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Understanding and predicting ocean carbon uptake using coupled climate models: Recent achievements and open challenges

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The global ocean is a major sink of anthropogenic CO_2, significantly slowing the CO_2 increase in the atmosphere due to anthropogenic emissions. However, the absorption of excess greenhouse gases and the warming trend of our climate over the last few decades affect the ocean circulation, biogeochemistry and ecosystem structure. Those changes, in turn, may have positive feedbacks on atmospheric CO_2 concentrations through the slowdown of oceanic carbon uptake, further enhancing global warming. Therefore, feedbacks between the carbon cycle and climate represent a mechanism by which the overall climate sensitivity to radiative forcing may be amplified. The strength of these feedbacks depends on the complex interplay between physical and biogeochemical processes. These feedbacks remain a major uncertainty in climate simulations due to the number of processes and associated temporal and spatial scales involved and the difficulties of parameterizing them.

The Coupled Model Intercomparison Project phase 5 (CMIP5) provided coordinated sets of climate simulations with an interactive carbon cycling component that represented a unique and time-sensitive opportunity to assess the strength of the climate-carbon cycle feedbacks in a multi-model context. In 2012, a working group on "Oceanic carbon update in the CMIP5 models" - jointly sponsored by the US Climate Variability and Predictability (CLIVAR) and Ocean Carbon and Biogeochemistry (OCB) programs - set out to investigate differences among model predictions across multiple time scales and in different ocean basins and understand the representation of such feedbacks to possibly narrow uncertainties in the next generation of Earth system models. This effort culminated in a community workshop held in December 2014 in San Francisco, CA, entitled: "Ocean's Carbon Uptake: Uncertainties and Metrics." This joint edition of the OCB and US CLIVAR newsletters is based on contributions spanning the range of topics covered at the workshop. It is representative of the challenges and advances across disciplines in modeling and understanding mechanisms, sensitivities, and feedbacks of ocean carbon uptake.

Ocean biogeochemistry in the fifth Coupled Model Intercomparison Project (CMIP5)

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Since model projections were used in the Intergovernmental Panel on Climate Change's (IPCC) First Assessment (Houghton et al. 1990), the trajectory of carbon dioxide (CO_2) has been a central player in climate projection and model intercomparison. Not until the Fifth Coupled Model Intercomparison Project (CMIP5; Taylor et al. 2012) in support of the IPCC 5th Assessment (IPCC 2013), however, were fully coupled climate-carbon cycle Earth system models mature and pervasive enough for explicit inclusion in the intercomparison. This article describes CMIP5 accomplishments and remaining challenges faced by the ocean biogeochemistry community for advancing coupled carbon-climate and marine ecosystem research.

Origins of CMIP5 ocean biogeochemistry

Since ocean biogeochemical general circulation models (OBGCMs; Sarmiento et al. 1993) began incorporating an explicit carbon cycle (Bacastow and Maier-Reimer 1990; Siegenthaler and Sarmiento 1993), global models of climate change response (Sarmiento and Le Quéré 1996; Bopp et al. 2001) and later, more 'intermediate' complexity models of coupled elemental cycles (Moore et al. 2004; Le Quéré et al. 2005) have been applied to the coupled carbon-climate problem. Typical OBGCM applications include tracking how much anthropogenic carbon uptake has occurred historically and its projection into the future, characterization of natural carbon cycle change, and description of ecosystem variability and change, all in the face of climate change.

A variety of OBGCMs are now in use, and they exhibit fundamentally different representations of regional patterns in productivity and sensitivity to climate warming (Steinacher 2010). At their core are distinct ecological modeling strategies to distill the vast complexity of natural systems in the face of limited, imperfect information into a discrete set of mathematical representations of nutrient-phytoplankton-zooplankton interactions. The more sophisticated of these focus on phytoplankton functional groups (CO_2-fixers, N_2-fixers, silicifiers, calcifiers) to conduct multi-element biogeochemistry (Le Quéré et al. 2005), either through calibration to particularly well-known species from laboratory and field studies (e.g., *Prochlorococcus, Trichodesmium, T. weissflogii, E. huxleya*) or through stoichiometrically-constrained empirical functions (Dunne et al. 2007).

Assessment and attribution of biases in OBGCMs is challenged by a variety of factors. The biological and biogeochemical constraints and theories on which these models are based represent only a small amount of the overall ecosystem variability observed in nature. Thus modelers are afforded much latitude in prioritizing and parameterizing a given ecosystem's constraints based on process studies, field-, and satellite-based observations. Key uncertainties include mechanistic controls on euphotic zone nutrient consumption and degree of residual nutrient, particulate and dissolved organic matter passive and active transport, deviations in stoichiometry from Redfield (e.g., N_2 fixation), and remineralization scales through the twilight zone. Ecological uncertainties include the general controls, functional traits, adaptation limits on phytoplankton physiology, the predictability, phenology, and niche gaps in biodiversity, and the spectrum of trophic interactions. Beyond the biological factors themselves, many of the fundamental controls on ocean biogeochemistry are physical in origin, including atmospheric wind, freshwater and buoyancy forcing, and ocean physics and circulation. Similarly, external factors such as light, deposition, and river and sediment interactions may also be key to ecosystem function. Each model thus represents a consortium of expert decisions towards a highly idealized representation of the coupled physical, biogeochemical, and ecological system.

CMIP5 OBGCMs

With respect to marine ecology, the CMIP5 suite spans a range of phytoplankton species diversity and ecological interactions. The models consider a range of elemental cycles of carbon, nitrogen, oxygen, phosphorus, silicon, iron, alkalinity, and lithogenic material and different parameterizations of the processes that couple and decouple these elements, including gas exchange, primary production, ecosystem processing, particle

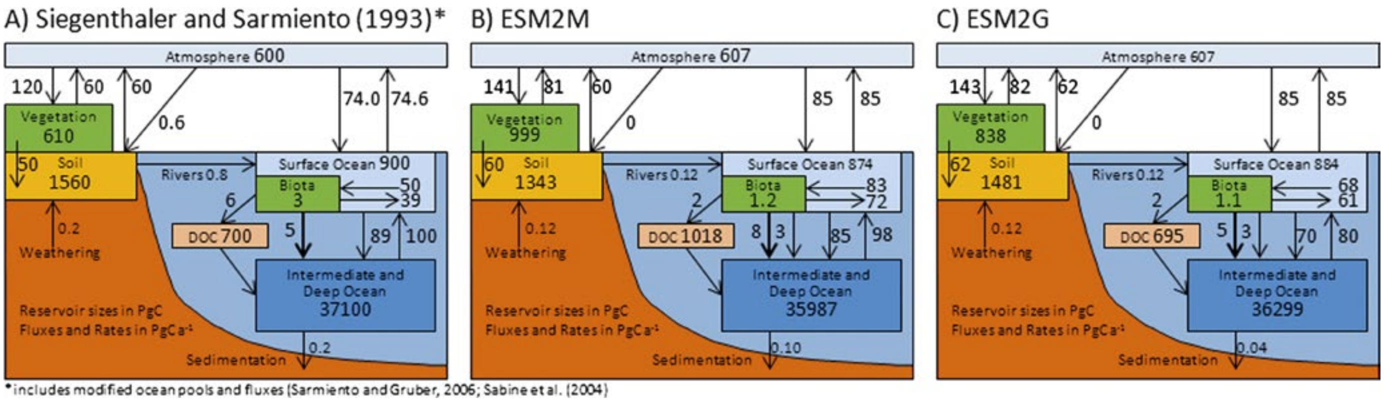

Figure 1: Global carbon cycle schematic comparison to estimate by Siegenthaler and Sarmiento (1993) with ocean additions from IPCC (Sabine et al. 2004). Reprinted from Figure 1 of Dunne et al. (2013).

sinking, dissolved organic matter cycling, atmospheric deposition, river input, scavenging, and sediment removal and supply. CMIP5 models include one to three of the following phytoplankton groups: Diatoms, picoplankton (*Prochlorococcos*), nanoplankton, flagellates, calcifiers, and diazotrophs (N_2-fixers). Most models distinguish between large diatoms and small phytoplankton and represent calcification implicitly as part of the small or large phytoplankton. Phytoplankton growth is limited by light, nutrients, and in most models by temperature (no temperature effect in HadGEM; The HadGEM2 development team 2011). Nitrogen is a limiting nutrient in all models; additionally, many models consider limitation by iron, silicate, and sometimes ammonium and phosphate. Most models assume Redfield C:N:P Ratio but allow for varying Si, Fe and Chl:C ratios. A few models (e.g., GFDL-TOPAZ; Dunne et al. 2013 and PELAGOS; Vichi et al. 2007) enable deviations from the Redfield ratio. While the underlying equations of phytoplankton growth, temperature, and light limitation are similar among models, models follow either Michaelis-Menten or quota equations for nutrient limitation and exhibit vast differences in parameter values. CMIP5 models include one to three zooplankton types to representing different size classes - and use a variety of different grazing functional forms - resulting in food web dynamics that differ greatly among models (Sailley et al. 2013). Particulate organic matter is produced during grazing and in some models by direct aggregation of phytoplankton. The equations describing particle sinking range from simplistic implementations of constant sinking speed and either a constant, temperature-, or depth-dependent remineralization (e.g., PELAGOS; Vichi et al. 2007) to more elaborate implementations, including particle aggregation, grazing of particles, mineral ballasting, or different particle sizes with different sinking speeds (e.g., IPSL-PISCES, Aumont et al. 2006; CESM-BEC, Moore et al. 2013; GFDL-TOPAZ Dunne et al., 2013).

Within several modeling centers, including GFDL (Dunne et al. 2012; 2013; Figure 1), GISS (Schmidt et al. 2014), IPSL (Dufresne et al. 2013), MPI (Ilyana et al. 2013), and others, alternative representations of the physical model underlying the biogeochemical algorithms were applied. These models were demonstrated to have vast differences in baseline simulation characteristics as a consequence of physics alone, as illustrated by particle export in GFDL's ESM2M (8 PgC/yr) being approximately 30% higher than that in the isopycnal coordinate ESM2G (5 PgC/yr), with similar overall fidelity and often opposing water column tracer biases (Dunne et al. 2013).

Comparison of CMIP5 OBGCM fidelity and sensitivity

Even in the face of such strong differences in baseline simulation (Figure 1; Dunne et al. 2013), anthropogenic carbon uptake across the CMIP5 suite of models (Figure 2; Frölicher et al. 2015) illustrates broad agreement at the 20% uncertainty level with relative dominance of the Southern Ocean in terms of uptake. Solubility and passive transport dominate CO_2 uptake along pathways of ocean gas exchange, surface ventilation, and interior propagation wherein this generation of model has demonstrated vast improvement over past generations of models in both carbon uptake (Doney et al. 2004; Matsumoto et al. 2004; Frölicher et al. 2015) and feedbacks (Arora et al. 2014; Friedlingstein et al. 2004). Key factors underlying this improved consensus across the CMIP5 suite likely include consistency in the implementation of aqueous geochemistry (algo-

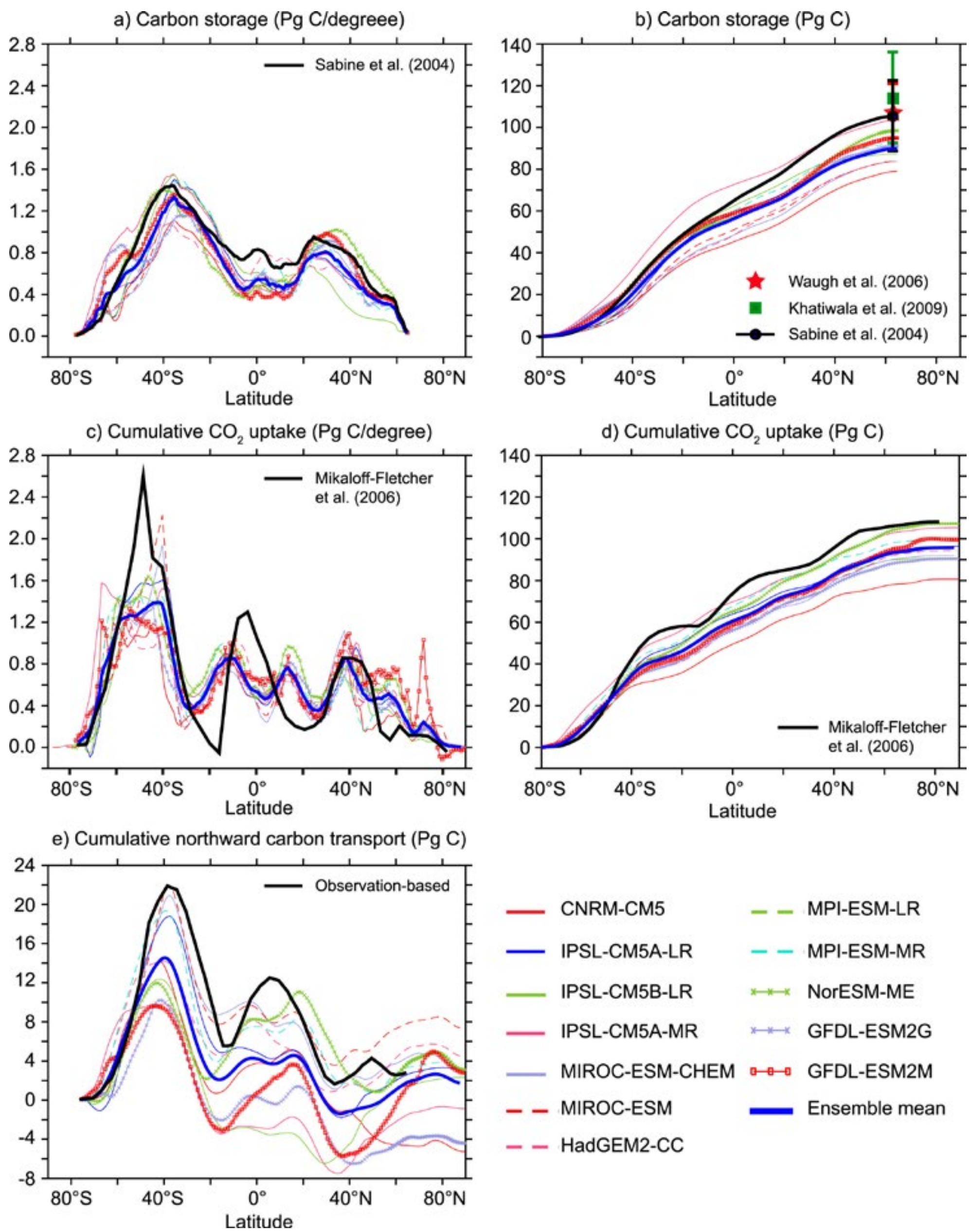

Figure 2: Changes in oceanic storage, uptake, and transport of anthropogenic carbon between 1870 (represented by mean of period 1861–80) and 1995 (represented by mean of period 1986–2005) simulated by 12 CMIP5 models. (a) Zonal integrated oceanic anthropogenic carbon storage, (b) zonal integrated oceanic anthropogenic carbon storage integrated from 90°S to 90°N such that the vertical scale goes from 0 at 90°S to the total storage at 90°N, (c) zonal integrated cumulative ocean anthropogenic CO_2 uptake, (d) zonal integrated cumulative ocean anthropogenic CO_2 uptake integrated from 90°S to 90°N such that the vertical scale goes from 0 at 90°S to the total uptake at 90°N, and (e) northward oceanic anthropogenic carbon transport. The transport of anthropogenic carbon is the divergence of the anthropogenic CO_2 uptake and the anthropogenic carbon storage. The observation-based estimate of oceanic anthropogenic carbon transport is the divergence of the anthropogenic carbon flux estimates of Mikaloff Fletcher et al. (2006) and the anthropogenic carbon storage estimates of Sabine et al. (2004). Anthropogenic carbon storage in (a) and (b) is given for the GLODAP dataset area only, which does not cover coastal regions and several marginal seas, most notably the Arctic, the Caribbean, and the Mediterranean Sea. Excluded regions from the GLODAP area account for 7% and 10% of the total anthropogenic carbon storage in the CMIP5 models and the observation-based estimates, respectively (Table 2 in Frölicher et al. 2015). Note that this has no impact when comparing results for the Southern Ocean (south of 30°S). Observation-based estimates are normalized to year 1994. Weighted mean estimates of inversion-based anthropogenic air-sea CO_2 fluxes are shown in (c) and (d). Reprinted from Frölicher et al. (2015).

rithm of OCMIP2 (Orr et al. 2001) based on Millero et al. (1995)) and gas exchange (algorithm of Wanninkhof 1992), and in the representation of the large-scale ocean circulation.

