Observations for Climate:
The NOAA Component of the CLIVAR CO_2 Repeat Hydrography Program

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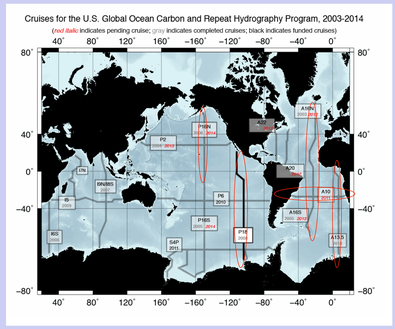
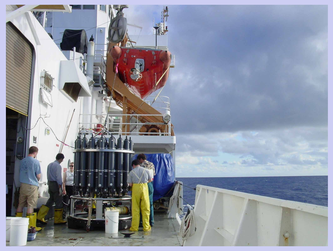
Program Objectives

The CLIVAR CO2 repeat hydrography program is a venture sponsored by the oceanography program of the US NSF and the Climate Observation Division of NOAA. The program is driven by the need to monitor the changing patterns of carbon dioxide (CO_2), fresh water, temperature and tracers in the ocean, and to provide the necessary data to support continuing model development that will lead to improved forecasting skill for oceans and global climate. Its observational strategy is based on repeating select sections of WOCE/JGOFS survey of the 1990s to determine decadal changes. The field effort is performed on Class1 Research ships, such as NOAA ship *Ronald H. Brown* shown above. The hydrographic sampling occurs primarily with CTD rosette systems capable of measuring temperature, salinity and oxygen at 1-m resolution and taking 24 to 36 bottles throughout the water column (bottom panel).



The lines occupied since the initiation of the field program in 2003 are shown above (years of occupation in gray, and dates of future cruises in red). The cruises circled in red are those lead by NOAA (A16, A13.5, and A10 in the Atlantic; P16N and P18 in the Pacific) Final data from cruises are provided to the community at large at two data sites:
The CLIVAR & Carbon Hydrographic Data Office: **http://cchdo.ucsd.edu/**:
The Carbon Dioxide Information Analysis Center: **http://cdiac.ornl.gov**

By integrating the scientific needs for monitoring natural variability, climate trends, and human induced perturbation of hydrographic variables, CO_2 system parameters and other tracers in the ocean, major synergies are achieved.
The U.S. GCRP Carbon Cycle Science Program (CCSP) has defined a need for systematic observations of the invasion of anthropogenic carbon in the ocean superimposed on a variable natural background, while other national and international programs (e.g. WCRP) have articulated the importance of these and other aspects.

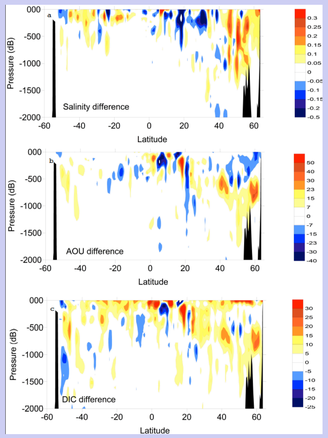


Scientific Highlights

The repeat occupations have provided a wealth of observations on decadal variability and trends in the ocean, several which were unexpected. Highlights include:

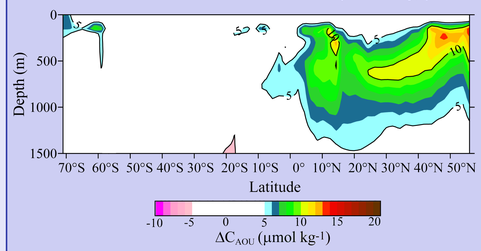
- Significantly greater variability in biogeochemical parameters at depth than anticipated
- A measurable change of anthropogenic carbon in the surface and intermediate waters
- Warming of the deep ocean
- A decrease of oxygen in the intermediate waters

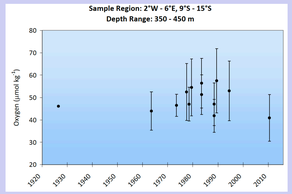
Natural and Climate Induced Variability



Decadal variability in biogeochemical and physical parameters are apparent throughout the upper water column. An example of changes in salinity, apparent oxygen utilization (AOU), and dissolved inorganic carbon (DIC) of the repeat occupation of A16 through the center of the North Atlantic is shown to the left (Wanninkhof et al. 2010) It is attributed to changes in circulation, fronts, isopycnal heave and changes in biogeochemical cycles. Changes of these magnitude have been observed in the latest ocean circulation models including biogeochemistry (Levine et al. 2008). This natural variability complicates detection of anthropogenic and climate trends

