Using Models to Improve our Ability to Monitor Ocean Uptake of Anthropogenic Carbon

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1. Abstract

How is the ocean carbon cycle changing in response to anthropogenic perturbations? What are the processes controlling these changes, and how can process understanding inform how we measure and interpret carbon in the ocean? My current work focuses on addressing these questions with five parallel approaches. The common thread linking this work is the application of models to the interpretation of carbon measurements, and to the general theme of "Ocean Carbon Uptake and Content".

The first project involves the development of an empirical method for estimating changes in the ocean inventory of anthropogenic carbon. The approach is general, but the specific focus being developed is on estimating the changes between the WOCE (1990s) and CLIVAR (2000s) decades. The second project involves the use of models to identify the pathways and mechanisms regulating the ocean uptake of anthropogenic carbon. This also involves an important component of community-wide WOCE/CLIVAR synthesis efforts. The third component of my work involves the use of the current generation of Earth System Models (ESMs) to understand how ocean uptake of anthropogenic carbon may change in the future, and to understand how changes in the seasonal cycle of the ocean carbon cycle may be important to understanding changes in uptake.

2. Project Summary

Work continued towards development of a new method that would reduce uncertainty in estimates of the oceanic carbon uptake rate between the WOCE and CLIVAR decades. As part of this project, I attended the joint IMBER/SOLAS synthesis meeting at UNESCO in Paris between 12-16 September 2011 entitled "The Ocean Carbon Cycle at a time of change: Synthesis and Vulnerabilities". As a continuation of work originally planned at the symposium in Switzerland in July 2009 entitled "Decadal Variations of the Ocean's Interior Carbon Cycle:

Synthesis and Vulnerabilities", the meeting at UNESCO facilitated planning for the publication of the decadal changes in ocean carbon between WOCE and CLIVAR. The preliminary results of the synthesis efforts will be presented at the 2012 AGU Ocean Sciences meeting in Salt Lake City (Gruber et al., 2012).

Within the context of these community-wide efforts, I am currently working in collaboration with Robert Key at Princeton and Yves Plancherel (finished his PhD at Princeton in December 2011, now starting a post-doc in Oxford England) on a global synthesis of ocean carbon inventory changes between the 1990s and 2090s. The first stage of this work (Plancherel et al., 2012) consists of an Observing System Simulation Experiment (OSSE) for uptake of anthropogenic carbon in the North Atlantic Ocean. This is described in more detail below. Current efforts with Repeat Hydrography data are focused on the calculation of global inventory changes between WOCE and CLIVAR.

As part of broader community efforts, I have also been participating in the Regional Carbon Cycle Assessment and Processes (RECCAP) project. My contributions to RECCAP will come through my co-authorship on the Southern Ocean study (Lenton et al., 2012) and the Pacific Ocean study (Ishii et al., 2012).

3. Scientific Accomplishments

3A. Basin-scale estimates of anthropogenic carbon between WOCE and CLIVAR

Work continued towards producing a three-dimensional estimate of ocean carbon inventory changes between the WOCE (1990s) and CLIVAR (2000s) decades. The main objective of this work ahs been to go beyond applying the extended multiple linear regression (eMLR) analysis of Friis et al. (2005) to individual Repeat Hydrography/CO2 sections, and to develop a three dimensional framework for calculating basin- and global-scale inventory changes.

Over the past year, work in this direction has continued through work done in collaboratin with Yves Plancherel (a PhD student at Princeton) (Plancherel et al., 2012). This work has focued on an Observing System Simulation Experiment (OSSE) for the North Atlantic, using the NOAA GFDL ocean carbon cycle model MOM4-TOPAZ. The main result of this study is that when the eMLR method is applied on basin-scale by layer rather than along sections, a skillfull estimate of basin-scale inventory changes over decadal timescales is possible. In fact, the errors found in the study of Plancherel et al. (2012) over the North Atlantic for carbon inventory changes between the 1990s and 2000s is of order 5%. This is well within the uncertainty range suggested by the LSCOP report of Bender et al. (2002).