Yet in the context of ocean acidification, a few surprises have arisen. Resplandy et al. (2013) demonstrated that the maximum acidification response to surface CO_2 forcing may somewhat quixotically be manifested in the subsurface as accumulation of the anthropogenic carbon signal in subtropical mode waters with naturally high levels of remineralized CO_2 combined with enhanced surface stratification and intensification and shoaling of the nutricline. Further work to identify key mechanisms in these models has demonstrated the importance of restratification and advection of interior temperature gradients that lead to strong divergence in the patterns of warming and anthropogenic CO_2 (Winton et al. 2013).

In strong contrast to the apparent overall agreement among CMIP5 models in terms of anthropogenic carbon uptake (Figure 2), the ecological response in these models is highly uncertain. As demonstrated in Bopp et al. (2013), CMIP5 models do a far better job at representing regional patterns in sea surface temperature than biogeochemical parameters such as surface pH, subsurface ocean oxygen, and net primary production (NPP). Laufkötter et al. (2015) compared differences with representations of surface chlorophyll, the most directly measurable, biogeochemically relevant variable from satellites, which illustrated vastly different spatial patterns and inter-model variance. Also compared were the field-based climatologies of surface nutrients in the form of nitrate, for which models clustered well, and silicate, for which models diverged. Anderson et al. (2015) further demonstrated vastly different patterns in surface dissolved organic matter distributions. While Bopp et al. (2013) demonstrated that some potential ecosystem stressors such as sea surface temperature and pH undergo robust patterns of change under projections of future climate change, they further illustrated that similar ecologically critical stressors, such as NPP and subsurface oxygen, undergo dramatic changes on the order of 50% in both the positive and negative directions, leading to vast uncertainty in the overall multi-stressor response.

At first order, warming increases stratification in CMIP5 models such that ventilation and nutrient supply to the euphotic zone decreases, NPP decreases, and phytoplankton composition shifts toward smaller size classes and the microbial loop (Cabre et al. 2014). Second, these models broadly experience a poleward expansion and slow-down of subtropical gyres, leading to a shoaling nutricline in the subtropical gyres and enhanced nutrients, hypoxia, and acidification in some areas (Bopp et al. 2013, Cabre et al. 2014). An intensified hydrological cycle and warming reduces North Atlantic overturning, leading to a shoaling northern subpolar Atlantic and deepening tropics (Winton et al. 2013).

Projections for the bottom-up drivers of NPP changes (i.e., temperature, light and particularly nutrient limitation) show a wide range of responses (Figure 3). As a result, between both models and regions, different mechanisms are responsible for the NPP changes. Uncertainties in sea ice projections and future NO_3 limitation lead to disagreement on Arctic NPP response (Vancoppenolle et al. 2013). In the subtropical gyres, few models show decreases in phytoplankton growth due to lower nutrient availability. In the majority of models, phytoplankton growth increases due to warming, despite lower nutrient concentrations. However, temperature-driven intensification of grazing pressure decreases biomass in most models, resulting in net decreases in NPP in almost all models (Laufkötter et al. 2015). Overall, a changing balance of processes creates intense regional structure in projected change that currently shows little consensus among CMIP5 models.

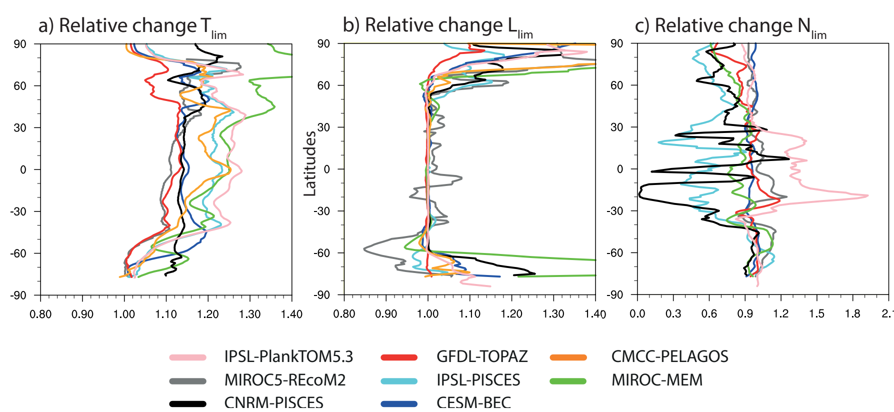

Figure 3: Zonal mean of the relative change in (a) temperature, (b) light, and (c) nutrient limitation factors for nine marine biogeochemistry models. Relative change is calculated as the 2081–2100 average divided by the 2012–2031 average. Based on Figure 6 of Laufkötter et al. (2015).

Moving forward on ocean biogeochemistry from CMIP5

CMIP5 has made a massive amount of model output available to data analysts through an easily accessible on-line data portal. Common data formats units, model grid descriptions, and variable names assist in the comparison of key variables. However, while descriptive comparison of key biogeochemical variables is straightforward and well supported in CMIP5, analysis of the underlying mechanisms is met with three main challenges. First, limitations in storage capacity severely curtail analysis necessary to understand the drivers of ecosystem changes, requiring either liberal use of correlation as indicator for causation (e.g., Cabre et al. 2014), or extensive re-calculation efforts, in which numerical inaccuracies are often unavoidable (Laufkötter et al. 2015). Second, the availability of output only on non-uniform grids forces analysis to be much more difficult than it would be if output for conservatively remapped variables were also available on a uniform grid. One such candidate uniform grid is that used for the World Ocean Atlas (WOA13; e.g. Locarnini et al. 2013). Finally, the full model documentation and parameter values are often difficult if not impossible to obtain. This severely limits the ability to both analyze internal mechanisms and compare with previous analyses. While the data restriction is logistically hard to overcome and requires expert decisions on the list of variables requested by the MIP, model documentation could be significantly improved by requiring that it include an updated list of parameter values for participation in the MIP.

With respect to individual science research, moving forward from CMIP5 will involve a multi-pronged approach of application of existing models, exploration of process representation for baseline fidelity and sensitivity, refined development towards increased comprehensiveness, and increasing resolution. Near-term priorities for application of these models include: Multi-member ensembles for detection and attribution, centennial-millennial scales, idealized sensitivity, diverse impacts application and assessment of potential for predictability and integration with seasonal-decadal climate prediction efforts, and exploring opportunities for experimental biogeochemistry prediction. Sensitivity priorities include physiological responses to temperature, acidification, oxygen, macro- and micro-nutrient limitation, and combined multi-stressor responses. Comprehensiveness priorities include going beyond closing the CO_2 cycle to fully comprehensive and internally consistent representation of aerosol, Fe, CH_4 and N cycles, and ecosystems. Finally, the ever-present challenge of resolution must be addressed to capture key mechanisms in regional atmosphere-land interactions, currents, and the mesoscale ocean for improved base state, change, and human and marine applications.

With respect to community engagement, moving forward from CMIP5 will involve a complementary multi-pronged approach. Past discontinuities in research support have been highly debilitating for long-term science investments such as carbon cycle science. In the face of the seeming agreement between models of ocean anthropogenic carbon uptake, the ocean carbon and acidification communities must better illustrate the remaining uncertainties requiring further research. For example, while CMIP5 models converged on ocean anthropogenic carbon uptake rates in general agreement with observational estimates, this consensus is limited to a set of very similar models with fixed biogeochemistry and parameterized mesoscale and submesoscale dynamics. There remain broad and critical gaps in this interdisciplinary and vigorous science field that will require long-term exploration of diverse modeling approaches for ocean circulation, physiological responsiveness, functional biodiversity, ecological thresholds, and other unresolved factors limiting robustness. The current generation of ocean carbon models must move past their currently simplistic, coarse, and similar parameterization to more adequately represent the spectrum of alternative approaches, future possible scenarios, and biodiversity in physiology and ecology. The relationship between ocean carbon uptake from a climate change feedback perspective and ocean acidification from an impacts perspective must remain vigilant and open across the broadening size and scope of the community. This will help to both maintain the high quality of carbon observations and analysis, while providing ever-more complex, species-specific, and site-specific information. Finally, as ocean carbon model analysis has grown into a broad analysis community, it must assure broad access and cooperation to maximize applicability of model intercomparison efforts to inform understanding of Earth system feedbacks and vulnerabilities.

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Ocean heat and carbon uptake in transient climate change: Identifying model uncertainty

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Introduction

Global warming on decadal and centennial timescales is mediated and ameliorated by the ocean sequestering heat and carbon into its interior. Transient climate change is a function of the efficiency by which anthropogenic heat and carbon are transported away from the surface into the ocean interior (Hansen et al. 1985). Gregory and Mitchell (1997) and Raper et al. (2002) were the first to identify the importance of the 'ocean heat uptake efficiency' in transient climate change. Observational estimates (Schwartz 2012) and inferences from coupled atmosphere-ocean general circulation models (AOGCMs; Gregory and Forster 2008; Marotzke et al. 2015), suggest that ocean heat uptake efficiency on decadal timescales lies in the range 0.5-1.5 W m^{-2} K^{-1} and is thus comparable to the climate feedback parameter (Murphy et al. 2009). Moreover, the ocean not only plays a key role in setting the timing of warming but also its regional patterns (Marshall et al. 2014), which is crucial to our understanding of regional climate, carbon and heat uptake, and sea-level change.

This short communication is based on a presentation given by A. Romanou at a recent workshop, *Ocean's Carbon and Heat Uptake: Uncertainties and Metrics*, co-hosted by US CLIVAR and OCB. As briefly reviewed below, we have incomplete but growing knowledge of how ocean models used in climate change projections sequester heat and carbon into the interior. To understand and thence reduce errors and biases in the ocean component of coupled models, as well as elucidate the key mechanisms at work, in the final section we outline a proposed model intercomparison project named FAFMIP. In FAFMIP, coupled integrations would be carried out with prescribed "overrides" of wind stress and freshwater and heat fluxes acting at the sea surface.

Ocean's role in shaping the patterns and timing of temperature response in a warming world

Mechanisms of ocean heat uptake

What ocean processes control the efficiency of ocean heat uptake? Mixing (across and along isopycnal surfaces) was identified by Sokolov et al. (2003), who also found that this "effective diffusion" varies significantly with latitude, as being somewhat small in the tropics but fifty-fold larger at high latitudes. Huang et al. (2003) showed that heat penetration to the deep ocean could be mediated by changes in convection and eddy stirring. On the other hand, Knutti et al. (2008) did not detect notable sensitivity of ocean heat uptake to the rate of diffusive mixing in their model. In a study of many CMIP5 models, Kostov et al. (2014) showed that the modeled Atlantic meridional overturning circulation (AMOC) plays a large role in transient ocean heat uptake through its control of deep ocean ventilation. They found (see Figures 1a and b) that the

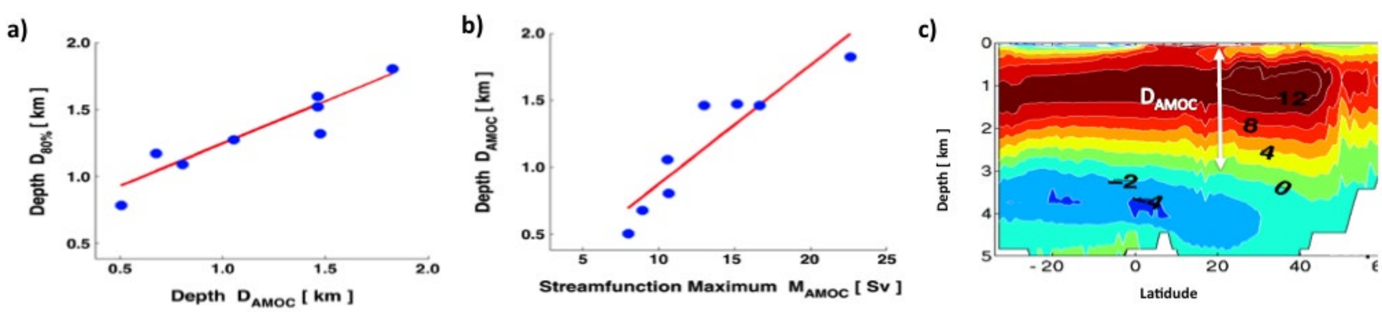

Figure 1: a) Depth of heat uptake ($D_{80\%}$) versus depth of the AMOC (D_{AMOC}); b) Depth of AMOC (D_{AMOC}) versus strength of AMOC (M_{AMOC}) (Kostov et al. 2013); and c) AMOC overturning streamfunction (Sv) from a typical climate model, with D_{AMOC} marked.

AMOC depth sets the depth to which heat is sequestered, and hence the effective heat capacity of the ocean in transient climate change, and that the strength of the AMOC influences the sequestration rates. Therefore, the spread in heat uptake across the models could be largely explained by differences in their AMOC properties. The importance of the AMOC (Figure 1c) is perhaps to be expected, given that 50% of the net heat uptake in the global ocean occurs in the Atlantic north of 35°N.

