APPENDIX

Underway CO_2 Measurements Aboard the RVIB Palmer and Data Management of the Global VOS Program

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1. Introduction

This proposal is a request for the third year continuation of the active NOAA grant ending August 31, 2009: **NAO80AR4320754** entitled "Underway CO_2 Measurements aboard the RVIB Palmer and Data Management of the Global VOS Program". In this proposal, the funds supporting the activities of the Lamont-Doherty Observatory (LDEO) and the Bermuda Institute for Ocean Sciences (BIOS) (as a subcontract) are requested jointly. Although these groups share a common goal for the elucidation of sea-air CO_2 flux over the oceans, the progresses made by each group are documented separately.

2. Scientific Objectives

The sea-air net flux of CO_2 is governed by the difference between pCO_2 in surface ocean water and the overlying atmosphere as well as by the gas transfer rate across the sea-air interface. The seawater pCO_2 depends primarily on the processes occurring within the sea (such as seawater temperature, biological productivity and upwelling of deep waters), whereas the gas transfer rate is regulated mainly by atmospheric processes including turbulence induced by winds. The primary objective of this proposed investigation is to determine the space-time distribution of the ocean surface pCO_2 and the sea-air pCO_2 difference. Combining the sea-air pCO_2 difference with the CO_2 gas transfer coefficient which is being investigated by other scientific groups, a reliable net sea-air flux of CO_2 over regional to global scales can be estimated using improved sea-air pCO_2 difference data. The work by the LDEO group is primarily focused in the southern high latitude areas surrounding the Antarctic continent, whereas the BIOS group is in the western North Atlantic Ocean. Thus, the results will give us an improved geographical coverage for the sea-air CO_2 transfer flux over the global ocean.

The LDEO group operates a semi-automated surface water pCO_2 system aboard the RVIB Nathaniel Palmer with significant operational assistance from the Raytheon Polar Support group (funded by NSF). RVIB Palmer is an ice-breaking research vessel, one of the few research ships operated in high latitude areas of the Southern Ocean even during winter months. Hence, the LDEO program yields observations critical to our understanding of the role of the high latitude Southern Ocean around Antarctica including the Weddell and Ross Seas in the global carbon cycle (see Fig. 1). The BIOS program is directed to the mid-latitude areas of the western North Atlantic Ocean and in the vicinity of the Bermuda Time Series Station (BATS) aboard a container ship Oleander and R/V Weatherbird II and Atlantic Explorer.

Our proposed work is a part of a consortium of investigators who operate their respective pCO_2 systems aboard other research and commercial vessels. The consortium includes the following groups: Richard Feely and his PMEL/NOAA group investigate mainly the equatorial Pacific aboard the NOAA ships; Rik Wanninkhof and his group at AOML/NOAA are primarily responsible for measurements over the Atlantic Ocean; Frank Millero and his group at the University of Miami investigates coastal waters and Caribbean

Sea. Pooling of the data among the participants will allow us to cover a large part of the global oceans. Under this grant, the Lamont-Doherty Observatory group is responsible for quality-control and management of the data produced by the NOAA-supported groups as well as those from international collaborators from Japan, Iceland, Germany and France. The data are processed into a single uniform format and are made accessible to the participants via the LDEO web site (www.ldeo.columbia.edu/CO2) as well as to the public through the Carbon Dioxide Information and Analysis Center (CIDAC) at the Oak Ridge National Laboratory, TN.

3. Progress To Date, The LDEO Program

The progress made during a period January, 2001 through April, 2010, is described in this section. The data acquired under this grant have been submitted to the Carbon Dioxide Information and Analysis Center, Oak Ridge, TN, for archiving and public access. To date, two versions have been published: Version 1.0 consists of about 3.6 million pCO2 data (Takahashi et al., v. 1.0, 2008) and Version 2007 consists of about 4.5 million pCO2 data (Takahashi et al., v. 2007, 2008). Version 2009 is being prepared for submission to CDIAC. A global synthesis of the Version 1.0 data has been published by Takahashi et al. (2009), which includes 28 national and international co-authors.

3.1. Highlights of Findings

3.1.1. The global ocean surface water pCO_2 database.

A newly updated, consisting of about 4.4 million pCO_2 observations have been assembled and made available to the public through the CDIAC. This is the most extensive database for world ocean surface water pCO_2.

3.1.2. Updated climatological mean distributions of surface water pCO_2 and the estimated sea-air CO_2 flux

These have been improved especially in the high latitude Southern Ocean areas. The waters under seasonal ice fields are found to be a CO_2 source to the atmosphere due to high CO_2 layers formed under ice by the vertical mixing of deep waters (see yellow areas along 60°S in Figure 1). The CO_2 uptake by the global oceans is estimated to be 1.4 ±0.7 Pg-C/yr during the decade of 1990-2000. The uncertainty in the flux depends on wind speed products used for estimating the sea-air gas transfer rates. Improved wind speed data over the global oceans would reduce the CO_2 flux uncertainty significantly.

3.1.3. The sea-air CO_2 fluxes estimated by various methods are in agreement

The Sea-air CO_2 fluxes over major ocean basins that are estimated using four independent methods are compared in Figure 2 (Gruber et al., BGC, 2009). The methods include a) an inversion of oceanic CO_2 concentration data using ocean GCM's, b) observed sea-air pCO_2

difference, c) inversion of atmospheric CO_2 concentration data using atmospheric GCM's, and d) ocean forward model using a marine biogeochemical model coupled with ocean GCM's. These estimates for a contemporary ocean up-take are in agreement with a mean value of 1.8±0.3 Pg-C/yr. However, the biogeochemical-ocean GCM's yield an excessively strong sink in the southern polar region. This may be attributed to over estimation of biological pump intensity in the high latitude waters. The atmospheric inversion methods yield a small source for the temperate South Pacific, whereas three other methods yield moderate sinks. This may be due to the lack of atmospheric CO_2 observations in the eastern South Pacific.

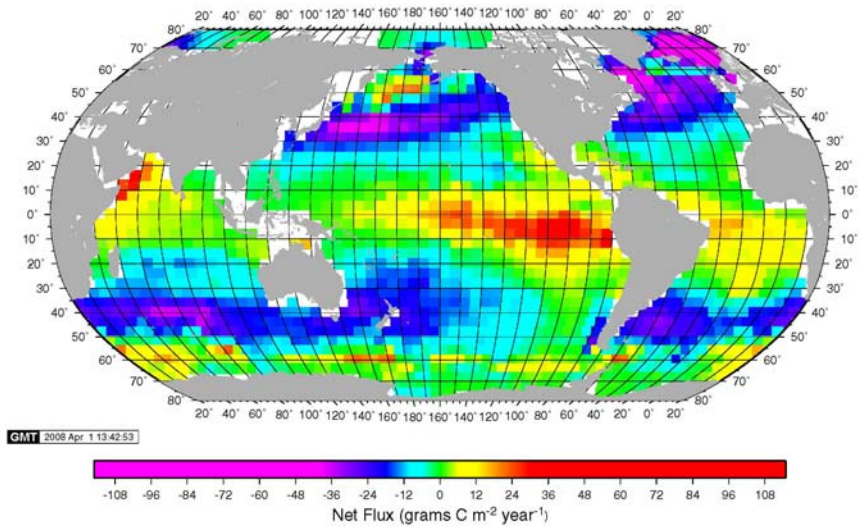

Figure 1 *– Sea-air CO_2 flux estimated using the climatological mean sea-air pCO_2 observations in a reference year 2000. Orange-yellow areas indicate that the ocean is a CO_2 source for the atmosphere, and magenta-blue areas, a sink for atmospheric CO_2. (Takahashi et al., Deep-Sea Res. II, 2009).*

3.1.4. Weakening of the Southern Ocean CO_2 sink

The winter-time surface water pCO_2 in the ice-free zone of the Southern Ocean has been found to be increasing over the past three decades at a mean rate of 2.1±0.6 uatm/yr that is faster than the atmospheric CO_2 concentrations of 1.5 uatm/yr (Figure 3). This suggests that the sea-air pCO_2 difference is reduced and the CO_2 sink intensity over the Southern Ocean is weakening during the recent three decades. Since the biological activities are minimum and the vertical mixing of subsurface waters is maximum during the winter months, the observed increase may be interpreted as a result of increased upwelling (or meridional overturning) rates. This is consistent with the conclusion by Le Quéré et al. (2007) who used the ocean biogeochemistry GCM,s and the inversion of atmospheric CO_2 data.