Current efforts are underway in collaboration with Robert Key at Princeton and Yves Plancherel to extend this work to global scales. The objective here is to provide a skillfull estimate of global ocean inventory changes between the WOCE and CLIVAR decades. It is our intention that this calculation be done in a way where changes are additive with respect to the GLODAP estimate of Sabine et al. (2004). In other words, it is our intention that the distribution we derive for the WOCE-to-CLIVAR change can be added to the GLODAP estimate to give the total ocean inventory of anthropogenic carbon in the 2000s.

3B. The formation of the ocean's anthropogenic carbon reservoir

I am currently working on a project that seeks to identify the processes controlling the uptake of anthropogenic carbon by the ocean. Researchers over the last several decade have developed a paradigm for understanding the ocean's impedance to removing anthropogenic carbon from the atmosphere, with this impedance being presented by the interplay between two primary processes: (a) gas exchange, and (b) subduction/mixing across the base of the ocean mixed layer. The new project (Iudicone et al., 2012) is testing that physical water mass transformations provide a critical third component of the impedence offered by the ocean to the uptake of carbon. This work builds on a prior collaboration (Iudicone et al., 2011) that demonstrated the critical importance of physical transformation processes for the natural ocean carbon cycle (pre-industrial) over the Southern Ocean.

An important result of the work involving anthropogenic carbon has been focused on the processes controlling sequestration of anthropogenic carbon in Subantarctic Mode Water (SAMW) over the Southern Ocean. The work to date has demonstrated that an important component of the anthropogenic carbon sequestered in SAMW has in fact entered the ocean in much lighter water within the subtropical cell spanning the subtropics and the tropics. It is only through surface densification of water parcels carrying anthropogenic carbon from the subtropics that this water is carried to SAMW densities, and it is within this SAMW density class that it enters the ocean interior below the base of the mixed layer. This unexpected new result has important implications for our understanding of how ocean uptake may change into the future under anthropogenic climate change. This work is focused squarely on the interpretation of both WOCE and CLIVAR/CO2 Repeat Hydrography data.

In a related effort, I am also conducting a new set of sensitivity experiments focusing more carefully on the specifics of how summer mixed layer depths can impact Southern Ocean biogeochemistry and uptake of anthropogenic carbon (Rodgers et al., 2012a).

3C. "Re-emergence" of anthropogenic carbon and Indo-Pacific Warm Pool acidification

Although estimates of ocean uptake of anthropogenic carbon have converged to estimates of 2.0-2.5PgCyr^{-1} for the 1990s and 2090s, to date consideration has not been given to estimating the rate of "re-emergence" of anthropogenic carbon driven by upwelling in the tropics. For the equatorial Pacific alone, ~30 Sverdrups of upwelling of upper- and core-density Equatorial Undercurrent water with an anthropogenic carbon concentration of 40 micromolar would be associated with a ~0.4 PgCyr^{-1} re-emergence of anthropogenic carbon in the NINO3 region. At approximately 20% of the global uptake rate, this number is very large, as it represents anthropogenic carbon from the ocean interior re-entering the ocean mixed layer after a transit time of approximately one decade. It will be important to make combined use of models and data to assess what fraction of this remains in the ocean, and its eventual fate with ocean transports.

Preliminary results (Rodgers et al., 2011b) indicate that a significant portion of this re-emergent carbon may contribute to acidificiation of the Indo-Pacific warm pool region. The Indo-Pacific warm pool is an important region for coral reefs and ecosystems. Due to the high human population density in this region, it is a priority to understand how 21st century climate change will impact this oceanic region. Climate models predict that the pH and aragonite saturation state of surface waters will decrease in this region over the 21st century. Controlled experiments on corals and shellfish suggest that calcification rates decrease with the aragonite saturation state, even under saturated conditions. Thus it is important for waters in the warm pool region to identify and understand the mechanisms driving acidification, and how this might impact life in the ocean.