Distinguishing different oceanic processes, Exarchou et al. (2015) showed from global diagnostics of a suite of climate models that diapycnal diffusion (below the mixed layer) is the least important process in controlling heat uptake, as compared to mixed layer physics and convection and advection by mean circulation.

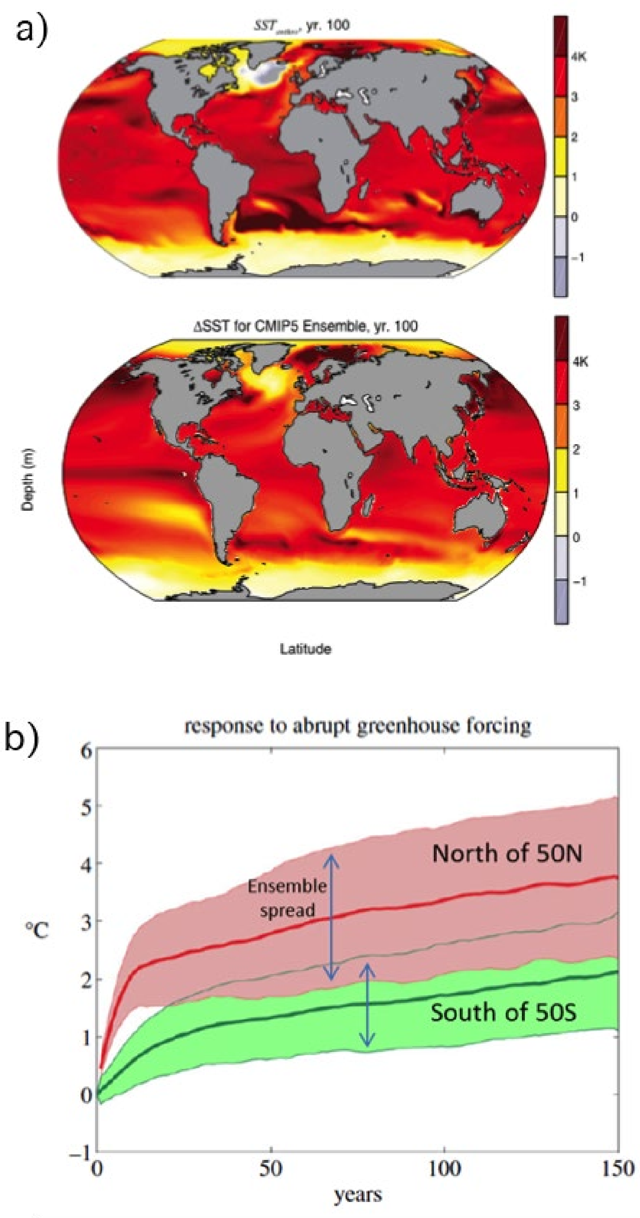

Figure 2: a) (top) SST perturbation (SST_{anthro}) from a 100-year run of a stand-alone ocean with specified, spatially uniform downwelling radiation and a linear damping of SST at the sea surface (from Marshall et al. 2014a); (bottom) SST change after 100 years from CMIP5 model runs of $4xCO_2$ forcing; (b) SST conditional random fields for greenhouse gas emissions forcing computed from an ensemble of 15 CMIP5 models under quadrupling of CO_2. The Arctic is defined as north of 50° N (in red) and the Antarctic between 50° S and 70° S (in green). Thick lines denote the ensemble mean and the shaded area spans 1 s.d. (from Marshall et al. 2014b).

Spatial patterns and timing of SST anomalies

Marshall et al. (2014a,b) employ a stand-alone ocean model run under Coordinated Ocean-ice Reference Experiment (CORE) forcing (Griffies et al. 2009) to study how ocean circulation shapes patterns of SST response in a warming world. They carry out "override" experiments, in which SST evolves in response to air-sea fluxes given by CORE, but augmented by a spatially uniform, constant-in-time downwelling radiative flux. Climate feedbacks are parameterized through an SST damping term at a rate that is constant in space and time. This setup, although highly idealized, is useful in investigating the role of the ocean in setting the patterns and timescales of the transient climate response.

Despite the idealized model framework, both Arctic amplification and delayed warming signals in the North Atlantic and around Antarctica are captured, and in common with CMIP5 climate change experiments with complex coupled models (note the marked similarity between Figure 2a, from the override experiment, with Figure 2b from an ensemble of coupled CMIP5 models). We conclude that these patterns can largely be attributed to ocean rather than atmospheric processes. Similarly, the regional climate response is, to the first order, not due to regional feedbacks since they are kept constant and uniform in our override experiments. That said, Armour et al. (2013) and Rose et al. (2014) emphasize the importance of regional atmospheric climate feedbacks in setting the time-evolving pattern of surface warming and ocean heat uptake.

Transient CO_2 and tracer uptake

The ocean also plays an important role in CO_2 uptake, reducing the airborne greenhouse gas concentrations and thus the rate of atmospheric warming. It is not yet clear how the ocean sink of anthropogenic CO_2 will change in a warming world (Le Quéré et a.l 2009; Gloor et al.

2010). Observations indicate that the outgassing of natural CO_2 from the interior ocean has increased in the last few decades, particularly in the Southern Ocean, offsetting the anthropogenic sink. Some studies argue that this may be linked to an increase in the westerly winds blowing over the Southern Ocean, whereas other studies question whether increased outgassing is occurring. The net (natural + anthropogenic) CO_2 flux depends on the strength of the wind, upwelling, and the mixed-layer cycle of carbon and nutrients, and is thus directly related to ocean dynamics. Indeed, uptake of CO_2 in models varies substantially, mostly due to differences in physical parameterizations (structural uncertainty), increasing the uncertainty of future climate projections (Krasting et al. 2014).

To address structural uncertainty, tracer uptake experiments, both realistic (CFC, SF6, etc.) and idealized (ventilation-tracer, ocean age, and passive temperature-like tracers as in Marshall et al. 2014), can be used to highlight heat and carbon uptake processes. Figure 3, for example, shows a ventilation tracer set equal to one at the surface of the subpolar North Atlantic Ocean and subsequently integrated forward in time. The experiments only differ in the strength of the AMOC. We find that as the depth and strength of the AMOC grow, additional tracer is sequestered to greater depths (Romanou et al. *in prep*). Therefore, the AMOC controls not only the rate and depth of heat uptake, but also that of many tracers, including anthropogenic CO_2.

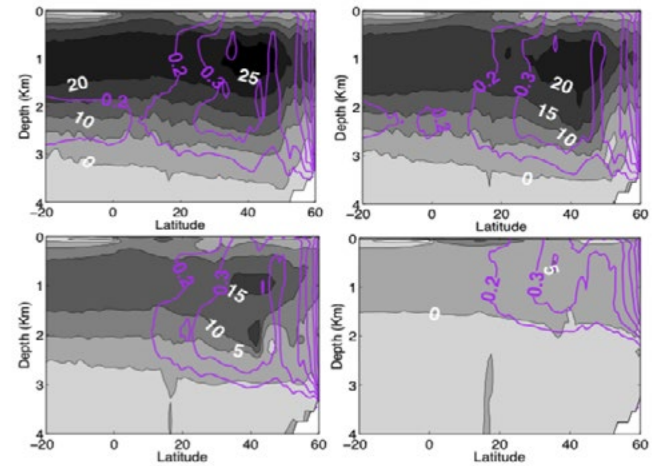

Figure 3: Zonally averaged section showing (purple contours) ventilation tracer concentration (from a stand-alone NASA GISS ocean run driven with CORE-1 forcing. The AMOC overturning streamfunction (Sv) is also plotted in gray shading with white labels.

Proposed Flux-Anomaly-Forced Model Intercomparison Project (FAFMIP)

A coordinated model intercomparison project could provide very useful information about how the ocean component of coupled models contributes to uncertainty in climate change projections. A focus might be regional sea-level change, coupled with global and regional SST patterns, heat and carbon uptake, AMOC change, etc. Knowledge of which ocean processes and phenomena have a large model spread may help us evaluate and refine our models. Ideally, one might couple the same atmosphere to different ocean models, but this would be difficult to organize. Alternatively, one could parameterize atmospheric climate feedbacks with a simple parameter and run ocean-only models (as in Marshall et al. 2014), but this would fail to capture the richness and the regional detail of the feedbacks. A viable way forward, we think, is to use existing coupled control runs and add air-sea flux "overrides" – i.e., wind stress, evaporation-precipitation, heat fluxes – chosen to be representative of those induced by climate change.

Such experiments are proposed within the Flux-Anomaly-Forced Model Intercomparison Project (FAFMIP, http://www.met.reading.ac.uk/~jonathan/FAFMIP/). Each modeling group would adopt the same protocol and run experiments ascribing the same override fields, computed from ensembles of CMIP5 models perturbed by climate change. We would then attempt to assess the spread in the resulting AMOC, heat and carbon uptake, and patterns of sea-level change, both regionally and globally, and identify their causes. The community has some familiarity already with override experiments – e.g., freshwater forcing (Stouffer et al. 2006); wind forcing (Gent and Danabasoglu 2011); or both heat and freshwater forcing experiments (Zhang and Vallis 2013). Due to the dominance of heat flux-SST feedbacks, it is not yet clear how to carry out meaningful heat flux override experiments. This is currently under study (http://www.met.reading.ac.uk/~jonathan/FAFMIP/FAFMIP_method_heat.pdf).

Acknowledgments

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Are anthropogenic changes in the tropical ocean carbon cycle masked by Pacific Decadal Variability?

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Observed changes in the tropical Pacific carbon cycle

The tropical Pacific is the ocean's largest natural source of CO_2 to the atmosphere, thus playing a key role in the global carbon cycle (Takahashi et al. 2009; Gruber et al. 2009). Strong equatorial upwelling of carbon-rich thermocline waters causes partial pressure of CO_2 (pCO_2) in the surface ocean to exceed that in the atmosphere. This pCO_2 difference, surface ocean pCO_2 minus the atmospheric pCO_2 (ΔpCO_2), drives outgassing of CO_2 into the atmosphere. Additional factors such as wind speed, and to a lesser degree salinity and temperature, modulate the CO_2 flux at the sea-air interface.

Anthropogenic emissions continue to drive increasing atmospheric CO_2 concentrations. Understanding and predicting how sea-air CO_2 fluxes respond to this change is a major challenge in carbon cycle research. Observational evidence on the mechanisms driving changes in outgassing over the equatorial Pacific is inconclusive. Studies using the near-continuous observational record of ocean pCO_2 in the central equatorial Pacific show that since 1980, ocean pCO_2 has risen at about the same rate as atmospheric pCO_2 (Feely et al. 2006; Fay and McKinley 2013). This near-zero trend in ΔpCO_2 implies a near-zero trend in sea-air CO_2 flux. The sea-air CO_2 flux, however, has increased in this region, mainly driven by increases in wind speed (Feely et al. 2006).

Anthropogenic response

The Earth System Models (ESMs) participating in the 5th phase of the Coupled Model Intercomparison Project (CMIP5) and a 28-member ensemble of simulations conducted with the Community Earth System Model (CESM) show a robust decrease in ΔpCO_2 and sea-air CO_2 flux in the equatorial Pacific over the 50-year period of 2030 to 2079 as atmospheric CO_2 concentration rises (Figure 1). The following two mechanisms could explain this response: (1) Water in the equatorial thermocline is mostly isolated from the anthropogenic CO_2 perturbation in the atmosphere. When this water upwells to the surface, it is exposed to an atmosphere with ever-increasing CO_2 concentration, resulting in a negative trend in ΔpCO_2 and sea-air CO_2 flux (Maier-Reimer and Hasselmann 1987). (2) Models also project reduced upwelling due to weaker equatorial easterly winds associated with a reduced Walker circulation in response to global warming (Vecchi and Soden 2007; DiNezio et al. 2009), which could drive decreases in ΔpCO_2 and sea-air CO_2 flux.

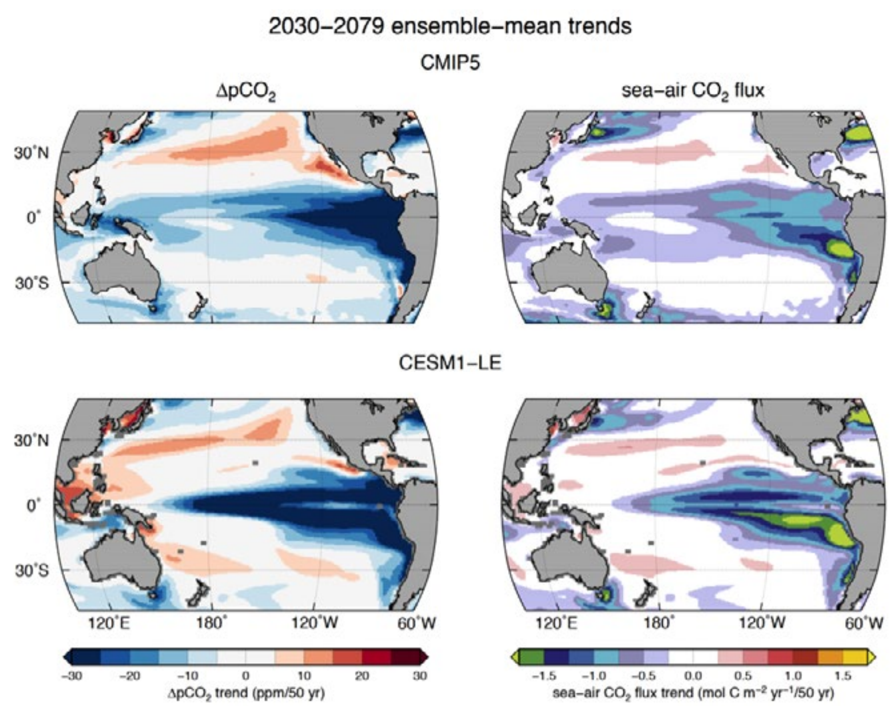

Figure 1: Ensemble-mean trends (2030-2079) in ΔpCO_2 (left; ppm/50 yr) and sea-air CO_2 flux (right; mol C m^{-2} yr^{-1}/50 yr) simulated by CMIP5 models (top) and the CESM1-LE (bottom). Positive sea-air CO_2 flux indicates increased outgassing.