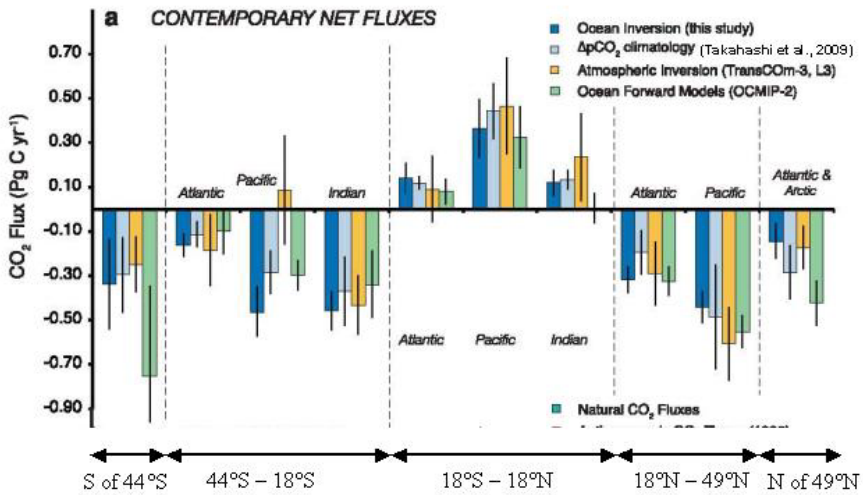

Figure 2 *– Comparison of sea-air CO_2 fluxes obtained by the four independent methods for the five major ocean basins for the contemporary oceans: a) ocean CO_2 inversion (Gruber et al., GBC, 2009), b) observations of sea-air pCO_2 differences (Takahashi et al., DSR II, 2009), c) atmospheric CO_2 inversion (TransCOm-3, L3) and d) biogeochemical ocean GCM's (OCMIP-2). The plot is from Gruber et al. (GBC, 2009).*

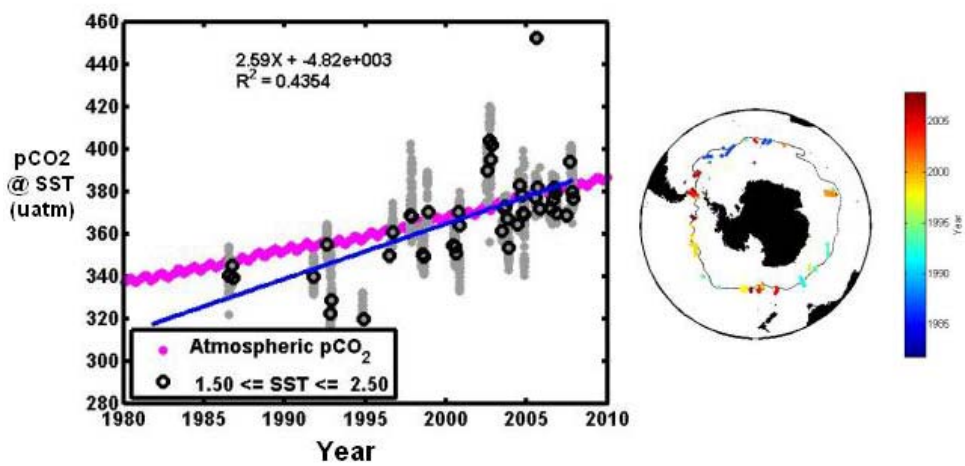

Figure 3 *– Time-trend of surface water pCO_2 in the ice-free zone of the Southern Ocean in temperatures between 1.5°C and 2.5°C observed during the winter months (late June through mid-November) 1980-2007. The linear regression trend line for the surface water pCO_2 (2.6 µatm/yr) is in blue, and is increasing faster than the atmospheric CO_2 trend shown in magenta. The time-space distribution of the seawater pCO_2 observations is shown on the right. An analysis of six temperature zones ranging from 0.8°C to 6.5°C yields a mean rate of* 2.1 ±0.6 µatm/yr.

3.2. LDEO Field Program

3.2.1. RVIB Palmer

The Lamont group is primarily responsible for the acquisition of the surface water pCO_2 data aboard the RVIB Palmer. Our pCO_2 system has been upgraded three years ago with the support from NOAA, and some new modifications are being added since in order to make the system more stable and reliable. As the data are obtained, they are processed and added to our global database, which consists presently of about 4.4 million pCO_2 measurements in surface waters plus supplemental information including the SST, salinity, wind speeds, barometric pressure and atmospheric CO_2 concentration.

The locations of our data obtained since the beginning of this project in 2001 are shown in Figure 4, and the dates, location and number of measurements are listed in Table 1. The total number of surface water pCO_2 data obtained to date is 851,618, of which about 32,528 measurements were added to the database during the current project period September, 2009-March, 2010. The data recovery % is computed as the ratio of the time period for successful observations to the total at-sea time. The mean data recovery rate since 2001 is 95.2%, while the average for the last three years is 98.7%. The high data recovery rate is credited to the diligent assistance provided by the on-board staff members of the Raytheon Polar Services Co.

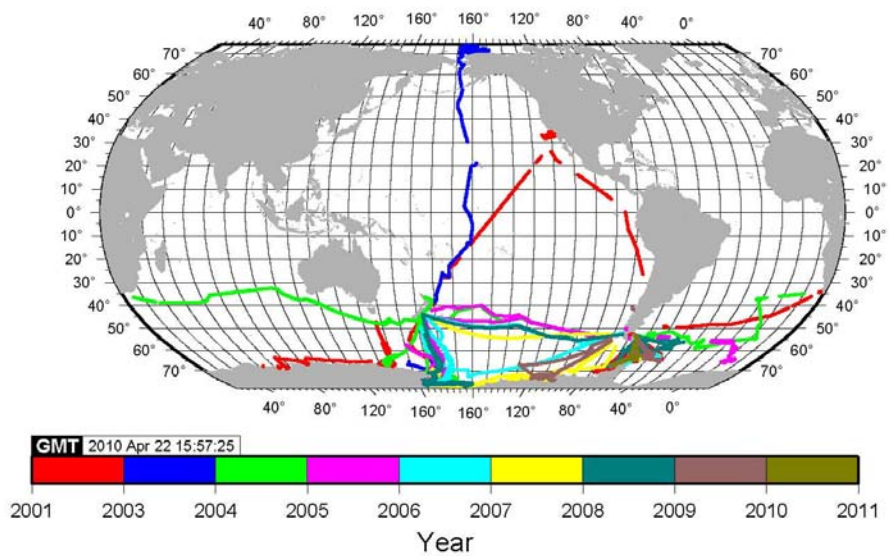

***Figure 4**. The locations of surface water pCO_2 measurements made aboard the RVIB Palmer since 2001. The years when the observations were made are color-coded. During the current project year Sept. 2009-March 2010, about 32,528 pCO_2 measurements were obtained, and have been added to our global VOS database.*

