**RVIB Nathaniel B. Palmer Cruise NBP-1102**
**Cruise "S4P" for the US Global Ocean Carbon and Repeat Hydrography Program**
**Overview and Cruise Plan - Version of 25 August 2010**
**James H. Swift, UCSD Scripps Institution of Oceanography**

| | |
|---|---|
| ship operator | Edison-Chouest Offshore (ECO) |
| NSF tech contractor | Raytheon Polar Services Corporation (RPSC) |
| Jim Swift | Chief scientist (858-534-3387; jswift@ucsd.edu) |
| Alex Orsi | Co-chief scientist (979-845-4014; aorsi@tamu.edu) |
| Adam Jenkins | RPSC contact (720-568-2497; Adam.Jenkins.Contractor@usap.gov) |

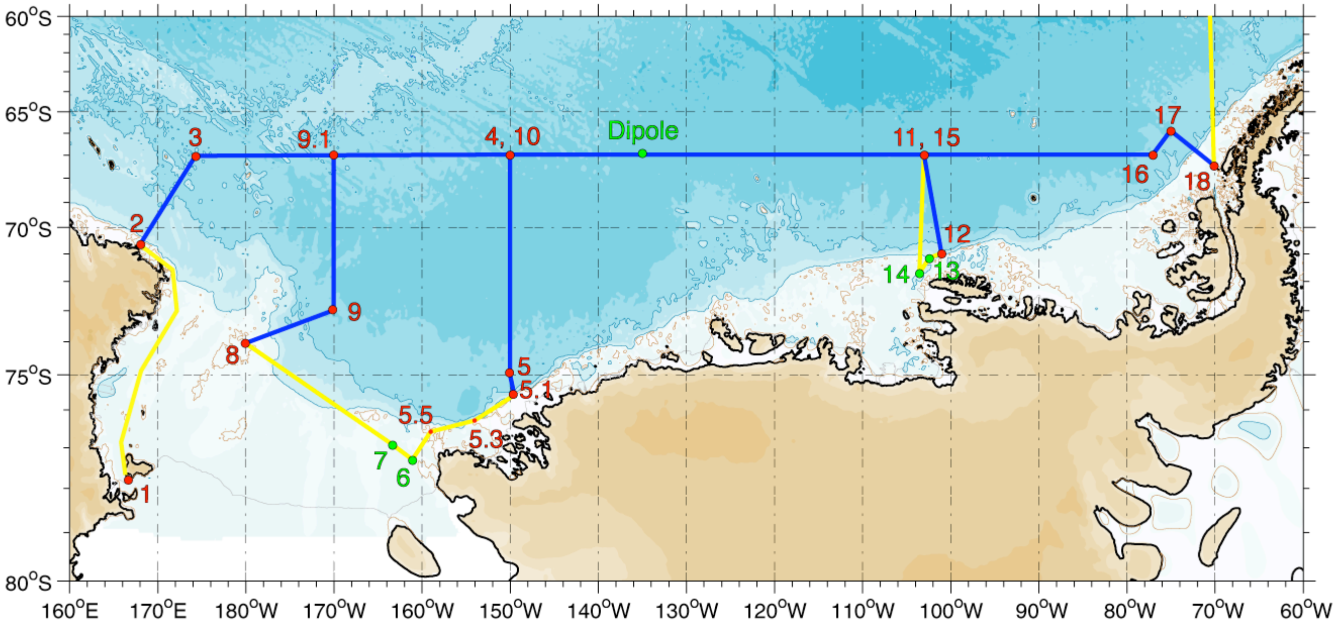
| | |
|---|---|
| 01 DEC 2010 | cargo to be at RPSC facility in Pt. Hueneme, CA |
| 13 FEB 2011 | pre-flight briefing and clothing issue in Christchurch, NZ |
| 14 FEB 2011 | flight from Christchurch, NZ, to McMurdo Base, AQ |
| 21 FEB 2011 | return flight from McMurdo to NZ, for set-up techs |
| 19 FEB 2011 | NBP departs McMurdo |
| 15 APR 2011 | scheduled date that NBP will arrive Ushuaia, AR |
| 25 APR 2011 | latest date that NBP will arrive Ushuaia, AR* |
| 28 APR 2011 | latest date NBP will arrive Punta Arenas, CL |
| ≈30 APR 2011 | latest date S4P unloading completed |

*Up to 10 "flex days" have been granted to allow completion of the S4P program and the mooring program, if fuel and other expendables permit, if the situation warrants, and at the direction of the captain, working with the chief scientist and RPSC. This is why both a "scheduled" end port date and a "latest" end port date are listed. The dates may change somewhat during final ship scheduling.

