Increasing Anthropogenic CO_2 Inventories in the Ocean

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Introduction:

The ocean plays a crucial role in mitigating the climate effects of rising atmospheric carbon dioxide (CO_2). Currently ~1/3 of annual human- derived (anthropogenic) CO_2 emissions are absorbed by the ocean. Understanding and quantifying the ocean sink for anthropogenic CO_2 (C_{ant}), thus remains one of the primary goals of ocean climate and biogeochemical research. However, estimating C_{ant} storage is a difficult task for a variety of reasons:

1) C_{ant} is not directly measurable so it has to be inferred using indirect means;

2) the ocean C_{ant} signal is a very small percentage of the background natural carbon;

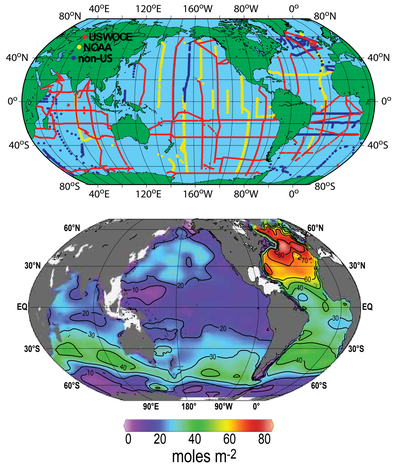
3) carbon in the ocean has a complex in situ biogeochemistry; and

4) slow mixing causes the C_{ant} distribution in the ocean to be highly heterogeneous.

Despite these limitations, with the increasing availability of high quality ocean interior carbon and tracer data as well as new techniques for estimating C_{ant}, the international ocean carbon community is making good progress in understanding the increasing anthropogenic CO_2 inventories in the ocean.

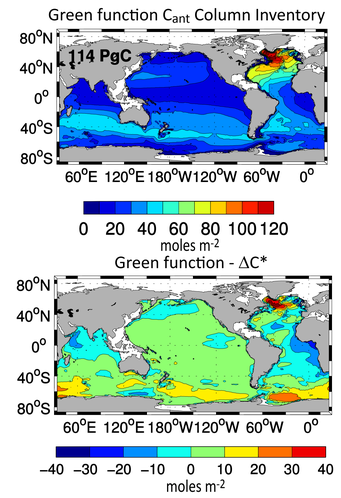
In the 1990s carbon samples were collected and analyzed from approximately 95 research cruises run as part of the international World Ocean Circulation Experiment (WOCE) and the Joint Global Ocean Flux Study (JGOFS). A map of the station locations is shown on the right.

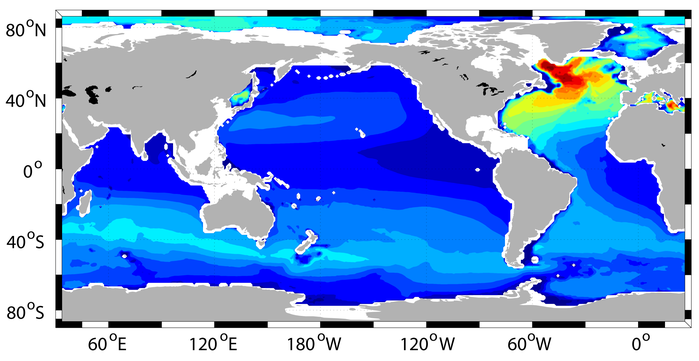
Based on these data, Sabine et al. [2004] used the ΔC^* technique to estimate that the open ocean inventory of anthropogenic CO_2 (C_{ant}) in the year 1994 was 106 ± 17 Pg C. The figure on the right shows the distribution of C_{ant} with a map of column inventory (sum of C_{ant} from the surface to the bottom in each square meter of ocean).