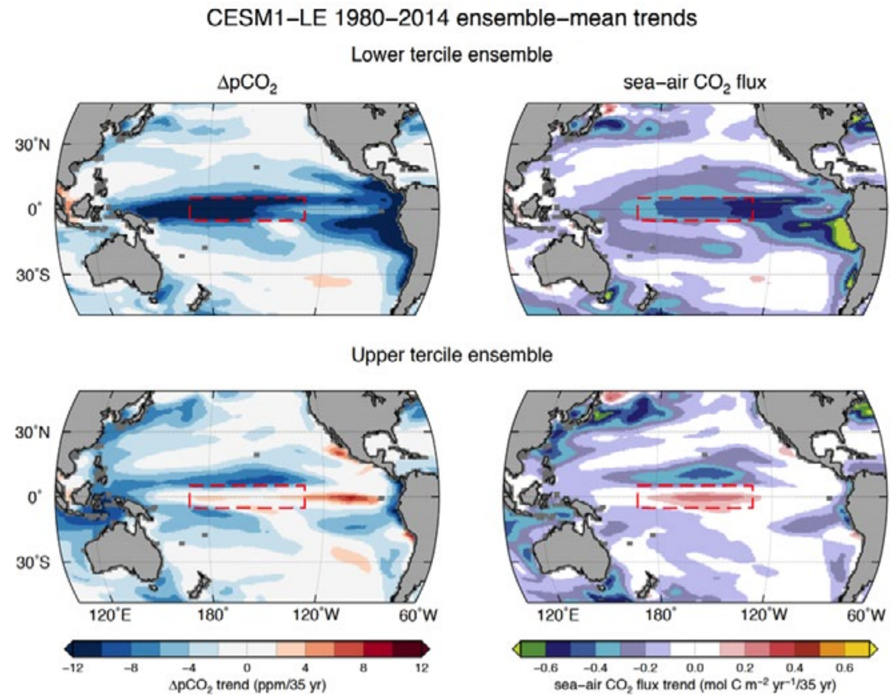

Figure 2: Trends (1980-2014) in ΔpCO_2 (left; ppm/35 yr) and sea-air CO_2 flux (right; mol C m^{-2} yr^{-1}/35 yr) simulated by the CESM1-LE, over grouped according to the lower and upper terciles of the ΔpCO_2 trends over the Nino-3.4m region. The lower tercile ensemble (top) contains 9 simulations with the most negative Nino-3.4m ΔpCO_2 trends. The upper tercile ensemble (bottom) contains 9 simulations with negligible trends. The red box over the central equatorial Pacific indicates the Nino-3.4m region. Positive sea-air CO_2 flux indicates increased outgassing.

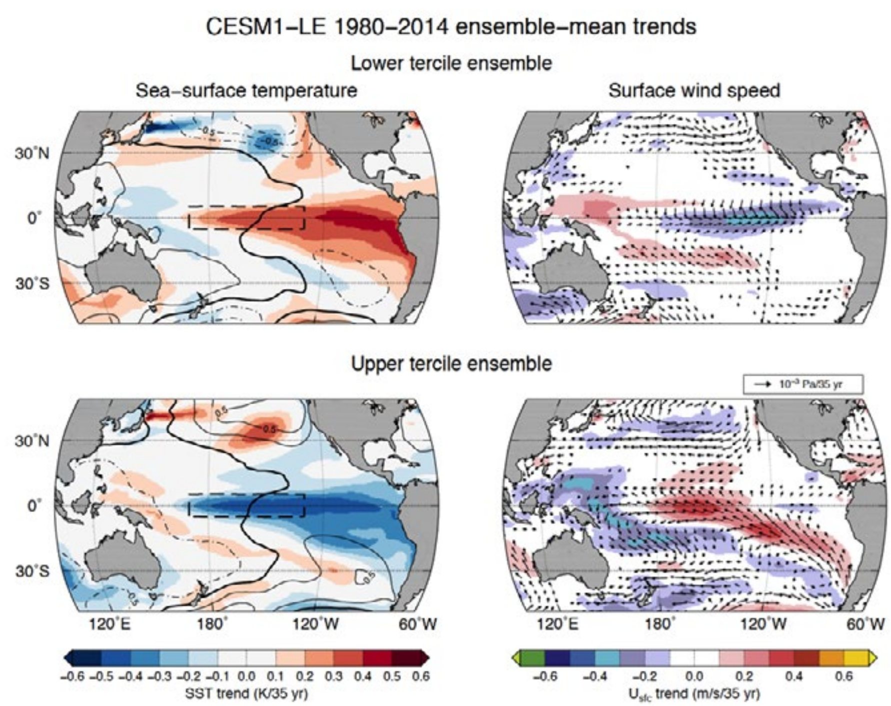

Figure 3: As in Figure 2, but for (left) sea-surface temperature (colors; K/35 yr) and sea-level pressure (contours) and (right) surface wind stress (vectors; 10^{-3} Pa/35 yr) and wind speed (colors; m/s/35 yr).

Impact of decadal climate variability

The fact that ΔpCO_2 has remained steady over the observation-rich historical period (1980-present) is inconsistent with the consensus among ESMs. Can these differences be reconciled? It is well known that climate variability associated with El Niño/Southern Oscillation (ENSO) can complicate the detection of anthropogenic changes (McKinley et al. 2004; Feely et al. 2006; Sutton et al. 2014). However, the effect of decadal variability has not been explored because the observational record is too short to span more than one realization of Pacific Decadal Variability (PDV) for a robust assessment.

The post-1980 period was characterized by a multi-decadal strengthening of the Pacific trade winds and an acceleration of the shallow overturning circulation and equatorial upwelling (McPhaden and Zhang 2004; Merrifield and Maltrud 2011). We hypothesize that during this period, stronger upwelling driven by strengthened trade winds led to increases in ΔpCO_2 and sea-air CO_2 flux that counteracted the decreases expected from the anthropogenic perturbation of atmospheric CO_2 concentration. Here, we test this hypothesis using an ensemble of simulations performed with CESM1, an ESM that simulates a realistic mean tropical carbon cycle as well as its seasonal and interannual variability (Long et al. 2013). The large number of realizations (28; hereafter referred to as the CESM1-LE; Kay et al. 2015) allows separation of internal decadal variability and externally forced changes.

For each realization of the CESM1-LE, we estimate the changes in both climate and biogeochemistry by computing linear trends over the period 1980-2014 when continuous observations of pCO_2 in the equatorial Pacific are available. We also focus on the central tropical Pacific defined by a modified Niño-3.4m box (170°E-130°W, 5°S-5°N). The 28 simulations of the CESM1-LE show ΔpCO_2 changes ranging from -12.6 ppm to +5.6 ppm, suggesting that multi-decadal climate variability has a sizable impact during this 35-year period. The ensemble-mean (forced) change is -6.2 ppm, consistent in sign with the response of ΔpCO_2 to anthropogenic increases in atmospheric CO_2 discussed above.

We extract two 9-member sub-ensembles, grouped according to the lower and upper terciles of the ΔpCO_2 trends over the Nino-3.4m box. The lower-tercile sub-ensemble shows a pronounced decrease in ΔpCO_2 over the tropical Pacific and associated reduction in outgassing (Figure 2 top), while the upper-tercile sub-ensemble shows negligible changes in ΔpCO_2 over the equatorial Pacific, and a slight increase in CO_2 sea-air flux (Figure 2 bottom). Moreover, the former shows climate anomalies consistent with the positive phase of PDV (Figure 3 top), while the latter shows climate anomalies consistent with its negative phase (Figure 3 bottom). This suggests that wind-driven changes in equatorial upwelling associated with the positive and negative phases of PDV could have a considerable influence on trends in the tropical Pacific carbon cycle.

Towards detection of anthropogenic changes

The CESM1-LE shows a strong reduction in ΔpCO_2 and outgassing when the PDV is trending positive (constructive effects of PDV and anthropogenic forcing). Conversely, it shows negligible changes in ΔpCO_2

Methods

Earth System Models (ESMs) simulate coupled interactions among the atmosphere, ocean, land, as well as ocean ecosystems and chemistry, and the ocean and terrestrial carbon cycle. We use output from two different types of ESM ensembles, each of which addresses a key source of uncertainty. The first is a multi-model ensemble of simulations of 21st Century climate and biogeochemistry (BGC) change coordinated by CMIP5 and performed with 11 ESMs run under the same external forcings defined by the RCP8.5 scenario. The models are: CESM1-BGC, MPI-ESM-LR, MPI-ESM-MR, HadGEM2-CC, HadGEM2-ES, IPSL-CM5A-MR, IPSL-CM5B-LR, IPSL-CM5A-LR, MIROC-ESM, GFDL-ESM2G, GFDL-ESM2M. This ensemble was specifically designed to explore the effect of model (structural) uncertainty, although they also contain uncertainty due to internal variability. We use this ensemble to explore the robustness of the anthropogenic response. We focused on the period 2030-2079 because this is when the forced response of the global ocean carbon cycle is more pronounced.

The second ensemble consists of 28 simulations performed with one single model, in this case the Community Earth System Model Version 1 (CESM1). All the simulations in this large ensemble (CESM1-LE) were started at year 1920 and run under historical forcings until year 2005 and under RCP8.5 scenario from year 2006 to year 2100. A small random perturbation was applied to each simulation in the initial air temperature at year 1920, which causes them to simulate independent weather and internal climate variability. All 28 simulations, however, have the same anthropogenic response because of the common forcing. Thus this large initial-condition ensemble is ideally suited to study the interplay between anthropogenic changes and natural climate variability (Kay et al. 2015). The 28-member ensemble analyzed here is made of 24 simulations with BGC from the 30-member CESM1-LE presented in Kay et al (2015) plus 4 additional simulations following the same experimental protocol.

For each simulation of the CESM1-LE we estimate the changes in climate and BGC by computing linear trends over the period 1980-2014. We focus on this period because it corresponds to when there are continuous observations of pCO_2 over the equatorial Pacific. We average the trends over a modified Nino-3.4 region (hereafter "Nino-3.4m": 170°E-130°W 5°S-5°N) for two reasons: 1) this is where the observational network is densest and 2) this is where CESM1 exhibits the strongest forced ΔpCO_2 change (Figure 1 bottom). This box is zonally wider than the conventional definition in order to capture the full spatial pattern of the forced response. During 1980-2014 the magnitude of the simulated Nino-3.4m ΔpCO_2 changes range from -12.6 to 5.6 ppm, suggesting a large influence of natural variability. The ensemble-mean change is -6.2 ppm and the median change is -7.5 ppm consistent in sign with the anthropogenic reduction discussed for the 2030-2079 period.

and a slight increase in outgassing when the PDV is trending negative (cancelling effects of PDV and anthropogenic forcing). The latter case is analogous to the changes observed during 1980-2014, when the Pacific Ocean has trended toward a negative PDV phase, characterized by stronger trade winds and stronger upwelling.

Within the context of the CESM1-LE, internally driven and forced trends can have similar magnitudes, suggesting that PDV can overwhelm the forced response in particular ensemble members. Translating this result to nature implies that equatorial outgassing could be already diminishing in response to increasing atmospheric CO_2. However, this signal has not emerged from the background of internal variability, particularly due to the ongoing multi-decadal changes in Pacific climate.

Therefore, the steady ΔpCO_2 trend seen in observations (Feely et al. 2006; Fay and McKinley 2013) could be indicative of an anthropogenic response; otherwise, ΔpCO_2 should be increasing following the observed multi-decadal acceleration of the tropical circulation (McPhaden and Zhang 2004; Merrifield and Maltrud 2011). Furthermore, we cannot reject the model projections of decreasing tropical Pacific outgassing in response to increasing atmospheric CO_2. The anthropogenic response could be masked by decadal variability in Pacific climate.

We expect that these ideas will stimulate further efforts to reconcile observations and model projections. A next step is a full attribution of the effects of natural and anthropogenic influences on the tropical Pacific carbon cycle. How much of the observed ΔpCO_2 change is anthropogenic, and how much is driven by the strengthening of the Pacific Ocean circulation? Could observations be used to determine whether the carbon content of upwelled waters is increasing more slowly than atmospheric CO_2, as proposed by Maier-Reimer and Hasselmann (1987)? Will the reduction in outgassing vanish once the tropical thermocline fully equilibrates with the atmospheric CO_2? Answering these questions requires process-based understanding of the observed and simulated changes and would ultimately lead to reduced uncertainty in model projections (Friedlingstein et al. 2014).

Changes in the CO_2 sources and sinks are highly uncertain, and they could have a significant influence on future atmospheric CO_2 levels (Le Quéré et al. 2009). It is therefore crucial to reduce these uncertainties. For instance, a recent trend in the airborne fraction of the total emissions suggests that the growth in uptake rate of CO_2 sinks is not keeping up with the increase in CO_2 emissions (Canadell et al. 2007; Le Quéré et al. 2009). For how long will the ocean continue to increase its CO_2 uptake? A more complete understanding of the role played by the tropical Pacific in the global carbon cycle is critical to answering these important questions.

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Present and projected climate variability at high latitudes and its impact on the ocean carbon cycle

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Introduction

Given that the ocean carbon reservoir is about fifty times greater than that of the atmosphere, a small perturbation to the ocean could theoretically produce a spectacular change in atmospheric concentrations. So it might at first seem surprising that atmospheric carbon dioxide (CO_2) concentrations have been so stable over the last millennium. High-resolution ice cores suggest that multidecadal- to century-scale variability of atmospheric CO_2 was less than 10 ppm (~3.5% of background concentrations, Ciais et al. 2013), despite climate and ocean circulation variability. Although climate and ocean circulation variability yield regional fluctuations in the ocean carbon cycle that can confound the detection of trends, these ice cores suggest that the preindustrial (or "natural") ocean carbon cycle, when integrated globally, was largely in steady state. This might reflect compensations between underlying climate-driven changes in the solubility and biological components of air-sea carbon fluxes (Marinov et al. 2011).

At the start of industrialization, anthropogenic emissions of CO_2 fundamentally altered this global steady state, as atmospheric concentrations began their rapid climb from about 270 ppm in the 18th century to their current concentration above 400 ppm. Throughout this time, the ocean has provided a major sink for anthropogenic CO_2, mitigating its radiative impact (Sabine et al. 2004). Yet the radiative impact of anthropogenic CO_2 remaining in the atmosphere has raised ocean temperatures, changed freshwater and alkalinity fluxes to the ocean, and altered large-scale ocean circulation patterns. Collectively, these changes are projected to influence both the natural carbon cycle and the uptake and storage of anthropogenic carbon as they continue into the future (Figure 1).

Here we review recent work that exposes how climate variability and change at high latitudes influence the ocean storage and uptake of natural and anthropogenic carbon. Particularly, we focus on the Southern Ocean and North Atlantic, which provide the dominant ocean sinks for anthropogenic carbon and have very dynamic natural carbon cycles (Gerber and Joos 2010; Sabine et al. 2004; Gruber et al. 2009).