**Overview**

This cruise is part of a program of global ocean measurements for the US contribution to the World Climate Research Program CLIVAR (Climate Variability) Repeat Hydrography Program and the UNESCO International Ocean Carbon Coordination Project. For the international programs see <http://www.clivar.org/carbon_hydro/> and <http://www.ioccp.org/>. The US science team also maintain a web site at <http://ushydro.ucsd.edu/>.

During the 2011 RVIB Nathaniel B. Palmer "S4P" expedition, the science team plans CTD/velocity/hydrographic/carbon/tracer measurements from Cape Adare to the Antarctic Peninsula (near the southern tip of Adelaide Island) along ca. 67°S, with additional transects south along approximately 170°W, 150°W, and 102°W. The continental ends of each transect will carry to the Antarctic shelf break, and onto the shelf when feasible. The nominal 67°S line follows the track of the Russia-US 1992 "S4P" cruise carried out from Akademik Ioffe. The nominal 150°W transect follows the "P16S" line (2005), and the nominal 102°W transect follows the "P18S" line (2008), completing both transects to the Antarctic continent and closing off geographic regions for calculations, as does the nominal 170°W transect.




A map of the planned track is shown above. The red numbers refer to positional waypoints provided to the vessel operator. The 67°S, 170°W, 150°W, and 102°W scientific transects are shown in blue. The yellow lines show transit legs where no science stations are planned, though underway systems will be in full operation, and. The five green dots show the locations of intended mooring recoveries (7, 8, 13, 14) and a deployment ("Dipole") being done for other programs. Near each mooring site there will be one or two CTD casts.

Our stations will be 30 nmiles apart except that near bathymetric boundaries we will keep between-station bathymetry changes to 800-1000 meters, so stations will sometimes be very close together there. When stations are very close together we will need extra time for water sampling, as usual.

If necessary to save time, station spacing on the S4P line from waypoint 10 to 11/15 to 16 & 17 will be lengthened from the standard 30 miles, recalling that we must cut approximately 5 stations to save one day of ship time. One other point where we can potentially cut a few stations is to do only minimum overlap with 2007/2008 P18 stations on the WP 11 to 12 P18 extension.

At each station we will deploy our 36-place, 10-liter rosette from the Baltic Room, and lower it to within 8-10 meters of the bottom. On the up casts we will collect water samples at levels based on a variation of the "3 scheme" plan used on other cruises for our program, customized to make certain we capture the primary variability and structure of the S4P-region water column. A typical cast time is four hours, i.e. one hour per 1000 meters of water depth, with a 1-hour minimum at shallow stations.

The primary CTD will be outfitted with dual T/S channels, pressure, dissolved oxygen, reference thermometer, transmissometer, and altimeter. We may have a fluorometer (chlorophyll and/or CDOM) on the CTD. There will also be an LADCP mounted on the rosette. Rosette water samples will be collected for S, O2, nutrients (NO3, NO2, PO4, SiO3), CFCs (F11, F12, SF6), DIC, ALK, pH, DOC, CDOM, helium, tritium, and 14C.

At every second station, there will be a one-hour trace metal rosette cast, carried out on deck (not from the Baltic Room) by the 5-person TM/aerosol team.

Once daily (probably before or after whatever 36-place rosette cast is near local noon) there will be 30 minutes devoted to a hand-lowered optical profile. A moderate-volume surface CDOM sample will sometimes be collected by pumping water during the main rosette cast.

We will operate the ship's ADCP system. We will operate the ship's underway seawater sampling system for its standard parameters plus our pCO2 system. We will operate the underway met system for its standard parameters. The ship will have available multibeam bathymetry (without extra processing) for use in assessing the bottom configuration at and between stations and at mooring sites. At RPSC's discretion, they may operate other ship's underway science systems (e.g., gravimeter) so long as they do not interfere with the primary science programs. RPSC will prepare for us the usual underway and on-station data files including, in addition to the above, time, navigation, centerline depth to bottom, and whatever other standard parameters they attend to.

There will be an aerosol/precipitation collection program.

There will be a solar radiation data collection program.

We will deploy Argo drifters along the track, as we leave CTD stations nearest deployment locations designated by the Argo float PI (Riser, UofWash).

