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 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. 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 existing and new autonomous sensors. The 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 end products are used by scientists to develop and validate models of ocean circulation changes, and models of 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 (Fig. 1) takes into consideration the program objectives, providing global coverage, and anticipated resources. Also considered is the timing of national and international research programs, including the focus of CLIVAR in the 2011-2014 timeframe; 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. Emphasis during FY 2013 was on the north-to-south section in the Atlantic Ocean (A16N) and a west-to-east section in the Pacific (P2). In addition, the recently occupied and proposed sections are selected so that there is roughly a decade between them and the previous occupations (Fig. 1).

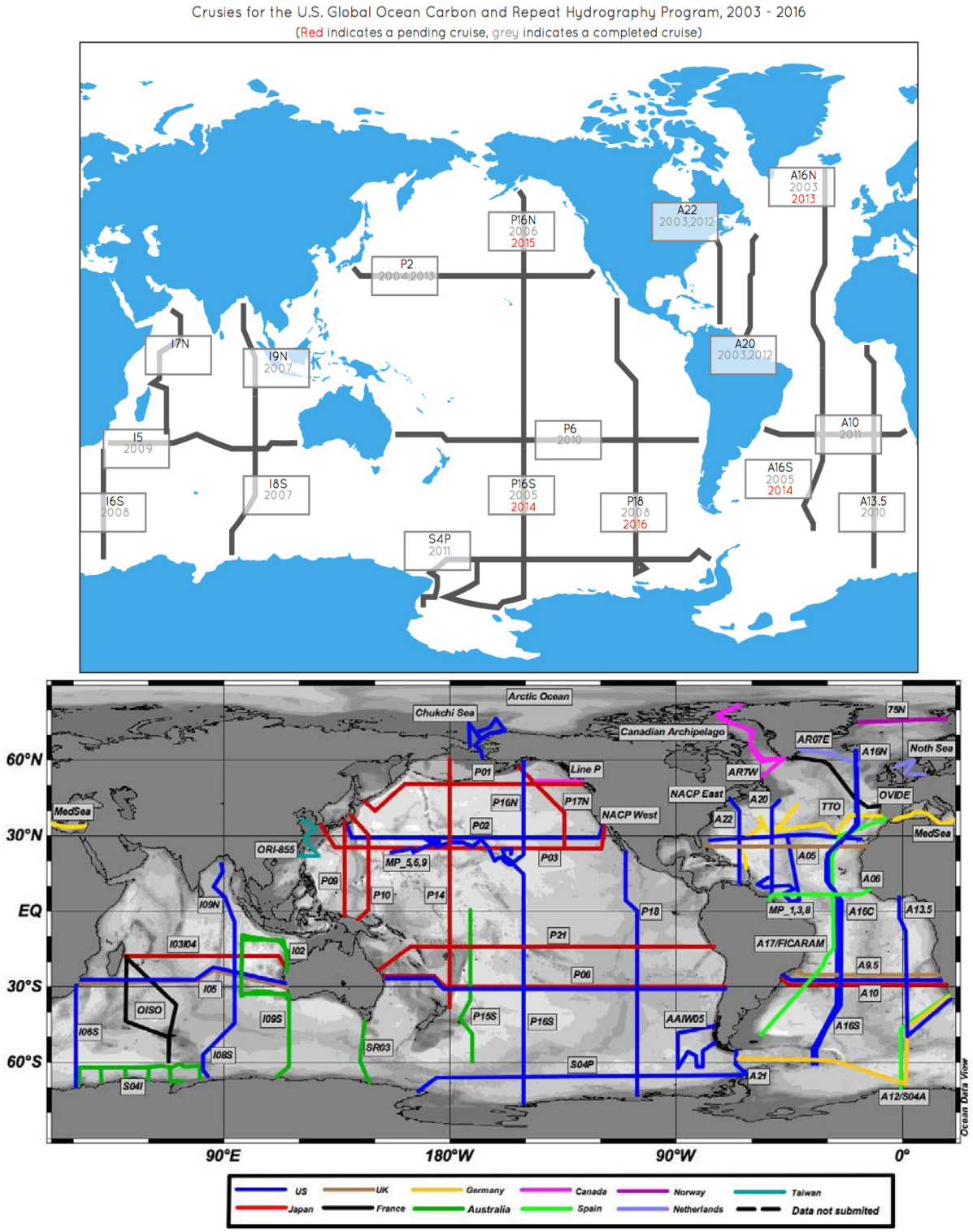

Figure 1. Global map of U.S (Top) and international (Bottom) CLIVAR/CO_2/Tracer Repeat Hydrography Program (GO-SHIP) hydrographic sections with carbon system measurements.

2. Scientific and Observing System Accomplishments

2.1 A16N_2013 Cruise Summary

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 (RHB). This meridional section spans the North Atlantic Ocean from Iceland to 6ºS, along latitudes ranging from 20–29ºW (see Fig. 2). 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.

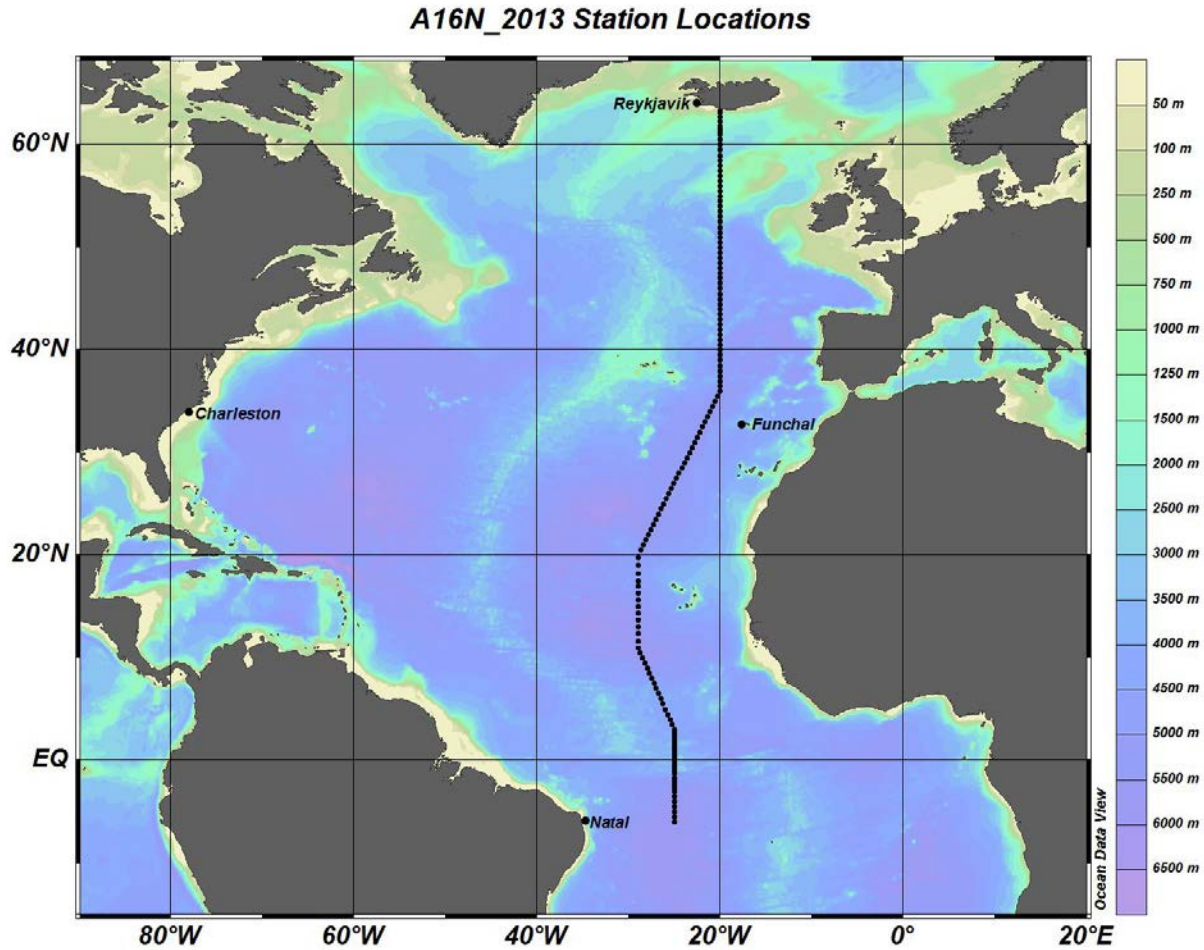

Figure 2. Locations of full-depth CTD/rosette stations on the A16N_2013 cruise.

