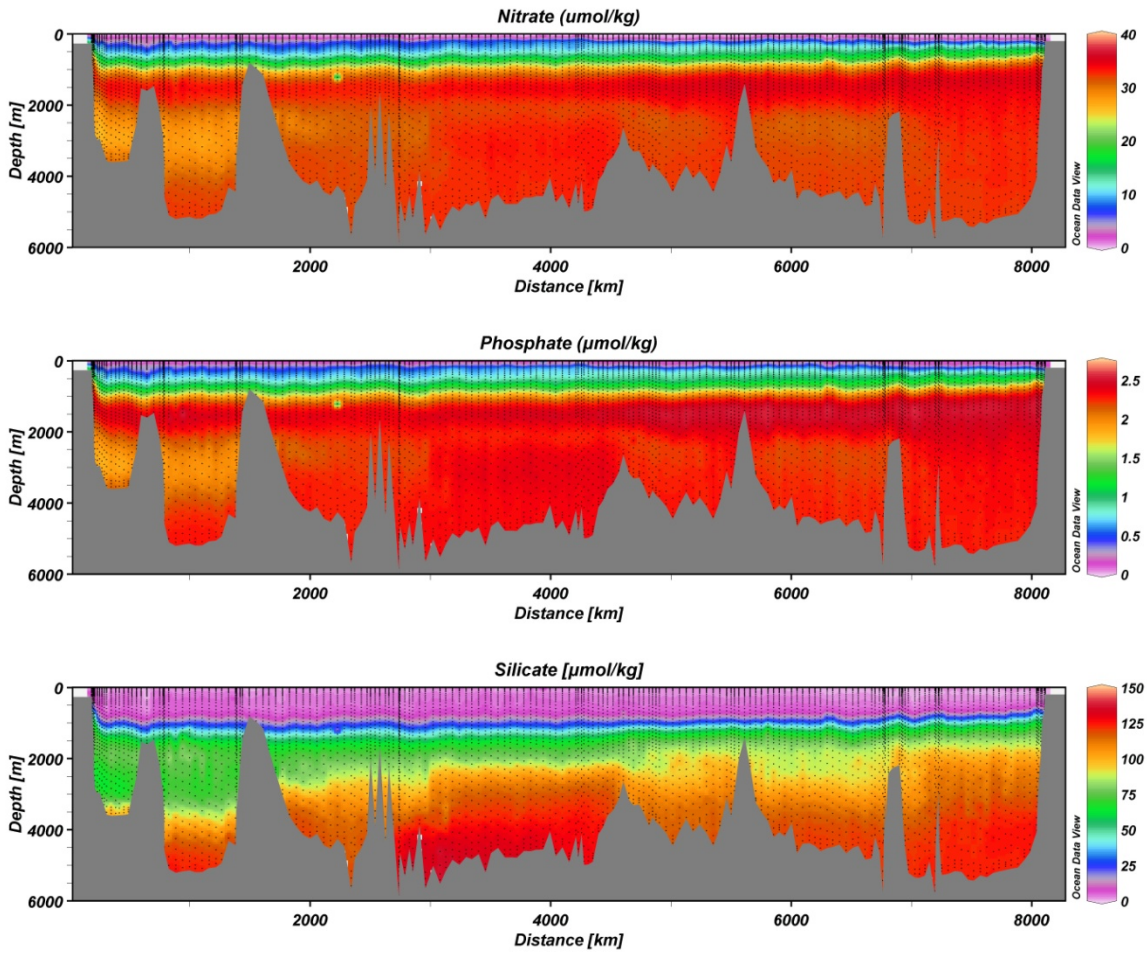

Figure 7. Sections of nitrate, phosphate and silicic acid along the I5 cruise track.

