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

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1. Project Summary

The Repeat Hydrography CO_2/Tracer Program (Global Ocean Ship-Based Hydrographic Investigations Program, GO-SHIP) 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. 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 the thermohaline overturning, can also be documented using long-term observations throughout the water column. Below the 2000-m depth of Argo, Repeat Hydrography provides the only global measurements for observing long-term trends in the ocean (Figure 1). The calibrated CTD data will be critical for validation of Deep-Argo temperature and salinity. The program also provides deployment opportunities and 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. 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 existing and new autonomous sensors. data products are posted on the CLIVAR and Carbon Hydrographic Data Office (http://cchdo.ucsd.edu/) and the Carbon dioxide Information Analysis Center (http://cdiac.ornl.gov/oceans/), and the results are used for research publications, atlases, and outreach materials. The synthesis products are used by scientists to develop and validate models of ocean circulation changes as well as the uptake of carbon dioxide and other anthropogenic trace gases. They are also used to access and validate models of future impacts to ocean biological ecosystems resulting from acidification, stratification, and circulation changes.

The program is co-sponsored by NOAA and the National Science Foundation and 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 of the Program Plan for Building a Sustained Observing Network for Climate. The sequence and timing for the sections (Figure 1) takes into consideration the program objectives, providing global coverage, and anticipated resources. Also considered is the timing of national and international research programs, such as CLIVAR; the SOLAS Program that emphasizes constraining the carbon uptake in the surface oceans, in part, in support of the North American Carbon Program (NACP); and the international Integrated Marine Biogeochemistry and Ecosystem Research (IMBER) program. In addition, the recently occupied and proposed sections are selected so that there is roughly a decade between them and the previous surveys.

Emphasis during FY 2014 was on the north-to-south section in the S. Atlantic Ocean (A16S) and a south-to-north section in the S. Pacific Ocean (P16S) both which were occupied in 2005.

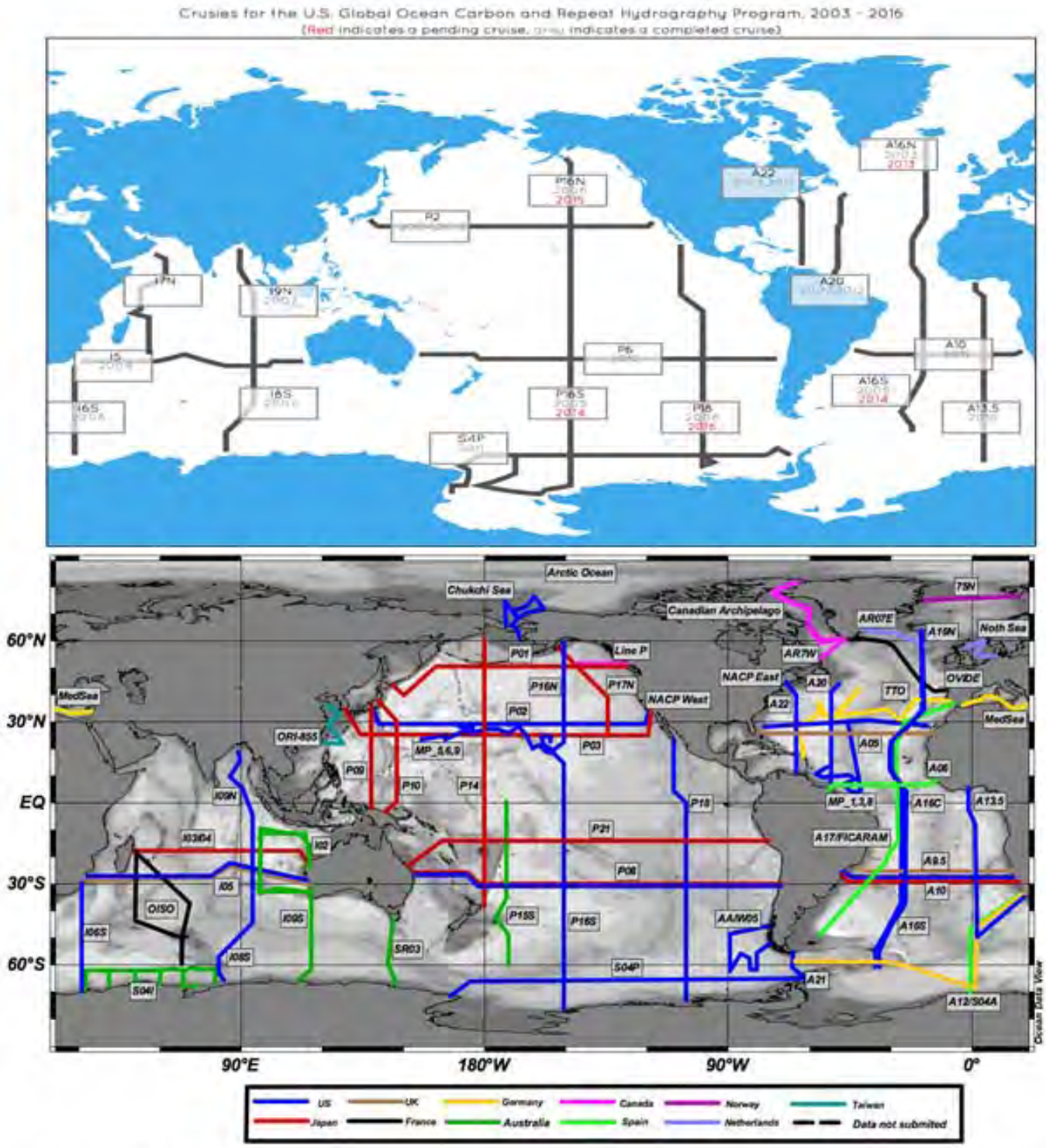

Figure 1. *Global map of U.S (Top) and international (Bottom) CLIVAR/CO_2/Tracer Repeat Hydrography Program (GO-SHIP) hydrographic sections with carbon system measurements.*

2. Scientific and Observing System Accomplishments

2.1 A16N 2013 Cruise Summary (Bullister, Baringer and Johnson)

The Boreal summer/fall 2013 reoccupation of WOCE Section A16N (A16N_2013) took place from 3 August - 3 October 2013 on NOAA Ship *Ronald H. Brown*. The chief scientists for leg 1 were Molly Baringer with Denis Volkov as co-chief, and for leg 2 John Bullister, with co-chief Rolf Sonnerup. This meridional section spans the North Atlantic Ocean from Iceland to 6ºS, along latitudes ranging from 20–29ºW (see Fig. 1). A total of 145 full-depth CTD/O_2/LADCP/rosette casts were completed along the A16N section, with approximately 3400 discrete seawater samples collected. The 2013 cruise repeated the A16N section occupied in 2003 on RHB as part of the CLIVAR Repeat Hydrography program as well as earlier A16N sections occupied in 1993 and 1988 as part of the OACES and WOCE programs. About 50 scientists from 7 countries (USA, Canada, United Kingdom, Norway, Spain, Germany and Russia) participated on the 2 legs of the A16N_2013 expedition. The scientific party included a significant number of graduate students and post-docs supported by NSF. The cruise was designed to provide full-depth oceanographic stations along the section at 30' latitude intervals poleward of 3º latitude, and 20' intervals equatorward of that latitude of continuous profiles of temperature, salinity, oxygen and velocity and discrete depth profiles of a host of carbon, nutrient and trace gas parameters at 24 depths for each station. This cruise, one of the first of the second global survey for repeat hydrography, was described in the FY2013 progress report. During FY2014 the data from this NOAA-led cruise were finalized and made public on the CCHDO and CDIAC web sites. In addition, replacements were bought or built for much of the equipment lost at sea during A16N when the ship's hydrographic cable parted owing to corrosion.

2.2 A16S 2014 Cruise Summary (Wanninkhof, Baringer and Johnson)

The Austral summer 2013/2014 revisit of WOCE Section A16S on the NOAA Ship *Ronald H. Brown* began on 23 December 2013, with a departure from Recife, Brazil, after a two-day delay to wait for the arrival of two drums of conducting cable for the CTD winch. This NOAA-led cruise successfully completed its objectives under the leadership of chief scientist Rik Wanninkhof with assistance from co-chief Leticia Barbero, and ended on 5 February 2014 in Punta Arenas, Chile.

The A16S meridional section samples the S. Atlantic Ocean from 6ºS to 60ºS, along longitudes ranging from 25 to 36ºW. When combined with A16N, summarized above, A16S spans the Atlantic Ocean from Iceland to the southern edge of the Scotia Sea. The 2014 revisit of A16S is a repeat of the section previously occupied by the U.S. in 1989 and 2005.

A total of 113 full-depth CTD/O_2/LADCP/rosette casts were completed along the A16S section at 30 nautical mile (nm) (54 km) spacing, with closer spacing at the basin boundaries near South Georgia Island. Measurements taken from the instrument package include temperature, salinity, oxygen, currents (LADCP), micro-turbulence structure (Chipod), particles (transmissometer), and colored dissolved organic matter, CDOM (fluorometry). Approximately 2700 Bullister bottle samples were collected on these casts and analyzed for a variety of parameters including salinity,

dissolved oxygen, nutrients, chlorofluorocarbons (CFCs), SF_6, N_2O, dissolved inorganic carbon (DIC), alkalinity, pCO_2, pH, carbon isotopes (^{14}C DIC), dissolved organic carbon (DOC), $^{18}O/^{16}O$, helium, tritium, density, and trace metals.

As described in the FY14 workplan, the AOML CTD group's main objectives for 2014 were to provide bottle salinities, engineering expertise and technical assistance for CTD operations for the A16S cruise. Due to loss of the AOML CTD frame near the end of the A16N cruise, there was considerable adjustments and accommodations facilitated to ensure quality data collection. As a result of using back-up equipment there were more problems with sampling bottles including mistrips and leaking than usual. AOML technicians facilitated the fabrication of frames, struts and brackets to accommodate the new instruments placed on the CTD frame including the Chip Pods, Fluorescence and Transmissometer measurements.