While the goals of the A16N_2013 cruise were almost completely accomplished, various ship's mechanical and weather difficulties increased costs in terms of lost equipment and increased time in port and at sea. Of the 150 planned stations, the cruise successfully completed 145 stations, resulting in a minimal impact to the science program. A brief cruise narrative follows.

The NOAA Ship Ronald H. Brown departed Charleston on 18 July. For the first leg, the ship departed Reykjavik on 3 August and arrived in Funchal on 23 August, completing 70 oceanographic stations, 4 more than planned. The second leg departed Funchal on 1 September, after a 5-day delay to address the ship's mechanical issues (air-conditioning and fuel pump). The second leg proceeded normally after a repeat of station 70 from the first leg until station 91. The ship broke off science work on 9 September after the completion of station 91 (at 20.5ºN) and headed east (then south) to avoid Tropical Storm Humberto (which transited directly north along the cruise track for some distance, and was at Hurricane strength from 13–14 September). Stations resumed after a delay, but moving from south to north. This was probably the most efficient action, allowing resumption of work, but required some back-tracking. All in all, about 3 days were lost owing to Hurricane Humberto. Shortly thereafter, level wind problems on the aft winch had intensified sufficiently to cause concern about damage to the sea-cable and possible loss of the sampling package. The decision was made to switch to the forward winch just prior to station 96. Unfortunately, although the outer few wraps of the sea-cable on that winch appeared to be in excellent condition, the cable was badly corroded below those outer wraps. While on station 96, that cable parted with about 2800 m of wire out, and about $252,000 worth of equipment was lost at sea. The back-up sampling package was quickly readied for deployment, and deployed on the aft winch, but at the completion of station 98, the decision was made that continuing with the aft winch as it was, with very bad level-wind problems was untenable and risked the loss of the backup CTD/rosette package. With a lot of hard work and after a few false starts, a way forward was found. The rest of the cable on the forward winch was corroded, and unusable. However, the level wind from the forward winch was switched to the aft winch, and almost the entire length of good cable (about 7800 meters) remaining on the aft winch was spooled out with a weight at the end and then re-spooled onto the aft winch. Rather miraculously, this last-ditch effort worked, and work continued at a normal rate thereafter. However, almost another 3 days had been lost because of these equipment failures. The cruise continued, with work concluding at 6°S on 1 October, and the ship arrived in Natal on 3 October.

All in all, over 6 days at sea were lost on the second leg of this cruise, between equipment failure and weather delays. Elimination of five stations (by increasing station spacing from 30' to 45' latitude between 17.5 and 20.5ºN and from 30' to 40' latitude between 11 and 17ºN) made up a bit more than a day of this lost time, and with the ship's advocacy, days at sea were added to the second leg to allow the cruise to be completed without cutting more stations. A total of 145 stations were occupied during the cruise, including a duplicate station at the break between the first and second leg. About 4200 discrete water samples were collected on the CTD and trace metal casts and analyzed for various water properties (Fig. 3).

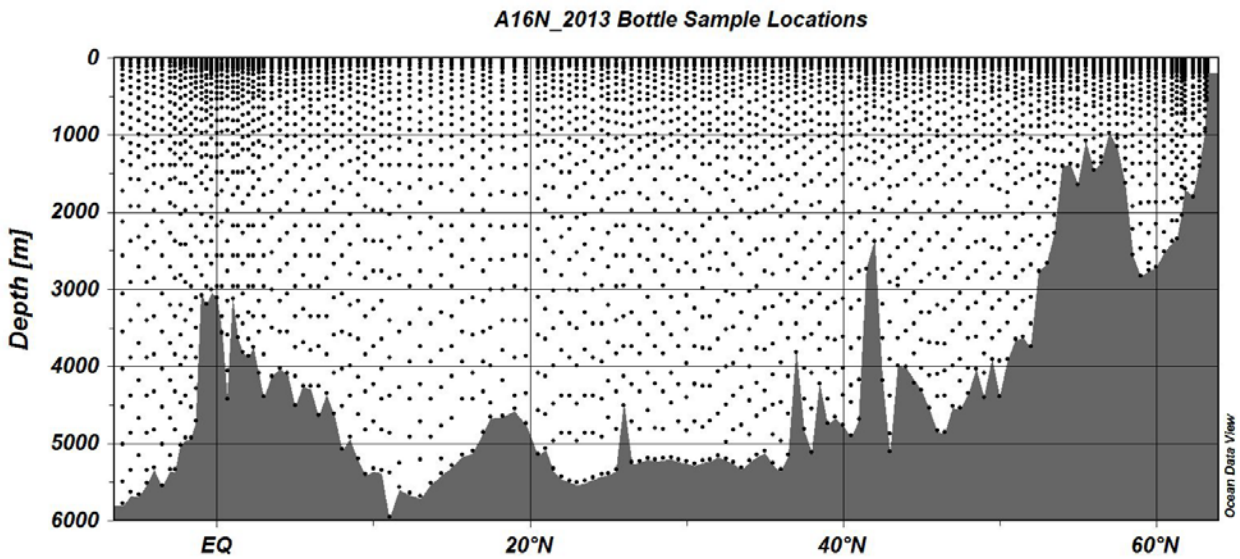

Figure 3. Locations of bottle samples collected on the A16N_2013 cruise.

In addition to the 145 CTD/rosette casts, about 61 separate casts were performed on the A16N_2013 cruise at about 1 degree (60 nautical mile) spacing for collection of water samples for trace metal analysis. These casts typically went to a depth of about 1000 m and used a separate trace-metal clean CTD and 12-position rosette sampler. Water samples from these casts will be analyzed for a wide variety of trace metals including aluminum, iron, cadmium, lead, cobalt, manganese, nickel, and zinc. Aerosol and dust particles were also collected along the cruise track for trace metal analysis.

NOAA funding allowed PMEL, AOML, JISAO, CIMAS, and RSMAS scientists to collect, analyze, and process CTD/O_2 profiles, as well as discrete samples for salinity, DIC and pCO_2, nutrients, dissolved oxygen, CFCs, SF_6, and to serve in the chief science party. Outside funding from NSF and other agencies allowed for data management, CTD and CFC watch-standers, as well as collection, analysis, and processing of alkalinity and pH data, tritium/helium data, DOM data, CDOM data, transmissometer data, LADCP data, trace metal data, various carbon isotope data, and nitrite and nitrite isotope data.

Obviously the data from this cruise have not yet been finalized and archived. That process will take place in the coming year. Much of the science gear used on A16N_2013 will remain onboard RHB for use on the southern half of the A16 section (A16S) now scheduled to continue from 6°S to 60°S starting in December 2013.

2.1.1 Hydrography Results (Johnson and Baringer)

The repeat hydrography data are revealing global-scale changes in the ocean heat that are useful for evaluating climate model performance, as well as analyzing and closing budgets for sea level, heat, and freshwater. In FY2013, a global analysis of repeat hydrography data (Purkey and Johnson, 2013) demonstrated that fresher varieties of Antarctic Bottom Water (AABW) are

present within the South Pacific and South Indian oceans in 2000s compared to the 1990s, with the strongest freshening in the newest waters adjacent to the Antarctic continental slope and rise, indicating a recent shift in the salinity of AABW produced in this region (Figure 4). In contrast, bottom waters in the Weddell Sea exhibit significantly less water-mass freshening than those in the other two southern basins. The water-mass freshening of AABW in the Indian and Pacific sectors is equivalent to a freshwater flux of 73 ±26 Gt yr^{-1} over this time period. This freshwater gain within the AABW is equal to roughly half of the estimated recent mass loss of the West Antarctic Ice Sheet (e.g., Rignot et al., 2008). This large change of AABW properties is linked to warming of AABW that contributes to the global uptake of heat by the climate system (Purkey and Johnson, 2010) and contraction of AABW at a rate of about 8×10^6 m^3 s^{-1} (Purkey and Johnson, 2012).

