CARBON TRACERS FOR OCEAN CIRCULATION

Christopher L. Sabine[1], R.A. Feely[2], R. Wanninkhof[3], R.M. Key[4], F.J. Millero[5], K. Lee[3], Tsung-Hung Peng[3], A. Kozyr[6], J.L. Bullister[2], M.F. Lamb[2], and D. Greeley[2]

[1]Joint Institute for the Study of Atmosphere and Ocean, University of Washington, c/o NOAA/PMEL, 7600 Sand Point Way NE, Seattle, WA 98115, sabine@pmel.noaa.gov
[2]NOAA/Pacific Marine Environmental Laboratory, 7600 Sandpoint Way NE, Seattle, WA 98115, USA. feely@pmel.noaa.edu
[3]NOAA/Atlantic Oceanographic and Meteorological Laboratory, 4301 Rickenbacker Causeway, Miami, FL 33149, USA. wanninkhof@aoml.noaa.gov
[4]AOS Program, Princeton University, Forrestal Campus/Sayre Hall, Princeton, NJ 08544, USA. key@princeton.edu
[5]University of Miami/ RSMAS, 4600 Rickenbacker Causeway, Miami, FL 33149, USA. key@princeton.edu
[6]Carbon Dioxide Information Analysis Center, ORNL, Oak Ridge, TN 37831, USA. akozyr@utk.edu

Both carbon system measurements and derived products can be used in ocean circulation studies to infer water mass transport. In this paper we give a brief overview of the global CO_2 survey effort; then we give a few examples of how carbon data can be used to examine ocean transport. Finally, we discuss the estimates of anthropogenic CO_2 from the global survey and the relation between anthropogenic tracers and ocean circulation.

In the 1990s, several programs, including the Joint Global Ocean Flux Study (JGOFS), the World Ocean Circulation Experiment (WOCE), and NOAA's Ocean-Atmosphere Carbon Exchange Study (OACES), conducted major field campaigns that included water column measurements of at least two inorganic carbon parameters in the major ocean basins. Working with international investigators, we have been striving to synthesize these data into a unified consistent data set. The synthesis effort began with the Indian Ocean (IO). The IO survey marked the culmination of the global CO_2 survey effort. Over 20,000 water samples collected between December 1994 and July 1996 were analyzed for both total dissolved carbon dioxide (TCO_2) and total alkalinity (TA) using coulometric and potentiometric techniques as outlined in the methods handbook prepared by the CO_2 survey science team [DOE, 1994]. Based on the analysis of certified reference materials (CRMs) provided by A. Dickson of Scripps Institution of Oceanography and a post cruise analysis of the data, the accuracy of the TCO_2 and TA measurements was estimated to be ± 2 and ± 4 μmol kg^{-1}, respectively. These data were combined with the French INDIGO and CIVA 1 results to provide the most comprehensive data set ever assembled for the IO.

Between 1991 and 1996, 24 survey cruises in the Pacific had measurements of at least two carbon parameters. The Pacific Ocean survey involved investigators from 15 different laboratories and 4 countries. On average, carbon samples were analyzed on one third of the total water samples collected on these cruises. TCO_2 was measured on all 24 cruises, but the second carbon parameter varied depending on the carbon group responsible for the cruise. An extensive assessment of the Pacific data quality is described by Lamb *et al.* [2001]. Several approaches aimed at assessing cruise-to-cruise differences in the deep waters were used to help evaluate the data. These approaches involved a range of assumptions, but adjustments were only proposed for cruises where several lines of evidence indicated that an adjustment was necessary. TCO_2 adjustments were proposed for three cruises to give an overall estimated accuracy of 3 μmol kg^{-1}. TA adjustments were proposed for five cruises to give an overall estimated accuracy of 5 μmol kg^{-1}.

The final basin-wide synthesized data sets contain a tremendous amount of information that can be used to infer and diagnose ocean circulation and estimates of ocean transport. For example, a north-south section of potential alkalinity (PA = (TA+nitrate)/salinity*35) looks very similar to a section of $\Delta^{14}C$, a commonly used tracer for deep-water circulation. Low alkalinity values can be seen in the northward moving bottom waters, while the mid-depth flow to the south has much higher alkalinity values because of the accumulation of alkalinity from the dissolution of carbonate particles as the waters age. The potential alkalinity of Pacific bottom waters (where the bottom is deeper than 3500 m) are much lower in the western side of the basin indicating that the northward flowing bottom waters are not zonally homogeneous, but concentrated into a western boundary flow that is somewhat controlled by topography. TCO_2 can also be a useful indicator of ocean circulation. For example, Goyet et al. [1999] showed that the bottom water flowing into the Arabian

Sea through the Owen Fracture zone was easily identified as a local minimum in a zonal section of TCO_2 from the I1 WOCE cruise.