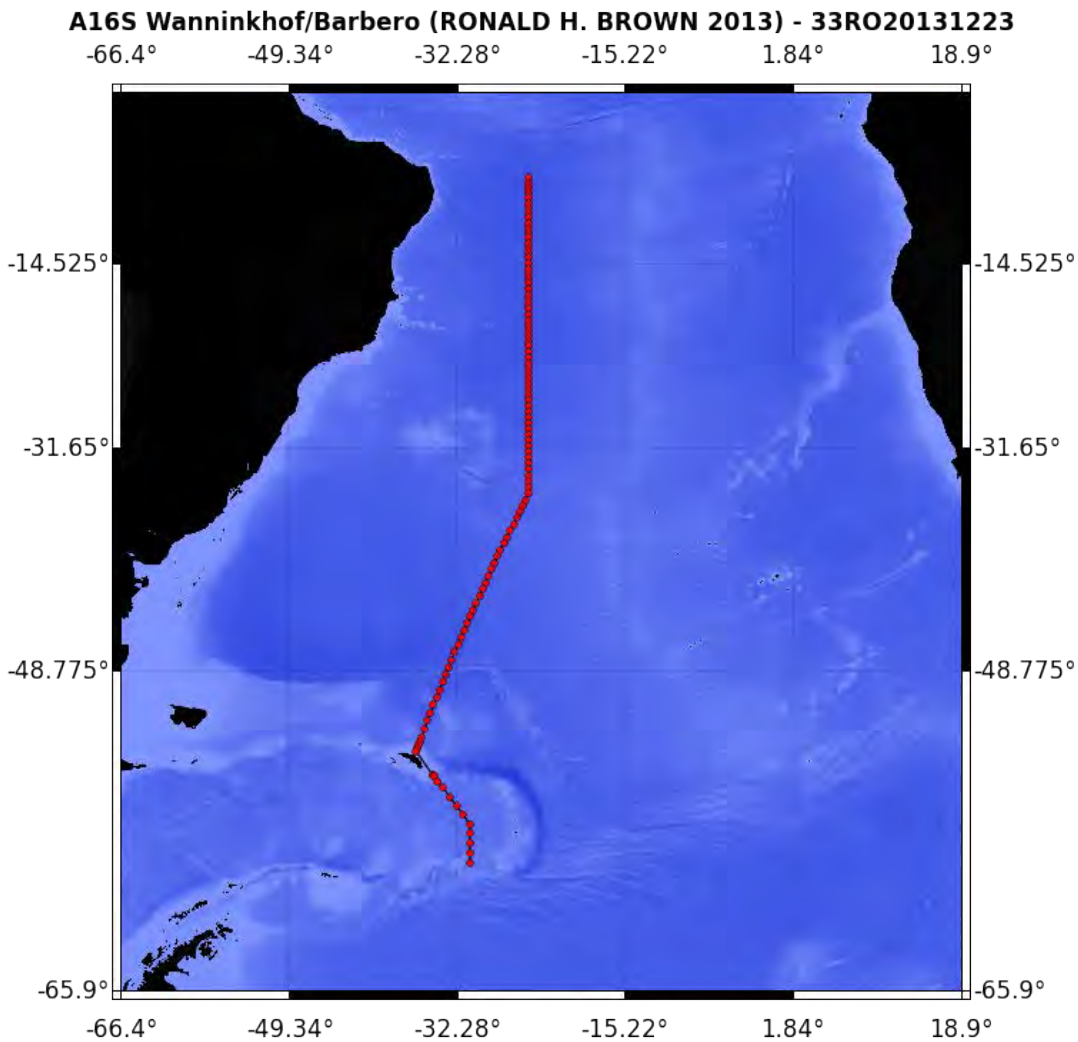

Figure 2. *Station location map of the 2013/2014 A16S cruise on the NOAA Ship Ronald H. Brown, which began on 23 December 2013 from Recife, Brazil and ended on 5 February 2014 in Punta Arenas, Chile.*

Underway data collection included upper-ocean current measurements from the shipboard ADCP, surface oceanographic (proxi-chlorophyll by fluorometry, temperature, salinity, CO_2) and meteorological parameters from the ship's scientific seawater supply, bathymetric data and atmospheric measurements of CO_2, CFCs, and SF_6.

Data from this cruise are available from CCHDO at:
http://cchdo.ucsd.edu/data_access/show_cruise?ExpoCode=33RO20131223

2.3 A16N and A16S Science Description and Results

Scientific accomplishments of the first global decadal repeat hydrographic survey are many and of significant import, as outlined by Feely et al. (2014). As that report notes: "Observations from this program have been critical to the following climate-related results: The abyssal ocean is warming, taking up to 30% of the excess heat in the entire Earth system. Ocean ventilation and circulation are variable and changing over timescales from several years to decades. Anthropogenic carbon uptake has been mapped and its impact on global carbon budgets quantified. The oceans are acidifying. Oxygen concentrations are declining in the thermocline, and tropical oxygen minimum zones are expanding." A description of the accomplishments during FY14 are outlined below.

2.3.1 CTD Group Science Results (Johnson and Baringer)

The repeat hydrography data are revealing global-scale changes in the ocean that are useful for evaluating climate model performance, as well as analyzing and closing budgets for sea level, heat, and freshwater. With the second revisit of the repeat hydrographic survey beginning, revisits of regional changes are possible. Temperature trends from 1989–2014 (Figure 3) show surface-intensified warming within the thermocline (remember that the near-surface ocean mixed-layer is very sensitive to seasonal aliasing). However, these data also reveal full-depth warming during that time-period in the Scotia Sea, as well as warming in the deep Argentine and Brazil basins. These high-latitude and deep changes in ocean temperature indicate changes in the global thermohaline circulation and are important in global energy budgets as well as seasonal sea level budgets.

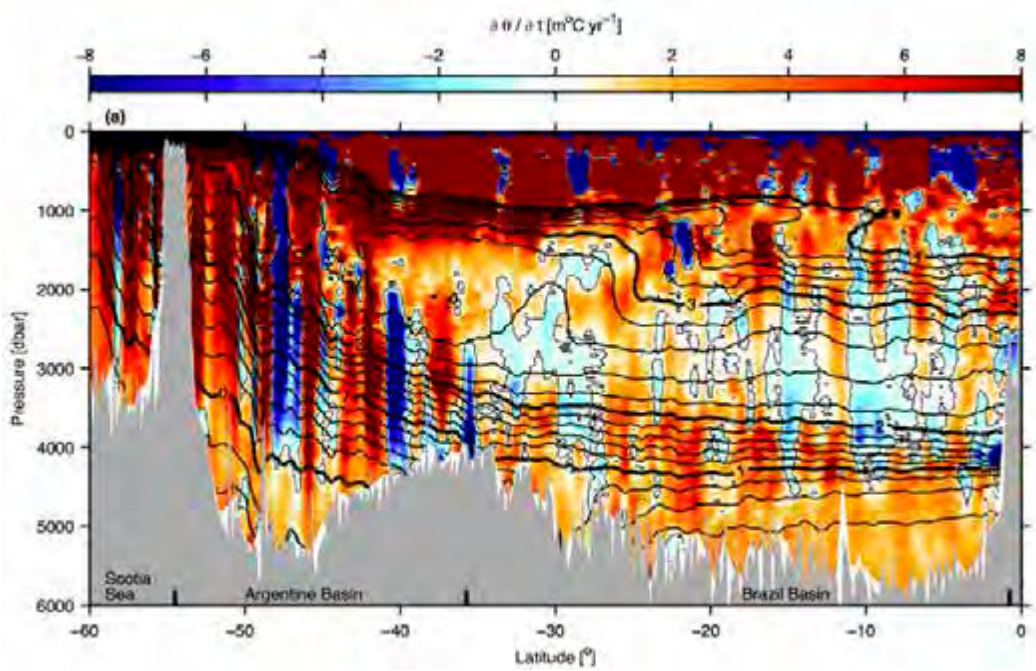

Figure 3. *Potential temperature trend ($\partial\theta/\partial t$) in m°C yr^{-1} (top colorbar) versus latitude and pressure for WOCE section A16S occupations in 1989, 2005, and 2014 with isotherms for the mean of all three sections (black lines) contoured at 0.2 °C intervals (thick black lines at 1 °C intervals, labeled) for water colder than 4 °C. Bathymetry is shaded gray. Basin names are given and boundaries denoted by thick black vertical lines at the bottoms of the sections. Figure adapted from Johnson, McTaggart, and Wanninkhof (2014, J. Geophys, Res., submitted).*

Analyses published in FY2014 using repeat hydrography data include reports on 2013 ocean heat content (Johnson et al., 2014a) and sea-surface salinity (Johnson et al., 2014b) for the annual *State of the Climate* report published as a supplement to the Bulletin of the American Meteorological Society (BAMS) that are discussed in the heat and freshwater analysis annual progress report, an analysis of long-term ocean heat content changes and ocean sampling (Lyman and Johnson, 2014), and an analysis of decadal time-scale trends in the California Undercurrent (Meinvielle and Johnson, 2013).

COD provided extra funds in FY-14 for much needed upgrades of seagoing instrumentation. This equipment refresh allowed for the purchase of two CTD rosette frames that can serve all the needs of the evolving program and provide the most accurate possible water sample and profile data. A CTD rosette frame is used on the Repeat Hydrography sections to collect all profile samples of level 1, level 2 and level 3 measurements. Frames must be able to accommodate both the large size of these instruments while also maintaining clean flow for the sensors and Niskin bottles. The Niskin bottles are required for all drawn and analyzed water samples. Over time, the Niskin bottles can become chipped and cracked, causing the o-rings not to seat properly, resulting in a leaking sample bottle. Leaking bottles compromise sample integrity. AOML revised the designs and built two complete frames in FY2014. Working with PMEL, AOML drafted plans for new Niskin bottles and end-caps oversaw the fabrication of 60 Niskin bottles. This much needed equipment refresh will provide the Repeat Hydrography program with two complete CTD rosette systems that should meet the needs of the program for the next decade.

2.3.2 AOML CO_2 Group (Wanninkhof)

As described in the FY14 workplan, the AOML CO_2 group had four objectives and four milestones. Each was completed successfully.

2.3.2.1 Lead logistics for A16S cruise in FY14

We lead the logistics and shipping for the groups from Miami participating in the A16S cruise in FY14 (Brazil to Chile). The groups include those of: Baringer, CTD; Zhang, nutrients; Langdon, O_2 and Millero, TAlk & pH. Preparations included interfacing with the repeat hydrography oversight group, planning ship track, negotiating ship time, writing the cruise instructions, processing medical and foreign national clearance, and obtaining country clearance. A web site was set up with details of the cruise for participants and interested parties: http://www.aoml.noaa.gov/ocd/gcc/A16S_2014/. This involved efforts from Betty Huss, and Esa Peltola. Furthermore there was appreciable instrument refurbishment, testing, and calibration that involved efforts of Sullivan, Barbero and Peltola. The associated milestone was fulfilled by the due date listed below

2.3.2.2 Lead DIC and discrete pCO_2 analyses in the A16S cruise

Robert Castle served as the lead DIC analyst on the A16S cruise and was assisted by Julie Arrington supported by the PMEL CO2 group. Castle oversaw the operation of the underway pCO_2 system. The chief scientists of the A16S cruise, Rik Wanninkhof, and Leticia Barbero (covered by the NSF scientific party funds distributed to SIO) operated the discrete pCO_2 analyzer. The cruise entailed 45 days of sea time.

The milestone and deliverables were completed ahead of the deadline. Approximately 2600 DIC samples and 800 discrete pCO_2 samples were analyzed. The cruise track, a contour plot of pCO_2 discrete analyzed at 20 ˚C $pCO_2(20)$, and a plot of DIC for A16S are provided below.

