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

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1. Project Summary

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? This project focuses on addressing these questions with four 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. Work to date has focused on testing the "skill" of a new implementation of an empirical (multiple linear regression) detection method on an ocean carbon cycle model. Results with the model indicate that the method is robust, with uncertainty of 5% lying well below the threshold of "acceptable" uncertainty of 10%. This demonstrates that the method is appropriate to apply to real-world ocean observations. New work has begun on an analysis of decadal carbon accumulation over the North Pacific.

The second phase of this work focuses on the mechanisms controlling carbon uptake by the ocean. This is being addressed through two different model analyses. One of the main findings of the work to date is that uptake of anthropogenic carbon is strongly impacted by water mass transformations. In particular, uptake over the subtropical gyres and tropics constitutes approximately 2/3 of the global total, but approximately ½ of this quantity is transferred through winter release of heat during winter in western boundary currents (as well as other related processes) to deeper densities. This understanding will have important implications for efforts of the observational community to synthesize surface pCO_2 measurements and ocean interior DIC measurements.

The third phase of this project focuses on how the seasonal cycle in the ocean carbon cycle may change over the 21st century. Given that the current observing system for pCO_2 is biased heavily towards summer measurements, it is important to know the degree to which a summer bias may introduce errors in pCO_2-based ocean uptake estimates in the future. Analyses with Earth System Models suggest that underestimates of order ~1 PgC/year may result by the 2040s from (a) using summer-only measurements, and (b) assuming that the seasonal cycle is stationary. By the 2090s, this bias may result in a ~3 PgC/year underestimate of ocean carbon uptake. This work underscores the potentially critical importance of full resolution of the seasonal cycle for future carbon monitoring.

The fourth phase of this work involves development of a new method for estimating pre-anthropogenic variability in the strength of the winds, and potentially the carbon cycle, over the Southern Ocean. Recent work by a number of international researchers has focused on the question of whether Southern Ocean uptake of carbon is slowing in response to a trend towards increasing winds over the Southern Ocean. This research has taken at face value that the recent multi-decadal trend in reanalysis products (NCEP) towards stronger winds is a secular trend, and focuses largely on whether ocean mesoscale eddies act to diminish an ocean carbon cycle response. We have instead set out to test the hypothesis that the secular trend in Southern Ocean winds is indistinguishable from the natural decadal variability in Southern Ocean winds. Through the use of models, we have interpreted variations in tree ring $\Delta^{14}C$ variations over the last millennium (850 – 1850AD) to indicate that natural decadal variations are in fact as large as the recent secular trend revealed in reanalysis products. This work points to the way in which elevated natural variability potentially complicates the task of detection of climate feedbacks ove the Southern Ocean, and the need for significantly longer time series measurements.

2. Scientific and Observing System Accomplishments

Work performed over the last year is described below, separated into four components of the project. All of these relate directly to the Program Deliverable of "Ocean Carbon Uptake and Content", while the fourth item below (2D) also pertains to "Air-Sea Exchanges of Momentum".

2A. 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 to date has been to develop a method that goes beyond an along-section application of the extended multiple linear regression (eMLR) analysis of Friis et al. [2005] to develop three-dimensional estimates of ocean carbon uptake between the 1990s and 2000s.

Work this year resulted in the submission of a manuscript [Plancherel et al., 2012] describing an observing system simulation experiment (OSSE) analysis of the three-dimensional distribution of ocean carbon changes over the North Atlantic in GFDL's MOM4-TOPAZ model. The main result of this work is that the three-dimensional application of the eMLR method produces and estimate of basin-scale inventory changes with uncertainty that is only of order 5% of the full

simulated changes. This is well within the uncertainty threshold of acceptability specified in the LSCOP report of Bender et al. [2002].

The expected deliverable for 2012 was publication of the method for basin-to-global-scale estimates of anthropogenic carbon change between the 1990s and 2000s. This has been accomplished through the submission of the study of Plancherel et al. [2012] to Biogeosciences Discussion. Current efforts are underway in collaboration with Robert Key at Princeton and Yves Plancherel to extend this work to global scales for observations. Preliminary results for the North Pacific reveal change patterns that are consistent with those found for the GLODAP/WOCE era cumulative inventories of Sabine et al. [2004]. In further developing this method for the Pacific and larger scales, 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.