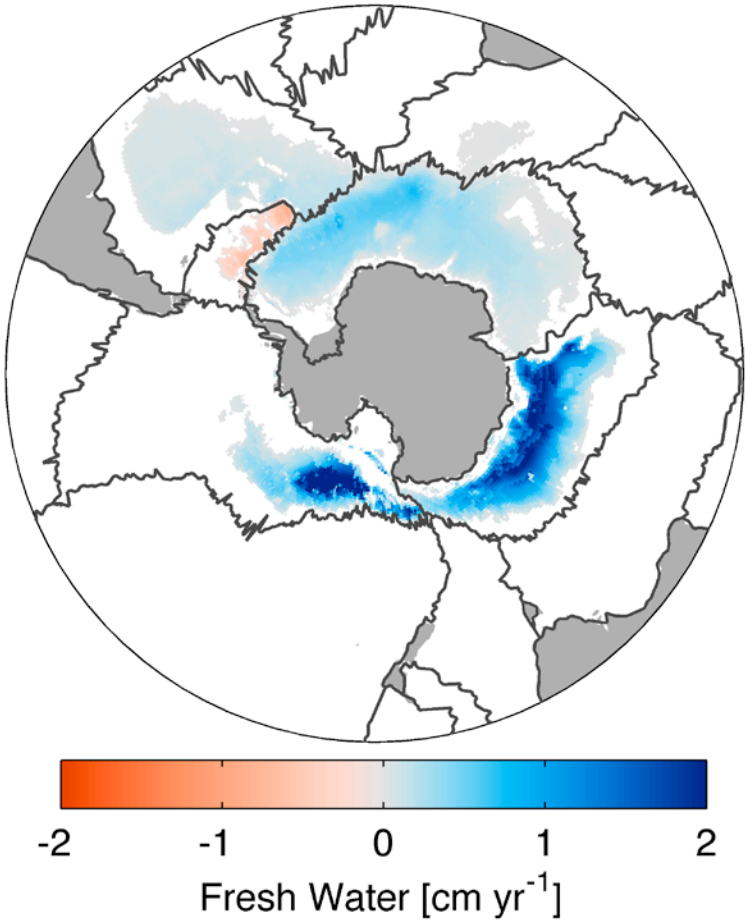

Figure 4. Local vertical column freshwater fluxes in cm yr^{-1} (color) needed to account for observed water-mass salinity changes below potential temperature of 0°C (within the Antarctic Bottom Water or AABW). Basin boundaries (gray lines) and land (gray shading) are shown. After Purkey and Johnson (2013, their Fig. 5).

Other analyses published this year using repeat hydrography data include a study of interannual to decadal variability in the oxygen mininum zone of the eastern equatorial Pacific (Czeschel et al., 2012), a study of the cycling of silicic acid (a nutrient) from the Southern Ocean into the subtropical South Pacific Ocean (de Souza et al., 2013), reports on 2012 ocean heat content

(Johnson et al., 2013a) and sea-surface salinity (Johnson et al., 2013b) 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, a sidebar on slowdown of the circulation of Antarctic Bottom Water (Johnson and Purkey, 2013) highlighted in the *State of the Climate* report, an updated estimate of the climate response to radiative forcing constrained by global surface temperature and energy uptake time-series (Otto et al., 2013), and an Monthly Isopycnal/Mixed-layer Ocean Climatology (MIMOC; Schimdtko et al., 2013) discussed in the U.S. Argo consortium annual progress report.

References:

Purkey, S. G., and G. C. Johnson, 2010, Warming of global abyssal and deep Southern Ocean waters between the 1990s and 2000s: Contributions to global heat and sea level rise budgets. *J. Climate*, **23**, 6336–6351. doi:10.1175/2010JCLI3682.1.

Purkey, S. G. and G. C. Johnson, 2012: Global contraction of Antarctic Bottom Water between 1980s and 2000s. *J. Climate*, **25**, 5830–5844. doi:10.1175/JCLI-D-11-00612.1

Rignot, E., J. L. Bamber, M. R. van Den Broeke, C. Davis, Y. Li, W. Jan Van De Berg, and E. van Meijgaard, 2008: Recent Antarctic ice mass loss from radar interferometry and regional climate modeling. *Nature Geoscience*, **1**, 106–110, doi:10.1038/ngeo102.

2.1.2 DIC Measurements on A16N (Wanninkhof)

During the A16N cruise, C. Featherstone and R. Castle 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 3225 samples were taken and > 99 % were considered "good" after initial on board quality control. 355 duplicate pairs of samples were taken to assess precision (Table 1).

Table 1. Duplicate samples for DIC analyzed on the A16N cruise

Instrument[a]	Average difference (*μmol kg^{-1}*)	Standard deviation	Number of samples
DICE 3	1.5	1.2	177
DICE 4	1.7	1.2	178

[a] DICE= Dissolved inorganic carbon extractor

A section of the preliminary DIC data from A16N cruise is shown in Figure 5. The features show the strong interplay between ocean currents and oxidation of organic material (OM). Lower surface values are caused by biological uptake and settling along with dilution by fresh water, particularly in the Intertropical Convergence zone (5-10˚N). The tongue of lower DIC centered around 2000 m in the South and reaching near the surface in the North is recently ventilated Labrador Sea water (LSW) and Upper North Atlantic Deep Water (NADW). High DIC values centered around 700 m in the South are caused a combination of Antarctic

Intermediate Water (AAIW) and oxidation of OM. The highest values of DIC are just South of the Mid-Atlantic Ridge in the Western Basin of the South Atlantic. This is old Antarctic Bottom water (AABW) coming from the South. The companion plots of nutrients, oxygen and CFC in other sections of this report show the age and remineralization signals in their own unique way. Once reduced, these data will be used to discern changes in anthropogenic uptake between 1993, 2003 and 2013.

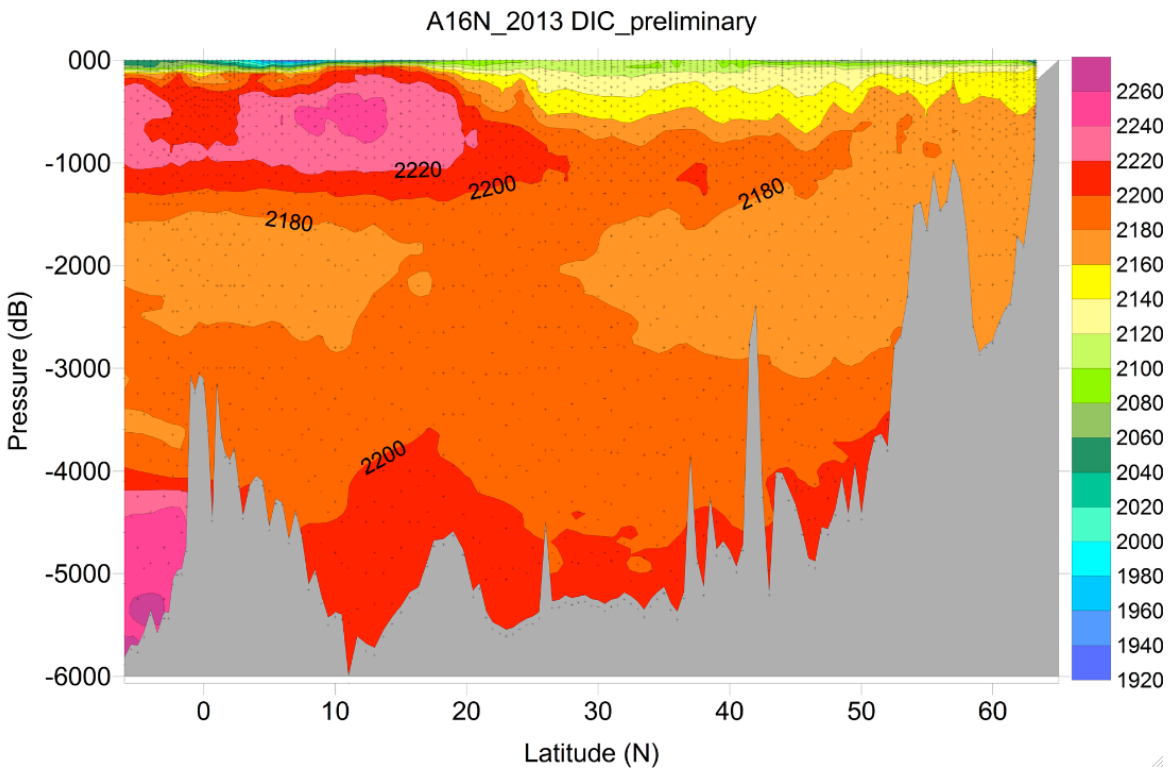

Figure 5. Vertical section of preliminary data for DIC for the 2013 occupation of A16N. The characteristic inorganic carbon fingerprints of the major water masses are apparent. The faint dots are the sample locations showing excellent coverage.