Table 1 *– List of the RVIB N. B. Palmer expeditions and the number of surface water pCO_2 measurements obtained from January, 2001 through March, 2010. Detailed monthly numbers of observations are presented only for the last three year period, 2007-2010.*

Cruise ID	Project Name	Dates	No. of Observations	% Recovery	Year Total
Calendar Year 2001					
	Annual Total			**82.0**	**129,414**
Calendar Year 2002					
	Annual Total			**89.7**	**113,329**
Calendar Year 2003					
	Annual Total			**96.0**	**93,590**
Calendar Year 2004					
	Annual Total			**97.9**	**118,906**
Calendar Year 2005					
	Annual Total			**97.1**	**72,455**
Calendar Year 2006					
	Annual Total			**98.6**	**103,502**
Calendar Year 2007					
07/1	Geological Research	22 Dec 06 - 29 Jan 07	14,963	100.0	
07/2	Amundsen Sea Research	03 Feb - 25 Mar	20,780	97.7	
07/3	Collaborative Research	31 Mar - 05 May	12,781	98.5	
07/4	Open Period	10 May - 20 Jun	no data		
07/5	Transit to Maintenance Period	21 - 25 Jun	no data		
07/6	Drydock	25 Jun - 28 Jul	no data		
07/7	Transit to Punta Arenas, Chile	28 Jul - 02 Aug	no data		
07/8	Open Period	02 - 27 Aug	no data		
07/9	Sea Ice Balance in the Antarctic	01 Sep - 31 Oct	14,616	97.8	
07/10	Palmer Station Resupply	14 Nov - 07 Dec	8,548	95.9	
07/11	Transit, Chile - New Zealand	14 - 30 Dec	6,355	100.0	
	Annual Total			**98.3**	**78,043**
Calendar Year 2008					
08/1	Ross Sea Research	08 - 27 Jan	6,876	98.5	
08/2	Ross Sea Research	29 Jan - 20 Feb	8,562	98.8	
08/3	Ross Sea Research	23 Feb - 23 Mar	8,330	99.9	
08/4	Transit Lyttleton, N.Z. - Punta Arenas, Chile	21 Mar - 14 Apr	9,300	100.0	
08/5	Drake Passage - S. Atlantic Research	18 Apr - 25 May	13,525	98.9	
08/6	Drake Passage - S. Atlantic Research	01 - 30 Jun	10,861	99.5	
08/7	No Cruise				
08/8	Drake Passage - Antarctic Penn.	11 Jul - 06 Aug	9,196	99.5	
08/9 - 08/11	No Cruise				
08/12	Drake Passage	20 Nov - 12 Dec	8,732	97.9	
	Annual Total			**99.1**	**75,382**
Calendar Year 2009					
09/1	Amundsen-Bellinghausen Sea	06 Jan - 26 Feb	19,310	99.1	
09/2	Drake Passage - S. Atlantic Research	06 May - 14 Apr	15,159	98.5	
09/3-09/4	Not Operational				
09/5	Dry dock				

09/5A	Equipment Test	08 - 17 Oct	984	99.4	
09/6	Open Period				
09/7	Not Operational				
09/8	Antarctic Circumpolar Current	19 Nov - 19 Dec	10,830	96.0	
	Annual Total			**98.3**	**46,283**
Calendar Year 2010					
10/1	Larsen Ice Shelf	02 Jan - 02 Mar	20,714	99.3	
	Annual Total			**99.3**	**20,714**
TOTAL SINCE 2001				**95.2**	**851,618**

3.2.2. RVIB L. M. Gould

Our underway pCO_2 system has been operated aboard R/V Laurence M. Gould, which is supported by NSF as a part of the Long-Term Research in Environmental Biology (LTRE) program in the Drake Passage area, Southern Ocean. The surface water pCO_2 program aboard the R/V L. M. Gould is maintained and the data are processed and managed with support of this grant. The sampling locations are shown in Figure 5, and the dates and the number of pCO_2 measurements made during each of these programs are summarized in Table 2. A total of 29,132 pCO_2 measurements were made aboard the R/V Gould during September, 2009-March, 2010. The relatively small number of measurements during this period is due to the long lay-off periods of the ship (April-Oct., 2009 and Oct.-Nov., 2009). The new data make a total of 497,623 pCO_2 measurements for the Gould program since its inception in March, 2002. The data recovery rate during this period is 98.2%, while the eight-year mean rate is 93.1%.

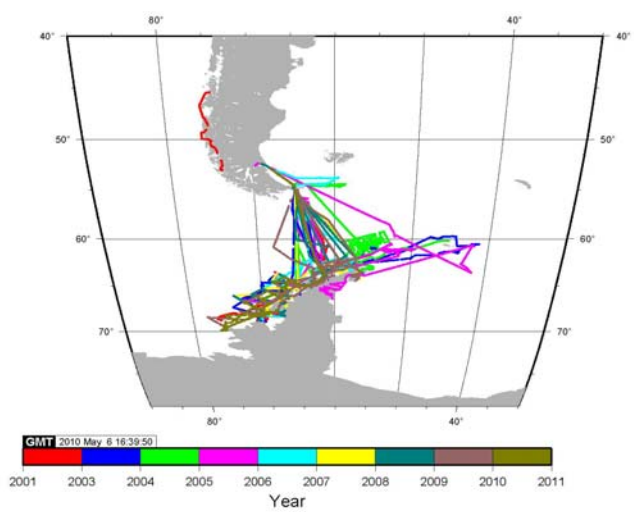

Figure 5 *– The locations of the surface water pCO_2 measurements obtained aboard the R/V Gould during this project, March, 2002 through March, 2010. A total of 497,623 pCO_2 measurements were made since the beginning of the project in 2002. During the current funding period, Sept.,2009-March 2010, 29,132 pCO_2 measurements were made. The years of the measurements are color-coded. These data have been processed and quality-controlled by this project.*

Table 2 *– List of the R/V Laurence M. Gould expeditions and the number of surface water pCO_2 observations added to the VOS database since 2002. Detailed monthly numbers of observations are presented only for the current funding period, September. 2009-March, 2010. 29,132 new observations have been added during this reporting period.*