Ishii et al. (2009) used al publicly available repeat oceanographic carbon measurements from the Pacific warm pool to produce the most systematic and complete analysis to date of trends in carbon concentrations in the Pacific warm pool region. They found a decadal trend towards increasing carbon concentrations in surface water over the last two decades. Importantly, their study also used available pCO2 measurements to argue that the surface carbon concentration trend is not driven by local air-sea exchange of CO2, but rather by the transport of carbon into this region from elsewhere. However, they concluded that from carbon measurements alone it is not possible to identify the pathways by which the carbon enters this region.

The work currently under way (Rodgers et al., 2012b) will contribute to understanding ocean dynamical controls on the fate of anthropogenic carbon, while at the same time linking this to ocean acidification.

3D. Seasonality in CO2 fluxes with Earth System Model

Work has also continued on an intercomparison project (Rodgers et al., 2012c) that evaluates the behavior of IPCC AR5 coupled carbon-climate earth system models to evaluate how the ocean carbon cycle will changes over the 21st century. We are currently evaluating a set of six state-of-the-art earth system models to evaluate both the mechanisms driving future changes to the ocean carbon cycle and the implications to the future extension of the current observing system. Each of the models has been initialized with a pre-anthropogenic climate state in 1860, and then run through a scenario with increasing atmospheric CO2 concentrations through the year 2100. Our analysis has begun with a consideration of climatologies (monthly mean structure of an average seasonal cycle) over the years 1990-1999 and 2090-2099.

The main result to date is that there are dramatic increases in the seasonal cycle of air-sea CO2 fluxes over the extra-tropics of both hemispheres, with these changes being especially pronounced in mode water formation regions. The increase in the seasonal cycle of pCO2 between the pre-industrial state and the climate state in 2090-2099 is approximately a factor of two, and this occurs despite only modest changes in the amplitude of seasonal variations in both DIC and SST. The changes are consistent across the models, with a trend towards increased uptake over the extra-qtropics in winter, but only modest or even slightly negative increases occurring over summer. Our analysis indicates that the underlying mechanism is the nonlinear effect of changes in DIC concentrations on the solubility of CO2 in the ocean. In other words, increased annual mean DIC concentrations in the surface ocean, in the absence of changes in the

amplitude of the seasonal cycle of DIC concentrations, can be expected to drive changes in the amplitude of pCO2 in the surface ocean.

The principal implication for the climate observing system is that it will be necessary to resolve the seasonal cycle in surface pCO2 measurements. Trends inferred from summer-only measurements will certainly lead to underestimates of the annual mean rate of uptake by the ocean, unless the effect of increased DIC concentrations on solubility is taken into account.

3E. $\Delta^{14}C$ (Radiocarbon) as a proxy for past variations in Southern Ocean winds

It is thought that the Southern Ocean will be an important player in determining the strength of carbon-climate feedbacks over the 21st century. The study of Le Quéré et al. (2007) argued that such feedbacks are already in evidence, relying heavily on hindcast ocean carbon model experiments with a focus on the period 1980-2004. It was argued that a secular trend over this period towards increasing winds over the Southern Ocean has perturbed the natural ocean carbon cycle in a way that drives a net release of carbon from the atmosphere to the ocean. Critical to this interpretation is the idea that natural decadal variability in Southern Ocean winds is significantly weaker than the secular trend towards strengthening winds inferred from observations over the last several decades.