2.1.3 Discrete pCO_2 measurements on A16N (Wanninkhof)

Discrete pCO_2 measured at 20˚C ($pCO_2(20)$) is a unique inorganic carbon parameter in that it has a large dynamic range and it is anti-correlated with pH. It therefor serves as a good indicator of ocean acidification and as a high-resolution tracer of anthropogenic CO_2 in the deep water (Wanninkhof et al, 2013). Over 2300 samples were drawn at 145 stations by Mr. Kevin Sullivan and Dr. Leticia Barbero of CIMAS/AOML on leg 1 and leg 2 respectively. About 100 samples were collected from the UW seawater line, mostly during stations for comparison with underway pCO_2 to gain a better understanding of the temperature dependency of pCO_2 as the discrete samples are measured at 20 ˚C and UW measurements are close to in situ temperature. More than fifty sets of duplicate bottles were drawn at numerous depths. The average relative error of these duplicate pairs was 0.18%, while the median relative error was 0.11% with the statistics provided in Table 2.

Table 2. Duplicate samples for $pCO_2(20)$ samples analyzed on the A16N cruise

Instrument[a]	Average difference (*µatm)*	Standard deviation	Number of duplicates
pCO2NewBee	4.4	5.0	41

[a]This colloquial name refers to the instrument built by T. Newberger (CIRES/GMD/ESRL) and on long-term loan from C. Sweeney (CIRES/GMD/ESRL).

A vertical section plot of $pCO_2(20)$ is shown in Figure 6. It shows broad similarities with DIC, particularly the remineralization signals. Of note is the absence of a strong NADW signal that is observed in DIC (Fig. 4). This is because the salty NADW water carries a high alkalinity load that depresses the $pCO_2(20)$ signal.

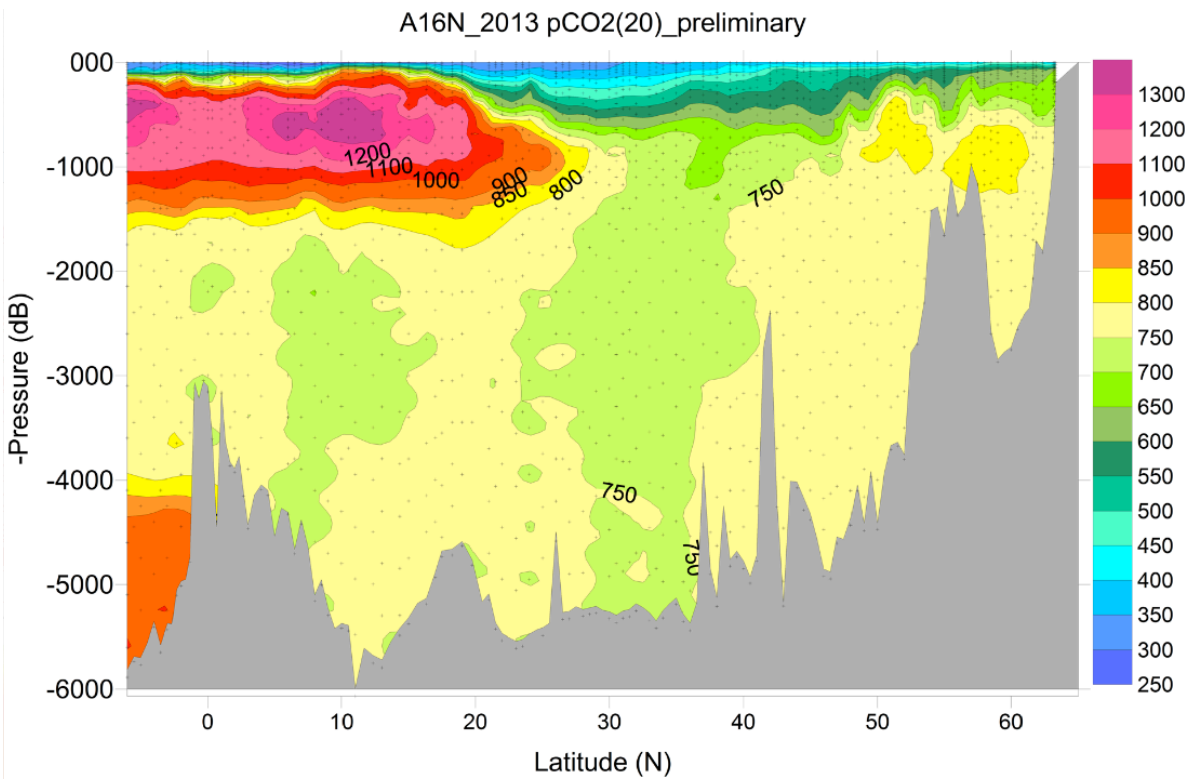

Figure 6. Vertical section of preliminary data for $pCO_2(20)$ for the 2013 occupation of A16N. The faint dots are the sample locations showing excellent coverage. Note, the samples are is pressure space and bottom topography is in depth space such that the bottom samples appear below the bottom.

2.1.4 Underway pCO_2 measurements on A16N (Wanninkhof)

Underway pCO_2, temperature and salinity are part of the core 1 measurements in the GOSHIP CLIVAR/CO_2 repeat hydrography. The NOAA ship *Ronald H. Brown* has a permanent installation of an underway pCO_2 system maintained by the ship's survey technician J.

Shannahoff and AOML scientist Robert Castle. Daily telemetry of all data facilitates rapid posting of all cruises of the *Ronald H. Brown* (http://www.aoml.noaa.gov/ocd/gcc/rvbrown_introduction.php). The preliminary data from A16N are shown in Figure 7. The blue dots are the water values and red dots are the air values. The trends are representative of the final pCO_2 values with a very strong CO_2 sink in the North due to the summer algal bloom. Mid-latitudes are CO_2 sources while there is a sink in the intertropical convergence zone.

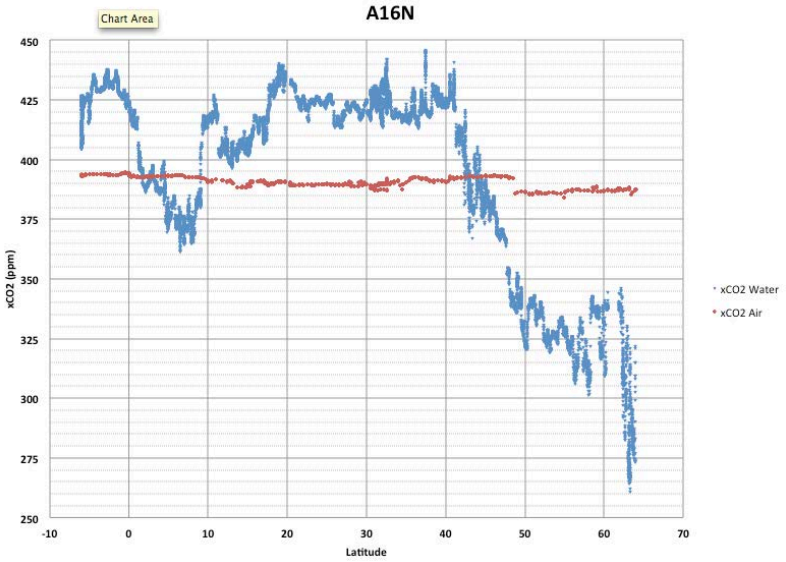

Figure 7. Underway XCO_2 measurements for A16N. The instrumental mole fraction values are shown rather than the reduced and corrected fCO_2. These values will be posted in FY14.

2.1.5 CFC Tracers (Bullister)

A primary deliverable was to make high precision measurements of dissolved chlorofluorocarbons (CFCs) and sulfur hexafluoride (SF_6) on the A16N_2013 CLIVAR Repeat Hydrography section. We were successful in reaching our goals. 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, 2008). D. Wisegarver from NOAA-PMEL coordinated preparation of the CFC/SF_6 equipment for the cruise. He was the lead analyst for the CFCs/SF_6 measurements, and will work with the PI in the processing and calibrating of the data sets and in maintaining the instruments. J. Bullister was Chief Scientist in Leg 2 of the A16N_2013 cruise.