Southern Ocean

South of the Antarctic Polar Front (PF), westerly winds drive upwelling of old, relatively warm, nutrient- and carbon-rich Circumpolar Deep Water (CDW). In preindustrial times, the upwelled CDW released large quantities of natural carbon into the atmosphere. At present, anthropogenic emissions are rapidly decreasing

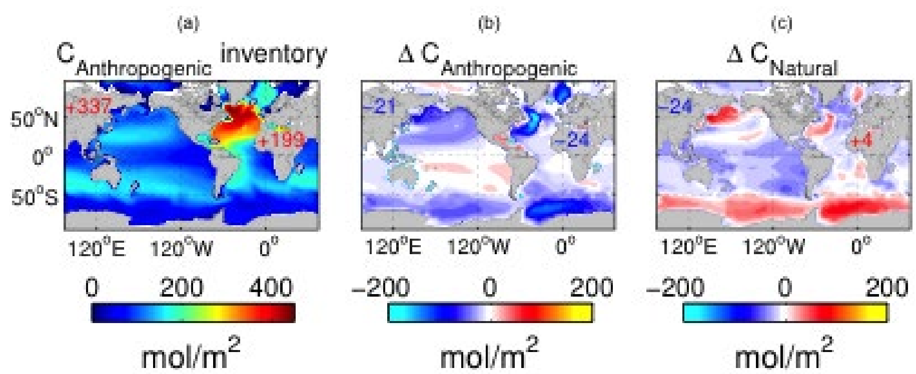

Figure 1: Three-member ensemble average of column-integrated DIC components from our coupled model, CM2Mc, averaged over the period 2081-2100. (a) Total anthropogenic carbon inventory in the ocean. Perturbation of carbon inventory due to climate change on (b) anthropogenic carbon and (c) natural carbon for the period 2081-2100 with respect to the preindustrial state. The climate change simulation was performed by prescribing historical+Representative Concentration Pathway 8.5 forcing (Meinshausen et al. 2011). Numbers over continents refer to total DIC gained or lost (PgC) for the Indo-Pacific (over Asia) and the Atlantic basins (over Africa) including the Southern Ocean. Climate change acts to reduce ocean storage of both anthropogenic and natural carbon.

the difference between the atmospheric and oceanic CO_2 partial pressures (pCO_2) with a resulting decrease in CO_2 degassing during CDW upwelling. Ekman transport of CDW north of the PF, together with air-sea interactions, result in the formation of intermediate and mode waters. At the surface, oceanic pCO_2, already reduced by degassing, is further lowered by phytoplankton uptake, which results in net CO_2 flux into the ocean north of the PF. Some CDW is also transported south towards the Antarctic continental shelf, providing source waters for Antarctic Bottom Water (AABW), which fills a large fraction of the global ocean volume.

Due to these ocean circulation patterns, the Southern Ocean south of 30°S is critically important for both setting the global strength of the natural ocean carbon pump and for determining atmospheric pCO_2 on long, equilibrium timescales (e.g., Marinov et al. 2006). It is responsible for about half of the annual global ocean uptake of anthropogenic carbon (Sabine et al. 2004; Gruber et al. 2009; Khatiwala et al. 2012), despite making up only a third of the ocean surface area. Here, we discuss two important modes of variability in the Southern Ocean and associated implications for the carbon cycle. The first is the Southern Annular Mode (SAM), the most important pattern of large-scale climate variability in the Southern Hemisphere middle and high latitudes which manifests as a variability in Southern Ocean westerlies. The second is the variability associated with deep Southern Ocean convection. Modeling studies show that variability in SAM and deep Southern Ocean convection results in strong variability in CO_2 fluxes in the subpolar (~40°S–55°S) and polar (~55°S–90°S) Southern Ocean regions, respectively (Resplandy et al. 2015).

SAM and carbon

There are strong links between subpolar variability associated with SAM and Southern Ocean CO_2 fluxes on interannual time scales (e.g., Lovenduski et al. 2007), which take on added importance as the combined effects of Antarctic ozone hole and greenhouse gas warming have resulted in a more positive SAM, i.e., strengthened and poleward-shifted mid-latitude westerlies. This recent trend is expected to continue into the 21st century, though with uncertainty arising from inter-model variability across the current generation of Earth System Models (ESMs) that contributed to the Coupled Model Intercomparison Project Phase 5 (CMIP5; Swart and Fyfe 2012).

If the SAM mechanisms that influence the carbon cycle on interannual timescales also operate on longer timescales associated with climate change, the continuing trend toward positive SAM is expected to drive an increase in the upwelling of old, carbon-rich CDW south of the PF, and subsequent outgassing of the natural CO_2 flux to the atmosphere (Lovenduski et al. 2007), effectively reducing the global oceanic carbon sink. This mechanism has been proposed to explain the apparent saturation in the Southern Ocean sink for atmospheric CO_2 in recent decades (Le Quéré et al. 2007). This claim, based primarily on atmospheric inverse models and coarse resolution Global Circulation Models, has been heavily debated by the ocean carbon research community.

Trends in CO_2 uptake are hard to detect in the observations due to effects of autocorrelation and monthly variability. Majkut et al. (2014a) show that directly detecting changes such as the one associated with the recent saturation of the Southern Ocean CO_2 sink (-0.08 PgC yr^{-1} $decade^{-1}$) will require up to three decades of observations. Based on this assessment, most currently available data sets are not long enough to differentiate natural variability from the anthropogenically driven trends in CO_2 fluxes (Keller et al. 2012). In contrast to Le Quéré et al. (2007), Fay and McKinley (2013) argue that the influence of a positive trend in SAM has waned and the Southern Ocean carbon sink has regained strength since the early 2000s, following a 1990s slowdown. Majkut et al. (2014b) merge observations and model pCO_2 estimates to find increasing ocean carbon uptake south of 45°S for 1980–2009 and attribute this increase to surface ocean cooling, which offsets the expected response to increased winds.

CMIP5 models simulate a small negative effect of climate change (~5 PgC) on the ocean carbon uptake over the historical period (Fröelicher et al. 2015). The model-projected overall response of the carbon cycle to future climate change is uncertain. Climate-driven warming is acting against the intensified winds to stratify the Southern Ocean water column, reducing convective mixing and outgassing of deep ocean natural carbon (Sarmiento et al. 1998). Bernardello et al. (2014a) showed that over the 21st century, enhanced stratification and reduced deep-water mass formation in both the North Atlantic and Southern Ocean promote increased storage of natural carbon in the ocean, particularly in high latitudes, and dominate over wind effects. However, thermal solubility effects decrease ocean carbon storage, particularly in low latitudes. The

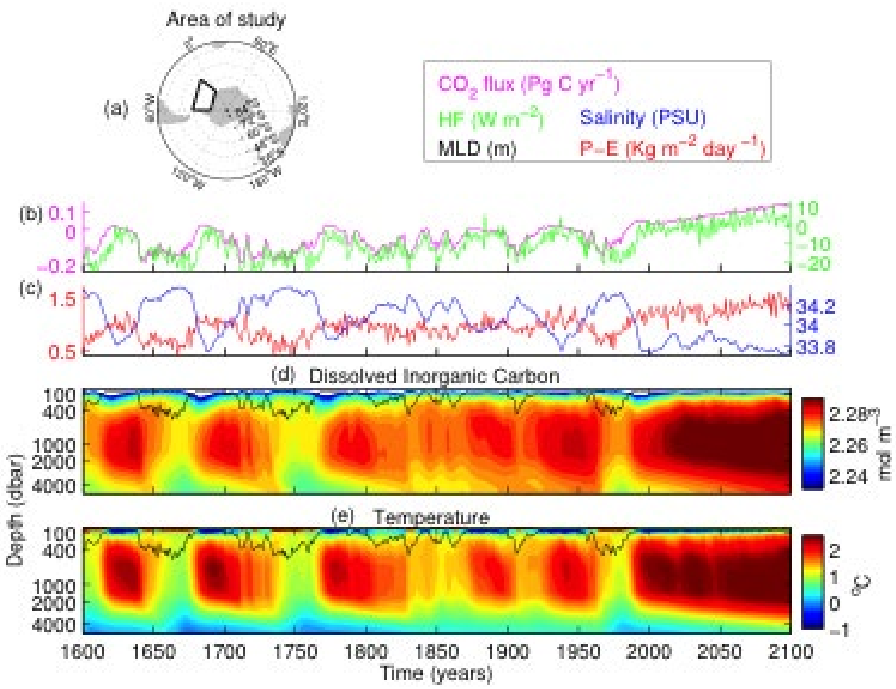

Figure 2: Regular Weddell Sea convection cycles in a 500-year segment composed of a preindustrial simulation (1600-1859) and a climate change simulation using historical + RCP8.5 forcing (1860-2100) in a coupled ocean-atmosphere model, CM2Mc. a) Area of study – dark black polygon; b) air-sea CO_2 and heat flux (HF) integrated over the study area; c) area-averaged precipitation minus evaporation (P-E) and salinity (0 to 50 m depth); d) area-averaged dissolved inorganic carbon (DIC); and e) area-averaged temperature and mixed layer depth (MLD). During convective years, the ocean loses heat and CO_2 to the atmosphere. Climate-induced freshening of the water column due to a trend in P-E after the 1970s stops convection and results in sub-surface storage of DIC and heat. Modified from Bernardello et al. (2014b).

net effect of climate change in the Bernardello et al. (2014a) model analysis is an overall reduction in natural ocean carbon storage (-20 PgC) from 1860-2100 (Figure 1c). The climate-driven perturbation to the anthropogenic carbon (-45 PgC) is higher than the impact on natural carbon, and is due primarily to reductions in mid- to high latitudes (Figure 1b).

Southern Ocean deep convection, AABW, and carbon

AABW formation sets the carbon, heat, and oxygen content of much of the deep ocean. Presently, AABW is formed at specific locations on the Antarctic continental shelf (Orsi et al. 1999). In the past, AABW was also known to form during open ocean deep convection events in the Weddell Sea (Gordon 1982; Killworth 1983; Carsey 1980), as observed for three consecutive winters in the 1970s. The current generation of climate models (CMIP5) forms AABW almost entirely through open ocean convection in the Weddell and Ross Seas, with little contribution from the continental shelf (Heuzé et al. 2013).

In 25 of the 33 CMIP5 ESMs, open ocean convection occurs as a natural oscillation in the preindustrial climate, with convective events occurring with different frequencies and durations (de Lavergne et al. 2014). This multi-decadal variability occurs in our control simulation of the GFDL CM2Mc model (Figure 2) with regular periodicity, and is similar to that observed on centennial timescales in the Kiel model (Martin et al. 2012; Latif et al. 2013; Martin et al. 2015). The system oscillates between convective periods (when heat and dissolved inorganic carbon (DIC) stored in the upper CDW (UCDW) are released to the atmosphere, melting the Antarctic sea ice) and non-convective intervals (when strong stratification isolates the surface from the warmer, DIC-rich UCDW below, decreasing atmospheric CO_2 and temperatures). Deep convective oscillations in the polar Southern Ocean promote large variability in CO_2 fluxes on multi-decadal timescales (Séférian et al. 2013; Bernardello et al. 2014b), contributing to the Southern Ocean dominance over the multidecadal global carbon flux variability in five CMIP5 models (Resplandy et al. 2015).

Strong increases in both surface heat and freshwater fluxes at Southern Ocean high latitudes are predicted under future climate forcing (Fyfe et al. 2012), with an expected increase in stratification. As a result, climate models show cessation of Southern Ocean open sea convection over the 21st century (de Lavergne et al. 2014), with important implications for Southern Ocean carbon uptake and storage. As an example, Figure 2 shows enhanced storage of subsurface natural carbon and less natural carbon outgassing following the climate-driven shutdown of Southern Ocean convection in the GFDL CM2Mc model experiments. While convective shutdown increases Southern Ocean natural carbon storage, it decreases the Southern Ocean anthropogenic uptake. The cessation of open ocean convection in the Weddell

Sea, which occurs in the model on average in year 1981 (Figure 2), is responsible for 22% of the Southern Ocean decrease in total (anthropogenic plus natural) ocean carbon uptake and 52% of the decrease in the anthropogenic component, despite the Weddell Sea representing only 4% of the area of the Southern Ocean (Bernardello et al. 2014b). Therefore, differences in representation of Southern Ocean deep convection could be an important source of inter-model spread for the projected future evolution of the carbon cycle.

North Atlantic

The North Atlantic is the next biggest ocean sink for anthropogenic carbon after the Southern Ocean (Sabine et al. 2004) and the most intense per unit area (Takahashi et al. 2009). Despite being one of our best-observed ocean basins, internal variability hinders the evaluation of climate change-driven trends. Here, the dominant mode of climate variability at the interannual time scale is the North Atlantic Oscillation (NAO), a fluctuation in the strength of the pressure gradient between the Icelandic low and Azores high (Hurrell 1995), which manifests as variability in the storm track and oceanic mixed layer depths (Dickson et al. 1996). The NAO has been linked to variability in North Atlantic carbon dynamics in observations (Gruber et al. 2002; Bates et al. 2002) and in modeling studies (Keller et al. 2012). Early speculation that a positive phase of the NAO could lead to a basin-wide increase in ocean carbon storage has been replaced with evidence for compensating responses between the subtropical gyre, where a positive phase of the NAO is linked to an enhanced carbon sink, and the subpolar gyre, where the opposite is true (Keller et al. 2012; Thomas et al. 2008). Thus, while NAO variability has confounded detection of trends in the oceanic uptake of anthropogenic CO_2 locally, it seems to have a small impact on uptake when averaged over the entire North Atlantic.

On longer time scales, the dominant mode of variability in the North Atlantic is expressed as swings in basin-average sea surface temperature (SST) of more than 0.4°K, with a period of 65-85 years, and is generally referred to as the Atlantic Multidecadal Oscillation (AMO) (Delworth and Mann 2000; Kushnir 1994). Though there is ongoing controversy over the degree to which external forcing has played a role in the amplitude and timing of AMO variability (Booth et al. 2012; Zhang et al. 2013; Mann et al. 2014), general circulation models and paleoclimate proxy data collectively suggest that internal variability associated with the Atlantic Meridional Overturning Circulation (AMOC) is largely responsible for this low-frequency SST oscillation. The SST variability alone, regardless of its cause, creates fluctuations in solubility with consequences for anthropogenic CO_2 uptake (McKinley et al. 2011; Löptien and Eden 2010). However, because the AMO is driven largely by fluctuations in the large-scale circulation, there can be competing effects of circulation on DIC, such that the total trend in the rate of carbon uptake may be opposite the temperature-driven trend alone (Fay and McKinley 2013; McKinley et al. 2011).