2B. The formation of the ocean's anthropogenic carbon reservoir

Although great efforts have been made by the observational community to identify the evolving ocean carbon cycle through ocean interior (hydrographic) measurements and sea surface pCO_2 measurements, to date there has been little progress in synthesis efforts to combine the view that emerges from interior and surface analyses of the carbon cycle. Clearly an important obstacle here is the lack of mechanistic understanding of the pathways by which carbon enters the ocean interior.

Through collaboration with Daniele Iudicone in Italy and Steve Griffies at GFDL, an effort is underway to use ocean models to identify the processes connecting surface and interior carbon changes. 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/CO_2 Repeat Hydrography data.

Further work has focused more specifically on the sensitivity of Southern Ocean carbon uptake to the parameterization of vertical mixing over the Southern Ocean, in particular how summer mixed layer depths carbon uptake by the ocean. This work was presented at the Ocean Sciences meeting in 2012 by Keith Rodgers, and is expected to be submitted for publication by March 2013 [Rodgers et al., 2013a].

The main expected deliverable of this work is a mechanistic framework that can then be applied to a synthesis of surface p CO_2 and ocean interior DIC trends. The two studies that have been conducted with a mechanistic focus have been developed in draft manuscript form, and it is expected that this work will be submitted for publication by March 2013 [Iudicone et al., 2013; Rodgers et al., 2013a].

2C. Seasonality in CO_2 fluxes with Earth System Model

Further work has been conducted with an intercomparison project [Rodgers et al., 2013b] focusing on the CMIP5 carbon-climate coupled models that are being used in the IPCC AR5 assessment. This work builds on the North Pacific study of Rodgers et al. [2008, GBC] where it was shown that decadal trends in sea surface p CO_2 diverge in winter and summer for mode water formation regions of the North Pacific. To investigate the implications for a carbon observing system, I am 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 CO_2 concentrations through the year 2100. The 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 analysis indicates that a trend towards large increases in the seasonal cycle of p CO_2 should be expected over the 21st century. In fact, the amplitude of the seasonal cycle of p CO_2 should double in the important mode water formation regions, largely due to a nonlinearity in the effect of increasing DIC concentrations on the solubility of CO_2 in the ocean. Building on the earlier stages of this work, where this was tested on IPCC AR4-generation models, the work has been repeated for the current generation of IPCC AR5 models.

This work has important implications for observing-system design. With the GFDL ESM, the results indicate that summer-only p CO_2 measurements, and the assumption of a stationary seasonal cycle, would lead to an underestimate of global carbon uptake in the 2040s of order 1 PgC/yr, and in the 2090s of order 3 PgC/yr. These results are qualitatively consistent with wht has been found with other Earth System Models participating in IPCC AR5. These results indicate the critical importance of full-seasonal resolution in p CO_2 for global monitoring efforts.

The principal deliverable for this work to date was an estimate of the potential bias in estimating ocean carbon uptake introduced by summer-intensive p CO_2 measurements. This estimate has been obtained, and this work will be submitted for publication early in 2013 [Rodgers et al., 2013b]. This work will prove important in considering future observing system design.

2D. $\Delta^{14}C$ (Radiocarbon) as a proxy for past variations in Southern Ocean winds

Is the Southern Ocean uptake of anthropogenic carbon changing? The study of Le Quéré et al. [2007] argued that it is, and identified this as an important “carbon-climate” positive feedback. However, this interpretation is complicated by the fact that the degree of natural decadal

variability in air-sea fluxes over the Southern Ocean for the pre-industrial climate state is not known. This is due in large part to the fact that marine paleo-proxy records are not available.

For this component of the project [Rodgers et al., 2011] , the hypothesis was tested that the presumed decadal carbon cycle changes in the Le Quéré et al. [2007] study are not distinguishable from natural background decadal variability. This was tested through the application of models to interpret tree ring $\Delta^{14}C$ records, for which high-resolution records are available in the Southern Hemisphere. This analysis revealed that natural decadal variability in Southern Ocean winds for the pre-industrial period were as large as the "secular trend" in NCEP and ECMWF reanalysis products over the last several decades. This calls into question our ability to detect the secular trend in Southern Ocean winds, given that the implied signal-to-noise ratio is lower than expected.