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_2013 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. The quality of the data appear to be excellent and are expected

to fully meet international 'WOCE' quality standards for these measurements. About 500 replicate samples were analyzed for dissolved CFC-11, CFC-12 and SF_6 on the cruise.

A preliminary version of the data collected on this cruise is available at: http://cchdo.ucsd.edu/cruise/33RO20130803

CFC concentrations along the A16N_2013 section (Fig. 8) are highest in the upper 500-1000 meters of the water column and in Labrador Sea Water (LSW) between 1000-1700 m along the northern end of the section, indicating the potential of this region to rapidly take up atmospheric gases (including CO_2) on decadal time scales. Our improved analytical techniques now allow greater sensitivity to CFCs and SF_6 at extraordinarily low concentrations and we can now reliably measure dissolved CFC-11 and CFC-12 at concentrations below 0.0025 pmol per kilogram seawater (pmol/kg), where 1 pmol = 1 picomole $=10^{-12}$ mole) and SF_6 at 0.02 fmol/kg (where 1 fmol = 1 femtomole $=10^{-15}$ mole). There were detectible levels of CFC-11 and CFC-12 throughout the deep and abyssal waters along the A16N_2013 section. The subsurface maxima centered at about 1700 m near the equator and at about 3800 m slightly south of the equator reflect the relatively rapid transit of LSW and of North Atlantic Deep Water (NADW) to this region. On decades-to century timescales, the deep ocean will be a major reservoir for anthropogenic CO_2 and climate warming signals. The CFC signals can provide valuable information on the rates and pathways by which surface-derived climate signals (e.g. anthropogenic CO_2 and warming) can be carried into this region of the deep ocean. The A16N_2013 section was also occupied on 2003 as part of the WOCE program. Differences in CFCs over decadal time intervals, gathered as part of the CLIVAR Repeat Hydrography Program, can be used to test ocean circulation models and help detect and quantify changes and variability in water formation and ventilation rates, which is of great relevance to ongoing climate studies.

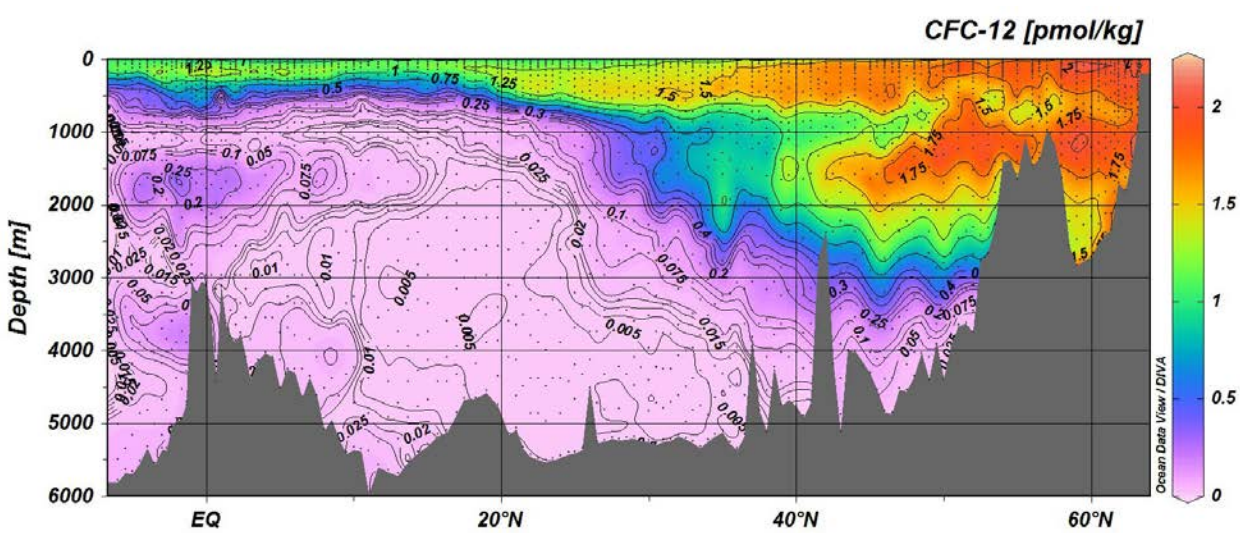

Figure 8. CFC-12 concentrations along the A16N_2013 section. Dots indicate locations where individual water samples were collected and analyzed for CFCs, SF_6 and N_2O

Sulfur hexafluoride (SF_6) is rapidly increasing in the atmosphere and has the potential to be a valuable time-dependent tracer of ocean circulation and mixing processes. The PMEL group pioneered the routine measurement of SF_6 as part of the CLIVAR Repeat Hydrography program, and measurements of this compound have been included on all subsequent CLIVAR cruises. Comparison of recent SF_6 measurements with CFC-12 measurements made on earlier cruises may be especially useful in detecting changes in ventilation processes on decadal timescales (Tanhua et al 2013).

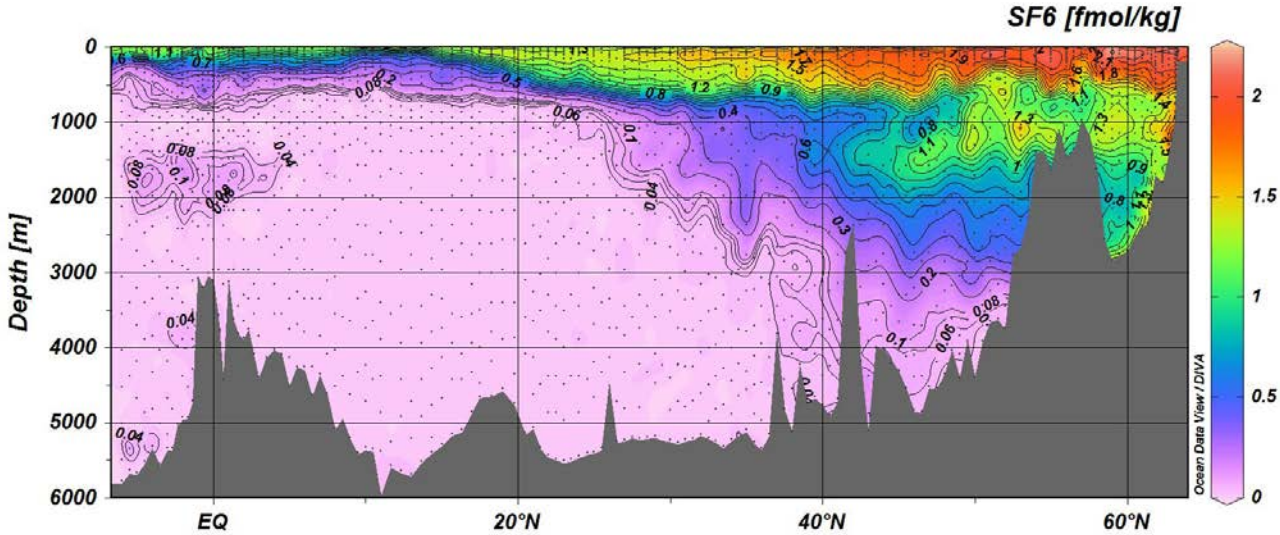

Figure 9. SF6 concentrations along the CLIVAR A16N_2013 section

Measurements of dissolved nitrous oxide (N_2O) were also made on the same samples analyzed for the CFCs and SF_6. 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.

