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

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Table of Contents

1. Project Summary 2
2. Scientific and Observing System Accomplishments 2
3. Outreach and Education 5
4. Publications and Reports 6
   4.1. Publications by Principal Investigators 6
   4.2. Other Relevant Publications 7
5. Slides 7

1. Project Summary

Given the importance of CO_2 as a greenhouse gas and driver of climate change, it is important to understand how much of the CO_2 produced through human activities is being absorbed by the ocean, and how that quantity is changing in time. A number of recent studies have suggested that ocean uptake of the anthropogenic perturbation to atmospheric CO_2 may be slowing, and if this were true it could imply that there has been a positive feedback in the climate system. This would implicate the ocean carbon cycle in an acceleration of the rate of warming.

I am currently working on four projects that address directly the way in which ocean uptake of anthropogenic carbon may be changing. The common thread with each state of this work is the use of ocean or climate models, which despite their numerous caveats and inherent uncertainties allow for fully consistent three-dimensional analyses of climate variables to be analyzed. Rather than attempting to validate the models, the objective is to evaluate how well different sampling strategies can allow one to characterize the globally integrated fields of interest.

There are two intended user communities that should benefit from the research described above. First, I am working directly in collaboration with an international group (being led by Niki Gruber at the ETH in Zurich Switzerland, and including NOAA researcher Rik Wanninkhof) to provide a global estimate of ocean interior carbon inventories between the mid-1990s and mid-2000s. The second intended beneficiary of this research should be the community of researchers measuring sea surface pCO_2 with the goal of quantifying whether the rate of uptake of carbon by the ocean is changing. My intention is that through the use of models, we can also provide a framework and methods for the synthesis between these user groups.

2. Scientific and Observing System Accomplishments

2.1 Historical reconstruction of pCO_2

In collaboration with Joe Majkut (a recently graduated PhD student at Princeton), a study was published this year consisting of a historical reconstruction of monthly global gridded sea surface pCO_2 product (Majkut et al., 2014a). Previously concerted community efforts have been devoted to producing an authoritative climatology of air-sea CO_2 fluxes, such as the successive climatology products produced by Taro Takahashi at Lamont Doherty over the last two decades. However, identifying decadal trends in CO_2 fluxes has proven to be more challenging. The available surface pCO_2 estimates are too sparse to separate long-term trends from decadal and seasonal variability using simple linear models.

We introduced Markov Chain Monte Carlo sampling as a novel technique for estimating the historical pCO_2 at the ocean surface. The result is a plausible history of surface pCO_2 based on available measurements and variability inferred from model simulations. Applying the method to a modern database of pCO_2 data, we found that two thirds of the ocean surface is trending towards increasing uptake of CO_2, with a mean (year 2000) uptake of 2.3 +/ 0.5 PgC yr^{-1} of anthropogenic carbon and in increase in the global annual uptake over the 30 year time period of 0.4 +/ 0.1 PgC yr^{-1} $decade^{-1}$. The results are particularly interesting in the Southern Ocean, where we find increasing uptake of carbon over this time period, in contrast to previous studies. We find evidence for increased ventilation of deep ocean carbon, in response to increased winds, which is more than offset by an associated surface cooling.

With the new pCO_2 product, we are participating in a new data-based sea-air CO_2 flux estimation project called The Surface Ocean pCO_2 Mapping intercomparison (SOCOM), being led by Christian Rödenbeck in Jena, Germany.

2.2 An observing system simulation for Southern Ocean carbon dioxide uptake

Additionally, we have considered the sampling strategy required by the observing system over the Southern Ocean using an Observing System Simulation Experiment using GFDL models of ocean biogeochemistry.

The Southern Ocean is critically important to the oceanic uptake of anthropogenic CO_2. Up to half of he excess CO_2 currently in the ocean entered through the Southern Ocean. That uptake helps to maintain the global balance and buffers transient climate change from fossil fuel emissions. However, the future evolution of the uptake is uncertain, because our understanding of the dynamics that govern the Southern Ocean CO_2 uptake is incomplete. Sparse observations and incomplete model formulations limit our ability to constrain the monthly and annual uptake, interannual variability and long-term trends. Float-based sampling of ocean biogeochemistry provides an opportunity for transforming our understanding of the Southern Ocean CO_2 flux. In the work of Majkut et al. (2014b), we review current estimates of the CO_2 uptake in the Southern Ocean and projections of its response to climate change. We then show, via an observational

system simulation experiment that float-based sampling provides a significant opportunity for measuring the mean fluxes and monitoring the mean uptake over decadal timescales.