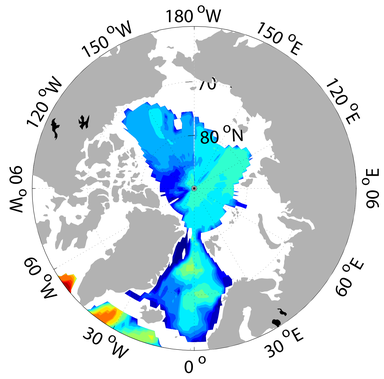
Since the Sabine et al. paper, two approaches that heavily rely on chlorofluorocarbon data have also published global inventory estimates for the reference year 1994: 94-121 Pg C based on the transient tracer distribution (TTD) method [Waugh et al., 2006] and 114 ± 22 Pg C using a Green function approach [Khatiwala et al., 2009]. The Green function distribution is shown on the right.

Although all three approaches give answers that are within the uncertainties of the methods, there are differences in the spatial patterns of all three distributions. For example, the figure to the right shows the differences in column inventory between the Green function and ΔC^*.

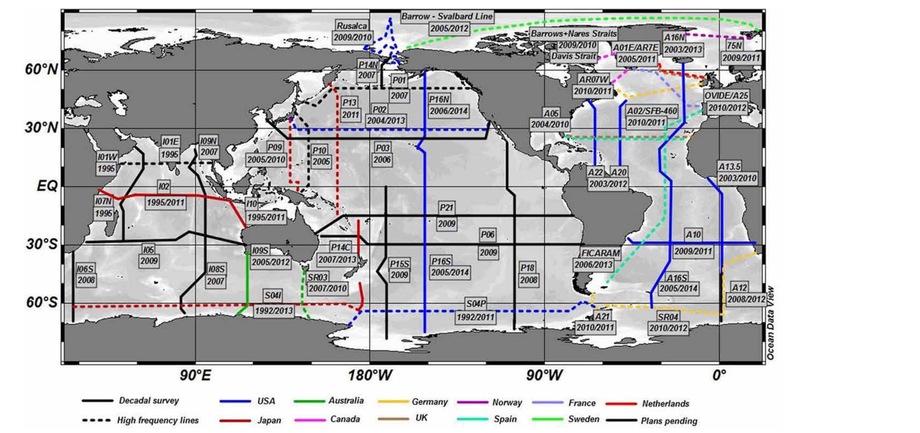




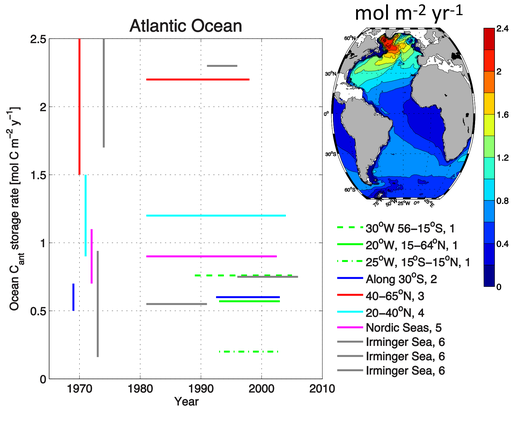
One advantage of the Green function approach is that it can provide C_{ant} estimates for any year that the atmospheric CO_2 is known. The figure above gives a total open ocean inventory of 151 ± 26 Pg C up through 2010, a 25% increase from the 1994 estimates. One disadvantage of the Green function is that changes in biological carbon cycling or variability in ocean circulation are not be captured by this approach. However, we can use continued ocean observations to assess how well the Green function estimates are working.