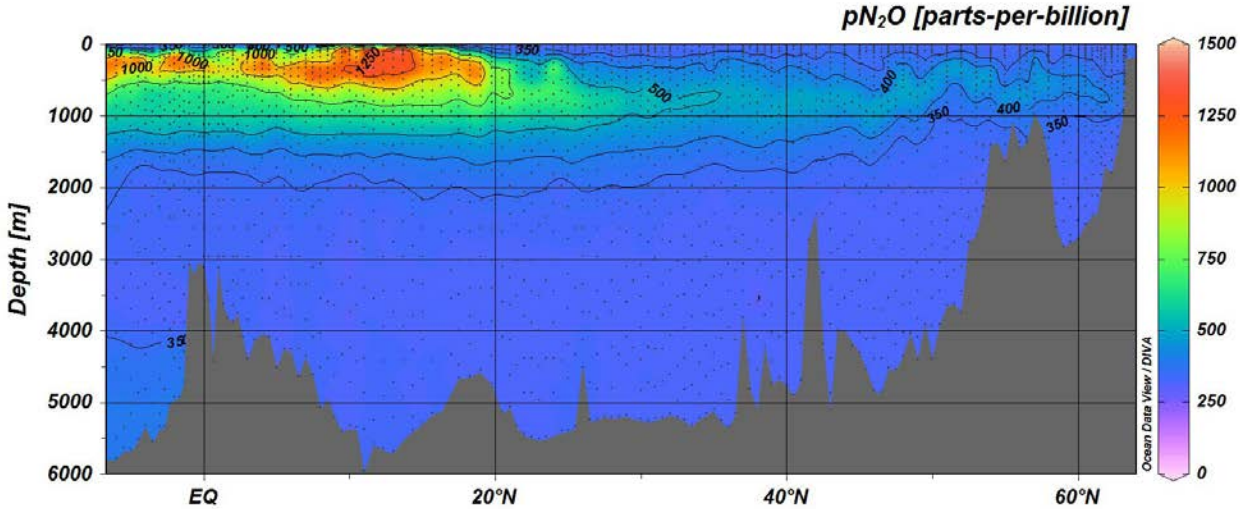

Figure 10. The partial pressure (in parts-per-billion) of dissolved N_2O (pN_2O) along the A16N_2013 section. The present atmospheric pN_2O is approximately 320 ppb. The strong sub-surface pN_2O maximum along the section indicates in-situ production of this gas and net loss of N_2O to the atmosphere by air-sea gas exchange.

We prepared and calibrated high-precision CFC and SF_6 gas-phase reference standards in our laboratory and distributed these standards for US and international groups participating in global ocean observing programs including CLIVAR. 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

2.1.6 Nutrients (Mordy and Zhang)

The primary task of the nutrient group was to collect nutrient data on the A16N repeat hydrographic section in the Atlantic Ocean. On the A16N cruise, E. Wisegarver and C. Fischer conducted high precision shipboard analysis of phosphate, nitrate, nitrite and silicic acid on 4155 samples collected from the CTD rosette and trace metal casts at discrete depths. Nutrients were analyzed with a continuous flow analyzer (CFA) using the standard and analysis protocols for the WOCE hydrographic program as set forth in the manual by Gordon et al. (1993) and recent updated manual by 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 Japanese Meteorological Institute were analyzed at a subset of stations. Mordy and Zhang will be responsible final data processing, quality control and submission.

The precision of nutrient analysis on A16N is shown in Table 3. The precision of all nutrient species meets international quality standards for these measurements. Data collected on this cruise will be archived at the CLIVAR & Carbon Hydrographic Data Office (CCHDO): http://cchdo.ucsd.edu/

Table 3. Precision of nutrient measurements on the A16N repeat hydrographic cruise determined from replicate analysis of deep-water samples (>10 µmol kg^{-1} nitrate).

	Phosphate	Silicic Acid	Nitrate
Total number of replicates	601	604	604
Standard deviation (µM)	0.004	0.06	0.04
Relative standard deviation	0.3%	0.2%	0.2%

Sections of the major nutrients from the A16N cruise are shown in Figure 11. Major features include low nutrient concentrations in surface waters; an intense sub-surface (~500 – 1000 m) phosphate and nitrate maximum in the tropics resulting from remineralization of sinking particulate organic matter; lower concentrations in North Atlantic Deep Water; and the presence of nutrient-rich Antarctic Bottom Water in the South Atlantic. These data will be used to examine changes in nutrient and oxygen content in the oceans, and examine to what extent such changes might be coupled to carbon inventory changes, all of which are similarly forced by

ocean circulation, biological productivity in surface waters and biogeochemical cycles. For example, compared with the occupation in 2003, the largest changes in nitrate and phosphate occur in the upper 1500 m most likely from decadal changes in the depth of the nutricline and the extent of ventilation in the N. Atlantic (Fig. 12). Also, from 40° – 50° N, decadal variability in overflow water may have contributed to changes in silicic acid concentrations observed between 2000 – 4000 m.

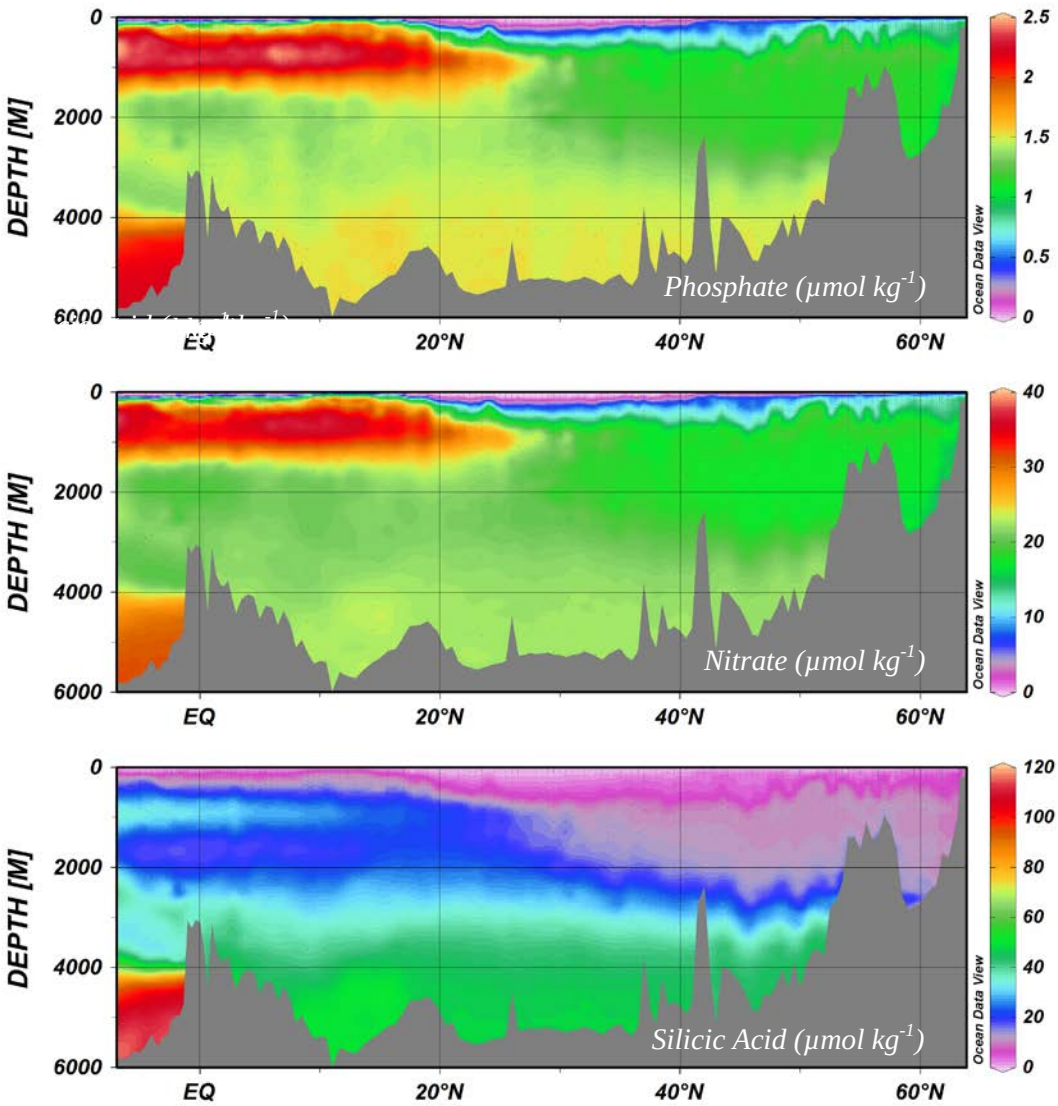

Figure 11. Preliminary sections of phosphate, nitrate and silicic acid along the A16N cruise track