Cruise ID	Project Name	Dates	No. Observations	% Recovery	Year Total
Calendar Year 2002					
	Annual Total			**77.8**	**41,486**
Calendar Year 2003					
	Annual Total			**93.1**	**69,952**
Calendar Year 2004					
	Annual Total			**98.6**	**67,664**
Calendar Year 2005					
	Annual Total			**86.7**	**63,087**
Calendar Year 2006					
	Annual Total			**92.6**	**59,602**
Calendar Year 2007					
07/1	LTER Antarctica	01 Jan - 11 Feb	12,376	94.2	
07/2	Peterman Is. Close Stations	16 Feb - 01 Mar	3,766	100.0	
07/3	Palmer Station Shuttle	08 - 19 Mar	2,439	100.0	
07/4	Palmer Turnover	23 Mar - 06 Apr	2,637	100.0	
07/5	Biological Research	11 Apr - 09 May	6,997	100.0	
07/6	Logistic Cruise	12 May - 03 Jun	5,290	99.6	
07/7	Hazardous Waste Shuttle	07 - 22 Jun	2,414	89.9	
07/8	Dry dock maintenance	23 June - Sept 12			
07/12	Palmer Station Opening	13 - 29 Sep	3,200	100.0	
07/13	COPA Opening	08 - 20 Oct	2,750	90.5	
07/14	Open Period, maintenance	21 Oct - 3 Nov			
07/15	Palmer Shuttle	04 - 16 Nov	3,395	100.0	
07/16	No Cruise				
07/17	Antarctic Penn. Research	22 Nov - 22 Dec	9,960	99.9	
	Annual Total			**97.6**	**55,224**
Calendar Year 2008					
08/1	LTER Antarctica	30 Dec 07 - 09 Feb 08	11,724	100.0	
08/2	COPA Opening	14 Feb - 17 Mar	9,121	100.0	
08/3	Palmer Turnover	22 Mar - 04 Apr	2,377	100.0	
08/4	Palmer Shuttle	08 - 23 Apr	4,178	98.3	
08/6	Drake Passage Research	27 Apr - 21 May	6,374	93.9	
08/7	Drake Passage Research	28 May - 15 Jun	4,730	100.0	
08/8	Palmer Shuttle	24 Jun - 08 Jul	3,972	99.9	
08/9	Palmer Shuttle	11 Jul - 08 Aug	6,172	100.0	
08/10	Palmer Shuttle	13 Aug - 10 Sep	8,198	98.8	
08/11	Palmer Shuttle	14 - 28 Sep	2,259	87.7	
08/12	Palmer Shuttle	16 - 28 Oct	3,587	100.0	
	Annual Total			**98.1**	**62,692**
Calendar Year 2009					
09/1	LTER Antarctica	31 Dec 08 - 05 Feb 09	11,692	99.9	

09/2	Drake Passage - Antarc. Penn.	11 Feb - 16 Mar	10,839	100.0	
09/3	Drake Passage - Antarc. Penn.	21 Mar - 09 Apr	5,577	99.8	
09/4	No Cruise				
09/5	Palmer Shuttle	21 Apr - 11 Jun	15,326	99.9	
09/6A	Hazmat Transit	15 Jun - 01 Jul	3,300	99.9	
09/7	Transit Chile - Louisiana	04 - 27 Jul	2,050	100.0	
09/8	Transit Louisana - Chile	16 Aug - 11 Sep	Pending		
09/9	Palmer Shuttle	16 Sep - 08 Oct	5,278	99.7	
09/10	Palmer Station Opening #2	13 - 28 Oct	3,885	100.0	
09/11	Geoscience Island Field Camps	23 Nov - 22 Dec	9,030	100.0	
	Annual Total			**99.9**	**66,977**
Calendar Year 2010					
10/1	Western Penninsula	30 Dec 09 - 02 Feb 10	10,939	92.9	
	Annual Total			**92.9**	**10,939**
GRANT TOTAL SINCE 2002				**93.1**	**497,623**

3.2.3. M/V Comer Turmoil

In 2007, an underway pCO_2 system was constructed and installed aboard the M/V Comer Turmoil with a grant from the Comer Education and Research Foundation. Presently, its operation and data processing are partially supported with the VOS/NOAA grant. Since Turmoil is a family yacht and has visited many coastal locations, a large portion of the data from this ship is for coastal waters, which have not been frequently sampled. During the current funding period, about 30,000 pCO_2 data were obtained, and these data have been processed and added to our global database, making the total of 164,918 pCO_2 measurements from this ship since the inception of this program in November, 2007. Figure 6 shows the surface water pCO_2 values (color-coded) along her tracks in 2007-2008. The number of pCO_2 measurements made in each year is listed in Table 3 along with other VOS ships. Since the number of hours at sea (excluding the harbor time) cannot be documented, the data recovery % is not given.

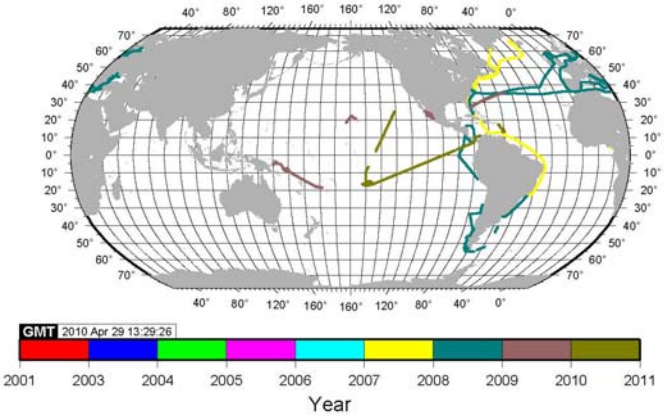

Figure 6 *– The locations of the surface water pCO_2 measurements obtained aboard the M/V Comer Turmoil since the inception of the program in 2007. The colors indicate the year of measurements. A total of about 30,000 new measurements have been added during the current funding period to our VOS database.*

3.2.4. LDEO R/V M. Langseth

R/V Marcus Langseth is operated by LDEO with funds from NSF mostly for geophysical studies. Since the ship is used for geophysical studies in small areas for month at a time, it is suited for investigating variability of pCO_2 in small ocean areas in details. An underway pCO_2 system has been constructed with funds from this grant and was installed in February 2008 aboard R/V Langseth. However, the old underway water pumping system aboard the ship has been found deficient in many ways, and a completely new system was installed in April, 2010, during the mid-life refit of the ship. The ship departed Astoria, OR, on May 8, 2010 for Hawaii and then to Guam, with Tim Newberger aboard to thoroughly test the underway pCO_2 system. As of May 10, he reported that the pCO_2 measurements are functioning well. The data will be transmitted weekly to the LDEO CO_2 laboratory, after Newberger's departure from the ship in Guam, and the quality-controlled data will be added to the VOS database.

3.2.5. USCGC Healy

USCGC Healy is one of the few US ships operating primarily in the Arctic, where seasonal CO_2 observations are lacking. Since waters flowing out of the Arctic basin should have a significant impact on the North Atlantic CO_2 budget, our understanding of the time-space variability of pCO_2 in surface waters in this basin is important. The installation of a new underway pumping system for scientific purposes and an underway pCO_2 system have been approved by the Arctic Icebreaker Coordinating Committee (Chaired by Carin Ashjian) in November, 2007. This pCO_2 system will become an integral part of a NSF-sponsored surface water measurement system (Dale Chayes, P.I. and coordinator) that includes underway measurements of temperature, salinity and bio-luminescence. The pumping system is being designed and evaluated by the US Coast Guard. It is expected to be installed in December, 2010, and our pCO_2 measurements will hopefully start in the spring of 2011.

3.3. CO_2 Data Processing and Management for the VOS Program

The Lamont group is responsible for processing and managing the surface water pCO_2 data acquired by the members of the Volunteer Ocean Survey (VOS) consortium, so that the participants of the program are able to access of the data in an uniform electronic format. For this purpose, we have established an open web site at the following URL: http://www.ldeo.columbia.edu/CO2. The site provides not only the numerical data, but also maps showing the ship's tracks for each data file. The new data will be accessible only to the VOS participants for a period of three years, and will be released to the public after this period through the Carbon Dioxide Information and Analysis Center, Oak Ridge, TN.

We have received the data from the following participating members of the VOS program and have added quality-controlled data to our database;

1) the NOAA's "Ronald Brown" program, mostly in the Atlantic Ocean (R. Wanninkhof);

2) the "Explorer of the Seas" program in and around the Caribbean Sea (R. Wanninkhof);

3) the "Kaimimoana" program in the equatorial Pacific (R. A. Feely);

4) the "Gordon Gunter" program, (R. Wanninkhof);

5) the "Columbus Waikato" program (R. Wanninkhof);

6) R/V Atlantic Explorer program of BIOS (N. Bates).