This work pertains to two of the Program Deliverables: Ocean Carbon Uptake, and Air-sea Exchanges of Momentum. This work has potentially important implications for interpretation of carbon cycle observations, 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 climate model CM2Mc [Galbraith et al., 2011].

Further details of the work conducted under the project are available through my work Home Page:

https://www.princeton.edu/aos/people/research_staff/rodgers/

2.1. Outreach and Education

Over the past year the PI has not engaged in specific outreach activity. In the summer of the coming year (FY 2013), the PI intends to mentor an undergraduate at Princeton through the Summer Intern Program and the Princeton Environmental Institute (PEI).

3. Publications and Reports

3.1. Publications by Principal Investigators

Published:

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.

Submitted:

Plancherel, Y., K.B. Rodgers, R.M. Key, A.R. Jacobson, and J.L. Sarmiento, 2012: Role of regression model selection and station distribution on the estimation of oceanic anthropgenic carbon change by eMLR, Biogeosciences Discuss., 9, 14589-14638, www.biogeosciences-discuss.net/9/14589/2012/doi:10.5194/bgd-9-14589-2012.

Proceedings from Conferences:

Rodgers, K.B., O. Aumont, D. Iudicone, and R. Wanninkhof, 2012: Storminess controls on Southern Ocean biogeochemistry and ecosystems, abstract, AGU Ocean Sciences Meeting, Salt Lake City.

Rodgers, K.B., M. Ishi, D. Iudicone, O. Aumont, M.C. Long, and J.A. Kleypas, 2012: Re-emergence of anthropogenic carbon and Pacific warm pool acidification, abstract, PICES Annual Meeting, Hiroshima, Japan, October 2012.

Froelicher, T.L., J.L. Sarmiento, S.M. Down, K.B. Rodgers, and H. Zanowsi, 2012: Anthropogenic ocean heat and carbon uptake in CMIP5 Earth System Models: The role of systematic and random uncertainty, abstract, AGU Ocean Sciences Meeting, Salt Lake City.

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., D. Sasano, N. Kosugi, T. Midorikawa, and K.B. Rodgers, 2012: Mode waters: the uptake window of natural and anthropogenic CO_2 into the ocean interior, abstract, AGU Ocean Sciences Meeting, Salt Lake City.

Mikaloff Fletcher, S.E., K.B. Rodgers, J.L. Sarmiento, J. Majkut, and A. Gnanadesikan, 2012: The influence of Southern Ocean dynamics on latitudinal gradients in atmospheric radiocarbon, abstract, AGU Ocean Sciences Meeting, Salt Lake City.

Plancherel, Y., K.B. Rodgers, R.M. Key, A. Jacobson, and J.L. Sarmiento, 2012: Quantification of the basin-scale decadal changes in the distribution of oceanic industrial carbon by eMLR, abstract, AGU Ocean Sciences Meeting, Salt Lake City.

Ridder, N.N., K.B. Rodgers, J.L. Sarmiento, J.P. Dunne, S.M. Griffies, and M.H. England, 2012: Impact of different diapycnal diffusivity parameterization schemes on oxygen concentrations in the east Pacific oxygen minimum zones in a global ocean model, abstract, AGU Ocean Sciences Meeting, Salt Lake City.

In Preparation, Submissions by March 2012:

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, 2013: 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.B., K.B. Rodgers, R.M. Key, Y. Plancherel, J.L. Sarmiento, G. Madec, O. Aumont, L. Bopp, and M. Ishii, 2013: The formation of the ocean's anthropogenic carbon reservoir, in preparation for Global Biogeochemical Cycles.

Rodgers, K.B., O. Aumont, D. Iudicone, M. Bender, L. Bopp, G. Madec, S. Mikaloff Fletcher, and R. Wanninkhof (2013a), Summer mixed layer depth controls on Southern Ocean biogeochemistry, in preparation for Global Biogeochemical Cycles.

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 (2013b), Large changes in seasonality of the ocean carbon cycle under anthropogenic climate change, in preparation for Nature Geoscience.

3.2. Other Relevant Publications

The study that initiated this project:

> 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.

has been cited six times since its publication in 2009.