2.3 Strong sensitivity of Southern Ocean carbon uptake to wind stirring

This year I published a modeling study as first author (Rodgers et al., 2014a) testing the hypothesis that winds have an important role in determining the rate of exchange of CO_2 between the atmosphere and the ocean through wind stirring over the Southern Ocean. This was tested with a sensitivity study using an ad hoc parameterization of wind stirring in an ocean carbon cycle model, where the objective was to identify the way in which perturbations to the vertical density structure of the planetary boundary layer of the ocean impact the ocean carbon cycle and ocean biogeochemistry.

The main result was that wind stirring leads to reduced uptake of CO_2 over the Southern Ocean over the period 2000-2006, with a relative reduction with wind stirring o the order of 0.9 PgCyr-1 over the region south of 45°S. This impacts not only the mean carbon uptake, but also the phasing of the seasonal cycle of carbon and other biogeochemical tracers. Enhanced wind stirring delays the seasonal onset of stratification and this has large impacts on both entrainment and the biological pump. It is also found that there is a strong reduction on the order of 25-30% in the concentration of NO_3 exported in Subantarctic Mode Water (SAMW) to wind stirring. This finds expression not only locally over the Southern Ocean, but also over larger scales through the impact on advected nutrients. In summary, the large sensitivity identified with the ad hoc wind stirring parameterization offers support for the importance of wind stirring for global ocean biogeochemistry through its impact over the Southern Ocean.

An important part of this study was the application of Atmospheric Potential Oxygen (APO) ratios measured at Scripps through the support of the NOAA Climate Program Office to assess uncertainties in ocean carbon uptake over the Southern Ocean. The was achieved through collaboration with Ralph Keeling at Scripps., as well as with Rik Wannihkof at NOAA.

2.4 Evaluation of Observing System Design with GFDL's Earth System Model ESM2M

Over the winter of 2013-2014, I ran a suite of 30 ensemble members with GFDL's Earth System Model ESM2M to evaluate the implications of natural variability in the climate system for observing system design. The 30 ensemble simulations were performed over the period 1950-2100 following historical and RCP8.5 concentration pathways. The initial conditions for the 30 ensemble members for January 1st 1950 differed in the initial state of the atmospheric component. This was accomplished by using model state snapshots for the ends of days 1-29 in January 1950 as the initial model state for January 1st 1950 for each of the ensemble members 2-30.

In collaboration with Sarah Schlunegger, a PhD student at Princeton (Schlunegger et al, 2014 AGU presentation), this ensemble runs have been used to evaluate the way in which natural variability in carbon uptake impacts the detection of trends in carbon uptake by the ocean. The analysis has revealed a significant tendency towards decreased ENSO variance over the 21st century in ESM2M, with this reducing the noise against which the secular trend is to be detected.

The analysis has also addressed the extent to which the multi-model spread of CMIP5 Earth System Models in their representation of carbon uptake by the ocean reflects differences in model architecture, and the extent to which it represents the underlying natural variability inherent to Earth System Models. The results to date indicate that as much as 25% of the CMIP5 multi-model ensemble spread in carbon uptake may reflect internal variability in the climate system.

In a separate study, the ensemble suite with ESM2M has also been applied to the question of detection of emergence of secular trends of marine ecosystem stressors (Rodgers et al., 2014b). Marine ecosystems are increasingly stressed by human-induced changes. These ocean stressors – including warming, acidification, deoxygenation and perturbations to biological productivity – can co-occur in space and time, but detecting their trends is complicated by the presence of noise associated with natural variability in the climate system. Here we use Large Initial-Condition Simulations with a comprehensive Earth System Model (GFDL's ESM2M) under a historical/RCP8.5 pathway over 1950-2100 to consider emergence characteristics for the four individual and combined stressors. Using a one-standard deviation (67% confidence) threshold of signal-to-noise to define emergence with a 30-year trend window, we show that ocean acidification emerges much earlier than other stressors, namely during the 20th century over most of the global ocean. For biological productivity, the anthropogenic signal does not emerge from the noise over most of the global ocean before the end of the 21st century. The early emergence pattern for sea surface temperature in low latitudes is reversed from that of subsurface oxygen inventories, where emergence occurs earlier in the Southern Ocean. For the combined multiple-stressor field, 41% of the global ocean exhibits emergence for the 2005-2014 period, and 63% for the 2075-2084 period. The combined multiple-stressor field reveals emergence patterns by the end of this century that are relatively high over much of the Southern Ocean, North Pacific, and Atlantic, but relatively low over the tropics and the South Pacific. It is precisely in the regions with pronounced emergence characteristics that marine ecosystems can be expected to be pushed outside of their comfort zone determined by the degree of natural background variability to which they are adapted. The results thus have implications not only for optimization of the ocean observing system, but also for risk assessment and mitigation strategies.