The data obtained from these groups are summarized in Table 3. During the current funding period, 332,185 pCO_2 data were added to the VOS database.

Table 3 *- Surface water pCO_2 data received from the AOML/NOAA and PMEL/NOAA groups for quality control and archiving. These data have been quality-controlled and 332,185 new pCO_2 observations have been added to the VOS database during this reporting period.*

Year	No. of Legs (Files)	No. of pCO2 Observations	Ship Total
Ship: Ronald Brown			
2001	12	41,358	
2002	13	26,341	
2003	10	26,291	
2004	10	23,449	
2005	10	26,714	
2006	11	32,537	
2007	8	26,287	
2008	1	5,926	
2009	0	0	
			208,903
Ship: Explorer of the Seas			
2002	30	39,262	
2003	39	76,322	
2004	50	82,043	
2005	44	67,231	
2006	39	57,576	
2007	35	53,268	
2008	3	6,673	
2009	9	7,448	

			389,823
Ship: Kaimimoana			
2001	2	5,641	
2002	5	15,017	
2003	5	28,597	
2004	4	13,742	
2005	0	0	
2006	0	0	
2007	2	34,009	
2008	7	137,875	
2009	0	0	
			234,881
Ship: Gordon Gunter			
2008	7	29,565	
2009	9	25,262	
			54,827
Ship: Columbus Waikato			
2004	6	42,907	
2005	16	84,134	
2006	1	8,737	
			135,778
Ship: Atlantic Explorer			
2006		48,592	
2007		73,285	
2008		88,355	
2009		0	
			210,232
Ship: Turmoil			
2007	9	22,489	
2008	11	83,896	
2009	4	30,781	
2010	3	27,752	
			164,918
Grand Total			**1,399,362**
New Data added during this funding period			**332,185**

3.4. LDEO Publications, Data Analysis and Synthesis

During this grant period, 2009-10, the following research papers and data reports have been published.

Takahashi, T., Sutherland, S. C., Wanninkhof, R., Sweeney, C., Feely, R. A., Chipman, D. W., Hales, B., Friederich, G., Chavez, F., Watson, A., Bakker, D. C. E., Schuster, U., Metzl, N., Yoshikawa-Inoue, H., Ishii, M., Midorikawa, T., Nojiri, Y., Sabine, C., Olafsson, J., Arnarson, T. S., Tilbrook, B., Johannessen, T., Olsen, A., Bellerby, R.,

Körtzinger, A., Steinhoff, T., Hoppema, M., de Baar, H. J. W., Wong, C. S., Delille, B. and Bates, N. R. (2009). Climatological mean and decadal changes in surface ocean pCO_2, and net sea-air CO_2 flux over the global oceans. Deep-Sea Res. II, doi: 10.1016/j.dsr2.2008.12.009.

Gruber, N., Gloor, M., Mikaloff Fletcher, S. E., Doney, S. C., Dutkiewicz, S., Follows, M., Gerber, M., Jacobson, A. R., Joos, F., Lindsay, K., Menemenlis, D., Mouchet, A., Műller, S. A., Sarmiento, J. L. and Takahashi, T. (2009). Oceanic sources, sinks, and transport of atmospheric CO_2. Glob. Biogeochem. Cycles., 23, GB1005, doi:10.1029/2008GB003349,2009.

Olafsson, J., Olafsdottir, S. R., Benoit-Cattin, A., Danielsen, M., Arnarson, T. S., and Takahashi, T. (2009). Rate of Iceland Sea acidification from time series measurements, Biogeosciences, 6, 2661-2668.

Takahashi, T., Sutherland, S. C., Wanninkhof, R., Sweeney, C., Feely, R. A., Chipman, D. W., Hales, B., Friederich, G., Chavez, F., Sabine, C., Watson, A., Bakker, D. C. E., Schuster, U., Metzl, N., Yoshikawa-Inoue, H., Ishii, M. Midorikawa, T., Nojiri, Y., Kortzinger, A., Steinhoff, T., Hoppema, M., Olafsson, J., Arnarson, T. S., Tillbrook, B., Johannessen, T., Olsen, A., Bellerby, R., Wong, C. S., Delille, B., Bates, N. R. and de Baar, H. J. W. (2009). Corrigendum to "Climatological mean and decadal change in surface ocean pCO_2 and net sea-air CO_2 flux over the global oceans" [Deep-Sea Res. II, 56, 554-577]. Deep-Sea Res. I 56, 2075-2076. doi:10.1016/j.dsr2009.07.007.

Le Quéré, C., Raupach, M. R., Canadell, J. G., Marland, G., Bopp, L. Ciais, P., Conway, T. J., Doney, S., Feely, R., Fester, P., Friedlingstein, P., Houghton, R. a., House, J., Huntingford, C., Levy, P., Lomas, M. R., Majkut, J., Metzl, N., Ometto, J., Peters, G. P., Prentice, I. C., Randerson, J. T., Rodenbeck, C., Running, S., Sarmiento, J., Schuster, U., Sitch, S., Takahashi, T., Vivoy, N., van der Werf, G. R., Woodward, F. I. (2009). Trends in the sources and sinks of carbon dioxide. Nature Geoscience, 2, 831-836, doi:10.1038/NGEO689.

Takahashi, T., S. C. Sutherland, and A. Kozyr. (2009). Global Ocean Surface Water Partial Pressure of CO2 Database: Measurements Performed during 1968-2008 (Version 2008). ORNL/CDIAC-152, NDP-088r. Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U. S. Department of Energy, Oak Ridge, Tennessee, doi: 10.3334/CDIAC/otg.ndp088r <http://cdiac.ornl.gov/oceans/LDEO_Underway Database/LDEO home.html_>

Olafsson, J., Olafsdottir, S. R., Benoit-Cattin, A. and Takahashi, T. (2010). The Irminger Sea and the Iceland Sea time series measurements of seawater carbon and nutrient chemistry 1983-2008. Earth System Science Data, 2, 99-104.

Le Quere, C., Takahashi, T., Buitenhuis, E. T., Rodenbeck, C. and Sutherland, S. C. (accepted for publication). Impact of climate change on the global oceanic sink of CO_2. Global Biogeochem. Cycles.

3.5. Public Services

Takahashi has served the following committee as a full member;

Member, Climate Research Committee (CRC), Board of Atmospheric Sciences (BASC), National Research Council/National Academy of Sciences, 2007-2009.

Member, Science Steering Committee, Ocean Carbon Biogeochemistry Program, (multi-agency supported) Woods Hole Oceanographic Institution, Woods Hole, MA, 2009-present.

3.6. Honors Received

"Champions of the Earth" Award, United Nations. April, 2010.

4. Progress To Date, The Bios Program

The main metric for this program is obtaining, reducing, quality controlling and disseminating high quality surface water and marine boundary layer atmospheric pCO_2 data. A short summary of efforts on ships in included below.

Please note that the BIOS PI (Bates) suffered a very serious illness during 2008 and early 2009 that restricted efforts on this grant.

4.1. BIOS Field Program

4.1.1. R/V Atlantic Explorer

The R/V *Atlantic Explorer* operates in the North Atlantic Ocean servicing four oceanographic time-series (e.g., Bermuda Atlantic Time-series Study, Hydrostation S, Bermuda Testbed Mooring, Ocean Flux Program) and other research projects. The geographic focus of data collection is primarily zone NA6, but included several transects between Bermuda and Puerto Rico (across an infrequently sampled part of the permanently stratified oligotrophic gyre of the North Atlantic) and Bermuda and Norfolk, Virginia.