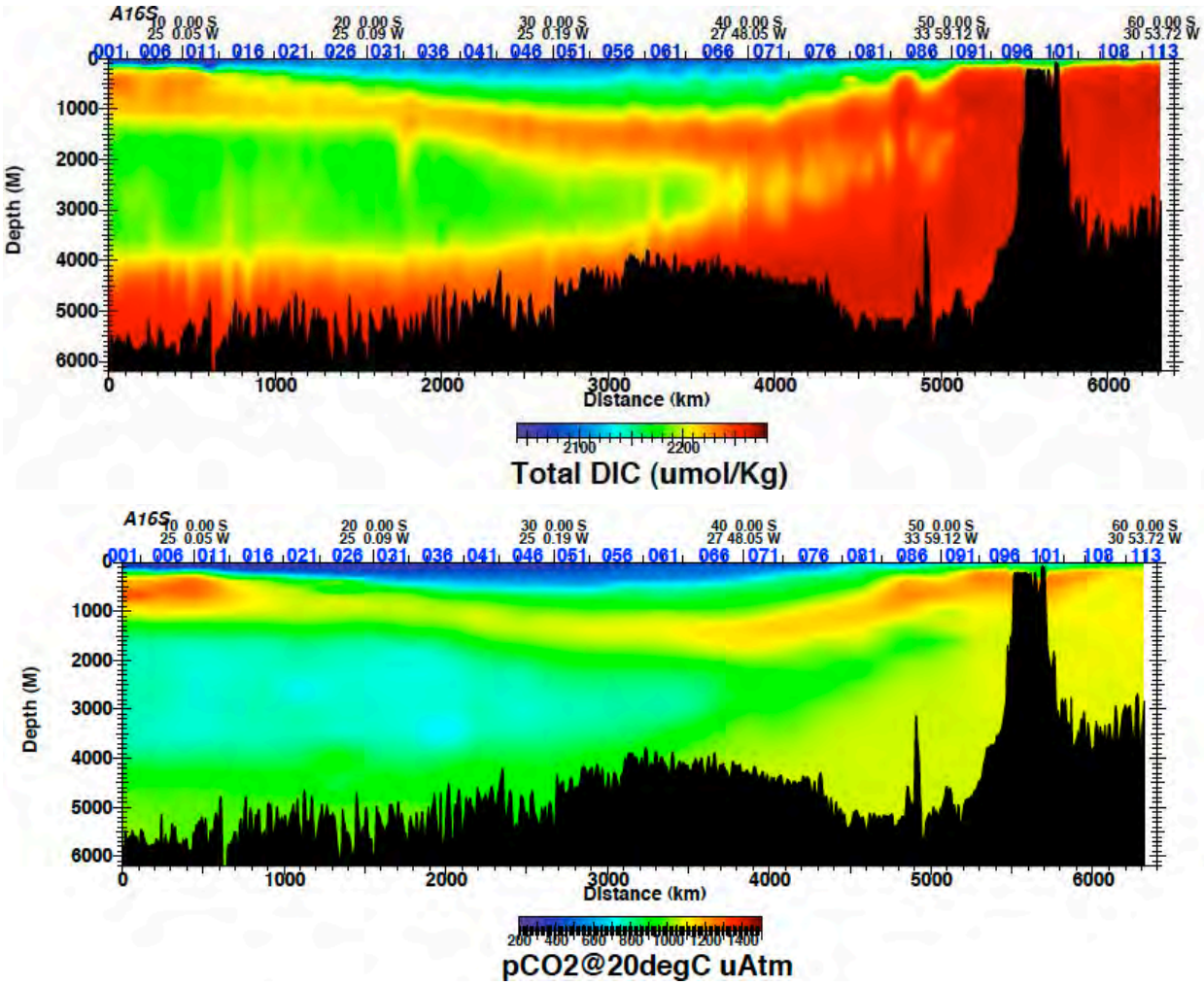

Figure 4. *Cruise track with station numbers, top; cross section of DIC, middle; and cross section of $pCO_2(20)$, bottom. The cross sections have station location and latitude listed on top and distance from first station on bottom with the south to the right. From the A16S cruise report (Wanninkhof et al. 2014b).*

The patterns of DIC and $pCO_2(20)$ are similar with high DIC and $pCO_2(20)$ in water masses of Antarctic origins to the South. Further north, the North Atlantic Deep waters with lower pCO_2 (20) and DIC enter in the middle of the water column enveloped by Antarctic intermediate waters in the 1000 to 2000 m range and Antarctic Bottom waters below 6000 m. The differences in magnitudes between $pCO_2(20)$ and DIC trends are largely due impacts of alkalinity with areas of high alkalinity decreasing the $pCO_2(20)$ relative to DIC.

Underway pCO_2 data were collected and reduced and provided at: http://www.aoml.noaa.gov/ocd/gcc/rvbrown_data2013.php. The highest values are in the subtropical gyre (20-30 ˚S) due to seasonal warming while the lowest values are almost 100 µatm less in the polar waters due to the teaming biological productivity, providing food and leading to an abundance of characteristic mega fauna such as whales and penguins.

2.3.2.3 Complete data reduction of DIC and discrete pCO_2 for A16N

Data reduction and contextual quality control of DIC for the A16N cruise of FY13 were completed during FY14 by Robert Castle, Chuck Featherstone and Kevin Sullivan. Data and meta-data were submitted to CDIAC and CCHDO. A combined cross-section for the A16N and A16S cruise is provided below along with the difference in the DIC concentration between this cruise and the cruise occupied in 2003/2005.

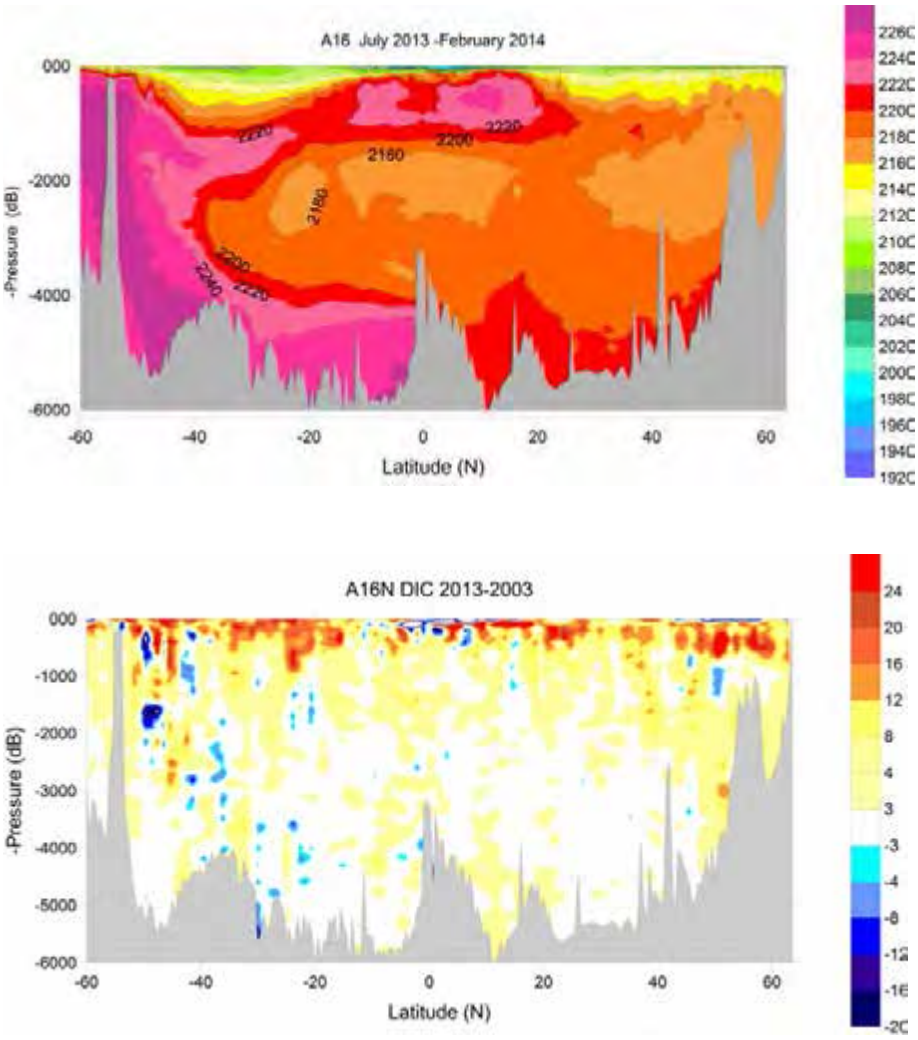

Figure 5. *Top: Cross-section of DIC combining the A16N and A16S cruises of 2013 and 2014 with South to the left. The large-scale impact of the Meridional Overturning Circulation (MOC), that is a key research component of NOAA's Climate Observations Division, on DIC is clearly apparent. Bottom: Changes in DIC over 10-years. The invasion of anthropogenic CO_2 over the last decade is clearly apparent in the upper water column. Variability and changes in DIC at depth are caused by changes in ocean circulation and biological processes that impact the carbon cycle in the ocean.*

2.3.2.4 Finalize data reduction of underway pCO_2 for 16N and A16S

The data reduction and quality control of underway data for the A16N and A16S cruises of FY13 and FY14 were completed by Robert Castle and provided to CDIAC as part of the A16 level-1 measurement suite. Data and metadata were also provided to the SOCAT and Takahashi/LDEO global pCO_2 database efforts. Milestones and deliverables as provided in the FY-14 workplan are listed in the Table below. They address the overall goal of the program to acquire quality surface and subsurface physical, biogeochemical, and carbon data to decrease the uncertainty in global ocean anthropogenic CO_2 inventories.

Table 1. Milestones provided in the FY-14 workplan. All milestones were delivered at or prior to due date (see footnotes)

Milestones	Deliverable	Date
Logistics for A16S cruise	Cruise Instructions [1]	December, 2013
Data reduction UWpCO_2 A16S &A16N	Data and metadata on web[2]	September, 2014
Data reduction DIC A16N	Submission to CDIAC[3]	September 2014
Completion A16S cruise	Cruise report[4]	May 2014

[1] http://www.aoml.noaa.gov/ocd/gcc/A16S_2014/Cruise_Instructions_RB-13-07.pdf
[2] http://www.aoml.noaa.gov/ocd/gcc/rvbrown_data2013.php
[3] http://cdiac.ornl.gov/oceans/RepeatSections/clivar_a16n.html
[4] http://cchdo.ucsd.edu/cruise/33RO20131223

2.3.3 Dissolved Oxygen Measurements (Langdon)

2.3.3.1 Scientific justification for O_2 bottle measurements

Measurement of dissolved oxygen is a core parameter in the program for two reasons. First, physical oceanographers use oxygen as a tracer of water movement in the ocean. They primarily rely on an oxygen sensor to profile the oxygen concentration at each station along the cruise line. However, this sensor offers good but not great stability over the duration of the cruise. The discrete oxygen analyses performed by the Langdon group are used to calibrate the oxygen sensor for each of the 100-130 stations on a typical cruise. These data allow the physical oceanographers to resolve very tiny changes in oxygen from place to place. The second usage of the dissolved oxygen data (along with nutrient data) is to assess the fraction of total dissolved inorganic carbon change is due to natural biological process (primary production and respiration) and how much is due to the uptake of anthropogenic CO_2 (Sabine et al. 2008).

2.3.3.2 Oxygen measurements on A16N and A16S

Measurement of dissolved oxygen is a core parameter in the program for two reasons. First, physical oceanographers use oxygen as a tracer of water movement in the ocean. They primarily rely on an oxygen sensor to profile the oxygen concentration at each station along the cruise line. However, this sensor offers good but not great stability over the duration of the cruise. The discrete oxygen analyses performed by the Langdon group are used to calibrate the oxygen sensor for each of the 100-130 stations on a typical cruise. These data allow the physical

oceanographers to resolve very tiny changes in oxygen from place to place. The second usage of the dissolved oxygen data (along with nutrient data) is to assess the fraction of total dissolved inorganic carbon change is due to natural biological process (primary production and respiration) and how much is due to the uptake of anthropogenic CO_2 (Sabine et al. 2008).

During the A16N cruise, C. Langdon and L. Stoltenberg performed dissolved oxygen (DO) measurements that are tier 1 core measurements in the GO-SHIP CLIVAR/CO_2 repeat hydrography effort. A total of 2753 samples were taken and > 96 % were considered "good" after initial on board quality control. 290 duplicate pairs of samples were taken to assess precision. The average standard deviation of the duplicates was 0.17 µmol kg^{-1}.