North Atlantic internal variability complicates the detection of climate-driven trends. For instance, McKinley et al. (2011) show that purported trends in the North Atlantic anthropogenic carbon uptake, diagnosed using the difference between trends in atmospheric and ocean pCO_2, are sensitive to start and end year of the trend calculation (Figure 3). In their work, trends of oceanic pCO_2 match trends in atmospheric pCO_2 throughout the entire North Atlantic when the full length of the observational record is taken into account (Figure 3a). However,

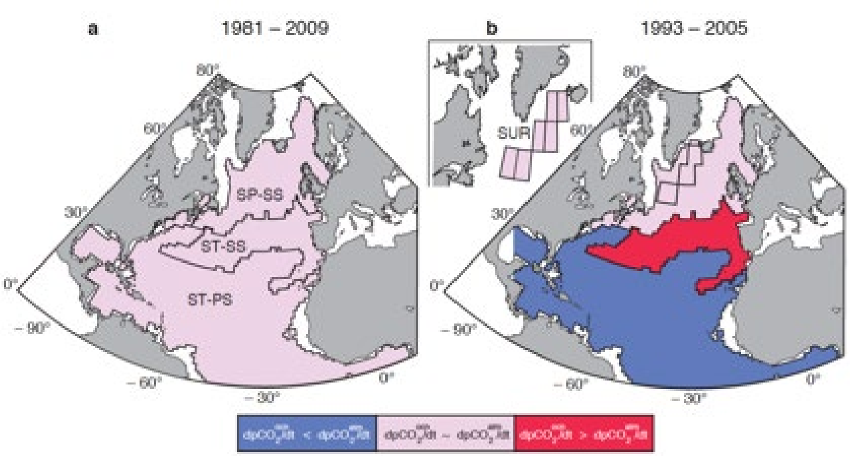

Figure 3: Trend in oceanic rCO_2 compared to atmospheric rCO_2 for two periods of different length: a) 1981-2009 and b) 1993-2005. Blue for oceanic rCO_2 trend less than atmospheric; pink for indistinguishable; and red for oceanic exceeding atmospheric. In this analysis, the North Atlantic is divided into three "biomes": subtropical - permanently stratified (ST-PS), subtropical - seasonally stratified (ST-SS), and subpolar - seasonally stratified (SP-SS). The inset shows a region of the SP-SS that had additional chemical data available. From McKinley et al. (2011).

when a shorter period is considered, the trend is regionally specific: the permanently stratified subtropical region sees increased uptake; the seasonally stratified subtropical region sees decreased uptake; and uptake in the subpolar region remains steady (Figure 3b). Thus, the observational record does not yet reveal any reduction in North Atlantic carbon uptake due to climate change, despite the contribution of rising SST to decreasing CO_2 solubility starting to emerge from background variability (Fay and McKinley 2013; Séférian et al. 2014, Majkut et al. 2014b).

In the coming decades, the AMOC is widely predicted to slow down (Stocker et al. 2013), with important implications for the storage of natural carbon and uptake of anthropogenic carbon. The AMOC slowdown is predicted to decrease the outgassing of natural carbon, as remineralized carbon accumulates in the subpolar North Atlantic and along the North Atlantic Deep Water pathway (Bernardello et al. 2014a; Sarmiento et al. 1998). This increase in natural carbon retained by the ocean, however, is more than offset by the reduction to the anthropogenic carbon uptake caused by the decreasing exposure of deep waters to the atmosphere reinforced by overall SST warming (Figure 1). Thus, in the coming decades, climate-driven changes in North Atlantic circulation and SST are likely to reduce the pace of oceanic uptake of anthropogenic carbon.

Conclusions

Understanding the response of the Southern Ocean and North Atlantic carbon uptake and storage to changing climate is a prerequisite for predicting future atmospheric CO_2 concentrations. The lack of long-term observations has thus far hampered a complete understanding of the carbon cycle in these regions. At the same time, the current generation of climate models is still affected by critical issues like the incomplete representation of ice sheet and ice shelf dynamics. Coarse resolution can result in the net Southern Ocean meridional overturning and the natural Southern Ocean carbon storage being too sensitive to changes in wind-stress compared to eddy-permitting ocean models (e.g., Hallberg and Gnanadesikan 2006; Munday et al. 2014). Models must also overcome challenges in accurately representing the export of deep water from continental shelves and marginal seas. Model biases in Labrador Sea convection can result in unrealistic links between the NAO and AMOC, while biases in Weddell Sea convection might affect Southern Ocean decadal to centennial variability (Martin et al. 2015; Marinov et al., in prep.), with carbon cycle implications. Importantly, the inter-model spread for air-sea CO_2 fluxes and anthropogenic C inventories is largest in the Southern Ocean, where intense vertical exchange occurs (e.g., Orr et al. 2001; Matsumoto et al. 2004).

We argue that the marriage of modeling and observational approaches will continue yielding insight into variability and trends in the ocean carbon cycle. Already, we have learned a great deal about ocean physics through a hierarchy of modeling approaches, such as idealized models aimed at understanding mesoscale eddies (e.g., Morrison and McC. Hogg 2013), the development and testing of parameterizations to transport deep and bottom water from the shelves and marginal seas to the open ocean (e.g., Snow et al. 2015), and the comparison of climate responses across high- and low-resolution models (Bryan et al. 2014; Griffies et al. 2014; Winton et al. 2014). We expect the same gains by the continued deployment of such tools to carbon cycle questions. Likewise, long-term sustained observations in the high latitude oceans are critical to reliably document the global changes in carbon uptake, storage, and transport; separate natural variability from anthropogenic forcing; and evaluate the success of our models. The future deployment of ~200 Argo floats with biogeochemical capabilities in the Southern Ocean by the newly-established Southern Ocean Carbon and Climate Observations and Modeling (SOCCOM) project, and the upcoming monitoring of the full annual cycle of gas exchange in the Labrador Sea deep convective region through the Canadian program, Ventilations, Interactions and Transports Across the Labrador Sea (VITALS), are steps in the right direction. Adding biogeochemical sensors to existing ocean arrays that monitor the AMOC (e.g., the OSNAP and RAPID arrays) could likewise provide a rich data source to understand this critical component of our Earth system.

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The future of the Southern Ocean carbon storage in CMIP5 models

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The oceans represent the largest carbon reservoir relevant to climate on human timescales (Sabine et al. 2004). Within this reservoir, the Southern Ocean serves as the dominant player in ocean carbon uptake relative to other basins (Marshall and Speer 2012), owing to the strength of the vertical exchanges between surface and deep waters that characterize its circulation. It is therefore imperative to diagnose the future evolution of the Southern Ocean sink in order to predict the global ocean response to increasing atmospheric carbon dioxide (CO_2) levels.

The Southern Ocean and the carbon storage problem in CMIP5

As indicated in Dunne and Laufkötter (2015), CMIP5 has provided new insights on the evolution of the ocean carbon storage, but attribution and understanding of long-term behaviors are limited by the intrinsic difficulties in modeling the complexity of the ocean biogeochemistry and its multiple feedbacks.

Here, using a suite of Earth System Model (ESM) simulations participating in the Fifth Coupled Model Intercomparison Project (CMIP5; Taylor et al. 2012), we investigate the Southern Ocean past carbon inventory and future projections, and we discuss advantages and limitations of the stored model outputs (Ito et al. 2015). We concentrate on the twentieth and twenty-first centuries

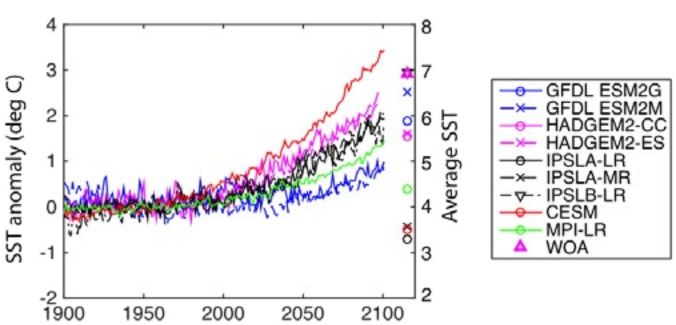

Figure 1: Area-weighted annual mean sea surface temperature (°C) over the extratropical Southern Hemisphere oceans (45°S-60°S). Average (1950-1960) and anomalies (1900-2100) calculated relative to the 1950-1960 mean sea surface temperature in all CMIP5 models considered and in the World Ocean Atlas.

and consider the Representative Concentration Pathway 8.5 (RCP8.5) scenario (Meinshausen et al. 2011). The RCP8.5 projections are forced with emissions such that the radiative forcing induced by greenhouse gases reaches ~8.5 Wm^{-2} in 2100.

The subset of models under consideration include the:

- Community Earth System Model, or CESM (Long et al. 2013; Moore et al. 2013);
- Max Plank Institute model, or MPI-LR (Giorgetta et al., 2013);
- Two versions of the Geophysical Fluid Dynamics Laboratory (GFDL) Earth System Model, GFDL-ESM2G and GFDL-ESM2M (Dunne et al. 2013), which differ in their ocean module, specifically in the choice of vertical coordinate system for each component;
- Two versions of the Global Environment Model version 2, HadGEM2-ES and HadGEM2-CC (Collins et al. 2011), whereby HadGEM2-CC adopts a vertical extension of the atmospheric module from 38 to 60 layers but does not include the atmospheric chemistry scheme; and
- Three versions of the Institute Pierre Simon Laplace model, IPSL-A-LR, IPSL-A-MR, and IPSL-B-LR (Dufresne et al. 2013), whereby differences between IPSL-A-LR and -MR are limited to the resolution of the atmospheric component (1.875° × 3.75° in the LR (low resolution) and 1.25° × 2.5° in the MR (medium resolution)), and IPSL-B-LR implements a recently developed, physically based parameterization scheme for clouds and convection.

These models exhibit substantial spread in their equilibrium climate sensitivity, both in the magnitude of temperature increase in response to a doubling of CO_2 and in their representation of biogeochemical processes. Despite those differences, however, most models predict similar changes into the future. In all of the models, the Southern Ocean surface waters warm, sea ice decreases, surface and intermediate layers freshen, and the deep layer warms (Sallée et al. 2013; Meijers 2014). However,

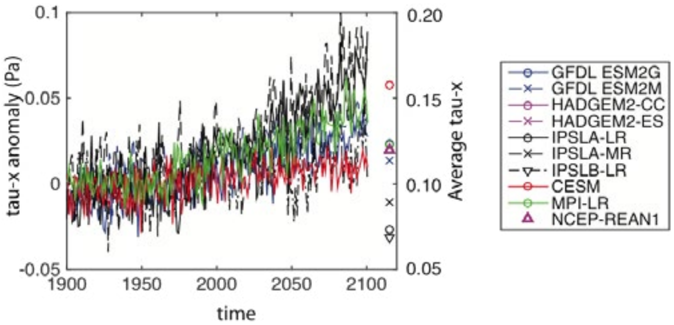

Figure 2: Area-weighted annual mean of zonal wind stress (Pa) over the extratropical Southern Hemisphere oceans (45°S-60°S). Average zonal wind stress (1950-1960) and zonal wind stress anomalies (1900-2100) calculated with respect to the 1950-1960 zonal wind stress mean in all CMIP5 models considered and in the NCEP reanalysis.

there are discrepancies among models in the magnitude of warming and freshening. For example, the sea surface temperature (SST) over the extratropical Southern Hemisphere (45°S-60°S) in the GFDL model increases by 1°C by 2100 when compared to the 1950-1960 average, independently of the version considered, while SST increases by more than 3°C in CESM (Figure 1). Each model family is characterized by its own temperature trend, with little variability across model versions, but not by a common SST mean state. For example, in IPSL, the mean SST from 1900-2100 over the extratropical Southern Hemisphere (45°S-60°S) is ~3.5°C in both IPSL-A realizations and close to 7°C in the IPSL-B-LR (with the new convective scheme) realization.

The observed warming in the models is linked to a slowdown in the formation of Antarctic bottom water (AABW; de Lavergne et al. 2014), which limits ocean uptake of atmospheric CO_2 (Sarmiento et al. 1998). On the other hand, upper ocean circulation associated with the formation of key mode and intermediate water masses is predicted to intensify (Waugh et al. 2013) due to stronger near-surface winds (Thompson et al. 2011). This is shown in Figure 2 with CESM and IPSL displaying the smallest and largest changes, respectively. Stronger winds have been shown to have contrasting effects on ocean carbon uptake. By increasing vertical mixing, they can increase the subduction of carbon into the thermocline and its transport equatorward (Ito et al. 2010); however, stronger winds can also increase outgassing of carbon-rich deep waters to the atmosphere (Lovenduski et al. 2013).

According to coupled global climate model (CGCM) projections, competing physical changes in the buoyancy and momentum forcing will therefore affect the carbon uptake in the Southern Ocean in the future. These physical changes must be considered together with changes in the ocean biological response. It is worth noting that the response of the ocean to increased greenhouse gases portrayed by current state-of-the-art CGCMs neglects changes in eddy activity due to resolution constraints. It has been hypothesized that on decadal time scales, the effect of eddies may rival that of wind variability in the Southern Ocean (Boning et al. 2008; Meredith et al. 2012) and is likely to represent the largest source of uncertainty in current model projections.

In the analysis of the evolution of ocean carbon uptake, two major contributions to the carbon inventory of an ocean basin must be considered: the "preformed" carbon and the "regenerated" carbon. The former is sequestered via physical processes and is transported from surface to depth in the form of dissolved inorganic carbon (DIC), including the anthropogenic DIC. Regenerated carbon, on the other hand, results from biological processes (i.e., photosynthesis and the subsequent formation of organic material). Organic material sinks and is remineralized back into inorganic carbon at depth, representing storage of CO_2 via the biological pump. Regenerated carbon is not a quantity commonly stored in models, but can be derived from the oxygen deficit relative to the atmospheric saturation (whenever this variable is available) under the assumption of a constant elemental stoichiometric ratio. A smaller, but still significant amount of regenerated carbon is sequestered through the formation of calcium carbonate,

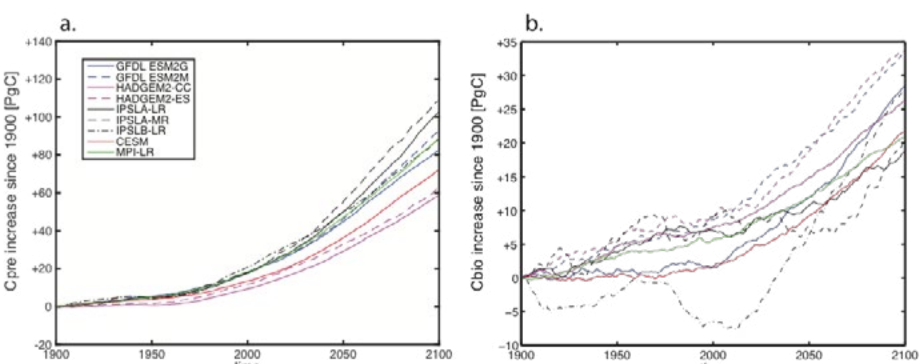

Figure 3. Southern Ocean carbon inventory change (in PgC) since 1900 in the subset of the CMIP5 archive analyzed; a) preformed carbon; b) regenerated carbon.

predominantly by calcitic coccoliths and planktonic foraminifera (Milliman 1993). This contribution can be evaluated via a calculation of excess alkalinity in the subsurface waters (Brewer, 1978).