There are currently four mooring recoveries and one mooring deployment - all for programs other than ours - during NBP 11-02. There will be an extra CTD cast at each mooring recovery site, and ca. two extra casts at each mooring deployment site (water samples optional).

## LIST OF SCIENTIFIC PROGRAMS

*CTDO/rosette/S/O2/nutrients/data processing*
Jim Swift, Scripps (jswift@ucsd.edu; ph 858-534-3387; fx 858-534-7383)

*Transmissometer*
Wilf Gardner, Texas A&M U (wgardner@ocean.tamu.edu; ph 979-845-7211)

*CO2 (alkalinity and pH)*
Andrew Dickson, Scripps (adickson@ucsd.edu; ph 858-534-2990)
Frank Millero, RSMAS/MIAMI (fmillero@rsmas.miami.edu; ph 305-361-4155)

*CO2 (DIC and underway pCO2)*
Chris Sabine PMEL/NOAA (chris.sabine@noaa.gov, 206-526-4809)

*DOC/TDN*
Dennis Hansel, RSMAS/Miami (dhansell@rsmas.miami.edu; 305-421-4078)
Craig Carlson, U California Santa Barbara (carlson@lifesci.ucsb.edu, 805-893-2541)

*CDOM & solar radiation*
Stan Hooker, NASA/GSFC (stanford.b.hooker@nasa.gov, 301-286-9503, 410-533-6451)
Craig Carlson, U California Santa Barbara (carlson@lifesci.ucsb.edu, 805-893-2541)

*13C/14C*
Ann McNichol, WHOI (amcnichol@whoi.edu; ph 508-289-3394; fx 508-457-2183)
Robert Key, Princeton (key@Princeton.EDU)

*CFCs*
Bill Smethie, LDEO (bsmeth@ldeo.columbia.edu; ph 845-365-8566)
David Ho, U Hawaii (ho@hawaii.edu; ph 808-956-3311)

*He/Tr*
Peter Schlosser, LDEO (peters@ldeo.columbia.edu; ph 845-365-8816; fx 914-365-8155)
Bill Jenkins, WHOI (wjenkins@whoi.edu; ph 508 289 2554)

*ADCP/LADCP*
Eric Firing, U Hawaii (efiring@soest.hawaii.edu; ph 808-956-7894)
Andreas Thurnherr, LDEO (ant@ldeo.columbia.edu; ph 845-365-8816; fx 914-365-8157)

*Trace elements*
Chris Measures, U Hawaii (chrism@soest.hawaii.edu; ph 808-956-8693)
Bill Landing, U Florida (landing@ocean.fsu.edu; ph 850-644-6037)

*ARGO floats*
Stephen Riser, U of Washington (riser@ocean.washington.edu; ph 206-543-1187)

*Aerosols*
Bill Landing, U Florida (landing@ocean.fsu.edu; ph 850-644-6037)

**Participants at sea**

| | | |
|---|---|---|
| 1 | Jim Swift | chief scientist |
| 2 | Alex Orsi | co-chief scientist |
| 3 | Jesse Anderson | PO student |
| 4 | Sam Billheimer | PO student |
| 5 | Eric Mortenson | PO student |
| 6 | Stuart Pearce | PO student |
| 7 | Mingxi Yang | CFC student |
| 8 | Thomas Decloedt | ADCP/LADCP specialist |
| 9 | TBN (Carl Mattson?) | ET/salts |

| | | |
|---|---|---|
| 10 | Mary Johnson | CTD processor |
| 11 | Kristin Sanborn | bottle processor |
| 12 | Dan Schuller | nutrient tech |
| 13 | Ben Gire | nutrient tech |
| 14 | Melissa Miller | MT/oxygens |
| 15 | Alex Quintero | MT/oxygens & salts |
| 16 | Courtney Schatzman | MT/oxygens & salts |
| 17 | Eugene Gorman | CFC analyst |
| 18 | Dana Erickson | CFC analyst |
| 19 | Kevin Sullivan | DIC analyst |
| 20 | TBN (Cynthia Peacock? Nancy Williams?) | DIC analyst |
| 21 | Ryan Jay Woosley | TA/pH analyst |
| 22 | Wilson Gallardo Mendoza | TA/pH analyst |
| 23 | Laura Fantozzi | ALK analyst |
| 24 | Emily Bockmon | ALK analyst |
| 25 | Charles Farmer | DOC/14C sampling |
| 26 | Aimee Neeley | CDOM sampling |
| 27 | Anthony Daschille | He/Tr sampling |
| 28 | Chris Measures | trace metals |
| 29 | Bill Landing | trace metals/aerosols |
| 30 | Maxime Grand | trace metals |
| 31 | Brian Kilgore | trace metals |
| 32 | Hugo Oliviera | trace metals |
| 33 | TBN | TBN |

In addition there will be two mooring techs (one of whom works for RPSC) and an additional 6 RPSC techs.