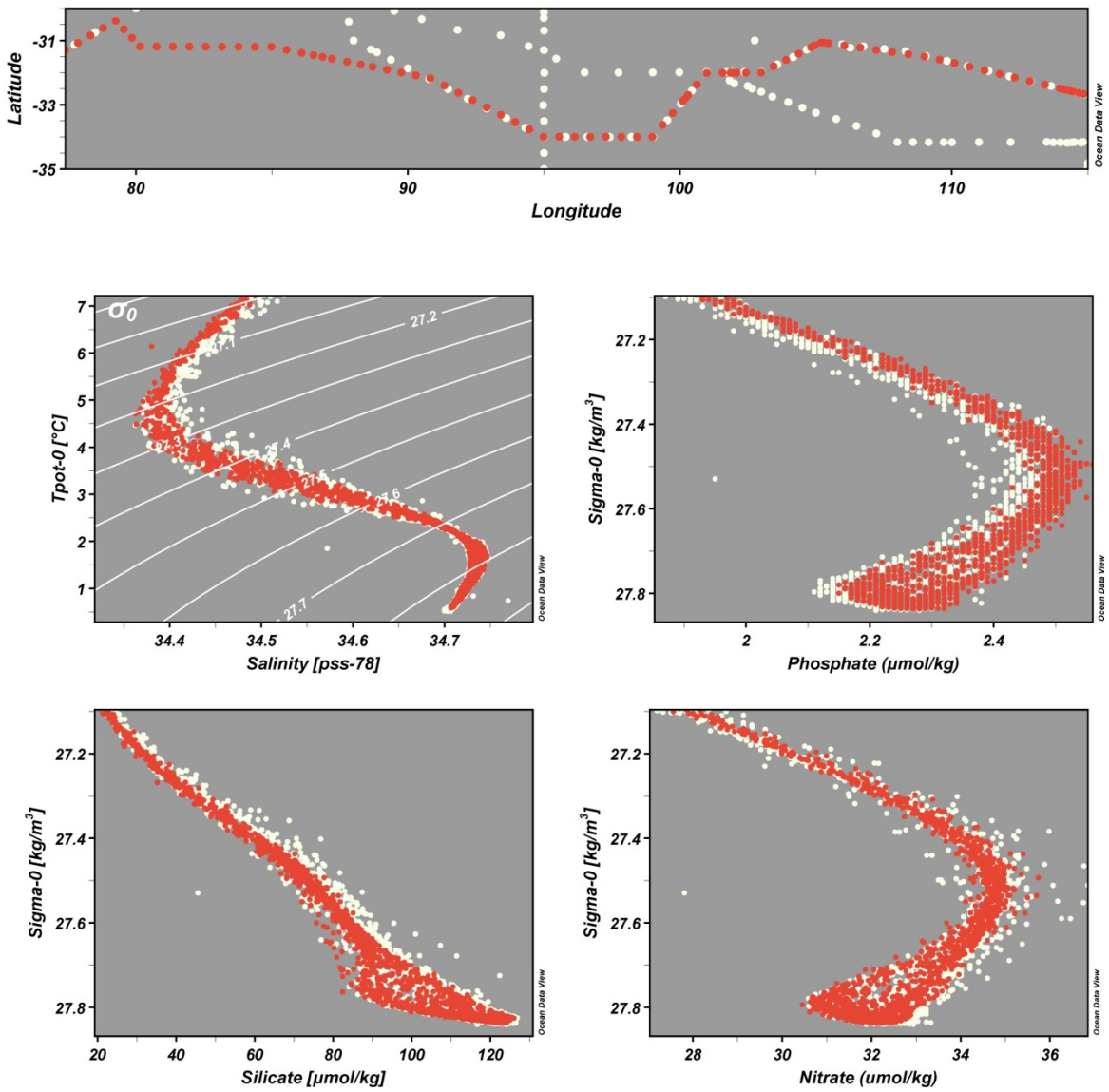

Figure 8. TS plot and vertical profiles of nitrate, phosphate and silicic acid in the southeastern Indian Ocean. 2009 I5 data are in red and historical data (1987, 1994, 1995) are in white.

3.5 Discrete Oxygen (Baringer and Langdon)

The FY09 funding request provided for the participation of F. Featherstone in the I5 cruise in March-May of 2009. In addition to cruise time and travel. Purchase of a back-up O_2 titrator was begun, but had been substantially delayed and will not be built in time for the A13.5 cruise. G. Berberian and U. Rivero maintained the O_2 titration equipment and prepared standards and reagents for the A13.5 cruise. C. Langdon oversees the O_2 group at AOML including training, operations and managements, post-cruise data reduction and quality control.

4. Education and Outreach

G. Johnson worked on research projects with three of the four student CTD watchstanders during the 2009 reoccupation of WOCE Section I05. S. Purkey (U. of Washington) and he worked on a global synthesis of deep temperature changes and their contributions to heat and sea level budgets that includes the I05 data. K. Kearney (Princeton) and he used data from all four modern occupations of I05 in a discussion of the role of climate-change amplified ocean mixing in attenuating ocean climate change signatures (Johnson and Kearney, 2009). C. Whalen (UCSD/SIO) and he investigated climate-related temperature and salinity variations that could be used to diagnose changes in the hydrological cycle with data from the same four I05 reoccupations. All of these efforts furthered science education, and at least two of them should result in refereed publications.

A graduate student from the Scripps Institution of Oceanography (UCSD) participated on the I5 expedition as part of the CFC team and was involved on all aspects of the CFC tracer program. J. Bullister participated in the 2009 NOAA Summer Science Camp at PMEL and as part of this worked with middle-school students on environmental science experiments.

5. Publications and Reports

5.1. Publications by Principal Investigators

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