The pCO_2 system was installed on the RV *Atlantic Explorer* in April 2006. This data stream provides ground-truthing pCO_2 datasets for the subtropical gyre of the North Atlantic Ocean. In 2007 and 2008, the R/V *Atlantic Explorer* had 173, and 170 ship-days, respectively. In 2009, the R/V *Atlantic Explorer* has been scheduled for 139 ship-days, with 1 ship-day pending. This includes work in zone NA06 but also transects between Bermuda, Puerto Rico and Norfolk, and several cruises in the central North Atlantic (between 20° and 30° N, 65° to 45°W). In 2010, we anticipate that the R/V *Atlantic Explorer* will have 131 ship-days, with 7 other ship-days pending. This schedule will also include four transects between Bermuda and Norfolk, and four transects between Bermuda

and Puerto Rico.

Data Return:

In 2007, the total data collected was ~99,996, with a ~73.3% good data recovery. Much of the data was collected in the NA06 region with several transects across the western North Atlantic Ocean. In 2008, the total data collected was ~100,119, with a ~88.3% good data recovery. As in 2008, much of the data was collected in the NA06 region with several transects across the western North Atlantic Ocean, with a couple of cruises to Puerto Rico.

The non-return rates of 26.7% and 11.7% represent data that were flagged mainly due to problems with low flow rates from the underway system, due to problems associated with the Valco multi-position valve and distribution of standards through the system, and delays in replacing the standards. However, it should be noted that maintenance of the pCO_2 system has become relatively routine during the ship's turnaround at the BIOS dock.

The seawater and atmospheric pCO_2 data from 2007 and 2008 have been submitted to LDEO. In addition to pCO_2 data, underway position, temperature and salinity data have also been submitted to LDEO. In addition several months of 2009 have also been submitted to LDEO. At present we are undertaking QC/QA analysis of 2009 data up to October 2009, undertaking the merging of thermosalinograph and navigational data, and expect submission of additional data to LDEO by the end of the year. We do not anticipate a more frequent turnaround of data since the comparison of pCO_2 system temperature, underway temperature, and CTD upper bottle and upper bin temperatures require sufficient time to evaluate sensor drift. All the SeaBIRD sensors from the underway and CTD systems are maintained by BIOS Marine Technicians, and calibrated every six months. We are in the process of preparing the metadata information and data QC/QA for submission of data to CDIAC in yearly reports. The seawater and atmospheric pCO_2 data will also be served at the following site (http://www.bios.edu/Labs/co2lab/vos.html).

Causes for non-return:

In 2007, the major problem with the R/V *Atlantic Explorer* system has been intermittent problems with the Valco multiposition valve. The valve has been replaced. We have had problems with the Ivisco valve that controls the flushing of the lines with freshwater. This valve has failed twice due to salt crystal buildup. We have also had problems with clogging of the flow meter impeller. We have also had problems with the Superlogic Module boards due to faulty power feed; these modules have had to be replaced. The acrodisk have also been clogged and in need of regular cleaning. We have also had a few problems with the GPS system, with a faulty 232 to 485 converter, and faulty comport. We also had non-return of data on scheduled BATS and Hydrostation S cruises due to shipyard maintenance and turnaround of the R/V *Atlantic Explorer*. In 2009, the pCO_2 system has worked very well, with no problems to report.

4.1.2. Container Ship MV Oleander

The MV *Oleander* crosses weekly between New Jersey and Hamilton, Bermuda. Given the ~100 crossings a year, this gives excellent temporal and spatial coverage of the North Atlantic subtropical gyre, Gulf Stream, Middle Atlantic Bight and coastal zone. The MV *Oleander* transits the region of Subtropical Mode Water (STMW) formation during the winter southeast of the Gulf Stream, and the highly productive coastal zone of the Eastern Seaboard.

Data Return:

During the performance period we have had major problems with the pCO_2 system. We have the pCO_2 system up and running again for the remainder of the performance period and expect routine data-return for the remainder of the year and following.

The seawater pCO_2 data from 2007 have been submitted to LDEO. We are in the process of evaluating 2008 data but have been hampered by the non-return of GPS data that has meant difficult merging of position data with NOAA ADCP datasets. Unfortunately, at this time, we cannot give return and flagged data statistics. We are in the process of preparing the metadata information and data QC/QA for submission of data to CDIAC in yearly reports. The seawater pCO_2 data will also be served at the following site (http://www.bios.edu/Labs/co2lab/vos.html).

Maintenance of the pCO_2 system occurs with weekly visits to the ship during the ship's turnaround (giving our team a couple of hours on Monday morning to work on the system) in Hamilton, Bermuda. Our group has developed a good rapport with the ship officers, engineers and crew, and their good will has contributed greatly to the success of the system installation on the ship.

Causes for non-return:

During the performance period we had major problems with the pCO_2 system. In mid-2008, during a routine maintenance visit to the Oleander, our technician was electrocuted (without injury, fortunately) and major components of the pCO_2 system were damaged. Although we had been informed during the installation of the pCO_2 system that the electrical supply was grounded, we discovered that the electrical supply had *not* been grounded and as a result, our technician and pCO_2 system suffered a serious electrical surge. We ultimately have not discovered the cause of the incident, as the heavy-duty surge protector on the pCO_2 system did not prevent the incident. A grounded electrical supply was requested, but frustratingly was not provided until routine ship maintenance at the end of 2008/beginning of 2009. All major damaged components have been replaced and the system was functional after a frustratingly long delay. The replacement of the CPU caused another problem with the GPS comport that has also been addressed. However, at present we have another computer failure that is being addressed. A temporary work around using a second hard-drive is being attempted with a solid-state bootable hard-drive to run the pCO_2 system software as a more permanent solution.

The ship turnaround in New Jersey and Bermuda has also been shortened and subsequently

access to the ship has been restricted to a few hours each week (making replacement and testing of new components a little difficult and drawn-out). Access to the engine room has also been denied at times due to problems with the ship engines and major maintenance work needed during the turnaround periods. We've also had several weeks where the weekly turnaround has been delayed due to much reduced container transport between New Jersey and Bermuda. Despite the difficulties in access and electrical supply repair, the MV *Oleander*, the crew remains highly motivated to help us in our efforts, and we anticipate good recovery of data in the remainder of this performance period and the next.

On the MV *Oleander*, additional causes for non-return have been associated with ship-related issues (seawater pump system turned off; delays getting on to the ship); failure of the waste reservoir and delays related to component replacement. Over the last two years there have been occasions when the seawater system were not turned on during the weekly turnaround of the ship. There have also been several occasions when our group has not been able to access the ship in port due to offload/onload pressures when the ship is undertaking very quick turnarounds due to weather delays. On a couple of occasions, the pump that drains seawater from the waste reservoir has failed and we have had delays in replacing the pump. The equilibrator is located in the Engine Room near the seawater system and TSG. It is located ~5' below the water line, requiring the equilibrator waste seawater to free drain into a waste reservoir, which in turn is drained by a pump back into the seawater line downstream of the tap off to the pCO_2 system. In 2007, the pump has failed twice with shutdown of the system after overflow into the ship's bilges. Recently, we have added a second, stronger pump to ensure that wastewater is pumped overboard. This heavy-duty pump has worked well. The primary filter on the seawater intake line has also needed to be cleaned each week; otherwise rust and debris from the *Oleander*'s internal plumbing clogs the line and slows the flow rate into the equilibrator. We have also had problems with the Superlogic Module boards; these modules have had to be replaced. The condenser tubes have clogged with salt crystals causing a shutdown of the system. The condenser tubes have been replaced.