**RATIONALE FOR REPEAT HYDROGRAPHY SURVEYS IN SUPPORT OF CLIVAR AND CARBON CYCLE OBJECTIVES (written in 2001)**

This summarizes the scientific rationale and scope of an integrated approach to a global observational program for carbon, hydrographic and tracer measurements. The program is driven by the need to monitor the changing patterns of carbon dioxide ($CO_2$) in the ocean and provide the necessary data to support continuing model development that will lead to improved forecasting skill for oceans and global climate. The WOCE/JGOFS survey during the 1990s has provided a full depth, baseline data set against which to measure future changes. By integrating the scientific needs in the following five areas, major synergies and cost savings will be achieved. These areas are of importance both for upcoming research programs, such as CLIVAR and the U.S. GCRP Carbon Cycle Science Program (CCSP), and for operational activities such as GOOS and GCOS. In this regard, consensus was reached at the First International Conference on Global Observations for Climate, held in St. Raphael, France in October 1999, that one component of a global observing system for the physical climate/CO2 system should include periodic observations of hydrographic variables, CO2 system parameters and other tracers (Smith and Koblinsky, 2000). The large scale observation component of the CCSP has also clearly defined a need for systematic observations of the invasion of anthropogenic carbon in the ocean superimposed on a variable natural background.

**A. Carbon system studies**

There is broad consensus based on a variety of atmospheric, oceanic and modeling constraints that the ocean that the ocean took up 2.0 +/- 0.6 Gt carbon annually during the last decade (Battle 2000, Takahashi, 1999; Orr et al, 2001). The data from the recent WOCE/JGOFS global carbon survey are providing the first comprehensive inventory of anthropogenic CO2 in the ocean. This survey provided a large data set on the total dissolved inorganic carbon (DIC) content of the ocean, at an unprecedented accuracy of 2 $\mu$mol/kg (or 0.1 % of the total concentration). This is equivalent to 1-2 year's uptake of anthropogenic carbon in surface waters. The total anthropogenic inventory of DIC into the ocean can be determined using concurrent, hydrographic, alkalinity, oxygen nutrient and tracer measurements (Gruber et al., 1996). Utilizing transport estimates, the fluxes of carbon within and between oceans and ocean basins can be better constrained, particularly interhemispheric exchange of carbon through the ocean. Atmospheric interhemispheric exchange is an important diagnostic for models and pre-industrial oceanic carbon transport is a key parameter to estimate interhemispheric differences of carbon sources and sinks. The WOCE/JGOFS sections provide a valuable baseline to determine the possible large scale effects of global warming on the ocean's biogeochemistry, whether due to changes in stratification, circulation, or perturbations such as a change in the dust deposition on the ocean's surface.

It is clearly important in terms of predicting long-term climate change and man's effect on the rate of change that we continue to sample the ocean for dissolved carbon components. Further justification on the need for continued oceanic observations of the carbon system are given in the U.S. GCRP publication "A U.S. Carbon Cycle Science Plan" (Sarmiento and Wofsy, 1999) and detailed in the implementation plan (Bender et al., 2001). The repeat observational plan should provide sufficient coverage to determine basin wide changes in DIC and related biogeochemical parameters over a period of approximately a decade. It would serve as a backbone to assess changes in the ocean's biogeochemical cycle in response to natural and/or man induced activity. The proposed cruises can also be a venue for other relevant measurements such as the determination of the partial pressure of CO2 in the surface water which is a critical component to assess the air-sea CO2 flux, and which is a sensitive indicator of changes in the functioning of the biological pump in surface waters.