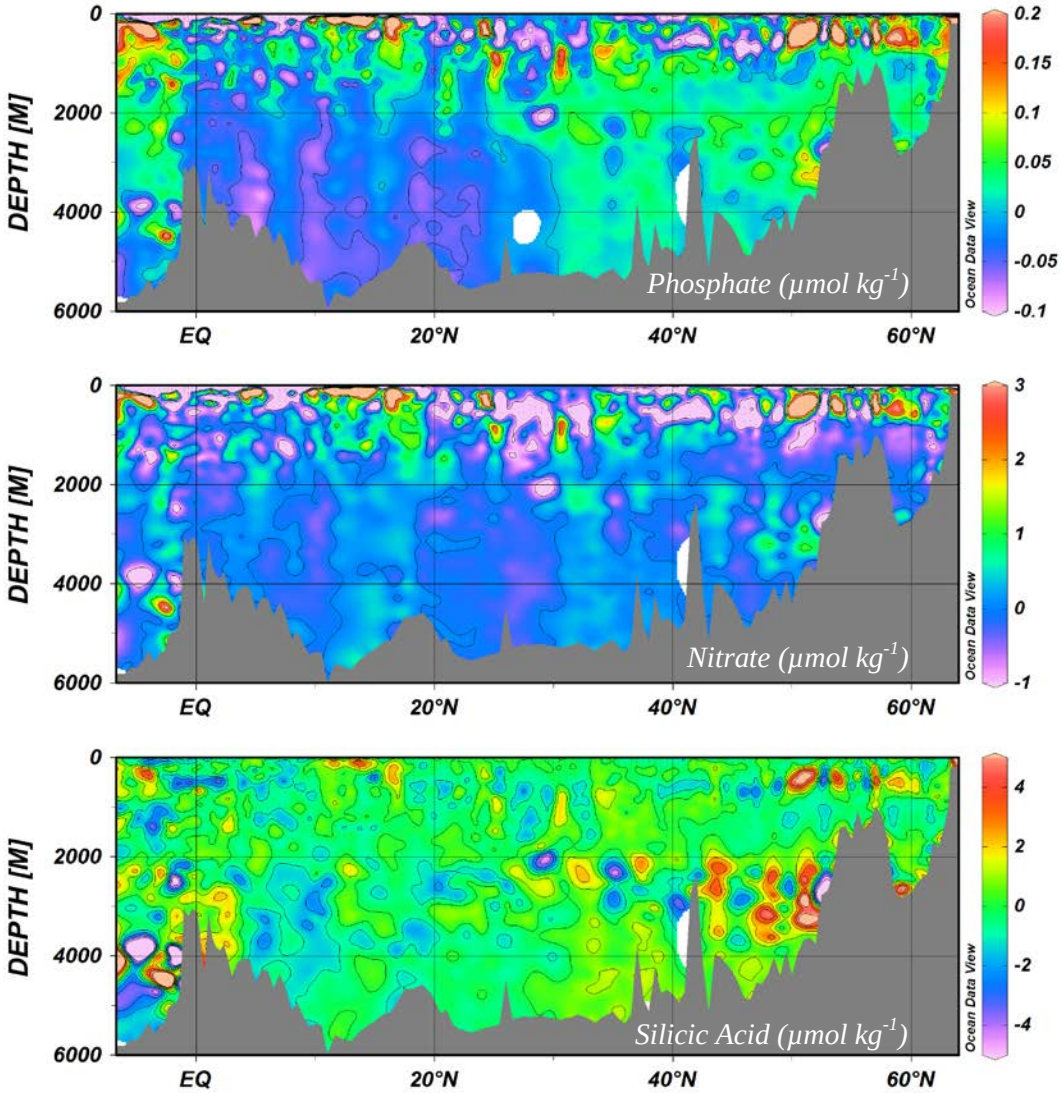

Figure 12. The decadal change in phosphate, nitrate and silicic acid along the A16N cruise track between the 2013 and 2003 occupations.

2.2 P2 Cruise Summary (Feely)

Leg 1 of the 2013 P2 Cruise departed Yokohama, Japan on March 21 on the RV Melville under the direction of Dr. James Swift as chief scientist. During the 87-day Leg the scientific party and crew occupied 87 stations. D. Greeley and J. Arrington performed the DIC and underway pCO_2 analyses. The Melville arrived in Honolulu in early May. After a brief import, the Melville departed Honolulu leg 2 under the direction of Dr. Sabine Mecking, who guided the occupation of 72 stations during a 27-day leg. C. Peacock and J. Arrington performed the DIC and underway pCO_2 measurements during Leg 2. The Melville arrived in San Diego in early June. NOAA

scientists from PMEL and AOML were responsible for the DIC and underway fCO_2 measurements.

2.2.1 DIC Measurements (Feely)

Figure 13 shows the preliminary section of DIC in µmol kg^{-1}. Over 2,000 samples were analyzed for discrete DIC. 185 of these samples were taken as replicates as a check of our precision. The absolute average difference from the mean of these replicates is 1.0 µmol kg^{-1}. The CRM certified value for this batch is 2015.7 µmol kg^{-1}. DIC data reported to the database have been corrected to the batch 124 CRM value. For Leg 2, Over 1,600 samples were analyzed for discrete DIC (Fig. 13). 135 of these samples were taken as replicates as a check of our precision. The absolute average difference from the mean of these replicates is 0.7 µmol kg^{-1}.

The results of these studies will be compared with the previous measurements collected in 1994 and 2004 and be discussed in the synthesis report.

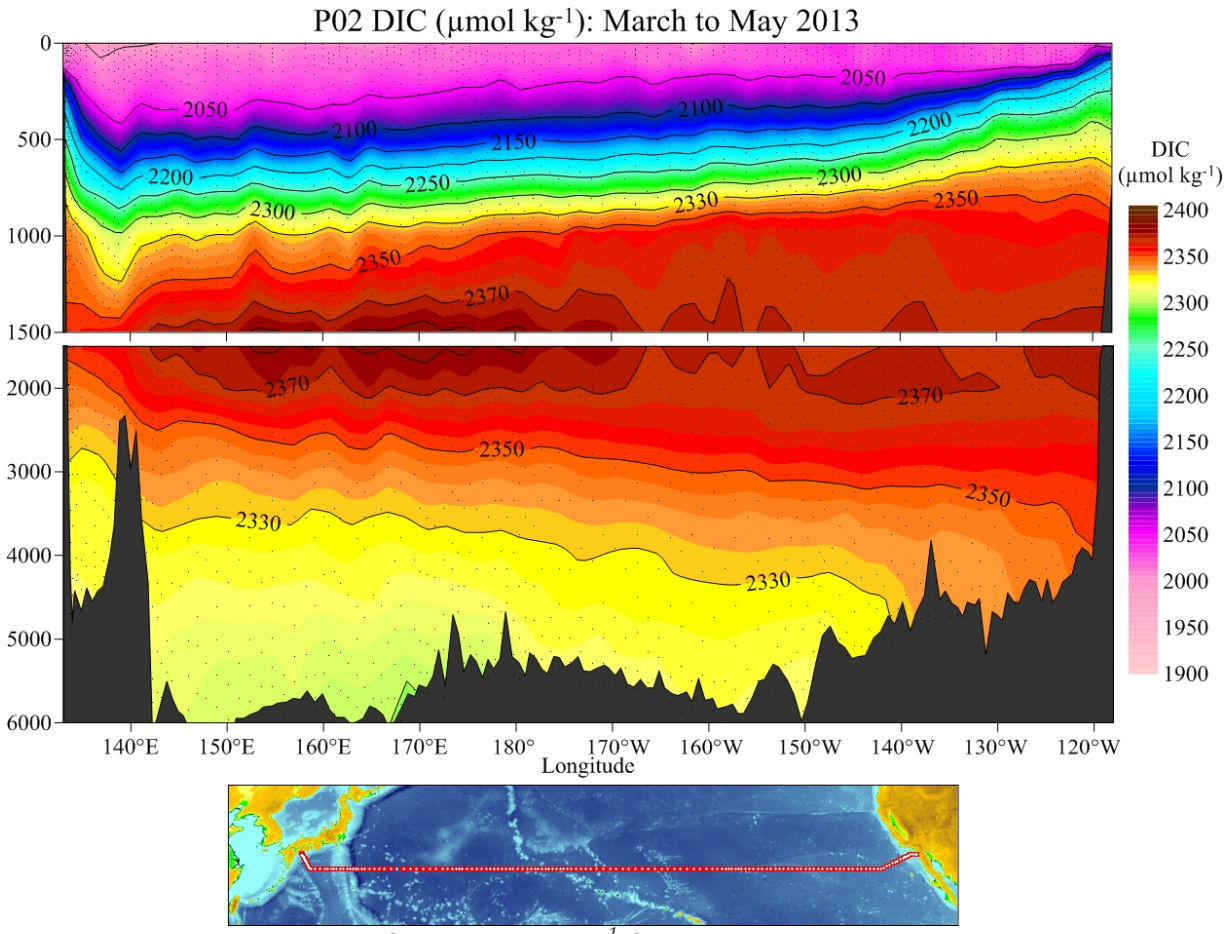

Figure 13. Vertical section of DIC in µmol kg^{-1} for the P2 Cruise onboard the R/V Melville. The P2 Cruise on the R/V Melville began in Yokohama in March and ended in San Diego in June 2013.