The average temperature of the engine room has been ~47°C with the CPU failing in 2006 due to temperatures over 60°C. We have modified the dry box, adding new fans, and replaced the CPU with one that has a higher temperature threshold (80°C) with no problems since. The engine room air is quite dirty requiring cleaning of all filters each week. As stated earlier, we will replace the system hard-drive with a solid-state bootable hard-drive to run the pCO_2 system software as high engine room temperatures and ship motion continues to exact a heavy toll on the pCO_2 system components.

4.2. Mooring pCO_2 Effort

The long-term goal of this program is to populate the network of OCEAN Sustained Interdisciplinary Time-series Environment observation System (OceanSITES; http://www.oceansites.org/) so that CO_2 fluxes will become a standard part of the global air-sea CO_2 flux mooring network.

4.2.1. Bermuda Testbed Mooring (64.2°W, 31.7°N):

A moored pCO_2 system was first deployed on the Bermuda Testbed Mooring (BTM) on October 22, 2005. The system was fully operational for the entire FY06, but was recovered in 2007, as funding to the PI from NSF was not renewed. A group of BIOS researchers led by Dr. Jerome Aucan, and colleagues at NOAA, and WHOI are planning the redeployment of a similar mooring in late 2009, and submitted a proposal to the NSF MRI program for support of this effort. However, we do not anticipate a decision from NSF on the proposal until early next year, with deployment of the mooring unlikely before the fall of 2010. However, two other moored pCO_2 systems will be collecting data in 2010.

4.2.2. Bermuda coral reef (~64°W, 32°N):

As part of an NSF supported award, the response of Bermuda's coral reef to ocean acidification will be investigated over the next few years. The project details are: NSF OCE-0928406. *BEACON: Bermuda Ocean Acidification and Coral Reef Investigation.* P.I.'s. A.J. Andersson, N.R. Bates, S. du Putron (BIOS), 1 Sept. 2009-31 Aug. 2012.

As part of the project, two moored pCO_2 systems will be deployed on the Bermuda coral reef under naturally different pCO_2 and $[CO_3^{2-}]$ conditions. The proposed pCO_2 buoys (MAPCO2) are the same design as the buoy previously deployed at the Bermuda Testbed Mooring (BTM; http://www.pmel.noaa.gov/co2/moorings/btm/btm_main.htm; P.I., C.L. Sabine, PMEL and N.R. Bates, BIOS). At each site shown in the attached figure, the pCO_2 buoy will be complemented by an Aanderaa RDCP current profiler and auxiliary sensors capable of continuously measuring temperature, salinity, dissolved oxygen, *p*H, PAR and turbidity. At present, Chris Sabine's group at PMEL is constructing the moored pCO_2 systems and we anticipate deployment of these systems in early 2010. Data from these moored pCO_2 systems will be entrained into the PMEL moored pCO_2 network. This data will be merged with other datasets collected as part of the NSF project.

4.3. Data management and dissemination

The efforts of the NOAA VOS pCO_2 group have met the important monitoring principle of uniform instrumentation with a quantifiable accuracy. All systems are calibrated with standards that are traceable to the WMO scale. An important part of the VOS effort is to disseminate quality controlled data to the community at large in an expedient fashion. The seawater and atmospheric pCO_2 data will also be served at the following site (http://www.bios.edu/Labs/co2lab/vos.html). After QC and QA, data will be transferred to LDEO.

4.4. Research and Publication Highlights

The VOS CO_2 data is providing valuable information on CO_2 variability in surface seawater over a wide range of time- and spatial scales that have not been fully examined. Between 2006 and present, both ships collected high frequency data in the region of the

subtropical gyre of the North Atlantic Ocean, Gulf Stream, Middle Atlantic Bight and coastal ocean of the eastern seaboard. Our data has contributed to the new pCO_2 climatology [Takahashi *et al*., 2009] and interpretations resulting from this data [Schuster *et al*., 2009; Watson et al., 2009]. Understanding generated from this project was also entrained into community effort to improve the global ocean observing system network [Borges *et al*., 2009; Feely *et al*., 2009] and assessment of gaps in knowledge [Birdsey *et al*., 2009; Dickey *et al*., 2009; Reid *et al.,* 2009].

Comparisons of underway seawater pCO_2 data collected from BIOS's ship, R/V *Atlantic Explorer* with the BTM pCO_2 sensor have been initiated. Over 15,000 seawater pCO_2 data points were collected from the Atlantic Explorer within 80 km of the BTM in 2006. Seawater pCO_2 data collected from the R/V *Atlantic Explorer* underway system within 10 km of the BTM (also within 3 minutes of each BTM data point) had an average difference of less than 0.5 µatm. A paper is being prepared on this effort.

The offshore seawater pCO_2 data is also being used as a constraint for estimating seasonal net ecosystem metabolism (net calcification and photosynthesis rates) for the Bermuda coral reef. Early attempts were made to access seasonal rates using underway seawater pCO_2 data [Bates, 2002], but the approach has been much improved [Bates *et al*., 2009a, b]. This effort is important as the Bermuda coral reef experiences relatively low carbonate ion concentrations compared to low-latitude coral reefs. Our other experimental studies show direct coupling between carbonate chemistry and coral calcification, and we anticipate that the Bermuda coral reef should begin to experience periods of net decalcification as early as 2030. As such, the Bermuda reef serves as an important bellweather for the impact of ocean acidification on coral reefs.

4.5. Community Service, Conferences, and Outreach

4.5.1. Community Service

Surface Ocean CO_2 Atlas (SOCAT) Project member. Co-sponsored by IOCCP, SOLAS, IMBER, and the Global Carbon Project (GCP), members of SOCAT are working to establish a global surface ocean CO_2 data set that would bring together, in a common format, all publicly available pCO_2 data for the surface oceans. Focus on the North Atlantic Ocean including the Arctic Ocean. Active service from 2008 to present.

Interior Ocean Carbon Synthesis. Arctic working group leaders (N. Bates and A. Olsen, University of Bergen). Active service from mid-2009 to present.

Scientific Steering Group Member. Member of the U.S. Carbon Cycle Scientific Steering Group (CCSSG) for the US federal interagency Carbon Cycle Interagency Working Group (CCIWG). Active service from 2007 to present.

Working Group Member. CarboOCEAN WG member for "North" and "Middle" groups for the Atlantic Ocean. Active service from 2007 to 2009.

4.5.2. Conferences Attended

IOCCP SSG meeting (2007); SOLAS-IMBER Carbon meeting (Paris, 2007); *Invited talk*, 2008 ASLO/AGU Ocean Sciences Meeting, Orlando, Florida, March 2008; CCSSG meeting December 2009.

4.5.3. Outreach

Panel Discussion with filmmakers on the Ocean Acidification documentary *Sea Change*, 5 November 2009, BIOS.

Participation in documentary (2009) on ocean acidification "*Altered Ocean-Acrid Seas*", an OceanVision film, 66 minutes, Dean Schweinler, George Monteiro and Jim Flagg, producers.

Bermuda TV channel ZBM interview (2009) about WWF report: *Arctic Climate Feedback.: Global Implications*.

BIOS press release (2009) on WWF report (Arctic Climate Feedbacks) and many other US and international press reports in September 2009

TV documentary (2008). Primary contributor to 30-minute documentary on global warming for Bermuda channel ZBM special on the Environment "*EnviroShorts*".

Press Conference (2008) on "Ocean Acidification". 2008 ASLO/AGU Ocean Sciences meeting, Orlando, Florida, March 2008.

TV documentary (2007). Scientific interview for Discover Channel/National Geographic documentary (2007) on hurricanes and climate change entitled "*Hyper Hurricanes*". First US airing on National Geographic Channel (October 18, 2007). Includes footage of the BIOS ship R/V *Atlantic Explorer*.