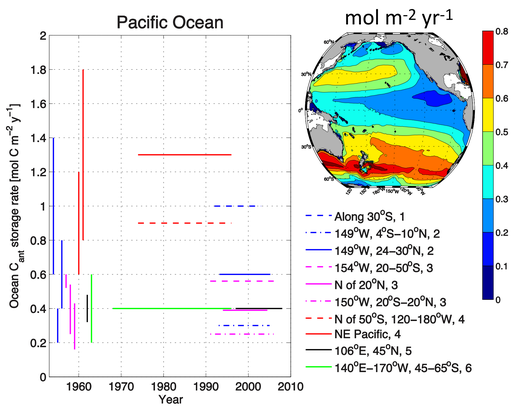
Recent work has shown that the marginal seas can contain proportionately more C_{ant} than the open ocean. Previous global estimates, however, did not include the Arctic or marginal seas. The maps above include C_{ant} inventory estimates from the Arctic Ocean [Tanhua et al., 2009], the Nordic Seas [Olsen et al., 2010], the Mediterranean Sea [Schneider et al., 2010], and the East/Japan Sea [Park et al., 2006] scaled to a common year of 2010.



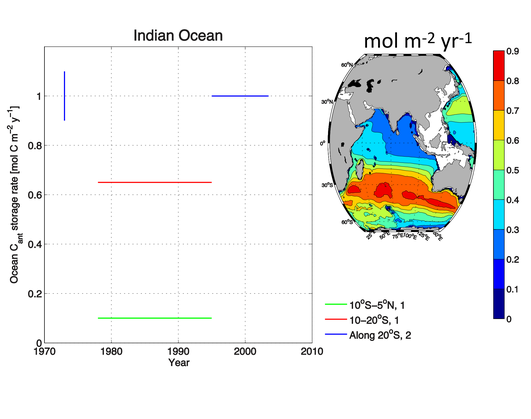
In an effort to quantify changes in the storage and transport of heat, fresh water, carbon, chlorofluoro-carbon (CFC) tracers and related parameters several countries have started programs to systematically re-occupy select hydrographic sections from the WOCE/JGOFS survey. The map above shows the sections that have been run over the last decade. This work is now coordinated at the international level by the Global Ocean Ship-based Hydrographic Investigations Program (http://www.go-ship.org).



Observed storage rates of C_{ant} (mol m^{-2} yr^{-1}) for the Atlantic Ocean. Horizontal bars are observations from repeat hydrography cruises with estimates of uncertainty shown with a corresponding vertical bar on the left. 1) Wanninkhof et al., 2010; 2) Murata et al., 2008; 3) Friis et al., 2005; 4) Tanhua et al., 2007; 5) Olsen et al., 2006. Map shows average annual C_{ant} increase between 1980 and 2005 estimated from Green function [Khatiwala et al., 2009].



Observed storage rates of C_{ant} (mol m^{-2} yr^{-1}) for the Pacific Ocean. Horizontal bars are observations from repeat hydrography cruises with estimates of uncertainty shown with a corresponding vertical bar on the left. 1) Murata et al., 2007; 2) Murata et al., 2009; 3) Sabine et al., 2008; 4) Peng et al., 2003; 5) Wakita et al., 2010; 6) Matear and McNeil, 2003. Map shows average annual C_{ant} increase between 1980 and 2005 estimated from Green function [Khatiwala et al., 2009].



Observed storage rates of C_{ant} (mol m^{-2} yr^{-1}) for the Pacific Ocean. Horizontal bars are observations from repeat hydrography cruises with estimates of uncertainty shown with a corresponding vertical bar on the left. 1) Peng et al., 1998; 2) Murata et al., 2010. Map shows average annual C_{ant} increase between 1980 and 2005 estimated from Green function [Khatiwala et al., 2009].

Conclusions:

On a global scale, it is reassuring that different methods lead to very similar estimates of the C_{ant} inventory in the ocean. The estimated errors are now all typically within ~20%. Using methods such Green functions, it is also possible to obtain the full time history of the distribution of C_{ant} in the ocean. Regionally, however, there are significant differences that can be traced to the assumptions and biases made by the various methods. The ongoing repeat hydrography program, coordinated through GO-SHIP, is documenting the changes in ocean carbon, provides a critical check on the indirect C_{ant} estimates and offers important insights into the processes controling the changing distribution of carbon in the ocean interior.

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