During the A16S cruise, L. Stoltenberg and A. Stefanic performed a total of 2866 samples were taken and > 94 % were considered "good" after initial on board quality control. 225 duplicate pairs of samples were taken to assess precision. The average standard deviation of the duplicates was 0.19 µmol kg^{-1}. Shipboard oxygen data are presented in Fig. 6 Further detail can be found in the GO-SHIP CLIVAR A16S cruise report (Wanninkhof et al. 2014b): http://cchdo.ucsd.edu/cruise/33RO20131223

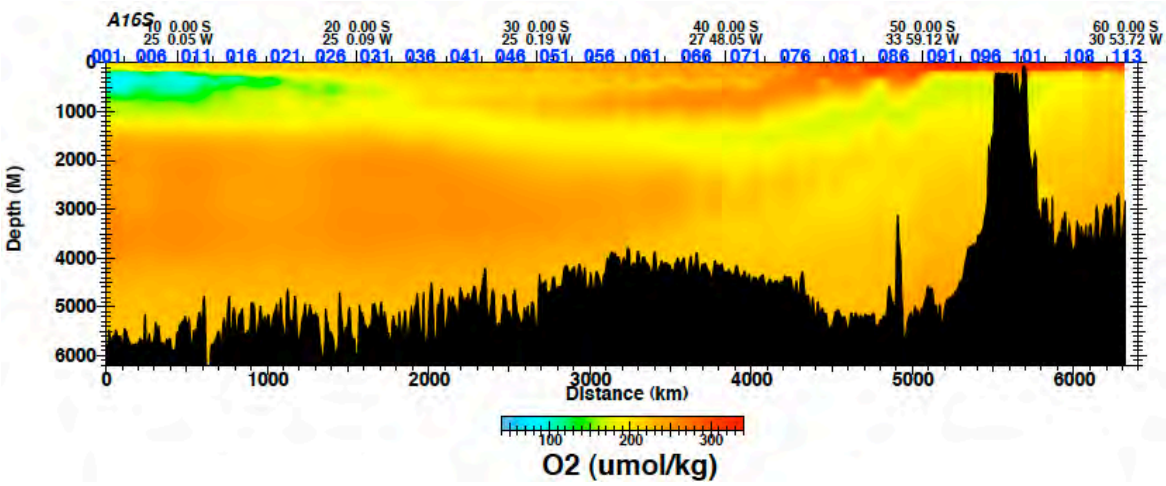

Figure 6. *Vertical section of O_2 measurements on A16S. Station location and latitude are listed on top and distance from first station on bottom with the south to the right. From the A16S cruise report (Wanninkhof et al. 2014b).*

The final A16N data are shown in the form of difference section that shows oxygen concentrations have increased or decreased since the previous occupation of the A16N line in 2003. The red regions of oxygen increase between 50˚N and 60˚N may be the result of fronts that had shifted position since 2003 or the passage of eddies that are abundant in this region. Below the zone where oxygen appears to have decreased is a layer centered at 1000 m depth where oxygen has increased by 10–30 µmol kg^{-1} over the last eleven years, possibly due to increase of ventilation of these waters over the same period. These features are an indication of the large effect climate variability and change have on biogeochemistry and carbon cycling. Similar decreases have been observed in the North Pacific (Mecking et al. 2008; Sabine et al. 2008) and may signal a decrease in the rate of ventilation of the intermediate depth zone due to

changes in wind speed in the region where the water of this density outcrops at the surface (~64˚N).

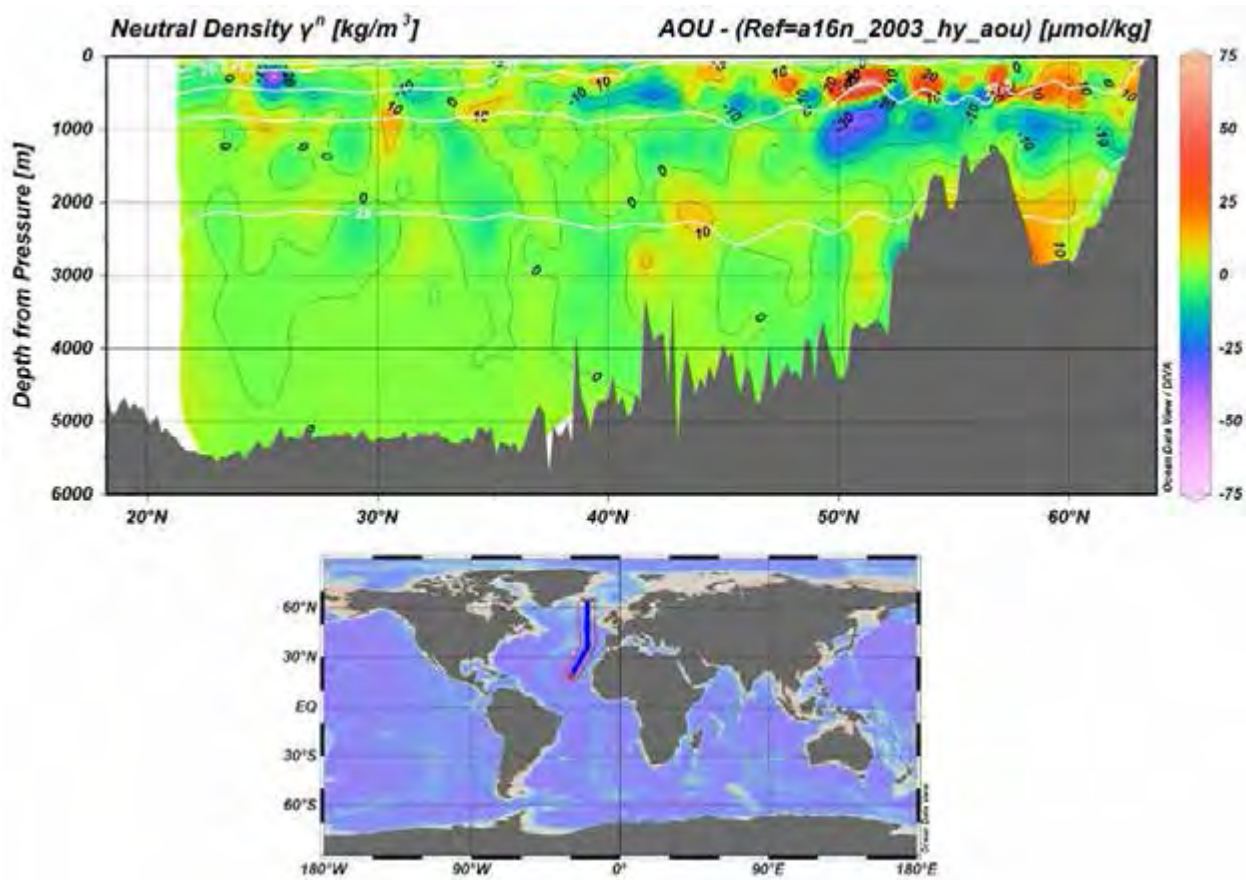

Figure 7. *Vertical section of the change in apparent oxygen utilization along the A16N line between 2003 and 2013 (top). The cruise track is shown in the bottom panel.*

2.3.4 Dissolved CFC and SF_6 Measurements (Bullister)

2.3.4.1 Scientific justification for CFC and SF_6 bottle measurements

These compounds are entirely anthropogenic, have well characterized input histories and are conservative in seawater. Extraordinarily sensitive analytical techniques are now available for the analyses of these compounds, with current detection limits: CFC-12=0.002 pmol kg^{-1}, SF_6=0.00002 pmol kg^{-1} (1 pmol=1 picomole=10^{-12} mole). These compounds dissolve in the surface ocean and measurements of the concentrations and ratios of these compounds can be used to provide useful age and rate information for a variety of ocean processes,

The primary scientific goals of the CFC and SF_6 tracer measurement program on Repeat Hydrography cruises are:

1) To determine the rates and pathways of ocean circulation and mixing processes

2) To estimate water mass formation rates (and determine long-term changes in these rates)
3) To estimate the rates of key biogeochemical processes in the ocean
4) To improve estimates of the rates of uptake and storage of anthropogenic CO_2 and other important trace gases in the ocean
5) To provide a unique way to test numerical ocean model simulations, evaluate strengths and weaknesses in the models, and suggest ways to improve the models

The decadal-scale tracer data sets collected as part of the Repeat Hydrography Program provide a unique way to monitor the rates of a variety of ocean processes and are critical in understanding how physical and biogeochemical processes the global ocean may change in the upcoming decades.

2.3.4.2 CFC and SF_6 measurements on A16N and A16S

The lead CFC analyst on both the A16N and A16S cruises was D. Wisegarver (PMEL). On both the A16N and A16S cruises, 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. The quality of the data is excellent and fully meets international 'WOCE' quality standards for these measurements. Samples for the analysis of dissolved CFC-11, CFC-12 and SF_6 were drawn from ~2610 of the 3420 water samples collected during the A16N expedition. About 500 replicate samples were analyzed for dissolved CFC-11, CFC-12 and SF_6 on the cruise.
On the A16S cruise, samples for the analysis of dissolved CFC-11, CFC-12 and SF_6 were drawn from 1054 of the 2600 water samples collected during the expedition. About 225 replicate samples were analyzed for dissolved CFC-11, CFC-12 and SF_6 on the cruise.

On the two expedition, based on the analysis of more than 700 pairs of duplicate samples, we estimate precisions (1 standard deviation) of about 1% or 0.002 pmol kg^{-1} (whichever is greater) for dissolved CFC-12, and 1% or 0.005 for CFC-11 measurements. The estimated precision for SF_6 was 2% or 0.02 fmol kg^{-1}, (whichever is greater). Overall accuracy of the measurements (a function of the absolute accuracy of the calibration gases, volumetric calibrations of the sample gas loops and purge chamber, errors in fits to the calibration curves and other factors) is estimated to be about 2% or 0.004 pmol kg^{-1} for CFC-11 and CFC-12 and 4% or 0.04 fmol kg^{-1} for SF_6.

Measurements of dissolved nitrous oxide (N_2O) were also made on the same samples analyzed for the CFCs and SF_6 on the A16N and A16S cruises. N_2O is an important greenhouse gas and plays a role in a variety of chemical processes in the atmosphere. Large-scale studies of dissolved N_2O in the ocean will improve understanding of the role of the compound in the nitrogen cycle in the ocean and of the ocean's contribution to the global N_2O budget.

CFC, SF_6 and N_2O data from the A16N and A16S cruises are available at:
http://cchdo.ucsd.edu/cruise/33RO20130803 and http://cchdo.ucsd.edu/cruise/33RO20131223

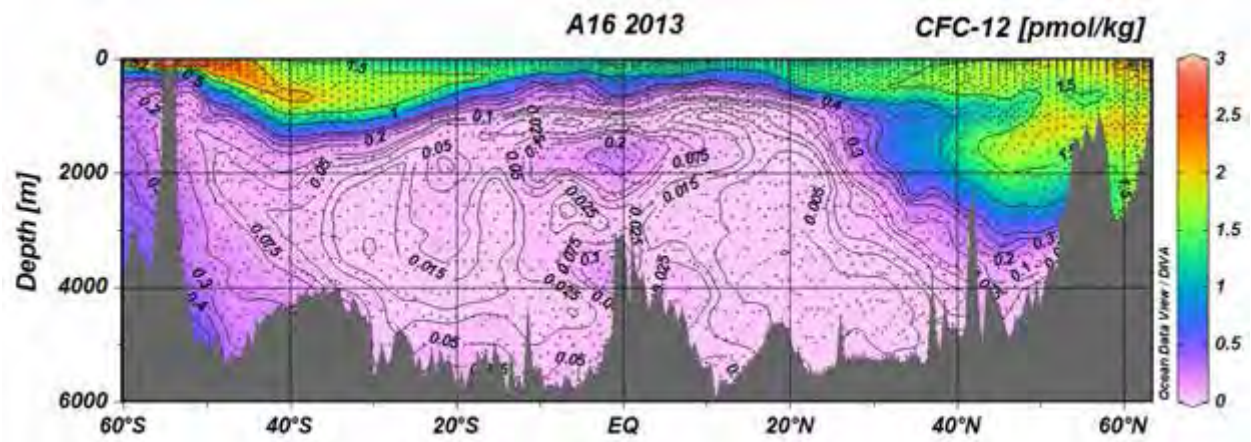

Figure 8. *CFC-12 concentrations along the A16 section. Dots indicate locations where individual water samples were collected and analyzed for CFCs, SF6 and N2O. These data highlight the complex ventilation pathways in the Atlantic. These extraordinarily sensitive measurements provide a tool to estimate the amount of anthropogenic CO_2 present in this region.*