Scientific interview (2007) for independent filmmaker Dean Schweinler's documentary on ocean acidification. Includes footage of the BIOS ship R/V *Atlantic Explorer* and laboratory activities.

TV documentary (2007). Footage of our laboratory activities included in James Martin's documentary on climate change and other environmental issues.

Several local TV interviews (2007) on global climate change, coral reefs and environmental issues for Bermuda TV channel ZBM.

Scientific interview (2007) on global climate change for a Bermuda TV channel ZBM 30 minute program, part of a series of programs on environmental issues.

Interview for Sea Education Association publication (2007).

Presentation (2007) on climate change and ocean acidification for CARILEC (an association of Caribbean and small island nation utility and energy generation companies).

Scientific advisor (2007) on climate change and ocean acidification issues for Bermuda non-governmental organization Greenrock.

Presentation (2007) on climate change and ocean acidification for the HSBC Bank of Bermuda foundation.

Profile for BIOS outreach publication *Meridian*, (2007).

Articles (2007) on climate change and ocean acidification for BIOS outreach publication *Meridian*. This includes a fall special issue on the contribution of BIOS scientists to the study of ocean acidification.

Advisor for the BIOS sponsored International Partners Program (TIP) in late 2007 on ocean acidification (2007).

4.6. Publications

Birdsey, R., Bates, N.R., Behrenfield, M., Davis, K., Doney, S.C., Feely, R.A., Hansell, D.A., Heath, L.S., Kasischke, E., Law, B.E., Lee, C., McGuire, D., Raymond, P., and Tucker, C.J., 2009. Carbon cycle observations: Gaps threaten climate mitigation policies. *EOS*, *Transactions, American Geophysical Union*, **90** (34), 292-293, 25 August 2009, Paper 2009ES002647.

Borges, A.V., Alin, S.R., Chavez, F.P., Vlahos, P., Johnson, K.S., Holt, J.T. (lead authors), Balch, W.M., Bates, N., Brainard, R., Cai, W.-J., Chen, C.T.A., Currie, K., Dai, M., Degrandpre, M., Delille, B., Dickson, A., Feely R.A., Friederich, G.E., Hales, B., Hardman-Mountford, N., Hendee, J., Hernandez-Ayon, J.M., Hood, M., Huertas, E., Hydes, D., Ianson, D., Krasakopoulou, E., Litt, E., Luchetta, A., Mathis, J., McGillis, W.R., Murata A., Newton, J., Ólafsson, J., Omar A., Perez, F.F., Sabine, C., Salisbury, J.E., Salm, R., Sarma, V.V.S.S., Schneider, B., Sigler, M., Thomas, H., Turk, D., Vandemark, D., Wanninkhof, R., Ward, B., (contributing authors) *in press*. A global sea surface carbon observing system: inorganic and organic carbon dynamics in coastal oceans. *Community White Paper, OceanObs09*, http://www.oceanobs09.net/

The CLIMODE Group* 2009. (Marshall, J., Andersson, A., Bates, N., Dewar, W., Doney, S., Edson, J., Ferrari, R., Fratantoni, D., Gregg, M., Joyce, T., Kelly, K., Lozier, S., Lumpkin, R., Samuelson, R., Skyllingstad, E., Straneo, F., Talley, L., Toole, J., and Weller, R.). Observing the cycle of convection and restratification over the Gulf Stream system and the subtropical gyre of the North Atlantic Ocean: preliminary results from the CLIMODE field campaign. *Bulletin of the American Meteorological Society*, September, 2009, 1337-1350, doi:10.1175/2009BAMS2706.1.

Dickey, T.D., Bates, N. Byrne, R.H., Chang, G., Chavez, F.P., Feely, R.H., Hansen, A., Karl, D., Moore, C., Wanninkhof, R., and Sabine C.L., 2009. The NOPP O-SCOPE and MOSEAN Projects: Advanced sensing for ocean observing systems. *Oceanography*, **22** (2), 168-181, June 2009.

Feely, R.A., Fabry, V., Dickson, A., Gattuso, J.-P., Bijma, J., Riebesell, U., Doney, S., Turley, C., Saino, T., Lee, K., Anthony, K., Kleypas, J. (lead authors), Johannessen, T., Bellerby, R., Luchetta, A., Trull, T., Tilbrook, B., Olafsson, J., Watanabe, S., O'Dowd, C., Ward, B., Bakker, D., Hall-Spencer, J., Hardman-Mountford, N., Blackford, J., Send, U., Langdon, C., Hönisch, B., Hernandez-Ayon, J.-M., Ianson, D., Kozyr, A.. Bates, N., Wanninkhof, R., Robbins, L., Hydes, D., Gledhill, D., Iglesias-Rodriguez, M.D., Lebrato, M., Balch, W.M., Newton, J., Hofmann, G., Brainard, R., Eakin, M., Salm, R., Hill, T., Sabine, C., Alin, S., Hales, B., Juranek, L., Hendee, J., Manzello, D., Musielewicz, S., Mathis, J., Sigler, M., Turk, D., Vandemark, D., Salisbury, J., Coble, P., Azetsu-Scott, K., Miller, L., Lohrenz, S., Thomas, H., and Cai, W.-J., (contributing authors), *in press*. An international observational network for ocean acidification. *Community White Paper, OceanObs09*, http://www.oceanobs09.net/

Reid, P.C., Fischer, A., Lewis-Brown, E., Meredith, M., Sparrow, M., Andersson, A.J., Antia, A., Bates, N.R., Bathmann, U., Beaugrand, G., Brix, H., Dye, S., Edwards, M., Furevik, T., Gangstø, R., Hátún, H., Hopcroft, R.R., Kendall, M., Kasten, S., Keeling, R., Corinne Le Quéré, C., Mackenzie, F.T., Malin, G., Mauritzen, C., Ólafsson, J., Paull, C., Rignot, E., Shimada, K., Vogt, M., Wallace, C., Wang, Z., and Washington R., 2009. Impacts of the oceans on climate change. *Advances In Marine Biology*, **56**, 1-150, doi: 10.1016/S0065-2881(09)56001-4.

Schuster, U., Watson, A.J., Bates, N.R., Corbiere, A., Gonzalez-Davila, M., Metzl, N., Pierrot, D., and Santana-Casiano, M., 2009. Trends in North Atlantic sea-surface fCO_2 from 1990 to 2006. *Deep-Sea Research II*, **56**, 620-629, doi:10.1016/j.dsr2.2008.12.011.

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Watson, A.J, Schuster, U., Bakker, D.C.E., Bates, N.R., Corbiere, A., Gonzalez-Davila, M., Friedrich, T., Hauck, J., Heinze, C., Johannessen, T., Körtzinger, A., Metzl, N., Olafsson, J., Olsen, A., Oschlies, A., Padin, X.A., Pfiel, B., Santana-Casiano, M., Steinhoff, T., Telszewski, M., Rios, A.F., Wallace, D.W.R., and Wanninkhof, R., *in press*. Accurately tracking the variation in the North Atlantic sink for atmospheric

CO_2. *Science*.

Abstracts

Andersson, A.J., Bates, N.R., and de Putron, S.J., 2010. BEACON: Bermuda ocean acidification and coral reef investigation - overview and early results. *ASLO/AGU Meeting,* Portland, February 2010.

Mathis, J.T., and Bates, N.R., 2010. Coupling primary production and terrestrial runoff to ocean acidification and carbonate mineral suppression in the Eastern Bering Sea. *ASLO/AGU Meeting,* Portland, February 2010.