**B. Heat and freshwater storage and flux studies**

While we have a reasonably good understanding of the pathways of large-scale transport of heat and freshwater in the ocean, we have no real idea of how these pathways change over decadal time scales. One hypothesis is that systematic changes in temperature-salinity relations in the subtropical and subpolar regions are related to changes in the hydrological cycle (Wong et al., 1999). Both modeling and paleo-oceanographic studies suggest the ocean's response to, for instance, changes in the forcing to be expected if atmospheric greenhouse gas concentrations continue to increase, can be rapid. Such changes might shut down the thermohaline circulation in the North Atlantic, for example, by capping the subpolar region with a layer of warmer, fresher water. Global warming-induced changes in the ocean's transport of heat and salt that could affect the circulation in this way can only be followed through long-term measurements at particular sites. (The necessary heating is forecast to be of the order of 2-4 $W/m^2$ for a doubling of carbon dioxide; this is too small to measure with any confidence in the ocean.) This component is vital for CLIVAR and for the CCSP as changes in circulation can dramatically change carbon transport and sequestration estimates (Sarmiento et al., 1998)

**C. Deep and shallow water mass and ventilation studies**

While we know that water mass characteristics can change on short-term timescales (for example, the North Atlantic "great salinity anomaly" or the El Nino/La Nina system) and often in a non-linear fashion (Doney et al., 1998), we still do not understand how and on what time scales the full-depth water mass structure of the ocean responds to atmospheric variability. Chemical tracers such as chlorofluorocarbons CFCs, 3H/3He or 14C add a time dimension, which can vary between days or centuries. This time dimension can be used to: identify newly-ventilated water masses and their formation rates; determine pathways, time scales and rates of water mass spreading along with its anthropogenic CO2 imprint; determine rates of ventilation/subduction and mixing; monitor freshwater input into high latitudes; constrain rates of biogeochemical processes; and constrain model-based estimates of ocean mixing and circulation processes and parameterizations. There is, at present, no alternative to using shipboard sampling for these tracers, and it makes sense to combine such a sampling scheme with any planned sampling of the ocean carbon system. This is particularly true because estimates of anthropogenic CO2 inventories rely heavily on the tracer measurements. Thus this aspect is of importance to both CLIVAR and carbon research.

**D. Calibration of autonomous sensors**

While the development of sensors for many parameters is ongoing, there is an immediate need for salinity calibration for the Argo program (www.argo.ucsd.edu). The release of some 3,000 PALACE-type floats in Argo is a major component of both the CLIVAR ocean program and the initial Global Ocean Observing System (GOOS). It is hoped that both temperature and salinity sensors will remain accurate to within about 0.01°C and 0.01 in salinity for the lifetime of each float (4-5 years). Temperature sensors seem to be stable (within specifications) for this length of time, but salinity sensors are not, being affected mainly by biofouling near the surface. Independent data are therefore necessary to check the salinities provided by these instruments, especially in regions such as the subpolar North Atlantic where deep T/S relationships are known to vary on decadal time scales. Other autonomous sensors, such as CO2, nutrient, and particle sensors, are presently being deployed. This new technology will need *in situ* validation and possibly calibration.

**E. Data for Model Calibration**

Data on the carbon dioxide system, hydrography and transient tracers provide key observational fields to validate process models, and for the calibration of (climate) models. To predict future atmospheric CO2 levels and global heat and freshwater balances, long-term model integrations must ensure water mass formation and transport occur at the correct rates. For example, large volumes of the ocean (e.g., the sub-thermocline Angola Basin or the deep North Pacific) are still free of either transient tracers. Thus, monitoring the penetration of tracers into these areas gives us a direct measure of the rate of uptake of greenhouse gases for comparison with model outputs. Similarly, regions of active ventilation, for instance, south of Iceland, or in the Labrador Sea, can be easily identified and provide a key diagnostic for ventilation rate estimates. Changes in carbon and heat inventory also provide strong constraints on models and their forcing functions.

**An integrated sampling strategy**

The scientific and logistical interests of the ocean carbon, hydrographic, and tracer communities presently overlap, and considerable synergism (and cost reduction) will be achieved by occupying a series of full-depth hydrographic cruises at decadal intervals. A suggested minimum set of such lines is given in Table 1 (see strawman plan on sections). While this set has been selected for looking at long-term changes, not seasonal changes, some lines will monitored more frequently in companion efforts. The choice and sequencing of lines takes into consideration the overall objectives of the program, dates of last occupation during WOCE/WHP, international plans, providing global coverage, and anticipated resources.