CMIP5 projections indicate that both preformed and regenerated carbon inventory in the Southern Ocean will increase in the future, at least up to 2100 (Figure 3; Ito et al. 2015). The preformed carbon inventory increases from 60 (HadGEM2) to 110 (IPSL-A-MR) PgC between 1900 and 2100. Such increase takes place primarily in the upper thermocline and reflects the surge in atmospheric CO_2. Each model's regenerated carbon inventory depends on its representation of ocean biological processes, so it is not surprising to see large model-model differences, given the distinct ecological modeling strategies applied by each model family (Dunne and Laufkötter 2015). Nonetheless, all models predict increased biological activity towards the end of the 21st century compared to present and past conditions, with highest accumulations in the Southern Ocean (Figure 4). The multi-model median inventory increase is 26 PgC, with the minimum of 18 PgC found in IPSL-A-LR and the maximum of 33 PgC in HadGEM2-ES and GFDL-ESM2M.

Moving forward

The analysis of a sample of CMIP5 models has revealed that the ability of the Southern Ocean to store CO_2 will continue to increase during this century, in agreement with recent investigations by Bernardello et al. (2013), Meijers (2014), and de Lavergne et al. (2014). However, the same models predict the opposite trend for the global uptake, i.e., a slowdown of atmospheric CO_2 uptake by the ocean (Doney et al. 2014).

Using only CMIP5 integrations, it is not possible to quantify the relative contributions of physical and biological processes, or to estimate the degree of nonlinearity of the interactions between processes. Experiments that include passive tracers such as CFCs and SF_6 could help constrain the roles of physical advection and mixing, and should be included in the next model intercomparison effort. Additionally, sensitivity experiments in which perturbations to physical or biological states are introduced in a controlled manner (e.g., Ito et al. 2015) represent an essential tool to improve mechanistic understanding. Such exercises could help identify strengths and weaknesses of CGCM projections and should be prioritized in the CMIP framework and timeline.

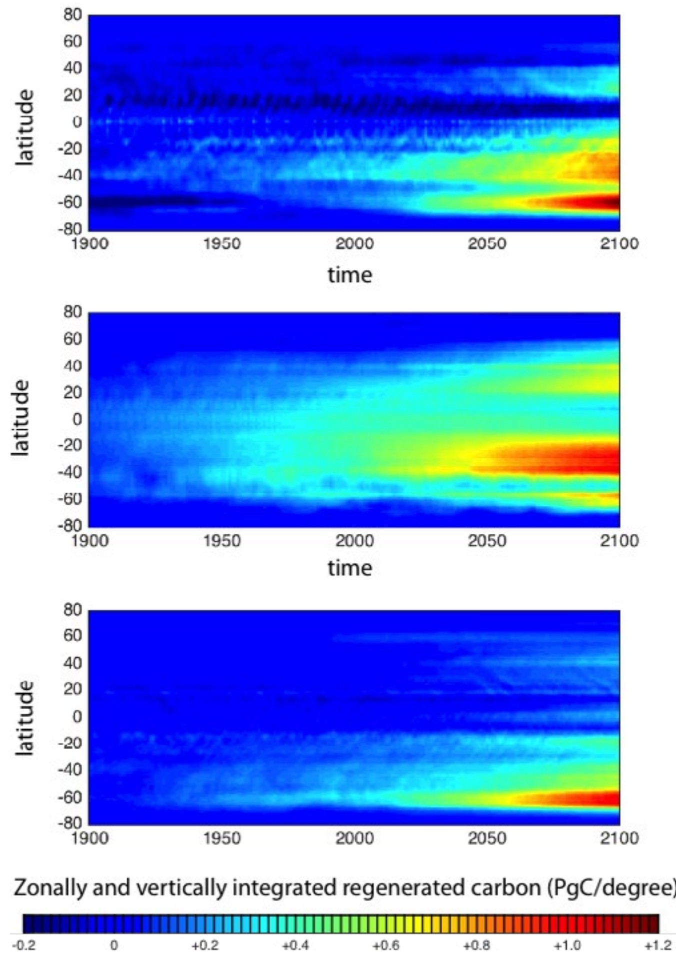

Figure 4: Zonally and vertically integrated annual mean regenerated carbon anomaly (PgC/degree) from 1900-2100 relative to 1860 in three of the models analyzed. Top: GFDL-ESM2M; Middle: IPSL-A-LR; Bottom: MPI-LR.

As a final note, the figures presented here suggest that the time-varying rate of change of various quantities may be significantly different across models, more so than the global time integral, for which a better convergence is achieved. Furthermore, the uncertainty associated with the inter-model spread in Southern Ocean carbon storage is greater than the uncertainty in the global average of ocean carbon uptake (Arora et al. 2013). This points to the existence of different compensating effects between basins in the various models and to the need to investigate the regional expression of carbon uptake at regional scales. In the few available integrations continuing out to 2300, those regional divergences amplify, severely eroding the global inter-model agreement. An unresolved question that must be answered before any consensus can be achieved pertains to the origin of those differences. Do they result from differences in the representation of mean state patterns, ventilation, and uptake, or are they linked to the spatial and temporal characteristics of the decadal variability modes?

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Important OCB Dates

June 9-11, 2015: 3rd US Ocean Acidification PI Meeting (Woods Hole, MA, NSF-supported OA PIs)

June 12, 2015: NOAA Ocean Acidification PI Meeting (Woods Hole, MA, NOAA-supported OA PIs)

June 22-July 1, 2015: Instrumenting our oceans for better observation: A training course on autonomous biogeochemical sensors (Sven Lovén Center for Marine Sciences, Kristineberg, Sweden)

July 20-23, 2015: OCB Summer Workshop (Woods Hole, MA) - **Registration deadline: June 15**

October 5-8, 2015: OCB Scoping Workshop Trait-based Approaches to Ocean Life (Waterville Valley, NH) – **Application deadline: May 31**

Mid-2016: Joint GEOTRACES-OCB Workshop on Micronutrients and Tracers of Carbon Flux (discussions about this activity will be held at 2015 OCB Summer Workshop)

Ocean Acidification News

- Outcomes of the December 2014 Ocean Acidification Stakeholder Workshop organized by Northeast Coastal Acidification Network (NECAN)
- New PBS NOVA documentary on ocean acidification *Lethal Seas*
- Apply to participate in Graduate Student Course: Research Methods in Ocean Acidification (July 20-August 22, 2015, Friday Harbor, WA, USA)
- Ocean Conservancy Blog - Where are the "Hotspots" For Ocean Acidification?
- New legislation, the Ocean Acidification Research Partnership Act, introduced to support research on ocean acidification through partnerships between the seafood industry and the academic community
- Formation of Southeast Ocean and Coastal Acidification Network (SOCAN) to support and encourage discussions on ocean and coastal acidification in the Southeast region (check out SOCAN state-of-the-science webinar series on ocean acidification)
- Open-access data sets of biological response to ocean acidification available at Pangaea (accepting contributions!)
- Recommended new version (3.0.6) of the R package seacarb for calculating seawater carbonate system parameters. Includes useful functions for ocean acidification research
- WMO Greenhouse Gas Bulletin reports on Ocean Acidification

North Atlantic-Arctic News

International North Atlantic-Arctic Science Plan is finalized

In April 2014, with support from the US National Science Foundation and the European Union Commission, the Ocean Carbon & Biogeochemistry (OCB) Program coordinated and convened an international North Atlantic-Arctic planning workshop to discuss the state of science in the North Atlantic-Arctic system and begin planning the next phase of interdisciplinary research, with an emphasis on mechanisms to facilitate international collaboration. The outcome of this planning workshop was a community-vetted international science plan that outlines a core science vision for advancing the next phase of research focused on the coupled North Atlantic-Arctic ocean-atmosphere system, including key biogeochemical and ecological processes and relevant socio-economic systems. This spring, NSF is expected to release a Dear Colleague Letter based on the recommendations put forth in the science plan. Other funding entities and opportunities, including the recent *Blue Growth: Unlocking the Potential of Seas and Oceans*, are listed at http://www.whoi.edu/website/NAtl_Arctic/funding-agencies.

OCB fosters national and international collaboration through the distribution of information via multiple communication outlets (email lists, a regular newsletter, and a strong web presence, including a website for international North Atlantic-Arctic research coordination). These various media represent a platform for developing international science teams to pursue collaborative research in the North Atlantic-Arctic system. OCB also maintains strong partnerships with related US and international programs such as Integrated Marine Biogeochemistry and Ecosystem Research (IMBER), Surface Ocean Lower Atmosphere Study (SOLAS), International Ocean Carbon Coordination Project (IOCCP), and US Climate Variability and Predictability (CLIVAR). OCB and its partner programs' collective access to the oceanographic research community will be pivotal in the formation of PI teams that span disciplines and national borders to address the important North Atlantic-Arctic science questions identified in the science plan. OCB plans to utilize its communication outlets to facilitate the development of international research teams and publicize funding opportunities and proposed and/or newly funded North Atlantic-Arctic projects.

Please submit information on new projects and funding opportunities to the OCB Office.

Ocean Time-Series News

Plenary Session at Upcoming 2015 OCB Summer Workshop: Studying Spatial and Temporal Variability in the Ocean with Shipboard and Autonomous Platforms

Session Chairs: Susanne Neuer, Angel White, Mike Lomas

This session will provide a forum for studies across the globe that exemplify successful combinations of shipboard time-series coupled with autonomous observations. Speakers in this session will highlight scientific insights based on these integrated observing strategies. This session is timely, as the development and capabilities of autonomous biogeochemical sensors are progressing rapidly. As more biogeochemical sensors become available, shipboard observations will be essential for sensor testing, calibration, and validation. Likewise, shipboard platforms are relatively limited in their spatiotemporal footprint, so autonomous measurements can provide the opportunity to enhance our understanding of marine biogeochemical and ecosystem processes across a wider range of spatial and temporal scales. We hope to see you for the OCB workshop July 20-23, 2015 in Woods Hole, MA!

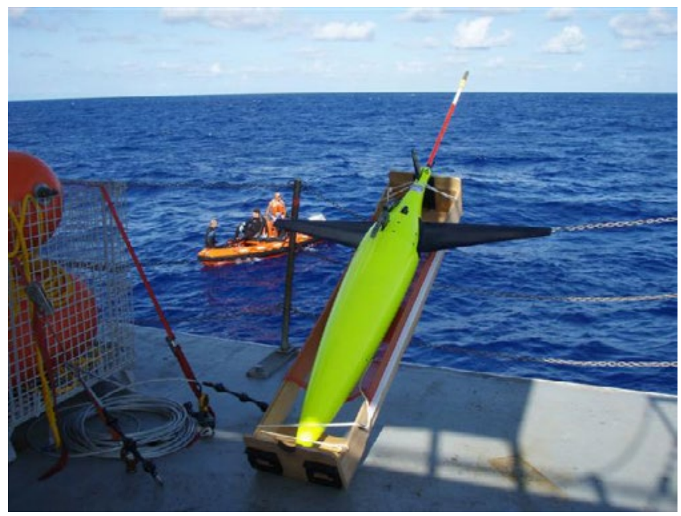

Image courtesy of School of Ocean and Earth Science and Technology (SOEST) at the University of Hawai'i at Mānoa

FixO3 - 2nd call for free access to European ocean observatories

Deadline for proposals: 20th of July 2015
Website: http://www.fixo3.eu/tna/

Research organizations and marine technology companies are invited to access 15 ocean observatories to conduct scientific studies or to test technology prototypes with full financial and logistics support. The submission process is now open until the 20th of July 2015. All material and guidelines for submission are now available on *http://www.fixo3.eu/tna/*

This opportunity comes from the Europe-funded Fixed-point Open Ocean Observatory network (FixO^3) project, coordinated by the UK's National Oceanography Centre (NOC). As part of this initiative private companies and research institutions working on marine technology or wanting to conduct scientific research, have the opportunity to apply for access to one or more observatories and receive full scientific and technological support.

The FixO^3 project started in September 2013 with a European Commission (EC) funded grant of €7m. It is a four-year project with 29 European partners from academia, research institutions and small and medium enterprises (SMEs). The project aims to integrate all infrastructures operated by European organizations and to enable continuity in ocean observations. It also aims to improve access for the wider community to these key installations and the data products and services.

Transnational access

As part of FixO³ activities, 'Transnational Access (TNA)' is about supporting external users with coordinated access and full logistics support at no cost to the user for 14 open-ocean observatories and 1 shallow water test site, available to successful applicants. To illustrate the opportunity and practicalities, you are invited to visit the results of the 1st TNA call on the FixO3 website where selected proposal abstracts are also available.

Observatory locations range from the polar regions of the Antarctic and Arctic, to the Atlantic Ocean and Mediterranean Sea with a choice of seafloor, mid-water and surface infrastructures with varying scientific focus due to each location's characteristics.

These observatories were selected as they offer the broadest scientific and technological capabilities for multidisciplinary observations such as atmosphere-ocean interactions at the sea surface and processes in the water column and seafloor. Gliders are also available for some of the sites. The observatories address a wide range of disciplines such as biology, biogeochemistry, chemistry, physics and geology.

Call for proposals

The call for proposals will close the 20th of July. Applicants are encouraged to start working on their proposals as soon as possible as they need to contact the observatory manager of the preferred FixO³ location for a pre-feasibility evaluation of their project and a letter of support prior to submitting the proposal. Applicants also need to write a short research proposal explaining the reasons why they would like to use one of the observatories offered under TNA.

The proposals will be evaluated by a panel of experts, based on scientific merit, technical quality and the novelty of the proposed activities. The selection process will start as soon as the FixO³ TNA Office closes the second call on the 20th of July and successful applications will be decided by the end of the year.

User groups, particularly those working in countries where no similar research infrastructure exists or with no prior experience of accessing similar infrastructure, are encouraged to apply. The TNA is a unique opportunity for scientists and engineers to access high-quality, interlinked instrumented infrastructures operating in open ocean observatories in order to carry out research and/or to test equipment.

For more information please visit http://www.fixo3.eu/tna/; email the FixO³ TNA office at fixo3.tna@plocan.eu or email the FixO³ Project Manager at fixo3@noc.ac.uk

Please note that **lead PI must be affiliated with a European institution/organization**, but international collaborative teams are encouraged. If you have **read the guidelines, are serious about submitting a proposal, and require assistance with identifying an EU-based partner**, please contact Richard Lampitt or the OCB Project Office.