For this stage of the work (Rodgers et al., 2011), I used tree ring $\Delta^{14}C$ records over the last millennium to test the hypothesis that natural decadal variations in Southern Ocean winds are in fact as large as the secular trend inferred over the period of the instrumental record (recent decades). Tree ring $\Delta^{14}C$ data indicate that atmospheric $\Delta^{14}C$ varied on multi-decadal to centennial timescales, in both hemispheres, over the period between AD950 and 1830. The Northern and Southern Hemispheric $\Delta^{14}C$ records display similar variability, but from the data alone it is not clear whether these variations are driven by the production of $^{14}CO_2$ in the stratosphere, or by perturbations to exchanges between carbon reservoirs. As the sea-air flux of $^{14}CO_2$ has a clear maximum in the open ocean regions of the Southern Ocean, relatively modest perturbations to the winds over this region drive significant perturbations to the interhemispheric gradient. In this study, model simulations are used to show that Southern Ocean winds are likely a main driver of the observed variability in the interhemispheric gradient over AD 950-1830, and further, that this variability may be larger than the Southern Ocean wind trends that have been reported for recent decades (notably 1980-2004). Our process-focused suite of perturbations experiments with models raises the possibility that the current generation of coupled climate and earth system models may underestimate the natural background multi-decadal- and centennial-timescale variations in the winds over the Southern Ocean.

This work has potentially important implications for efforts to understand the carbon cycle, and for an evaluation of the amplitude of natural background variability against which the anthropogenic trend will need to be detected. This work has also benefitted from collaborations involving the use of the GFDL coupled model (Galbraith et al., 2011) as well as the interpretation of $\Delta^{14}C$ observations over the Southern Ocean to interpret secular trends in the carbon cycle (Sweeney et al., 2012). A comparison of WOCE and CLIVAR/CO2 Repeat Hydrography data plays an important role in this research.

4. Education and Outreach

During the summer of 2011, the Principle Investigator hosted (shared with Thomas Froelicher at Princeton University) a summer undergraduate intern named Jonathan Moch, with Jonathan having been between his junior and senior years at Princeton during the internship. The title of Johnathan's internship was "Quantifying carbon cycle-climate feedbacks with the GFDL Earth System Model". For this work, the diagnostic framework presented in Friedlingstein et al. (2006) was applied to the newest models of GFDL contributing to the IPCC AR5 assessment.

5. Publications and Reports

5.1. Publications by Principal Investigator

Galbraith et al., E.D., E.Y. Kwon, A. Gnanadesikan, K.B. Rodgers, S.M. Griffies, D. Bianchi, J.L. Sarmiento, J.P. Dunne, J. Simeon, R.D. Slater, A.T. Wittenberg, and I.M. Held (2011), The Impact of Climate Variability on the Distribution of Radiocarbon in CM2Mc, a New Earth System Model, J. Climate, 24, 4230-4254.

Gruber, N., D. Clement, T. Tanhua, M. Ishii, R.M. Key, K. Rodgers, R. Wanninkhof, M. Hoppema, F.F. Perez, and S. van Heuven (2012), Toward a global data-based estimate of the oceanic accumulation of anthropogenic CO_2 since the WOCE era, abstract, AGU Ocean Sciences Meeting, Salt Lake City.

Ishii, M., R.A. Feely, K.B. Rodgers, P. Patra, Y. Niwa, S. Mikaloff-Fletcher, H. Nakano, D. Sasano, V. Valsala, H. Sigimoto, G.-H. Park, R. Wanninkhof, S. Doney, O. Aumont, J.P. Dunne, and A. Lenton (2012), Sea-air CO_2 flux in the pacific Ocean for the past two decades: the impact of ENSO on the strong oceanic source in the equatorial zone [*PACIFIC RECCAP CHAPTER*], in preparation for Biogeosciences Discussions.

Iudicone, D., K.B. Rodgers, I. Stendardo, O. Aumont, G. Madec, L. Bopp, O. Mangoni, and M. Riberta d'Alcala (2011), Watermasses as a unifying framework for understanding the Southern Ocean carbon cycle, in Biogeosciences, 8, 1031-1052, doi:10.4195/gb-8-1031-2011.

Iudicone, D.B., K.B. Rodgers, R.M. Key, Y. Plancherel, J.L. Sarmiento, G. Madec, O. Aumont, L. Bopp, and M. Ishii (2012), The formation of the ocean's anthropogenic carbon reservoir, in preparation for Global Biogeochemical Cycles.