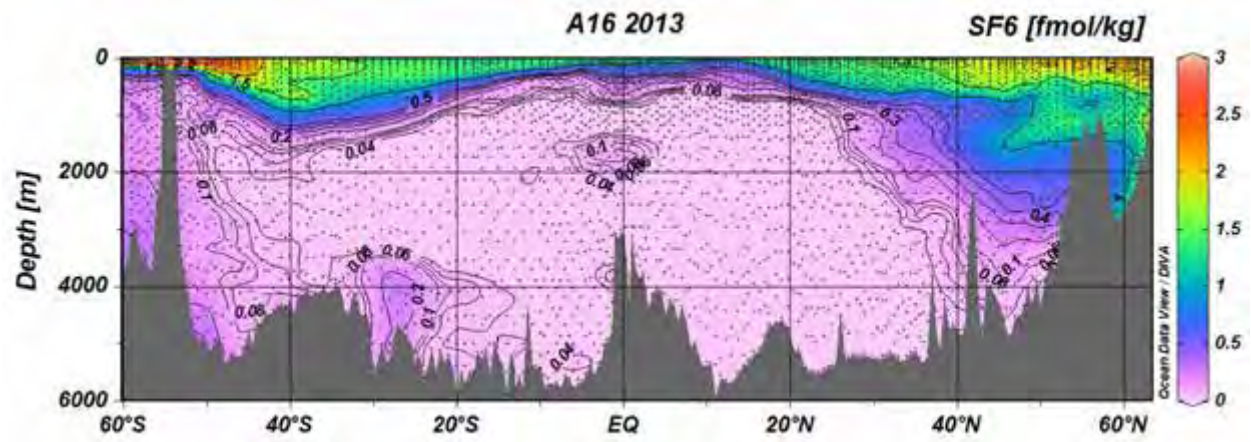

Figure 9. *SF_6 concentrations along the CLIVAR A16 section. SF_6 has a quasi-linear increase rate in the atmosphere and provides a unique tool to estimate anthropogenic CO_2 uptake during the past several decades.*

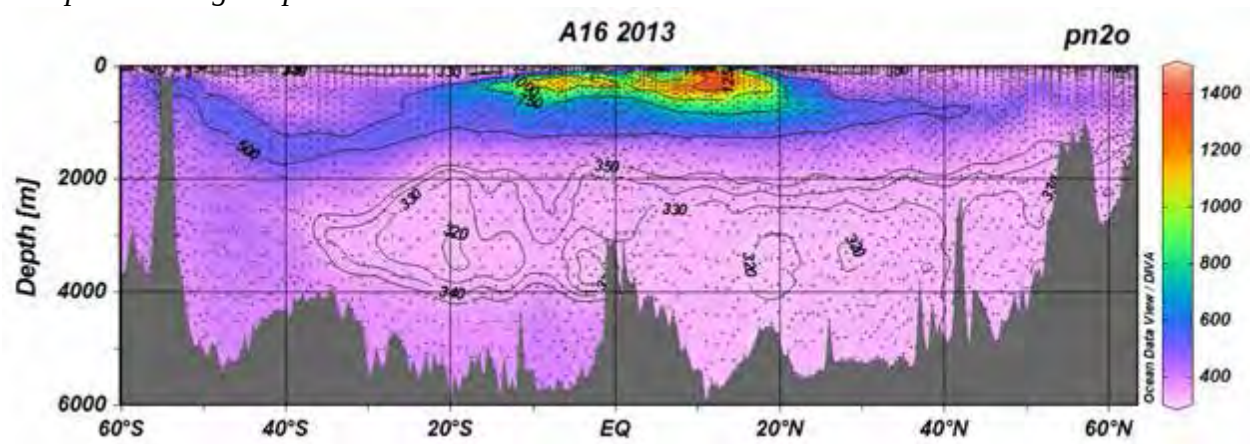

Figure 10. *Vertical distribution of the partial pressure (in parts-per-billion) of dissolved N_2O*

(pN2O) along the A16 section. The present atmospheric pN_2O is approximately 320 ppb. The strong sub-surface pN_2O maximum along the section indicates in-situ production of this gas and net loss of N_2O to the atmosphere by air-sea gas exchange.

The PMEL tracer group prepared and calibrated high-precision gas-phase reference standards in our laboratory and distributed these standards for US and international groups participating in global ocean observing programs including CLIVAR/GO-SHIP and SCOR. The accurate calibration of atmospheric and dissolved CFC and SF_6 measurements is essential for combining data sets collected by different groups and for determining long term changes in the global distributions of these compounds

Along with other NOAA groups involved in the Repeat Hydrography Program, the PMEL Tracer group received a supplement of $18,000 from CPO/COD in FY 2014 for the purchase of Gas Chromatographs which are essential for the measurement program. This will allow adequate backups of these instruments on future cruises.

2.3.5 Nutrients (Zhang and Mordy)

2.3.5.1 Nutrient Group Science Results

The primary task of the nutrient group during FY 2014 was to collect nutrient data on the A16S repeat hydrographic section in the Atlantic Ocean. On the A16S cruise, C. Fischer (AOML) and E. Wisegarver (PMEL) performed high precision shipboard analysis of phosphate, nitrate, nitrite and silicic acid on 3408 samples collected from the CTD rosette and trace metal casts at discrete depths. Nutrients were analyzed with a continuous flow analyzer (CFA) using standard protocols for the WOCE hydrographic program (Gordon et al., 1993) that were recently updated (GOSHIP Manual, Hydes et al., 2010) including calibration of labware, preparation of primary and secondary standards, and corrections for blanks and refractive index. Standard concentrations were validated against commercial standards from OSIL (http://www.osil.co.uk/). In addition, reference standards prepared by the Meteorological Institute of Japan were analyzed daily. Final data processing and quality control has been completed, and the data has been submitted to the CLIVAR & Carbon Hydrographic Data Office (http://cchdo.ucsd.edu/).

The precision of nutrient analysis on A16S is shown in Table 3. The precision of all analytes meets international quality standards for these measurements.

Table 2. Precision of nutrient measurements on the A16S repeat hydrographic cruise determined from replicate analysis of deep-water samples (>10 μmol kg^{-1} nitrate).

	Phosphate	Silicic Acid	Nitrate
Total number of replicates	626	607	632
Standard deviation (μM)	0.005	0.18	0.06
Relative standard deviation	0.2%	0.4%	0.2%

Nutrient data from the A16N and A16S cruises have been combined, and are plotted as sections of nitrate, phosphate and silicic acid (Fig. 11). Biological uptake results in low nutrients in surface waters. Recently ventilated Labrador Sea water and Upper North Atlantic Deep Water have relatively lower nutrient content because of younger water masses. Antarctic Intermediate

Water is evident as a high nutrient tongue extending to 25ºN at approximately 1000 m depth. Antarctic Bottom water in South Atlantic has the highest nutrients content, and reaches the Mid-Atlantic Ridge around the equator. Concurrent measurements of physical parameters, nutrients, DIC, oxygen and CFC in the repeat hydrography program will be used to evaluate the change in oceanic heat, freshwater, carbon and nutrient contents over decadal time scales, providing valuable information on ocean circulation and biogeochemical processes in the Atlantic Ocean.

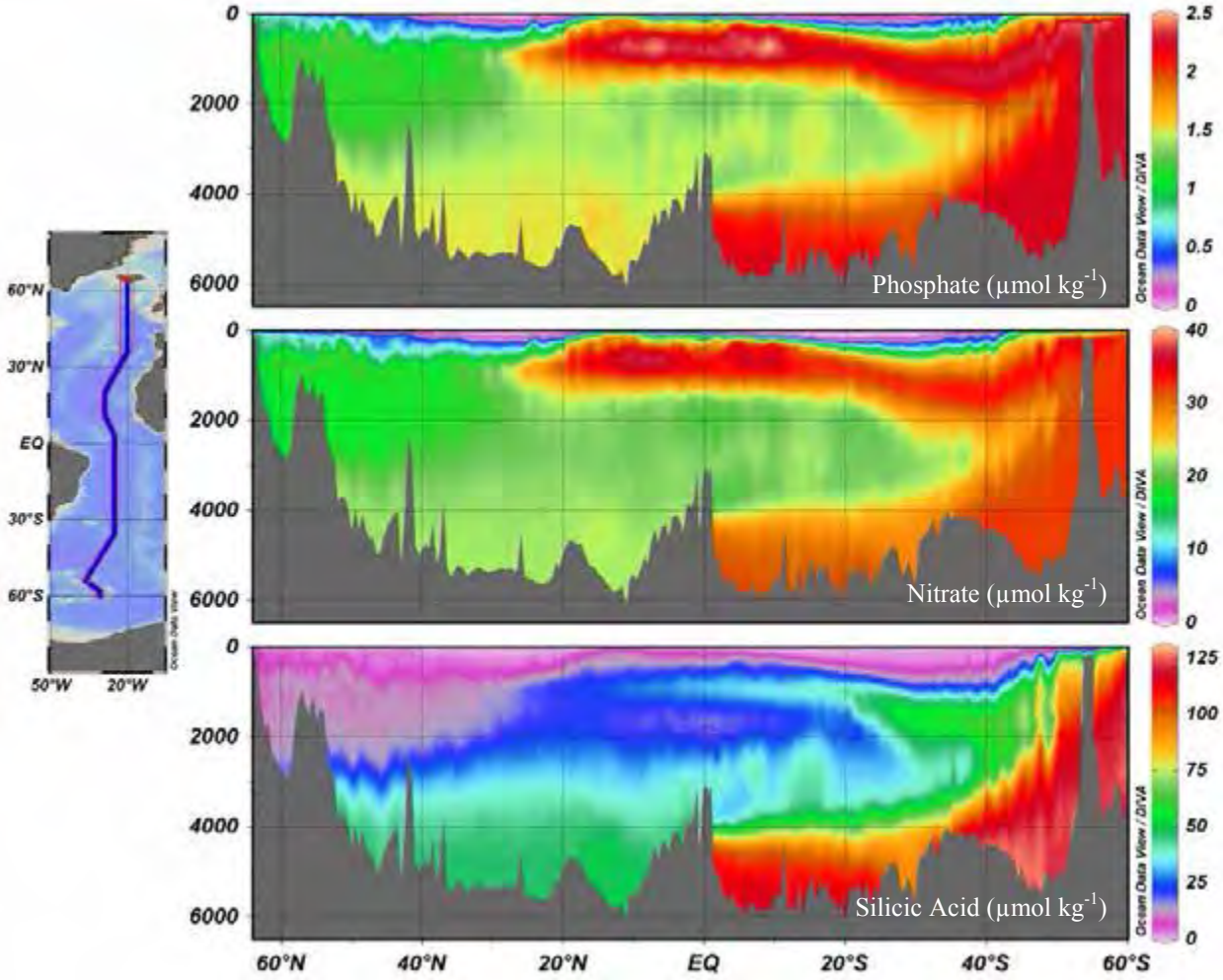

Figure 11. *Sections of phosphate (top), nitrate (middle) and silicic acid (bottom) along the A16 cruise track in Atlantic Ocean.*

2.3.5.2 Nutrient Group Instrument Supplement

The PMEL and AOML nutrient groups joined forces to purchase two autoanalyzers (one at PMEL and one at AOML) used for accurate high-precision nutrient analyses at sea. These are replacements for units that were purchased over 20-years ago, and refurbished over time. The bundled purchase offered an opportunity to negotiate a discount with the company (Seal Analytical), and to ensure that both instruments were re-configured for seawater analysis matching the design used at Scripps Institution of Oceanography, our partner in nutrient analysis within the US Repeat Hydrographic Program. Two new autoanlyzers have been purchased and installed at AOML and PMEL. These much needed upgrades will provide uniformity in the analytical systems used for nutrient analysis in the Repeat Hydrography program (eliminating one possible source of error), thereby increasing accuracy and precision of the measurement program for the next decade.