In addition to the identification of deep circulation features, carbon data can be used to identify surface phenomenon. For example, pCO_2 is a very sensitive indicator of upwelling features in the surface ocean. In the Indian Ocean, the Southwest monsoon in the summer months causes intense upwelling off the Arabian Penninsula. This upwelling can be seen as a small temperature anomaly, but if one looks at a T-S diagram from surface waters in the Arabian Sea it is not readily evident which samples are from the upwelled waters because both the upwelled waters and the non-upwelled surface waters generally show a positive correlation between temperature and salinity. pCO_2, on the other hand, exhibits a very strong upwelling signature. The thermodynamic response of CO_2 to increasing temperature is an increase in pCO_2 giving a positive correlation for non-upwelled waters. The upwelled waters, however, have a negative correlation with temperature and the signal to noise is much larger for pCO_2 than for temperature.

One of the principle products of the global CO_2 synthesis effort is an assessment of the global inventories of anthropogenic CO_2. Anthropogenic CO_2 distributions have been estimated from the survey data in the Indian and Pacific using the ΔC^* technique [Gruber et al. 1996; Sabine et al., 1999; Sabine et al., 2001]. Efforts are currently underway to synthesize a collection of 1990s data for the Atlantic. The distribution of time-dependent tracers, like anthropogenic CO_2, can provide valuable information on thermocline ventilation and circulation rates. To a first order, the distribution of anthropogenic CO_2 in the water column is controlled by uptake at the surface and ocean circulation. The deepest penetrations of anthropogenic CO_2 are observed in water mass formation regions like the subpolar North Atlantic and the subtropical convergence zones. Relatively low penetrations are observed in upwelling regions like the equatorial Pacific or much of the high latitude Southern Ocean.

A comparison of different anthropogenic tracers such as bomb C-14, anthropogenic CO_2, and pCFC-12 show very similar large scale distributions because of the strong control of ocean circulation on these tracers. When examined in detail, however, there are real differences in the regional distributions that can be attributed to differing atmospheric histories and equilibration times. These differences can be exploited to gain a better understanding of the short-term ventilation rates within the thermocline.

In conclusion, the global CO_2 synthesis effort is nearly complete. The Indian and Pacific data sets have been compiled and examined for data quality. The Atlantic synthesis is under way. When completed, the global carbon data set will encompass nearly 100,000 unique sample locations. These data can be used in a number of ways to examine transport issues with in the oceans. For more information on the synthesis program visit the Global Ocean Data Analysis Project (GLODAP) at: http://cdiac.esd.ornl.gov/oceans/glodap/

References

DOE, *Handbook of methods for the analysis of the various parameters of the carbon dioxide system in sea water; version 2*, A.G. Dickson and C. Goyet, eds. ORNL/CDIAC-74 Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, Oak Ridge, Tenn., 1994.

Goyet, C., C. Coatanoan, G. Eischeid, T. Amaoka, K. Okuda, R. Healy and S. Tsunogai, Spatial variation of total CO_2 and total alkalinity in the northern Indian Ocean: A novel approach for the quantification of anthropogenic CO_2 in seawater, *J. Mar. Res*., *57*, 135-163, 1999.

Lamb, M.F., C.L. Sabine, R.A. Feely, R. Wanninkhof, R.M. Key, G.C. Johnson, F.J. Millero, K. Lee, T.-H. Peng, A. Kozyr, J.L. Bullister, D. Greeley, R.H. Byrne, D.W. Chipman, A.G. Dickson, C. Goyet, P.R. Guenther, M. Ishii, K.M. Johnson, C.A. Keeling, T. Ono, K. Shitashima, B. Tilbrook, T. Takahashi, D.W.R. Wallace, Y. W. Watanabe, C. Winn, and C.S. Wong, Internal consistency and synthesis of Pacific Ocean CO_2 survey data, *Deep-Sea Res. II*, in press, 2001.

Sabine, C.L., R.M. Key, K.M. Johnson, F.J. Millero, A. Poisson, J.L. Sarmiento, D.W.R. Wallace and C.D. Winn, Anthropogenic CO_2 inventory of the Indian Ocean, *Global Biogeochem. Cycles*, 13, 179-198, 1999.

Sabine, C.L., R.A. Feely, R.M. Key, J. Bullister, F.J. Millero, K. Lee, B. Tilbrook, T. Ono, and C.S. Wong, Anthropogenic CO_2 inventory of the Indian Ocean, *Global Biogeochem. Cycles*, in prep., 2001.