2.2.2 Underway fCO_2 During the P2 Cruise (Feely)

The Repeat Hydrography Program includes Underway fCO_2, temperature and salinity as core measurements. Figure 14 shows the underway fCO_2, temperature and salinity for the Melville cruise. The preliminary data indicate a very strong sink for CO_2 in the Western North Pacific due to the springtime algal bloom and a moderate source in the eastern North Pacific beginning at about 170°W due to an increase in SST and local upwelling further to the east.

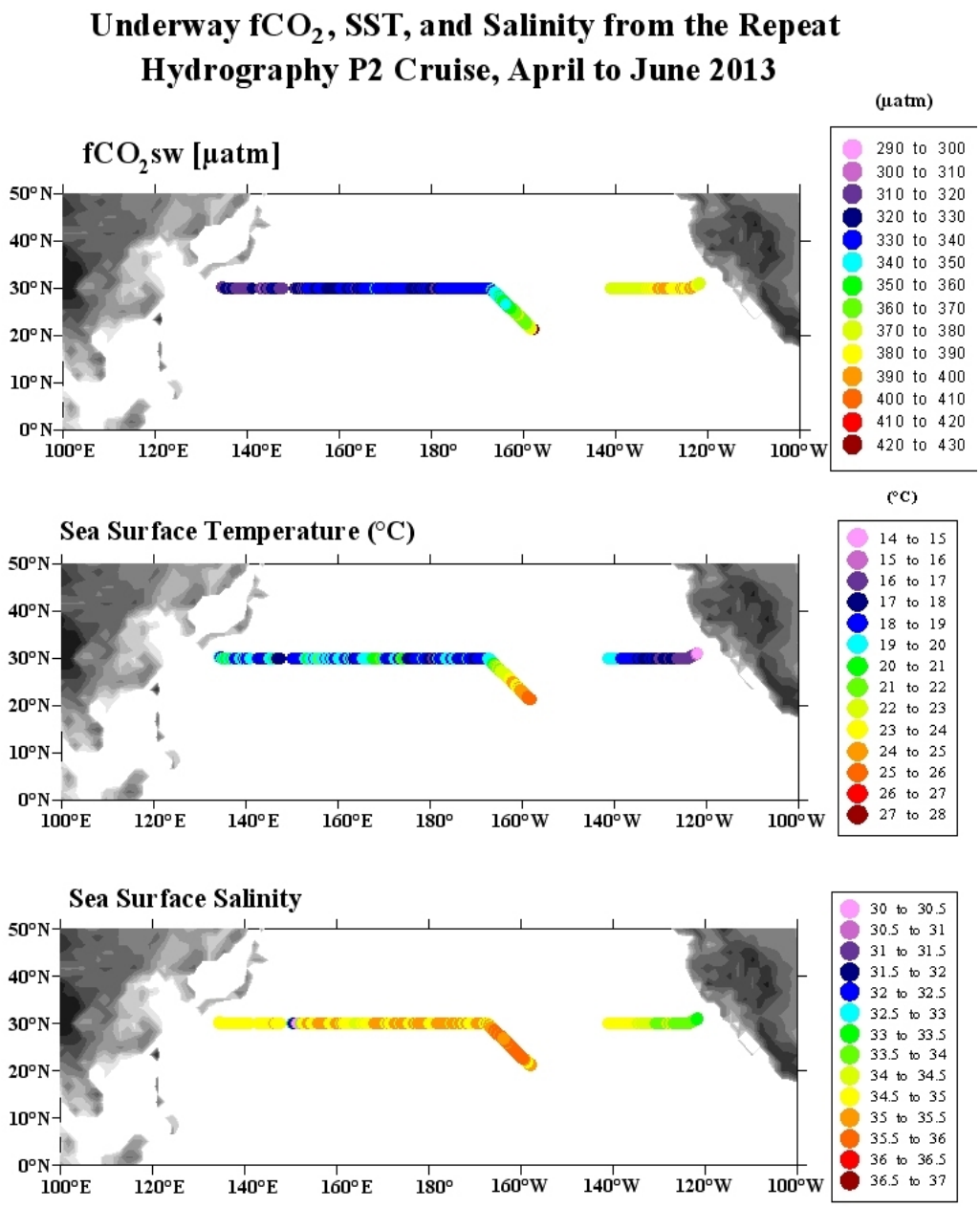

Figure 14. Underway fCO_2, SST and Salinity during the P2 Repeat Hydrography Cruise onboard the R/V Melville from March to June 2013.

3.0 Outreach and Education

Several principle 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.

Johnson advises a University of Washington School of Oceanography Graduate Student, Sarah Purkey, and an NRC Postdoctoral Research Fellow, Dr. Marion Meinvielle. On 31 July 2013, he gave a public lecture on "The Warming Ocean's Role in Climate" at the Nisqually Wildlife Refuge Summer Lecture Series to a full auditorium. Feely supervises a University of Washington School of Oceanography Graduate Student, Nancy Williams, who works on the Southern Ocean S4P data set. Bullister participated in the 2013 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 and were involved on all aspects of the at-sea programs.

The following are links to news stories reported in FY2013 regarding on various publications co-authored by principle investigators of this project which use repeat hydrography data:

Abraham, John (28 August 2013). Global warming and oceans: what are the known unknowns?. Climate Consensus - the 97%, hosted by The Guardian.

Clarke, Sarah, and Katie Hamann (20 May 2013). New reports suggests global warming could be slower than first thought. ABC News.

Marshall, Michael (19 May 2013). A second chance to save the climate . New Scientist.

Harvey, Fiona (19 May 2013). Climate change: human disaster looms, claims new research. The Guardian.

McGrath, Matt (19 May 2013). Climate slowdown means extreme rates of warming 'not as likely'. BBC News.

Schultz, Colin (21 May 2013). A global map of the ocean's climate. EOS-Transactions American Geophysical Union, Vol. 94, Issue 21, pages 196-197.

Kennedy, Caitlyn (30 July 2013). 2012 State of the Climate: Ocean Heat Content. ClimateWatch Magazine.

Newton, Alicia (27 March 2013). Oceanography: Rise from below. Nature Geoscience.

Qiu, Jane (16 November 2012). Winds of Change. Science.

Purkey, Sarah and Gregory Johnson (27 March 2013). Surprising Depth to Global Warming's Effects. Live Science.

Kennedy, Caitlyn (28 August 2013). Ocean Saltiness Provides Clues to Precipitation Patterns. ClimateWatch Magazine.

4. Publications and Reports

4.1 Publications by Principal Investigators

Abraham, J. P., M. Baringer, N. L. Bindoff, T. Boyer, L. J. Cheng, J. A. Church, J. L. Conroy, C. M. Domingues, J. T. Fasullo, J. Gilson, G. Goni, S. A. Good, J. M. Gorman, V. Gouretski, M. Ishii, G. C. Johnson, S. Kizu, J. M. Lyman, A. M. Macdonald, W. J. Minkowycz, S. E. Moffitt, M. D. Palmer, A. R. Piola, F. Reseghetti, K. Schuckmann, K. E. Trenberth, I. Velicogna, and J. K. Willis, 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.

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Baringer, M. O., W. E. Johns, G. McCarthy, J. Willis, S. Garzoli, M. Lankhorst, C. S. Meinen, U. Send, W. R. Hobbs, S. A. Cunningham, D. Rayner, D. A. Smeed, T. O. Kanzow, P. Heimback, E. Frajka-Williams, A. Macdonald, S. Dong, and J. Marotzke, Global oceans: Meridional overturning circulation and heat transport observations in the Atlantic, in State of the Climate in 2012, J. Blunden and D.S. Arndt (eds.), Bull. Am. Met. Soc., 94, S65-S68, 2013.

Czeschel, R., L. Stramma, and G. C. Johnson, 2012: Oxygen decreases and variability in the eastern equatorial Pacific. J. Geophys. Res., 117, C11019, doi: 10.1029/2012JC008043.

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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. View full report online, 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.

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4.2 Other Relevant Publications

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