Lenton, A., B. Tilbrook, S.E. Mikaloff Fletcher, S. Doney, K.B. Rodgers et al. (2012), RECCAP Southern Ocean Summary [*SOUTHERN OCEAN RECCAP CHAPTER*], in preparation for Biogeoscience Discussions.

Plancherel, Y., K.B. Rodgers, R.M. Key, A.R. Jacobson, and J.L. Sarmiento (2012), An evaluation of regression methods used to quantify changes in the oceanic industrial carbon inventory from repeated quasi-synoptic DIC measurement programs, in preparation for Journal of Geophys. Res.

Rodgers, K.B., S.E. Mikaloff-Fletcher, D. Bianchi, C. Beaulieu, E.D. Galbraith, A. Gnanadesikan, A.G. Hogg, D. Iudicone, B. Lintner, T. Naegler, P.J. Reimer, J.L. Sarmiento, and R.D. Slater (2011), Interhemispheric gradient of atmospheric radiocarbon reveals natural variability of Southern Ocean Winds, Climate of the Past, 7, doi:10.4195/cp-7-1123-2011.

Rodgers, K.B., O. Aumont, D. Iudicone, M. Bender, L. Bopp, G. Madec, S. Mikaloff Fletcher, and R. Wanninkhof (2012a), Summer mixed layer depth controls on Southern Ocean biogeochemistry, in preparation for Global Biogeochemical Cycles.

Rodgers, K.B., M. Ishii, D. Iudicone, O. Aumont, and R. Feely (2012b), Cold tongue re-emergence of anthropogenic carbon and Pacific warm pool acidification, in preparation for Biogeosciences Discussion.

Rodgers, K.B., M. Ishii, Y. Plancherel, O. Aumont, L. Bopp, J. Christian, J. Dunne, T. Froelicher, A. Gnanadesikan, T. Gorgues, D. Iudicone, M. Jochum, M. Kawamiya, K. Lindsay, H. Nakano, H. Okajima, S. Peacock, J. Segschneider, J.F. Tjiputra, and R. Wanninkhof (2012c), Large changes in seasonality of the ocean carbon cycle under anthropogenic climate change, in preparation for Nature Geoscience.

Sweeney, C., T. Takahashi, T. Guilderson, N.S. Lovenduski, T. Newberger, R.M. Key, J.L. Sarmiento, J. Majkut, K.B. Rodgers, and C. Le Quéré (2012), Evidence of increased vertical transport south of the Antarctic Polar Front, submitted to Geophys. Res. Lett.

5.2. Other Relevant Publications

The first publication to be published as part of this project (Rodgers et al., 2009) has now been cited five time according to the “Web of Knowledge” database. The Rodgers et al. (2011) paper is sufficiently recent that it has not yet even appeared in the database.

5.3. Other Publication Cited Here

Bender, M., et al. (2002), A Large-Scale CO_2 Observing Plan: In Situ Oceans and Atmosphere, U.S. Dept. of Commerce, Washington, D.C.

Friis, K., A. Körtzinger, J. Pätsch, and D.W.R. Wallace (2005), On the temporal increase of anthropogenic CO_2 in the subpolar North Atlantic, Deep-Sea Research I 52, 681-698.

Ishii, M., et al. (2009), Spatial variability and decadal trend of the oceanic CO_2 in the western equatorial warm/fresh water, Deep Sea Research, II, 56, 591-606.

Le Quéré, C., C. Rödenbeck, E.T. Buitenhuis, T.J. Conway, R. Langenfelds, A. Gomez, C. Labuschagne, M. Ramonet, T. Nakazawa, N. Metzl, N. Gillett, and M. Heimann (2007),

Saturation of the Southern Ocean CO_2 sink due to recent climate change, Science, 316, 1735-1738.

Rodgers, K.B., et al. (2009), Using altimetry to help explain patchy changes in hydrographic carbon measurements, J. Geophys. Res., 114, C09013, doi:10.1029/2008JC005183.