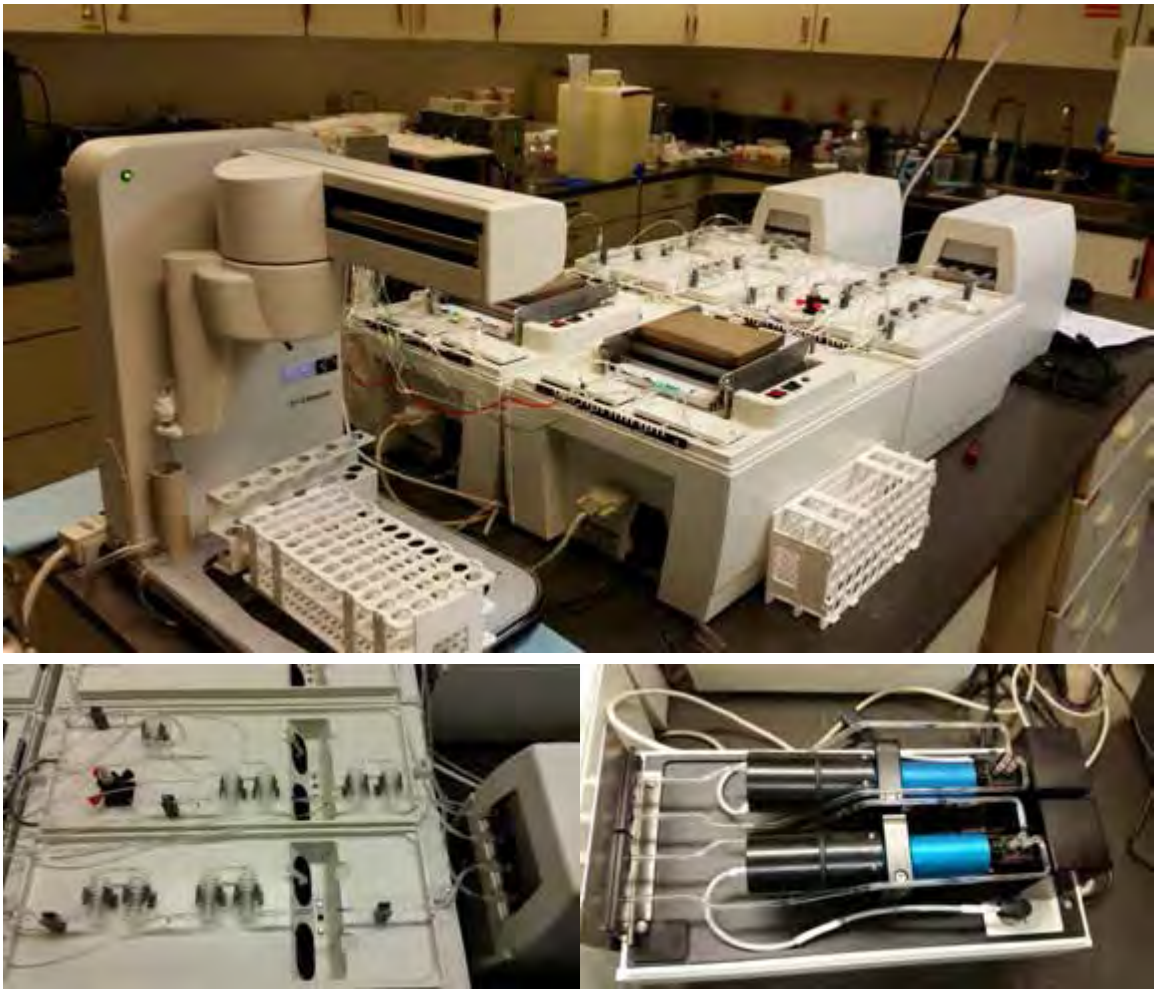

Figure 12. *Validation testing one of the new nutrient autoanalyzers at PMEL. In the foreground (top) is the 2-dimensional matrix multi-sampler for automated sample processing along with the chemistry manifolds (bottom-left) and the heart of a two-channel detector (bottom-right).*

2.4 P16S Cruise Summary (Feely)

The Austral summer 2014 revisit of WOCE Section P16S began on 20 March, 2014 from Hobart, Tasmania on the U.S. Antarctic Program's *Nathaniel B. Palmer* with the stations starting at 67°S, 150°W and ending in Tahiti on May 5, completing 90 stations with physical and chemical measurements from surface to bottom. The cruise involved sampling or deploying instruments for approximately 18 different principal investigators, from NSF funding, NOAA and NASA. The science party of 29 includes 9 grad students from all over the U.S. and the world. The stations occupied along 150°W were repeats of two earlier transects in 1991 as part of that decades' global observing program WOCE, and then again in 2005 as part of the international repeat hydrography program, now called GO-SHIP.

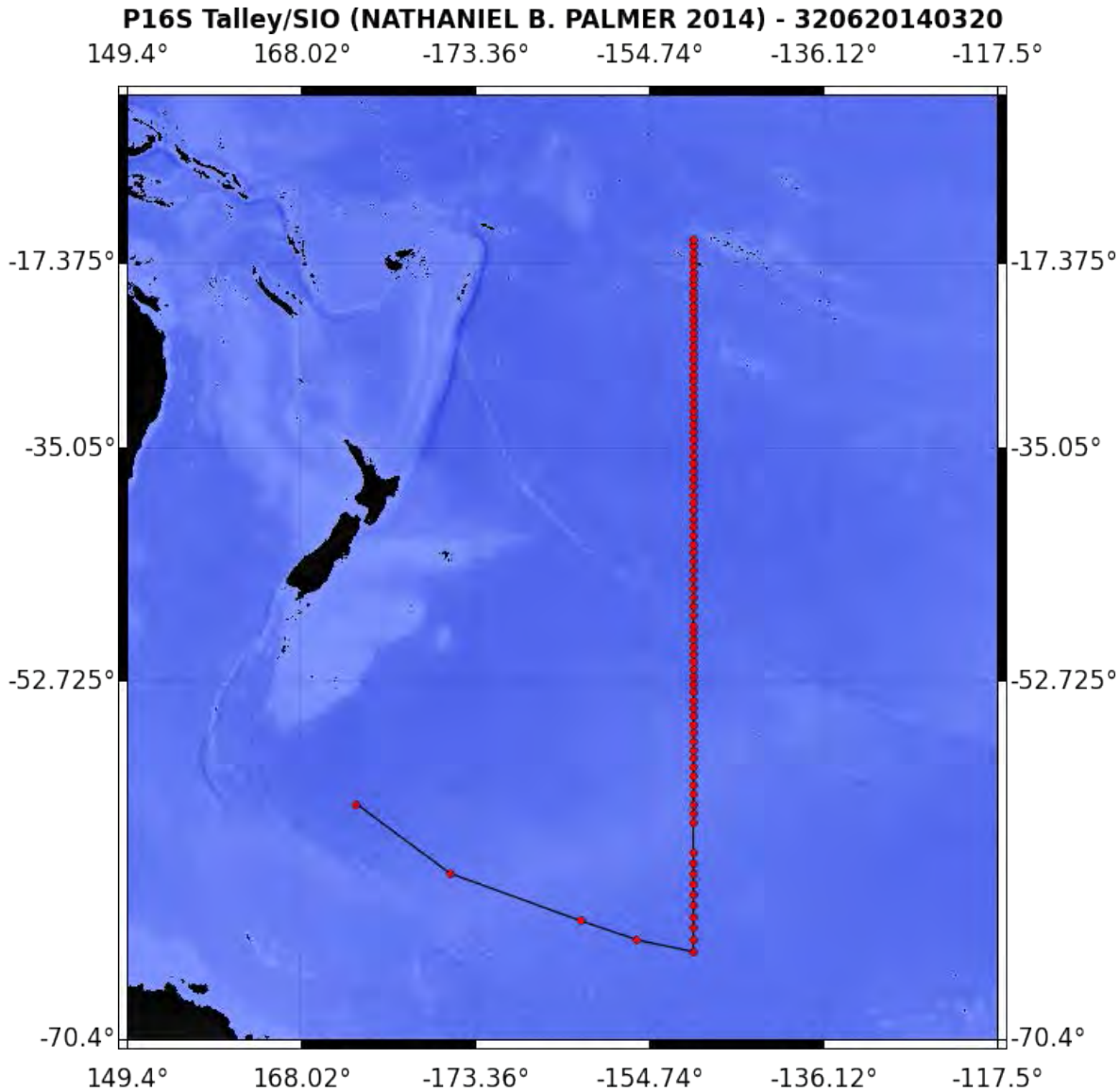

Figure 13. *Station location map of the 2014 P16S cruise on the U.S. Antarctic Program's Nathaniel B. Palmer, which began on 20 March and ended on 5 May.*

A total of 90 full-depth CTD/O_2/LADCP/rosette casts were completed along the P16S section at 30 nautical mile (nm) (54 km) spacing. Measurements taken from the instrument package include temperature, salinity, oxygen, currents (LADCP), particles (transmissometer), and colored dissolved organic matter, CDOM (fluorometry). Approximately 2775 Bullister bottle samples were collected on these casts and analyzed for a variety of parameters including salinity, dissolved oxygen, nutrients, chlorofluorocarbons (CFCs), SF_6, dissolved inorganic carbon (DIC), alkalinity, pCO_2, pH, carbon isotopes (^{14}C DIC), dissolved organic carbon (DOC), $^{18}O/^{16}O$, and helium/tritium. Further detail can be found in the cruise report, which can be found here: http://cchdo.ucsd.edu/cruise/320620140320

2.5 P16S Science Results (Feely)

2.5.1 DIC Measurements (Feely)

During the P16C cruise, D. Greeley of PMEL and C. Featherstone of AOML performed dissolved inorganic carbon (DIC) measurements that are tier 1 core measurements in the GO-SHIP CLIVAR/CO_2 repeat hydrography effort. A total of 2775 samples were taken and > 99 % were considered "good" after initial on board quality control. 265 duplicate pairs of samples were taken to assess precision (Table 3).

Table 3. Duplicate samples for DIC analyzed on the P16S cruise

Instrument[a]	Average difference (µmol kg^{-1})	Number of samples
DICE 1	0.44	130
DICE 2	0.45	135

The precision of the two DICE systems can be demonstrated via the replicate samples. Approximately 10% of the niskins sampled were duplicates taken as a check of our precision. These replicate samples were interspersed throughout the station analysis for quality assurance and integrity of the coulometer cell solutions. The average absolute difference from the mean of these replicates is 0.44 µmol/kg - No systematic differences between the replicates were observed. CRM batch certified value was 2036.96. System 1 averaged 2035.18 and system 2 averaged 2036.50.

The overall performance of the analytical equipment was very good during the cruise. Once the station spacing went to 40 NM we were able to sample every niskin made available to us. It was only at the end of the cruise, when the lab temperature rose significantly and cut down on the efficiency of our equipment, that we started to cut back on our coverage. At the very start of the cruise, pinch valve #7 failed on PMEL1 but was replaced immediately and without complications. The display for the UIC 5011 coulometer on PMEL1 froze on a few occasions but fortunately not during analysis of a water sample. Near the end, when the lab temperature went above 28°C, one of the water bath's temperature sensors failed and was replaced with a spare.

A section of the preliminary DIC data from P16S cruise is shown in Figure 14. The features show the strong interplay between ocean circulation and DIC distributions. Lower surface

values are caused by biological uptake and settling. High DIC values south of 55°S are caused by the formation and horizontal transport of Antarctic Intermediate Water (AAIW) and oxidation of organic matter. Once reduced, the 2014 data will be used to discern changes in anthropogenic uptake between 1992, 2005 and 2014.