The repeat hydrography program has contributed to detection of warming of the thermocline and deep ocean (see e.g. poster of Garzoli et al., this session). This has had direct and indirect impacts on biogeochemical cycling. Most measurements of dissolved oxygen on the CLIVAR/CO2 cruises have revealed significant decrease in mi-depth oxygen values consistent with previous studies. Changes in ocean circulation and the rate at which sinking particles decompose in the water column affect the distribution of both DIC and dissolved oxygen in proportion to the elemental ratios (Redfield ratios) of the decomposing organic particles. An example of decadal oxygen changes, expressed as apparent oxygen utilization (AOU), in the North Pacific along P16N is shown to the left below (Sabine et al. 2008). A 60-yeartime series of oxygen levels in the Eastern tropical Atlantic thermocline is shown in the right panel suggesting a recent decline in oxygen based on the A13.5 cruise of 2010 (C. Mordy, pers. com.).



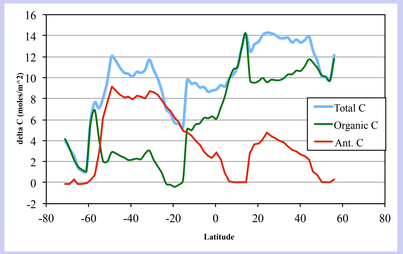


The increase AOU will correspond to an increase in DIC and this will impact the estimate of changes in anthropogenic CO_2 inventory. The changes in AOU between the CLIVAR/ CO_2 cruises and the WOCE/JGOFS cruises can be used to evaluate the effects on the DIC using the C:O elemental ratios corresponding to remineralization.
Subtracting these changes from the total change in DIC gives the inventory changes resulting from the uptake of CO_2 from the atmosphere (i.e. anthropogenic CO2).

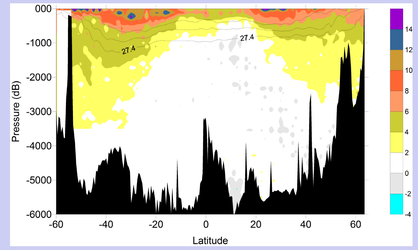
Scientific highlights, ***continued***

Anthropogenic changes

The CLIVAR CO2 repeat hydrography cruises have met their objectives of quantifying changes in heat, fresh water, and carbon, and obtaining a mechanistic understanding of the changes. From the work on the P16 line in the North Pacific the decadal inventory change of anthropogenic CO_2 and that caused by natural variability have been determined showing that regionally natural changes can be larger than the anthropogenic imprints (Sabine et al.2008). (see below)



The penetration of the anthropogenic CO_2 signal in the Atlantic is shown below. The results suggest a decrease in uptake in the Northern hemisphere and an enhancement in the South compared to the total anthropogenic CO_2 inventory change since 1850. Part of the changed North-South asymmetry could be due to the Northern part of the transect going through the less ventilated Eastern Basin compared to the Southern section through the Western basin.



The estimates of ocean column inventory changes in anthropogenic carbon over the last decade from the cruises is presented below showing the large differences in uptake between basins

From: Sabine et al. 2009	**Atlantic (25°W)**	**Pacific (152°W)**	**Indian (90°E)**
In: Mol m^{-2} yr^{-1}	1993-2005	1991-2006	1995-2007
Northern Hemisphere	0.63	0.25	0.63
Southern Hemisphere	0.75	0.41	0.83

Future

Sustaining the hydrographic observations is required to assess the influence of the ocean on global climate. However, additional requirements have been recently highlighted. These include focus on the ecological health of the ocean by, for instance, including measurements in support of determining causes and trends in Ocean Acidification. Measurement of changes in the deep ocean will become increasingly important as climate and anthropogenic signals are entering this realm. Improved international coordination and collaboration is needed to improve efficiency of the program. The GOSHIP program (http://www.go-ship.org/) is actively pursuing these goals in an international context.
New avenues to sample the ocean are being investigated including improved analyses approaches and instruments on ships, and further development of biogeochemical sensors for autonomous platform such as profiling floats and moorings.
These enhancements will be an important part of the third high-quality decadal survey that will commence in the North Atlantic Ocean in 2012.

Levine, N. M., S. C. Doney, R. Wanninkhof, K. Lindsay, and I. Y. Fung (2008), The impact of ocean carbon system variability on the detection of temporal increases in anthropogenic CO_2,J Geophys. Res., 113, doi:10.1029/2007JC004153.
Sabine, C., R. A. Feely, R. Wanninkhof, and T. Takahashi (2009), The global ocean carbon cycle, Bull. Amer. Meteor. Soc., 90, S65-S68.
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Wanninkhof, R., S. Doney, J. L. Bullister, N. M. Levine, M. J. Warner, and N. Gruber (2010), Detecting anthropogenic CO_2 changes in the interior Atlantic Ocean between 1989 and 2005, J Geophys. Res., 115, C11028, doi:11010.11029/12010JC006251.