OCB Ocean Time-series Committee

Did you know that OCB has an Ocean Time-series Committee (OTC) as a subcommittee of its scientific steering committee? The OTC's focus is to highlight the importance of shipboard time-series as unique observing assets to the oceanographic community, and to encourage synergistic and collaborative technology and methods development, including development and validation of sensors and autonomous devices, and their possible integration into existing time-series observations. A major emphasis of the OTC has been to improve communication and collaboration among U.S. and international scientists engaged in ocean time-series science. For example, in 2012, OCB/OTC and the International Ocean Carbon Coordination Project (IOCCP) co-organized an international time-series workshop in Bermuda focused on biogeochemical time-series methods and data intercomparison. A key outcome of this workshop was a best practices guide for shipboard sampling and analytical protocols used at biogeochemical time-series sites and the development of a global time-series network to improve international coordination and communication among the operators of the >150 marine biogeochemical time-series. For more information about this subcommittee or to view its charge, please visit the OCB website. **We would love to hear your ideas about common goals and visions for the future of time-series observations and ways to enhance collaboration among the international time-series community. Please contact the OTC chair or the OCB Project Office to get involved!**

OCB to co-sponsor an international biogeochemical sensors course

The IOCCP is convening a 10-day international Summer Course on best practices for selected biogeochemical sensors (oxygen, pH, pCO_2, nitrate) *Instrumenting our oceans for better observation: A training course on autonomous biogeochemical sensors*. The course will be held at the Sven Lovén Center for Marine Sciences in Kristineberg, Sweden, June 22-July 1, 2015. The goal of the course is to further develop proficiency in the use of a suite of biogeochemical sensors and to improve the quality of the data currently generated by autonomous biogeochemical sensors. This intensive, 10-day Summer Course will provide trainees with lectures, hands-on in-situ and laboratory experiences, and informal interactions to improve in-depth knowledge on instrument know-how, troubleshooting, data management, data reduction and quality control. A full report on the course and its outcomes will be given at the 2015 OCB summer workshop.

Community News and Resources

Science and outreach tools

- Web-based Interactive Global Carbon Cycle Exhibit at Woods Hole Oceanographic Institution developed by Heather Benway (OCB/WHOI), Sarah Cooley (Ocean Conservancy), and WHOI Graphic Designers and Communication Experts
- US Global Change Research Program set of climate change indicators
- New L&O e-lecture on biological pump: Neuer, S., M. Iversen, and G. Fischer. 2014. The Ocean's Biological Carbon Pump as Part of the Global Carbon Cycle. *Limnol. Oceanogr.* e-Lectures, doi:10.4319/lol.2014.sneuer.miversen.gfischer.9

Scientific planning resources

- USGCRP seeks public comment on draft climate and human health assessment
- Oceans 2015 Reports *Climate Change Impacts on the Ocean*
    - The Oceans 2015 Initiative, **Part I**. An updated synthesis of the observed and projected impacts of climate change on physical and biological processes in the oceans --- E. Howes, F. Joos, M. Eakin, J.-P. Gattuso
    - The Oceans 2015 Initiative, **Part II**. An updated understanding of the observed and projected impacts of ocean warming and acidification on marine and coastal socioeconomic activities/sectors --- L. Weatherdon, A. Rogers, R. Sumaila, A. Magnan, W.L. Cheung
- Status of the Ocean Observatories Initiative (OOI) marine and cyber infrastructure and planned data release
- National Research Council reports *Climate Intervention: Carbon Dioxide Removal and Reliable Sequestration* and *Climate Intervention: Reflecting Sunlight to Cool Earth* (4-page brief available here)
- New NRC report: Decadal Survey of Ocean Sciences and NSF response to report
- International North Atlantic-Arctic science plan now final and updates and opportunities to get involved in new collaborative research projects will be posted on International North Atlantic-Arctic research planning website

Funding and collaboration

- Alliance for Coastal Technologies looking to stimulate development of low cost, accurate nutrient sensors - For details, see http://www.act-us.info/nutrients-challenge/
- Fixed-point Open Ocean Observatory ($FixO^3$) Transnational Access (TNA) funding opportunity to obtain financial and logistical support for using open ocean infrastructures that are part of the FixO3 network (informational brochure)

Partner Programs

IMBER

- IMBER IMBIZO IV October 26-30, 2015 (Trieste, Italy) - abstracts due May 30!
- IMBER seeking comments on Science Plan and Implementation Strategy (SPIS) for the next decade of research
- Join webinar on IMBER-ADApT decision support tool (May 28, 12 noon EDT)

SOLAS

- Register and submit abstracts for SOLAS Open Science Conference (September 7-11, 2015, Kiel, Germany, Abstract submissions due May 27, Registration deadline: July 1)
- SOLAS Science Plan for 2015-2025
- SOLAS/CLIVAR session The Earth's energy imbalance and exchanges at the atmosphere-ocean interface: from fundamental research to societal concern at Our Common Future Under Climate Change conference

IOCCP

- Summer Course on biogeochemical sensors: Instrumenting our oceans for better observation (June 22-July 1, 2015, Sven Lovén Center for Marine Sciences, Kristineberg, Sweden)

GEOTRACES

- Survey on the 2014 GEOTRACES Intermediate Data Product to help improve the data product for the next release (2017)

US CLIVAR

- Seventh annual report for the US AMOC Science Team
- Draft agenda for 2015 US CLIVAR Summit (August 4-6, 2015, Tucson, AZ)
- Take the 2015 US CLIVAR Community Engagement Survey
- Save the date for the CLIVAR Open Science Conference: Charting the course for future climate and ocean research September 19-23, 2016 (Qingdao, China)

center for microbial oceanography: research and education

C·MORE *linking genomes to biomes*

Create your own science communication materials

By Elisha M. Wood-Charlson (C-MORE, Univ. Hawai'i) and Melissa Varga (UCS)

Science communication has grown from a small buzz term at conferences into a very active field, and for some, a full-time profession. This grassroots movement has already been endorsed by many scientific journals and funding agencies, and it continues to gain support within government and academic institutions. However, at the level of the individual scientist, the benefits and expectations surrounding science communication are sometimes not well defined.

In an effort to streamline engagement in science communication, from the perspective of an individual researcher, the Center for Microbial Oceanography: Research and Education (C-MORE) and the Union of Concerned Scientists (UCS) have partnered to produce a *time-sensitive, independent training guide to creating your own* ***Science Communication Portfolio***.

The **Science Communication Portfolio** is designed to complement a research manuscript, proposal, or technical report. The guide begins with an in-depth introduction to science communication, such as stating your goals, understanding your audience and identifying jargon, and establishing your take-home message(s). It also contains instructions for creating verbal (sound bites, elevator pitch, three-minute talk, and a general presentation) and written (Tweet, Facebook post, memo for policymakers, Op-Ed, and a blog) science communication products. Each module can be completed independently of the other modules, with the *time-sensitive* feature of providing training when it is convenient for you. Let's say that you are spending the weekend working on a manuscript, but you are getting bogged down in the details of describing a new method or visualizing new time-series data. Stepping back from your technical writing and reminding yourself how your research fits into the bigger picture might be beneficial. This is a perfect time to work on a module for your manuscript's science communication portfolio!

The goals of the **Science Communication Portfolio** are to 1) provide you with a mechanism to practice and improve your science communication skills in a *time-sensitive and independent manner*, and 2) create a portfolio of communication products that are ready to be shared. For example, you may want to announce that a recently accepted manuscript is now available online, or a recently funded proposal means you can start working on those broader impact ideas. After using this guide, you will have sound bites for a press interview, be prepared to pitch your work to your Program Manager, and be ready to share your science as a guest blogger.

Word cloud created from content in the Science Communication Portfolio.

In addition to the training guide, C-MORE and UCS have provided a sample portfolio, focused on the topic of sea level rise. This sample guide contains examples of each module (verbal and written) in case you get stuck or need a place to start. One great module from the sample portfolio is a 3-minute talk video starring Phil Thompson, Associate Director of the University of Hawai'i Sea Level Center. Finally, if you are curious and want to check out these resources, there is also a very short questionnaire where you can provide feedback/comments and submit your contact information for updates as this project continues to develop.

Science communication tools, like the **Science Communication Portfolio,** will hopefully encourage and enable research scientists to become better communicators overall. Effective science communication expresses both the knowledge and the passion behind everything we do. Communicating our science to a broader audience is the key to a greater understanding of science in general. These small communication efforts can help build trust and respect, and therefore support, for scientists and the amazing science we do.

OCB hosts four C-MORE Science Kits in Woods Hole

OCB currently hosts three C-MORE Science Kits: Ocean acidification, marine mystery, and ocean conveyor belt. The **ocean acidification kit** (two lessons, grades 6-12) familiarizes students with the causes and consequences of ocean acidification. The **ocean conveyor belt kit** (four lessons, grades 8-12) introduces students to some fundamental concepts in oceanography, including ocean circulation, nutrient cycling, and variations in the chemical, biological, and physical properties of seawater through hands-on and computer-based experiments. With the **marine mystery kit** (grades 3-8) students learn about the causes of coral reef destruction by assuming various character roles in this marine murder-mystery. The **marine debris kit** focuses primarily on plastic marine debris. Students critically examine data and samples and take part in activities that explore the causes, geographical distribution, and biological impacts of marine debris. Teachers along the eastern seaboard may use these kits for free. To reserve a kit, please submit a request.

Calendar

Please note that we maintain an up-to-date calendar on the OCB website.
**OCB-led activity **OCB co-sponsorship or travel support*

May 26-June 26	C-MORE Summer Course (Honolulu, HI)
May 27-29	2nd Blue Planet Symposium (Cairns, Australia)
June 9-11*	3rd US Ocean Acidification PI Meeting (Woods Hole, MA)
June 12	NOAA Ocean Acidification PI Meeting (Woods Hole, MA)
June 10-12	SOOS Workshop on Implementing a Southern Ocean Observing System (Hobart, Australia)
June 15-17	ESSAS Symposium on the Role of Ice in the Sea (Seattle, WA)
June 16-18	International Ocean Color Science Meeting (San Francisco, CA)
June 22-July 1**	Summer Course on best practices for selected biogeochemical sensors *Instrumenting our oceans for better observation* (Sven Lovén Center for Marine Sciences in Kristineberg, Sweden)
June 23-25	Atlantic Meridional Transect (AMT) Open Science Conference (Plymouth, UK)
July 5-31**	Ocean Optics Summer Course C*alibration & Validation for Ocean Color Remote Sensing* (Walpole, ME)
July 6-10	Ramon Margalef Summer Colloquia: Patterns and processes in boundary marine ecosystems (Barcelona, Spain)
July 7-10	Our Common Future Under Climate Change (Paris, France)
July 20-August 22	Graduate Student Course on Research Methods in Ocean Acidification (Friday Harbor, WA)
July 20-23*	2015 OCB Summer Workshop (Woods Hole, MA)
July 21-24	RAPID/US AMOC International Science Meeting: Towards a holistic picture of the Atlantic Meridional Overturning Circulation (Bristol, UK)
July 25-26	Gordon Research Seminar for students and postdocs (Holderness, NH)
July 26-31	Gordon Conference Chemical Oceanography (Holderness, NH)
August 2-7	Marine Molecular Ecology Gordon Research Conference Linking Molecular Mechanisms with Ecological Outcomes (Hong Kong, China)
August 4-6	2015 US CLIVAR Summit (Tucson, AZ)
August 16-21	25th Goldschmidt Conference (Prague, Czech Republic)
August 31-September 4	1st Altimetry for Regional and Coastal Ocean Models Workshop (Pilot ARCOM Workshop) (Lisbon, Portugal)
August 31-September 4	Hjort Summer School: Fishing and physics as drivers of marine ecosystem dynamics (Bergen, Norway)
September 7-11	SOLAS Open Science Conference 2015 (Kiel, Germany), **Note**: Joint Surface Ocean CO2 Atlas (SOCAT) & Surface Ocean pCO2 Mapping Intercomparison (SOCOM) event on September 7 Abstracts due May 27!
September 14-18	"Sustained ocean observing for the next decade" A combined GO-SHIP/Argo/ IOCCP conference on physical and biogeochemical measurements of the water column (Galway, Ireland)
September 14-18	3rd CLIOTOP Symposium - Future of oceanic animals in a changing ocean (San Sebastián, Spain)

September 21-25	2015 ICES Annual Science Conference (Copenhagen, Denmark)
October 4-9	19th International Congress on Nitrogen Fixation (Pacific Grove, CA)
October 5-8*	OCB Scoping Workshop Trait-based Approaches to Ocean Life (Waterville Valley, NH)
October 5-9	9th Symposium of the International Society for Digital Earth (ISDE) "Towards a One-World Vision for the Blue Planet" (Halifax, Canada)
October 26-30	IMBER IMBIZO IV - Marine and human systems *Addressing multiple scales and multiple stressors* (Trieste, Italy) Abstracts due May 30!
November 8-12	Coastal and Estuarine Research Federation (CERF) 2015 (Portland, OR)
November 30-December 4	Indian Ocean Symposium (Goa, India)
December 9-11	Atlantic Summit – Workshop on the Atlantic Ecosystem Model (Honolulu, HI)
December 14-18	2015 Fall AGU Meeting (San Francisco, CA) Abstracts due August 5!
February 9-12, 2016	Species on the Move International Conference (Hobart, Australia)
February 21-26, 2016	2016 Ocean Sciences Meeting (New Orleans, LA) Abstracts due September 23!
July 16-17, 2016	Ocean Global Change Biology Gordon Research Seminar (Waterville Valley, NH)
July 17-22, 2016	Ocean Global Change Biology Gordon Research Conference (Waterville Valley, NH)
September 19-23, 2016	CLIVAR Open Science Conference: Charting the course for future climate and ocean research (Qingdao, China)
August 20-25, 2017	10th International Carbon Dioxide Conference (Interlaken, Switzerland)

Upcoming Funding Opportunities

For more information, please visit OCB's funding opportunities web page. The OCB calendar also lists upcoming deadlines.

Rolling submission: NSF Research Coordination Networks (RCN)

June 3	NASA ROSES 2015 Advancing Collaborative Connections for Earth System Science proposal deadline (NOIs due April 3)
June 15	SCOR Working Group proposal deadline
July 20	FixO3 Transnational Access proposal deadline
July 23	NSF Faculty Early Career Development Program (CAREER) proposal deadline (Directorate for Geosciences)
August 1	NSF Long Term Research in Environmental Biology (LTREB) proposal deadline
August 15	NSF Chemical Oceanography and Biological Oceanography proposal targets
August 26	NSF Research Experiences for Undergraduates (REU) proposal deadline
September 8	NASA ROSES 2015 Satellite Calibration Inconsistency Studies proposal deadline (NOIs due July 15)
October 2	NSF Coastal SEES proposal deadline

October 15	NSF Paleo Perspectives on Climate Change (P2C2) proposal deadline
October 19	NSF Arctic Research Opportunities proposal deadline
November 17	NSF Dynamics of Coupled Natural and Human Systems (CNH) proposal deadline
February 15, 2016	NSF Ocean Technology and Interdisciplinary Coordination, Chemical Oceanography, and Biological Oceanography proposal deadlines

OCB News

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