In both cases, our results point to the importance of maintaining a sustained multi-decadal observing system for ocean biogeochemistry and ecosystem stressors. For both the carbon uptake fields and the four ecosystem stressors considered in the two studies, the analysis reveals that even with a perfectly resolving (all time and space scales) ocean biogeochemical observing system, an observing system may need to be sustained in order to distinguish the anthropogenic or secular trend from background natural decadal variability. Of course the global observing system will always be imperfect, and this fact will only increase the duration of sustained measurements needed to provide a satisfactory accounting of emergence.

3. Outreach and Education

During the summer of 2014, I hosted two summer undergraduate interns through the Princeton Environmental Institute's Grand Challenges Program. The students, Paul Yi and Jonathan Lin, are undergraduates at Princeton. Both of them worked intensively with GFDL's coupled Earth

System Model ESM2M. The work with Jonathan Lin has led to a manuscript submitted for publication to Biogeosciences Discussions (Rodgers, Lin, and Frölicher, 2014), and the work with Paul Yi is currently being prepared for publication.

4. Publications and Reports

4.1. Publications by Principal Investigator

Published

Rodgers, K.B., O. Aumont, S.E. Mikaloff Fletcher, Y. Plancherel, L. Bopp, C. de Boyer Montégut, D. Iudicone, R.F. Keeling, G. Madec, and R. Wanninkhof (2014a), Strong sensitivity of Southern Ocean carbon uptake and nutrient cycling to wind stirring, Biogeosciences, 11 4077-4098.

Ishii, M., R.A. Feely, K.B. Rodgers, G.-H. Park, R. Wanninkhof, D. Sasano, H. Sugimoto, C.E. Cosca, S. Nakaoka, M. Telszewski, Y. Nofiri, S.E. Mikaloff Fletcher, Y. Niwa, P.K. Patra, V. Valsala, H. Nakano, I. Lima, S.C. Doney, E.T. Buitenhuis, O. Aumont, J.P. Dunne, A. Lenton, and T. Takahashi (2014), Air-sea CO_2 flux in the Pacific Ocean for the period 1990-2009, Biogeosciences, 11, 709-234.

Majkut, J.D., J.L. Sarmiento, and K.B. Rodgers (2014a), A growing oceanic carbon uptake: Results from an inversion study of surface pCO_2 data, Global Biogeochem. Cycles, 28, doi:10.1002/2013GB004585.

Majkut, J.D., B.R. Carter, T.L. Frölicher, C.O. Dufour, K.B. Rodgers, and J.L. Sarmiento (2014b), An observing system simulation for Southern Ocean carbon dioxide uptake, Phil. Trans. R. Soc. A, 372, 20130046.

Under Review

Rodgers, K.B. J. Lin, and T.L. Frölicher (2014b), Emergence of multiple ecosystem stressors in a large ensemble suite with an Earth System Model, submitted to Biogeosciences Discussions.

Iudicone, D., K.B. Rodgers, Y. Plancherel, O. Aumont, T. Ito, R. Key, G. Madec, and M. Ishii (2014), The formation of the ocean's anthropogenic carbon reservoir, submitted to Proceedings of the National Academy of Sciences.

Conference Abstracts

Rodgers, K.B. T.L. Frölicher, and J. Lin (2014), Time of emergence of multiple ecosystem stressors in a large suite with an Earth System Model, 2014 AGU Fall Meeting, San Francisco.

Schlunegger, S., K.B. Rodgers, J.L. Sarmiento, and T. Frölicher (2014), Trends in Secular Mean State and Variance Changes in Ocean Carbon Uptake in RCP8.5 Large Ensemble Experiments with Two Earth System Models, 2014 AGU Fall Meeting San Francisco.

4.2. Other Relevant Publications

Publications by Principal Investigator

3.2.1 The original publication from this grant (Rodgers et al., 2009) has now been cited 10 times, with the most recent citation being the global ocean carbon synthesis paper of Kouketsu et al. (2014) that appeared in Geophysical Research Letters earlier this year.

3.2.2 The more recent study of Rodgers et al. (2011) has now been cited seven times, with three of those citations occurring the year 2014 to date

Other Relevant Publications

The study of Iudicone et al. (2011) has now been cited 13 times, with 7 of these citations occurring during 2014. The study of Galbraith et al. (2011) has now been cited 14 times.

5. Slides

See the attached Powerpoint file showing the main new result with the Large Initial Condition suite of Ensemble Runs with GFDL's ESM2M.