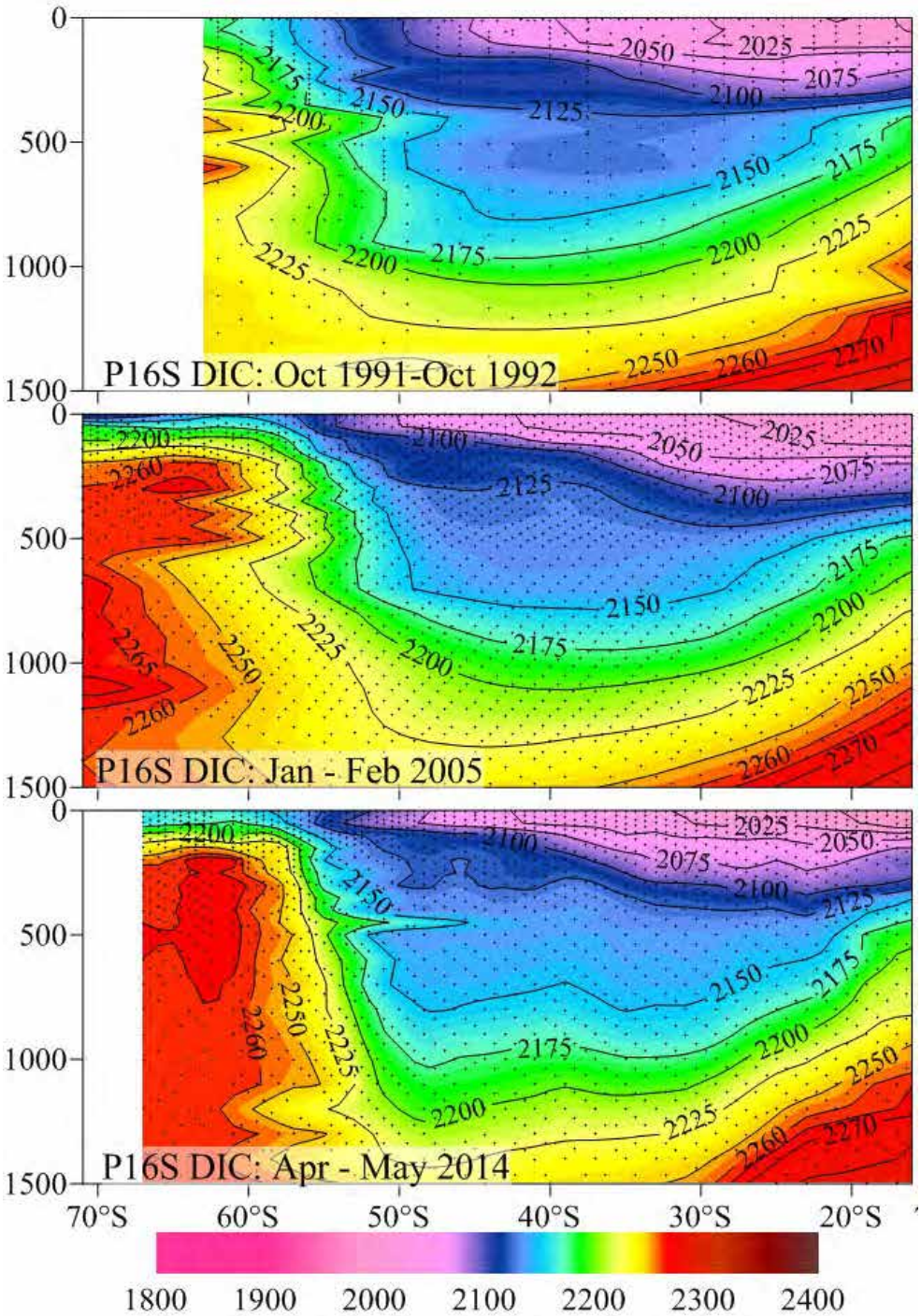

Figure 14. *Vertical sections of the top 1500 m data for DIC for the 1992, 2005 and 2014 occupations of P16S. The characteristic inorganic carbon fingerprints of the major water masses are apparent. The black dots are the sample locations.*

2.5.2 Instrument Supplement

Below is a picture of two of the four new coulometers for dissolved inorganic carbon analyses (DIC). They recently passed our tests for the accuracy requirements for the GO-SHIP repeat hydro efforts. The buying power of purchasing four units (two at PMEL and two at AOML) offered the opportunity to negotiate with the company (UIC) to improve the specifications of the units for greater accuracy and stability. We discussed our needs with the company president who visited AOML, and they made the modifications of improved electronics, form factor, and emulation mode. They loaned us test a unit before we committed to purchase. UIC will be offering these "souped up" units for sale to the ocean carbon community, providing a means to continue the DIC measurements to highest quality world-wide. The process benefited from close interactions and cooperation between the AOML and PMEL ocean carbon groups, and the PMEL purchasing department who processed the large order.

Figure 15. *Two new coulometers (displaying CM5011 Emulation) for dissolved inorganic carbon analyses (DIC) purchased for GO-SHIP Repeat Hydro work.*

2.6 Answers to questions involved with data collection

- *Are your data distributed in real time on the Global Telecommunications System?*
  Answer: No, data are provided in delayed mode due to need for post-cruise calibration and data reduction

- *Where do your real time data reside? Are the data available online?*
  Answer: There are no publically distributed real-time data

- *Where do your delayed mode data reside? Are the data available online?*
  All data are publically available following set time lines as described on the CCHDO website. Carbon data are also at CDIAC: http://cdiac.ornl.gov/
  All bottle data are at CCHDO: http://cchdo.ucsd.edu/

- *When did you make your most recent data publicly available?*
  Answer: A16N 2013, A16S 2014, and P16S 2014 data are at CCHDO and CDIAC (http://cdiac.ornl.gov/).
  A16 N: http://cchdo.ucsd.edu/cruise/33RO20130803
  A16 S: http://cchdo.ucsd.edu/cruise/33RO20131223
  P16S: http://cchdo.ucsd.edu/cruise/320620140320

- What is the significance of these advances?
  Answer. These data are assimilated into the global database, widely used within the oceanographic community, and provide initial/boundary conditions in biogeochemical and global climate models. The hydrographic, carbon, tracer, and nutrient component of the CLIVAR Repeat Hydrographic Program observing system directly addresses all of the objectives within NOAA's long-term goal: Climate Adaptation and Mitigation - An informed society anticipating and responding to climate and its impacts. Towards those objectives, these observations are a critical to (1) improve our understanding of the climate system, and the impacts of a changing climate on that system, (2) provide an assessment of the current state of the ocean, and modeling future states of the system; (3) provide reliable information to inform science and help guide policy decisions, (4) help educate the public, and identify it's vulnerabilities to a changing climate.

- What, if any, impediments were encountered and what information was jeopardized due to a lack of funding, lack of instrumentation, or inability to carry out the work?
  Answer. These measurements were carried out on instruments that were nearing the end of their lifetime. Supplemental funding was provided for new instrumentation.

- What is the website for your program?
  Answer: http://ushydro.ucsd.edu/
  http://www.aoml.noaa.gov/ocd/ocdweb/occ_goship.html
  http://www.pmel.noaa.gov/co2/story/Hydrographic+Cruises

- When did you make your most recent data publicly available? November 2014

- Where are your data archived and with what frequency?
  Answer: http://ushydro.ucsd.edu/ We follow GO-SHIP data submission protocols facilitating open and rapid data distribution to he community

  To ensure Stewardship and Preservation, all data and metadata is also stored on the core PMEL network. The PMEL system is a government-owned system managed by the Computing and Network Services Division (CNSD) at PMEL. The network does not have publically accessible servers, and is kept up-to-date with operating system patches

and anti-virus software, and adheres to all DOC, NOAA, and PMEL IT policies. In addition, data is submitted to the US Repeat Hydrographic web site as UCSD. http://ushydro.ucsd.edu/

- Have you successfully retrieved your program's data from the website or Data Assembly Center where your data reside to ensure the accessibility of the data?
  Answer: YES

- How are you tracking uptake and use of the data and products produced by your project? Some have found it helpful to establish a standard and recognizable name (e.g.. Argo, OceanSITES)?
  Answer: Tracking is performed by the parent groups: US Repeat Hydro, and GO-SHIP

- How do you direct users of your data to acknowledge its use?
  Answer: Through references to data at websites in publications

- Do web pages that provide data and products from COD support acknowledge CPO/COD support?
  Answer: Yes. Front page CCHDO data page: http://cchdo.ucsd.edu/ : "This site is funded by the National Science Foundation and the National Oceanic and Atmospheric Administration's Climate Observations Division."

- Please describe in a paragraph your activities to inform (e.g., through websites, articles in mass media) the wider community of your work.
  Answer: This is described in our education and outreach section.

3. Outreach and Education

Several principal investigators contributed to Working Group I to the Intergovernmental Panel on Climate Change Fifth Assessment Report (AR5). Johnson and Feely served as lead authors for Chapter 3: Observations: Oceans for Climate Change 2013: The Physical Science Basis, Contribution of Working Group I to the Intergovernmental Panel on Climate Change Fifth Assessment Report. Wanninkhof and Baringer served as contributing authors to Chapter 3. Furthermore, Wanninkhof and Feely served on the US government review team of IPCC AR5 Working group II Chapter 6 and 30.

In FY2014 Dr. Johnson advised Sarah Purkey, a University of Washington School of Oceanography graduate student who successfully defended her Ph.D. in Summer 2014. He is also advising incoming graduate student Paige Logan, who is working with Argo and Deep Argo data. He currently serves on the advisory committees for two other graduate students at the University of Washington and another one at the University of South Florida. In FY2014 he also advised an NRC Postdoctoral Research Fellow, Marion Meinvielle, and served as mentor to an undergraduate summer intern, Madeleine Youngs, a NOAA Hollings Scholar (look for the resulting scientific manuscript, characterizing equatorial deep jets in all three oceans using Argo and shipboard CTD data, in next year's progress report). Johnson presented a tutorial talk on ocean heat content and the IPCC report at the 2014 Ocean Sciences meeting that is available

online (http://www.oceansciencesmeeting.org/2014_resources#tutorials). Off-hours he gave an outreach talk on the IPCC for Earth Day at the Roosevelt Neighborhood Association (http://rooseveltseattle.org/2014/04/sustainability-earth-day-program-special-guest/). Work of his group on ocean heat and salt content was featured in a few other articles as follows:
Abraham, John (11 June 2014). Scientists in focus – Lyman and Johnson explore the rapidly warming oceans. *Climate Consensus - the 97%, hosted by The Guardian*.
2013 State of the Climate: Ocean heat content. *ClimateWatch Magazine*. 12 July 2014.
Shifting ocean surface saltiness from 2004-2013. *ClimateWatch Magazine*. 28 July 2014.
2013 State of the Climate: Ocean salinity. *ClimateWatch Magazine*. 12 July 2014.

Dr. Molly Baringer mentored a summer intern from the Mentoring Physical Oceanographers to Increase Retention (MPOWIR) program names Lindsay Roupe. Ms. Roupe is a masters degree student at Stoney Brook and completed a 10 week internship at AOML and is preparing a paper to submit for scientific publication. Dr. Baringer mentored a summer intern from the Marine &Science Technology Senior High (MAST) names Ryan Winslow. Ryan completed his 8-week internship with a written report and oral presentation of his results. Several outreach activites included providing tours of the AOML facilities including in August 2014 for RSMAS undergraduate students, in July 2014 a tour for congressional staffer. Dr. Baringer worked with G. Rawson for the creation of two project videos now hosted on the PHOD web site (one about the AOML Argo project and one about the Western Boundary Time Series project. Dr. Baringer joined Mentoring Physical Oceanography Women to Increase Retention (MPOWIR) executive team. The goal of the team is to apply for funding for NOAA to continue to support NOAA MPOWIR interns (June 2014).

Dr. Feely provides outreach presentations at the rate of approximately one per month on his carbon and climate research at local, local national and international meeting and symposia. He advises two graduate students, Nancy Williams and Andrea Fassbender (both from the University of Washington). Nancy Williams will complete her Master's thesis in December 2015. The title of her thesis is "Quantifying Anthropogenic Carbon Inventory Changes in the Pacific Sector of the Southern Ocean" which will be submitted for publication in Marine Chemistry. Dr. Feely also provides regular interviews to the press on his research.

Dr. John Bullister participated in the 2014 NOAA Summer Science Camp and worked with middle-school students on environmental science projects. About 8 graduate students participated on the A16N_2013 expedition as part of the science teams. The students were supervised by John Bullister and were involved on all aspects of the at-sea programs.

Dr.Wanninkhof acted as Chief Scientist of the A16S cruise. The joint NSF/NOAA repeat hydrography program has a strong outreach component sponsored largely by NSF. The co-chief scientist on the A16S cruise, Dr. Leticia Barbero was a CIMAS post-doctoral fellow who was trained and educated by the chief scientist in leading cruise efforts. This approach executed on many repeat hydrography cruises is in recognition that a new generation of scientists needs to be trained to take over this complex and multi-facetted responsibility in the future. Six graduate students and one undergraduate participated in A16S either as part of an analyses team (CFC, TAlk, pH) or as the chief scientist party.