Beyond the repeat hydrography program, a limited number of time-series stations is recommended but not proposed here. These can help determine whether observed changes are local, regional, or basin-wide, monitor temporal changes between survey cruises, and possibly even alert us to unexpected rapid changes associated with air-sea forcing such as the PDO or NAO that may need to be reassessed with survey cruises sooner than planned. Potential sites for such monitoring include the sites of the Ocean Weather Ships (e.g., Mike in the Norwegian Sea and Bravo in the Labrador Sea), as well as off Hawaii and Bermuda where observations have been taken throughout WOCE and JGOFS. Additional sites might take advantage of ongoing activities such as the TAO and PIRATA moorings to monitor the air-sea CO2 fluxes in the equatorial Pacific and Atlantic oceans. The necessary instrumentation to support such fixed stations either exists, or are in development, which will reduce the present heavy reliance on shipboard sampling. The large scale observational fields will also serve to put time series and process studies in proper spatial context.

As outlined in Table 1 the U.S. program likely will consist of one or two cruises per year on a 10-14 year rotation. For costing purposes , it is assumed that each cruise will last about 45 days. Using WOCE sampling rates of four full-depth stations per day, 30-mile station spacing, and a cruising speed of 10 kt, this gives a cruise track of about 5,500 miles/10,000 km. Obviously this will not suffice for a zonal section in the equatorial Pacific (>16,000 km), but it is overgenerous for almost all other lines. Costs, based on those of the U.S. WOCE Indian Ocean expedition of 1994-1996 adjusted for inflation and the higher costs of doing fewer lines per year, is estimated at $3,000 K. This estimate includes approximately $700 K for survey or basin specific ancillary measurements.

The integrated approach and multi-year proposal mechanism provides many scientific benefits as outlined above and also significant logistic advantages. Ship time requirements can be planned well in advance and it provides continued support for groups of trained seagoing technicians for the analyses, together with the associated quality control and data archiving. It also facilitates investments in upgrades in quality control, data management and instruments necessary for the US to remain on the forefront of this type of research. Mechanisms must be put in place to ensure that data is rapidly disseminated to the community at large, and that opportunities are available to interpret the data and use the data in a meaningful fashion in modeling exercises. Without a commitment for long-term funding of such efforts, the full long-term potential of these measurements will not be realized.

**References**

Battle, M., M. Bender, P. Tans, J.W.C. White, J.T. Ellis, T. Conway, and R.J. Francey, 2000. Global carbon sinks and their variability inferred from atmospheric O2 and d13C, *Science*, *287*, 2467-2470.

Doney, S.C., J.L. Bullister, and R. Wanninkhof, 1998. Climatic variability in ocean ventilation rates diagnosed using chlorofluorocarbons, *Geophys. Res. Let.*, *25*, 1399-1402.

Gruber, N., J. L. Sarmiento and T. F. Stocker, 1996. An improved method for detecting anthropogenic CO2 in the oceans. Global Biogeochem. Cycles, 10, 809-837.

Sarmiento, J. L. and S. C. Wofsy, 1999. *A U.S. Carbon Cycle Science Plan*. U.S. GCRP, Washington, D.C., 69 pp.

Bender , M. et al., LSCOP, Large Scale Carbon Observation plan: oceans and atmosphere. <http://www.ogp.noaa.gov/mpe/gcc/co2/observingplan/>

Orr, J. C, E. Maier Reimer, et al. 2001 Estimates of anthropogenic carbon uptake from four three-dimensional global ocean models. *Global Biogeochem.Cycles, 15*, 43-60.

Sarmiento, J.L., T.M.C. Hughes, R.J. Stouffer, and S. Manabe, 1998. Simulated response of the ocean carbon cycle to anthropogenic climate warming, *Nature*, *393*, 245-249.

Smith, N. and C. Koblinsky, 2000. Ocean Obs Conference Statement. Proceedings Ocean Observation 1999 Conference, St. Raphael France.

Takahashi, T., R.H. Wanninkhof, R.A. Feely, R.F. Weiss, D.W. Chipman, N. Bates, J. Olafsson, C. Sabine, and S.C. Sutherland, Net sea-air CO2 flux over the global oceans: An improved estimate based on the sea-air pCO2 difference, in *Proceedings of the 2nd International Symposium on CO2 in the Oceans*, edited by Y. Nojiri, pp. 9-15, Center for Global Environmental Research, NIEST, Tsukuba, JAPAN, 1999.

Wong, A. P. S., N. L. Bindoff and J. A. Church. 1999. Large-scale freshening of the intermediate waters in the Pacific and Indian Oceans. Nature, 400, 440-443.