Several of the other outreach activities associated with the cruise can be found on the comprehensive webpage developed to facilitate exchange and communication (see: http://www.aoml.noaa.gov/ocd/gcc/A16S_2014/). Weekly cruise updates were distributed to over 300 e-mail recipients and one "official" cruise blog (Rachel Shelley, U. Hawaii), along with several informal ones, kept the public eye on the cruise.

4. Publications and Reports

4.1 Publications by Principal Investigators

Peer-reviewed

Barrett, P.M., J.A. Resing, N.J. Buck, R.A. Feely, J.L. Bullister, C.S. Buck, W.M. Landing, and C.I. Measures, 2014: Calcium carbonate dissolution in the upper 1000 m of the eastern North Atlantic. *Global Biogeochem. Cycles*, **28**(4), doi: 10.1002/2013GB004619, 386–397.

Bullister, J.L., M. Rhein, and C. Mauritzen, 2013: Deep water formation. In Ocean Circulation and Climate, 2nd Ed. A 21st Century Perspective, G. Siedler, S. Griffies, J. Gould, and J. Church (eds.), International Geophysics Series, Academic Press, **103**, ISBN: 9780123918512.

Feely, R.A., R. Wanninkhof, C.L. Sabine, J.T. Mathis, T. Takahashi, and S. Khatiwala, 2014: Global ocean carbon cycle. In State of the Climate in 2013, Global Oceans. *Bull. Am. Meteorol. Soc.*, **95**(7), S73–S80.

Johnson, G. C., J. M. Lyman, G. S. E. Lagerloef, and H.-Y. Kao, 2014b: Sea surface salinity. In State of the Climate in 2013, Global Oceans. *Bull. Am. Meteorol. Soc.*, **95**(7), S60–S62.

Johnson, G. C., J. M. Lyman, J. K. Willis, T. Boyer, J. Antonov, S. A. Good, C. M. Domingues, and N. Bindoff, 2014a: Ocean heat content. In State of the Climate in 2013, *Global Oceans. Bull. Am. Meteorol. Soc*., **95**(7), S54–S57.

Ko, Y.H., K. Lee, P.D. Quay, and R.A. Feely, 2014: Decadal (1994–2008) change in the carbon isotope ratio in the eastern South Pacific Ocean. Global Biogeochem. Cycles, **28**(8), doi: 10.1002/2013GB004786, 775–785.

Lyman, J. M., and G. C. Johnson, 2014: Estimating global ocean heat content changes in the upper 1800 m since 1950 and the influence of climatology choice. *J. Climate*, **27**, 1946–1958, doi: 10.1175/JCLI-D-12-00752.1.

Meinvielle, M., and G. C. Johnson, 2013: Decadal water-property trends in the California Undercurrent, with implications for ocean acidification. *J. Geophys. Res.,* **118**, 6687–6703, doi:10.1002/2013JC009299.

Technical reports

Feely, R. A., and Coauthors, 2014: The US Repeat Hydrography CO2/Tracer Program (GO-SHIP): Accomplishments from the first decadal survey. A US CLIVAR and OCB Report, 2014-5, U.S. CLIVAR Project Office, Washington, DC, Published online at US OCB.

Mathis, J.T., and Coauthors, 2014: TPOS Whitepaper #6. Tropical Pacific biogeochemistry: Status, implementation and gaps. In Proceedings of the Tropical Pacific Observing System 2020 Workshop, A Future Sustained Tropical Pacific Ocean Observing System for Research and Forecasting, La Jolla, CA, 27–30 January 2014.

Robbins, L. L., and Coauthors, 2014: Air–Sea Exchange, Report of The US Gulf of Mexico Carbon Cycle Synthesis Workshop, Ocean Carbon and Biogeochemistry Program and North American Carbon Program, 63 pp.

Wanninkhof, R., and Coauthors, 2014: Dissolved inorganic carbon, total alkalinity, pH, fugacity of carbon dioxide, and other variables from profile and surface observations using CTD, Niskin bottle, flow through pump and other instruments from the Ronald H. Brown in the Gulf of Mexico and East Coast of the United States from 2012-07-22 to 2012-08-13. National Oceanographic Data Center, NOAA. Dataset doi:10.7289/V5542KJ

Wanninkhof, R, Barbero, L., McTaggart, K. E. Quintero. GO-SHIP CLIVAR A16S, A16S cruise report. 2104b
http://cchdo.ucsd.edu/data/co2clivar/atlantic/a16/a16s_33RO20131223/Queue/unprocessed/20140501_02_54_Alex_Quintero/A16S_Doc.pdf

In press
Kim, I.-N., K. Lee, N. Gruber, D.M. Karl, J.L. Bullister, S. Yang, and T.-W. Kim, 2014: Increasing anthropogenic nitrogen in the North Pacific Ocean. *Science*.

Patsavas, M. C., R. H. Byrne, B. Yang, R. A. Easley, R. Wanninkhof, and X. Liu, 2014: Procedures for Direct Spectrophotometric Measurements of Carbonate Ion Concentrations: Measurements in Gulf of Mexico and East Coast US Waters. *Marine Chemistry*.

4.2 Other Relevant Publications

Abraham, J. P., and Coauthors, 2013: A review of global ocean temperature observations: Implications for ocean heat content estimates and climate change. *Rev. Geophys*., **51**, 450–483, doi: 10.1002/rog.20022.

Amornthammarong, N., J-Z. Zhang, P. B. Ortner, J. Stamates, M. Shoemaker, and M. W. Kindel, 2013: A Portable Analyzer for the Measurement of Ammonium in Marine Waters**.** Environ. Sci.: *Processes Impacts*, 2013, **15**, 579-584. DOI: 10.1039/C2EM30793F**.**

Ayers, J. M., and P. G. Strutton, 2013: Nutrient variability in Subantarctic Mode Waters forced by the Southern Annular Mode and ENSO. *Geophys. Res. Lett.*, **40**(13), 3419-3423, doi: 10.1002/grl.50638.

Feely, R.A., R. Wanninkhof, C.L. Sabine, J.T. Mathis, T. Takahashi, S. Khatiwala, and G.-H. Park (2013): Global ocean carbon cycle. In State of the Climate in 2012, Global Oceans, *Bull. Am. Meteorol. Soc*., **94**(8), S72–S75.

Feely, R.A., C.L. Sabine, R.H. Byrne, F.J. Millero, A.G. Dickson, R. Wanninkhof, A. Murata, L.A. Miller, and D. Greeley, 2012: Decadal changes in the aragonite and calcite saturation state of the Pacific Ocean. *Global Biogeochem. Cycles*, **26**, GB3001, doi: 10.1029/2011GB004157.

Garzoli, S.L., M.O. Baringer, S. Dong, R.C. Perez, and Q. Yao, 2012: South Atlantic meridional fluxes. *Deep-Sea Res. II*, **71**, 21-32, doi:10.1016/j.dsr.2012.09.003, Nov, 2012.

Khatiwala, S., T. Tanhua, S. Mikaloff Fletcher, M. Gerber, S.C. Doney, H.D. Graven, N. Gruber, G.A. McKinley, A. Murata, A.F. Ríos, and C.L. Sabine, 2013: Global ocean storage of anthropogenic carbon. *Biogeosci.*, **10**, 2169-2191, doi: 10.5194/bg-10-2169-2013.

Kim, I. N., D. H. Min, and A. M. Macdonald, 2013: Water column denitrification rates in the oxygen minimum layer of the Pacific Ocean along 32°S. *Global Biogeochem. Cycles*, **27**(3), 816-827.

Ko, Y. H., K. Lee, P. D. Quay, and R. A. Feely, 2014: Decadal (1994–2008) change in the carbon isotope ratio in the eastern South Pacific Ocean. *Global Biogeochem Cycles*, **28**(8), 775-785.

Otto, A., F. E. L. and Coauthors, 2013: Energy budget constraints on climate response. *Nature Geosci.*, **6**, 415–416, doi: 10.1038/ngeo1836.

Rafter, P. A., P. J. DiFiore, and D. M. Sigman, 2013: Coupled nitrate nitrogen and oxygen isotopes and organic matter remineralization in the Southern and Pacific Oceans. *J. Geophys. Res.*, **118**(10), 4781-4794, doi: 10.1002/jgrc.20316.

Rodgers, K. B., and Coauthors, 2013: Srong sensitvitiy of Southern Ocean carbon uptake and nutrient cycling to wind stirring. *Biogeosci. Disc.*, **10**, p. 1-44, doi: 10.5194/bgd-10-15033-2013.

Schmidtko, S., G. C. Johnson, and J. M. Lyman, 2013: MIMOC: A global monthly isopycnal upper-ocean climatology with mixed layers. *J. Geophys. Res.*, **118**, 1658–1672, doi: 10.1002/jgrc.20122.

Srokosz, M., M. Baringer, H. Bryden, S. Cunningham, T. Delworth, S. Lozier, J. Marotzke and R. Sutton, 2012: Past, present and future change in the Atlantic meridional overturning circulation. *Bull. Am. Met. Soc.*, **93**, 1663-1676, doi: 10.1175/BAMS-D-11-00151.1.

Sonnerup, R., S. Mecking, and J. Bullister, 2013: Transit time distributions and oxygen utilization rates in the northeast Pacific Ocean from chlorofluorocarbons and sulfur hexafluoride. *Deep-Sea Res. I*, **72**, 61–71, doi:10.1016/j.dsr.2012.10.013.

Talley, L.D., and R. Feely, 2012: Ship-based repeat hydrography: U.S. contributions to GO-SHIP. In U.S. IOOS Summit Community White Papers, Interagency Ocean Observation Committee (IOOC), Herndon, VA, 13–16 November 2012.

Tanhua, T., D.W. Waugh, and J.L. Bullister, 2013: Estimating changes in ocean ventilation from early 1990s CFC-12 and late 2000s SF_6 measurements. *Geophys. Res. Lett.*, **40**(5), doi: 10.1002/grl.50251, 927–932.

Von Dassow, P., and S. Collado-Fabbri, 2014: Biological oceanography, biogeochemical cycles, and pelagic ecosystem functioning of the east-central South Pacific Gyre: focus on Easter Island and Salas y Gómez Island. *Lat. Am. J. Aquat. Res.*, **42**(4), 703-742, doi: 10.3856/vol42-issue4-fulltext-4.

Wang, Z. A., R. Wanninkhof, T.-H. Peng, W.-J. Cai, X. Hu, W.-J. Huang, and R. Byrne, 2013: The marine inorganic carbon system along the Gulf of Mexico and Atlantic coasts of the United States: Insights from a transregional coastal carbon study: *Limnol and Oceanogr*., **58**(1), p. 325-342, doi**:** 10.4319/lo.2013.58.1.0325.

Wanninkhof, R., G.-H. Park, T. Takahashi, R.A. Feely, J.L. Bullister, and S.C. Doney, 2013: Changes in deep-water CO_2 concentrations over the last several decades determined from discrete pCO_2 measurements. *Deep-Sea Res. I*, **74**, doi: 10.1016/j.dsr.2012.12.005, 48–63.

Wanninkhof, R., and Coauthors, 2013: Global ocean carbon uptake: magnitude, variability and trends: *Biogeosci.*, **10**, 1983-2000.

Woosley, R. J., F. Huang, and F. J. Millero,2014: Estimating absolute salinity (S_A) in the world′s oceans using density and composition. *Deep Sea Res. I*, **93**, 14-20.

Zhang, J-Z., C. J. Fischer, 2014: Carbon dynamics of Florida Bay: spatiotemporal patterns and biological control, *Environ. Sci. Technol*., **48,** 9161-9169, doi: 10.1021/es500510z.

5. Slides

Relevant slides are attached to this report.